

**Continuous
Univariate
Distributions
Volume 1**

Continuous Univariate Distributions

Volume 1

Second Edition

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Preface

As a continuation of *Univariate Discrete Distributions*, second edition, this book is the first of two volumes to discuss continuous univariate distributions. The second edition of *Continuous Univariate Distributions* differs from the first, published in 1970, in two important aspects: (1) Professor N. Balakrishnan has joined the two original authors as a coauthor. (2) Because of substantial advances in theory, methodology, and application of continuous distributions, especially gamma, Weibull, and inverse Gaussian during the last two decades, we have decided to move the chapter on extreme value distributions to the next volume. The chapter on gamma distributions has been split into two chapters, one dealing only with chi-squared distributions. Even so, as in the revision of the volume on *Discrete Distributions*, the **great** amount of additional information accruing since the first edition has led to a substantial increase in length.

In accordance with the principle stated in the original General Preface, we continue to aim at "excluding theoretical minutiae of no apparent practical importance," although we do include material on characterizations that some may regard as being of doubtful practical value. The more general Chapter 12 has been expanded relatively less than the other chapters that deal with specific distributions.

Even with omission of the extreme value distribution chapter, the great amount of new information available has forced us to be very selective for inclusion in the new work. One of our main preoccupations has been to assist the struggle against fragmentation, the necessity for which has been elegantly expressed by Professor A. P. Dawid, new editor of *Biometrika* [*Biometrika*, 80, 1 (1993)]. We realize that some authors may be affronted at omission of their work, but we hope that it will not be regarded as unfriendly action, or at "best" a consequence of ignorance. These volumes are intended to be useful to readers, rather than an "honor roll" of contributors.

We acknowledge with thanks the invaluable assistance of Mrs. Lisa Brooks (University of North Carolina), Mrs. **Cyndi** Patterson (Bowling Green State University), and Mrs. Debbie Iscoe (Hamilton, Canada) in their skillful typing of the manuscript. We also thank the Librarians of the University of

North Carolina, Bowling Green State University, **McMaster** University, University of Waterloo, and the University of Maryland for their help in library research. Samuel **Kotz's** contribution to this volume was, to a large extent, executed as a Distinguished Visiting Lukacs Professor in the Department of Mathematics and Statistics at Bowling Green State University (Bowling Green, Ohio) during September–December 1992. Likewise N. Balakrishnan's work for this volume was carried out mostly in the Department of Statistics and Actuarial Science at the University of Waterloo where he was on research leave during July 1992—June 1993.

Special thanks are also due to Mrs. Kate Roach and Mr. Ed Cantillon at John Wiley & Sons in New York for their sincere efforts in the fine production of this volume. We also thank Ms. Dana **Andrus** for all her efforts in copy-editing the long manuscript.

Thanks are offered to the Institute of Mathematical Statistics, the American Statistical Association, the Biometrika Trustees, the Institute of Electrical and Electronics Engineerings, the Association for Computing Machinery, Marcel Dekker, Inc., the Royal Statistical Society, the American Society for Quality Control, the Australian Statistical Society, Gordon and Breach Science Publishers, Blackwell Publishers, and the editors of *Biometrical Journal*, *Sankhyā* and *Tamkang Journal of Mathematics*, for their kind permission to reproduce previously published tables and figures.

Authors of this kind of informational survey—designed primarily for nonspecialists—encounter the problem of having to explain results that may be obvious for a specialist but are not part and parcel of the common knowledge, and still have enough space for information that would be new and valuable for experts. There is a danger of "high vulgarization" (over simplification) on the one hand and an overemphasis on obscure "learned" points—which many readers will not need—on the other hand. We have tried to avoid these pitfalls, to the best of our ability.

It is our sincere hope that these volumes will provide useful **facts**—**coherently** stated—for a "lay reader," and also arouse perceptions and memories among well-informed readers, stimulating introspection and further research.

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Continuous
Univariate
Distributions

Volume 1

CHAPTER 12

Continuous Distributions (General)

1 INTRODUCTION

Chapters 1 and 2 (of Volume 1) contain some general results and methods that are also useful in our discussion of continuous distributions. In this chapter we will supplement this information with techniques that are relevant to continuous distributions. As in Chapter 2, some general systems of (continuous) distributions will be described.

Continuous distributions are generally amenable to more elegant mathematical treatment than are discrete distributions. This makes them especially useful as approximations to discrete distributions. Continuous distributions are used in this way in most applications, both in the construction of models and in **applying** statistical techniques. Continuous distributions have been used in approximating discrete distributions of discrete statistics in Volume 1. The fact that most uses of continuous distributions in model building are as approximations to discrete distributions may be less widely appreciated but is no less true. Very rarely is it more reasonable, in an absolute sense, to represent an observed value by a continuous, rather than a discrete, random variable. Rather this representation is a convenient approximation, facilitating mathematical and statistical analysis.

An essential property of a continuous random variable is that there is zero probability that it takes any specified numerical value, but **in** general a nonzero probability, calculable as a definite integral of a probability density function (see Section 1.4) that it takes a value in specified (finite or infinite) intervals. When an observed value is represented by a continuous random variable, the recorded value is, of necessity “**discretized**.” For example, if measurements are made to the nearest 0.01 units, then all values actually in the **interval** (8.665, 8.675) will be recorded as 8.67. The data are therefore grouped. Adjustments in the estimation of population moments, to correct (on average) for this effect, were proposed by Sheppard (1896). These may be summarized for the case of equal group widths h (with μ'_r, μ''_r denoting the

r th original moment and r th grouped moment, respectively):

$$\mu'_1 = {}_g\mu'_1, \quad (12.1a)$$

$$\mu'_2 = {}_g\mu'_2 - \frac{1}{12}h^2, \quad (12.1b)$$

$$\mu'_3 = {}_g\mu'_3 - \frac{1}{4}{}_g\mu'_3h^3, \quad (12.1c)$$

$$\mu'_4 = {}_g\mu'_4 - \frac{1}{2}{}_g\mu'_2h^2 + \frac{7}{240}h^4. \quad (12.1d)$$

The general formula is [Sheppard (1896); Wold (1934)]

$$\mu'_r = \sum_{j=0}^r (2^{1-j} - 1) \binom{r}{j} B_j {}_g\mu'_{r-j} h^j, \quad (12.2)$$

where B_j is the j th Bernoulli number (see Chapter 1, Section A9).

These results depend on the assumption that if the centers of groups are

$$\dots, a - h, a, a + h, \dots \quad (|a| < \frac{1}{2}h),$$

then a has a uniform distribution (Chapter 26) between $-\frac{1}{2}h$ and $+\frac{1}{2}h$ [see also Haitovsky (1983)]. Effects of invalidity of this assumption have been evaluated by Tricker (1984), who showed that the characteristic function (Chapter 1, Section B8) of ${}_gX$ (the grouped variable corresponding to a random variable X) is

$$\varphi_{{}_gX}(t) = \sum_{j=-\infty}^{\infty} \frac{\sin(\frac{1}{2}th + j\pi)}{\frac{1}{2}th + j\pi} \exp(1 - i \cdot 2\pi jh) \cdot \varphi_X(th + 2\pi j), \quad (12.3)$$

where $i = \sqrt{-1}$ and $\varphi_X(t)$ is the characteristic function of X .

In the same paper, effects of rounding when the distribution of X is normal (Chapter 13), Laplace (Chapter 24), or gamma (Chapter 17) are evaluated numerically for selected cases. For a given group width h , the magnitude of the correction for grouping tends to increase with the magnitude of the skewness, as measured by $|\sqrt{\beta_1}|$; it is quite small for symmetrical distributions.

Some concepts that have great value for discrete distributions are much less valuable in the discussion of continuous distributions. **Probability-generating functions**, in particular, are little used in this part of the book. Factorial moments also rarely offer the advantages of conciseness and simplicity that they do for discrete distributions, although they can be calculated.

On the other hand, *standardization* (use of the transformed variable

$$\frac{(X - E[X])}{\sqrt{\text{var}(X)}}$$

to produce a distribution with zero mean and unit standard deviation) is much more useful for continuous distributions. In particular, the shape of a distribution can be conveniently summarized by giving standardized values of a number of *quantiles* (i.e., values of the variable for which the cumulative distribution function has specified values). Care should be taken to distinguish between *standardized* and *standard* forms of distributions. The latter are usually convenient ways of writing the mathematical formulas for probability density functions. They *may* happen to be standardized, but this is not essential.

MacGillivray (1992) has introduced the *skewness function*

$$\gamma_X(u) = \frac{F^{-1}(u) + F^{-1}(1-u) - 2F^{-1}(\frac{1}{2})}{F^{-1}(u) - F^{-1}(1-u)}. \quad (12.4a)$$

Note that $F^{-1}(\frac{1}{2}) = \text{median}(X)$ and $\gamma_X(\frac{3}{4})$ is Galton's measure of skewness:

$$\frac{(\text{Upper quartile} - \text{Median}) - (\text{Median} - \text{Lower quartile})}{\text{Interquartile distance}}$$

MacGillivray proposes

$$\sup_{\frac{1}{2} \leq u < 1} |\gamma_X(u)| \quad (12.4b)$$

as "a measure of overall asymmetry for the central $100(1 - 2\alpha)\%$ of the distribution."

At this point we introduce indices that are applied more commonly to continuous than to discrete distributions:

1. *Gini's mean differences*, $\gamma(X)$, for the distribution of X is the expected value, $E[|X_1 - X_2|]$ of the absolute value of the difference between two independent variables X_1, X_2 , each distributed as X .

If X_1, \dots, X_n are i.i.d., then the statistic

$$g = \binom{n}{2}^{-1} \sum_{i < j}^n \sum_{i < j}^n |X_i - X_j| \quad (12.5)$$

is an unbiased estimator of

$$\gamma(X) = E[|X_1 - X_2|]. \quad (12.6)$$

2. The Lorenz curve, for a positive random variable X , is defined as the graph of the ratio

$$L(F_X(x)) = \frac{E[X|X \leq x]F_X(x)}{E[X]} \quad (12.7)$$

against $F_X(x)$. If X represents annual income, $L(p)$ is the proportion of total income that accrues to individuals having the $100p\%$ lowest incomes.

It is easy to see that

$$L(p) \leq p,$$

$$L(0) = 0,$$

$$L(1) = 1.$$

A typical Lorenz curve is shown in Figure 12.1. If all individuals earn the same income, $L(p) = p$. The area between the line $L(p) = p$ and the Lorenz curve may be regarded as a measure of inequality of income, or more generally, of variability in the distribution of X . There is extensive discussion of Lorenz curves in Gail and Gastwirth (1978), and a concise account of their properties in Dagum (1985).

Gastwirth (1971) has given the following definition of the Lorenz function $L(p)$:

$$L(p) = \{E[X]\}^{-1} \int_0^p F_X^{-1}(t) dt, \quad (12.8)$$

where

$$F_X^{-1}(t) = \inf_x \{x : F_X(x) \geq t\}.$$

This equation is equivalent to (12.7) for continuous distributions, but it also applies to discrete distributions.

Lorenz ordering is sometimes used to compare the amounts of inequality in two or more distributions. It is based on comparisons of the values of $L(p)$ for the distributions. If their difference is of the same sign for all p , the distributions are Lorenz ordered appropriately. If the sign changes, Lorenz ordering does not apply. There is a useful description of Lorenz ordering in Arnold (1987); see also Chapter 33.

The area between the line $L(p) = p$ and the actual Lorenz curve is called the area of concentration. The Gini concentration index $C(X)$ is twice this

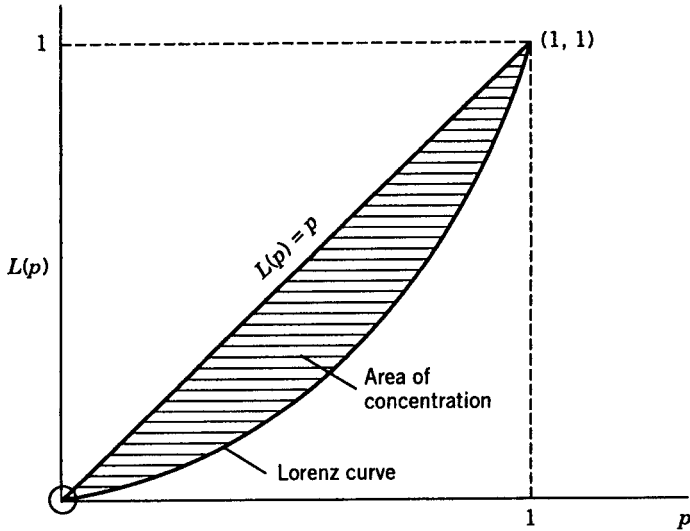


Figure 12.1 Lorenz Curve

area. It is related to *Gini's* mean difference, defined as in (12.5):

$$C(X) = 2 \int_0^1 \{p - L(p)\} dp = 1 - 2 \int_0^1 L(p) dp.$$

Now

$$\begin{aligned} \int_0^1 L(p) dp &= \frac{1}{E[X]} \int_0^1 E[X|X < x] F_X(x) dF_X(x) \\ &= \frac{1}{E[X]} \int_{-\infty}^{\infty} \left\{ \int_{-\infty}^x tp_X(t) dt \right\} p_X(x) dx \\ &= \frac{1}{E[X]} E[X_1|X_1 < X_2] \Pr[X_1 < X_2], \end{aligned}$$

with X_1, X_2 independently distributed as X . Since X_1 and X_2 are continuous and independent,

$$\Pr[X_1 < X_2] = \Pr[X_1 > X_2] = \frac{1}{2};$$

thus

$$C(X) = 1 - \frac{E[X_1|X_1 < X_2]}{E[X]}$$

Since

$$\frac{1}{2}\{E[X_1|X_1 < X_2] + E[X_1|X_1 > X_2]\} = E[X]$$

and

$$\gamma(X) = E[|X_1 - X_2|] = E[X_1|X_1 > X_2] - E[X_1|X_1 < X_2],$$

we have

$$E[X_1|X_1 < X_2] = E[X] - \frac{1}{2}\gamma(X).$$

Hence

$$C(X) = \frac{\frac{1}{2}\gamma(X)}{E[X]}. \quad (12.9a)$$

The ratio $\gamma(X)/E[X] = E[|X_1 - X_2|]/E[X]$ is analogous to the coefficient of variation. Tziazefas (1989) obtains the alternative form:

$$C(X) = \frac{\text{Cov}(X, F_X(X))}{E[X]} \quad (12.9b)$$

Order statistics are of much greater use, and simpler in theoretical analysis, for continuous than for discrete distributions. The next section will be devoted to a general discussion of order statistics for continuous variables, with particular reference to their use in statistical analysis.

2 ORDER STATISTICS

If X_1, X_2, \dots, X_n are random variables, and $X'_1 \leq X'_2 \leq \dots \leq X'_n$ are the same variables arranged in ascending order of magnitude [so that $X'_1 = \min(X_1, X_2, \dots, X_n)$, $X'_n = \max(X_1, X_2, \dots, X_n)$], then X'_1, X'_2, \dots, X'_n are called the order *statistics* corresponding to X_1, X_2, \dots, X_n (see also Chapter 1, Section B10). If it is necessary to indicate the total number of variables explicitly, the symbols $X'_{1:n}, \dots, X'_{n:n}$ will be used.

If the differences $\{X_i - X_j\}$ are continuous random variables, then the events $\{X_i = X_j\}$ all have zero probability. Being finite in number, they can be neglected in probability calculations. We will suppose, from now on, that this is the case, so we can assume that $X'_1 < X'_2 < \dots < X'_n$, without altering any probabilities that relate to the joint distribution of X'_1, X'_2, \dots, X'_n .

The cumulative distribution function of X'_n is defined by

$$\Pr[X'_n \leq x] = \Pr\left[\bigcap_{j=1}^n (X_j \leq x)\right]. \quad (12.10)$$

If X_1, X_2, \dots, X_n are mutually independent, then

$$\Pr[X'_n \leq x] = \prod_{j=1}^n \Pr[X_j \leq x], \quad (12.11)$$

and the probability density function of X'_n is equal to

$$\left(\begin{array}{c} \text{Cumulative distribution} \\ \text{function of } X'_n \end{array}\right) \times \sum_{j=1}^n \left(\frac{\text{Probability density function of } X_j}{\text{Cumulative distribution function of } X_j} \right). \quad (12.12)$$

If all X_j 's have identical distributions with $\Pr[X_j \leq x] = F(x)$, and $dF(x)/dx = p(x)$, then the probability density function of X'_n is

$$n[F(x)]^{n-1}p(x). \quad (12.13a)$$

Similarly (again assuming that all X_j 's are independent and identically distributed) the probability density function of X'_1 is

$$n[1 - F(x)]^{n-1}p(x). \quad (12.13b)$$

More generally, in this case, with $1 \leq a_1 < a_2 < \dots < a_s \leq n$ (and setting $a_0 = 0$, $a_{s+1} = n$, $F(x_{a_0}) = 0$, $F(x_{a_{s+1}}) = 1$), the joint probability density function of $X'_{a_1}, X'_{a_2}, \dots, X'_{a_s}$ is (in an obvious notation)

$$\frac{n!}{\prod_{j=1}^s (a_j - a_{j-1} - 1)!} \left[\prod_{j=1}^{s+1} \{F(x_{a_j}) - F(x_{a_{j-1}})\}^{a_j - a_{j-1} - 1} \right] \prod_{j=1}^s p(x_{a_j}) \\ (x_{a_1} \leq x_{a_2} \leq \dots \leq x_{a_s}). \quad (12.14)$$

In particular, the joint probability density function of X'_1 and X'_n is

$$n(n-1)p(x_1)p(x_n)[F(x_n) - F(x_1)]^{n-2} \quad (x_1 \leq x_n). \quad (12.15)$$

From this joint distribution it is possible to evaluate the cumulative distribution function of the range ($W = X'_n - X'_1$). The formulas

$$\Pr[W \leq w] = n \int_{-\infty}^{\infty} p(x) [F(x) - F(x-w)]^{n-1} dx \quad (12.16)$$

and

$$E[W] = \int_{-\infty}^{\infty} \{1 - [F(x)]^n - [1 - F(x)]^n\} dx \quad (12.17)$$

are of interest.

If $n = 2m + 1$ is odd (i.e., m is an integer), then X'_{m+1} represents the (sample) median of X_1, X_2, \dots, X_n . Its probability density function is

$$\frac{(2m+1)!}{(m!)^2} [F(x)\{1 - F(x)\}]^m p(x) \quad (12.18)$$

Generally the $100p\%$ sample percentile is represented by $X'_{(n+1)p}$ and is defined only if $(n+1)p$ is an integer. The median corresponds to $p = \frac{1}{2}$; we have the lower and upper quartile for $p = \frac{1}{4}, \frac{3}{4}$, respectively.

Often under certain conditions of regularity, it is possible to obtain useful approximations to the moments of order statistics in terms of the common probability density function of the X 's. This approach makes use of the fact that the statistics $Y_1 = F(X_1), Y_2 = F(X_2), \dots, Y_n = F(X_n)$ are independently distributed with common rectangular distribution (see Chapter 26) over the range 0 to 1. The corresponding order statistics Y'_1, Y'_2, \dots, Y'_n have the joint probability density function

$$p_{Y'_1, \dots, Y'_n}(y_1, \dots, y_n) = n! \quad (0 \leq y_1 \leq y_2 \leq \dots \leq y_n \leq 1).$$

The joint probability density function of any subset $Y'_{a_1}, \dots, Y'_{a_s}$ ($1 \leq a_1 < a_2 < \dots < a_s \leq n$) is [using (12.14)]

$$p_{Y'_{a_1}, \dots, Y'_{a_s}}(y_{a_1}, \dots, y_{a_s}) = \frac{n!}{\prod_{j=1}^{s+1} (a_j - a_{j-1} - 1)!} \prod_{j=1}^{s+1} (y_{a_j} - y_{a_{j-1}})^{a_j - a_{j-1} - 1}, \quad (12.19)$$

with $a_0 = 0, a_{s+1} = n + 1; y_{a_0} = 0; y_{a_{s+1}} = 1$, and where $Y'_{a_1}, \dots, Y'_{a_s}$ is denoted by $\{Y'_a\}$. The moments and product moments of the Y'_i 's are given by the

formula

$$E \left[\prod_{j=1}^s Y_{a_j}^{r_j} \right] = \frac{n!}{(n + \sum_{j=1}^s r_j)!} \prod_{j=1}^s \left\{ \frac{\left(a_j + \sum_{i=1}^j r_i - 1 \right)!}{\left(a_j + \sum_{i=1}^{j-1} r_i - 1 \right)!} \right\}. \quad (12.20)$$

We now expand X'_r , as a function of Y'_r , about the value $E[Y'_r] = r/(n+1)$; thus

$$\begin{aligned} X'_r = F^{-1} \left(\frac{r}{n+1} \right) + \left(Y'_r - \frac{r}{n+1} \right) \left[\frac{dF^{-1}(y)}{dy} \right]_{y=r/(n+1)} \\ + \frac{1}{2} \left(Y'_r - \frac{r}{n+1} \right)^2 \left[\frac{d^2F^{-1}(y)}{dy^2} \right]_{y=r/(n+1)} + \dots \end{aligned} \quad (12.21)$$

So we can take expected values of each side of (12.13) (using the method of statistical differentials, described in Chapter 1). Note that since

$$y = F(x) = \int_{-\infty}^x p(t) dt,$$

$$\frac{dF^{-1}}{dy} = \frac{dx}{dy} = \frac{1}{dy/dx} = \frac{1}{p(x)}$$

and

$$\frac{dF^{-1}(y)}{dy} \bigg|_{y=r/(n+1)} = \frac{1}{p(\xi'_r)},$$

where ξ'_r satisfies the equation

$$\frac{r}{n+1} = \int_{-\infty}^{\xi'_r} p(x) dx. \quad (12.22)$$

Similarly $d^2F^{-1}/dy^2 = -[p(x)]^{-2}[dp(x)/dy] = -[p(x)]^{-3}[dp(x)/dx]$, and so on.

David and Johnson (1954) found it convenient to arrange the series so obtained in descending powers of $(n+2)$. Some of their results follow. [In

these formulas, $p_s = s/(n+1)$; $q_r = 1 - p_s$; $(F^{-1})_r = dF^{-1}/dy|_{y=r/(n+1)}$; $(F^{-1})'_r = d^2F^{-1}/dy^2|_{y=r/(n+1)}$, etc.]

$$E[X'_r] = \xi'_r + \frac{p_r q_r}{2(n+2)} (F^{-1})''_r + \frac{p_r q_r}{(n+2)^2} \times \left[\frac{1}{3} (q_r - p_r) (F^{-1})'''_r + \frac{1}{8} p_r q_r (F^{-1})^{iv}_r \right] + \dots, \quad (12.23a)$$

$$\text{Var}(X'_r) = \frac{p_r q_r}{n+2} \{ (F^{-1})'_r \}^2 + \frac{p_r q_r}{(n+2)^2} \left[2(q_r - p_r) (F^{-1})'_r (F^{-1})''_r + p_r q_r \left\{ (F^{-1})'_r (F^{-1})'''_r + \frac{1}{2} [(F^{-1})''_r]^2 \right\} \right] + \dots, \quad (12.23b)$$

$$\begin{aligned} \text{Cov}(X'_r, X'_s) &= \frac{p_r q_s}{n+2} \{ (F^{-1})'_r (F^{-1})'_s \} \\ &+ \frac{p_r q_s}{(n+2)^2} \left[(q_r - p_r) (F^{-1})''_r (F^{-1})'_s + (q_s - p_s) (F^{-1})'_r (F^{-1})''_s \right. \\ &\quad \left. + \frac{1}{2} p_r q_r (F^{-1})'''_r (F^{-1})'_s + \frac{1}{2} p_s q_s (F^{-1})'_r (F^{-1})'''_s \right. \\ &\quad \left. + \frac{1}{2} p_r q_s (F^{-1})''_r (F^{-1})''_s \right] + \dots, \quad r < s, \quad (12.23c) \end{aligned}$$

$$\begin{aligned} \mu_3(X'_r) &= \frac{p_r q_r}{(n+2)^2} \left[2(q_r - p_r) \{ (F^{-1})'_r \}^3 \right. \\ &\quad \left. + 3p_r q_r \{ (F^{-1})'_r \}^2 (F^{-1})''_r \right] + \dots, \quad (12.23d) \end{aligned}$$

$$\begin{aligned} \mu_4(X'_r) &= \frac{3p_r^2 q_r^2}{(n+2)^2} \{ (F^{-1})'_r \}^4 \\ &+ \frac{p_r q_r}{(n+2)^3} \left[6\{ (q_r - p_r)^2 - p_r q_r \} \{ (F^{-1})'_r \}^4 \right. \\ &\quad \left. + 36p_r q_r (q_r - p_r) \{ (F^{-1})'_r \}^3 (F^{-1})''_r \right. \\ &\quad \left. + 5p_r^2 q_r^2 \{ 2\{ (F^{-1})'_r \}^3 (F^{-1})''_r + 3\{ (F^{-1})'_r (F^{-1})''_r \}^2 \} \right] + \dots \quad (12.23e) \end{aligned}$$

By inserting the values of $\xi'_r, (F^{-1})'_r, (F^{-1})'_r$, and so on, appropriate to the particular distribution, approximate formulas can be obtained that correspond to any absolutely continuous common distribution of the original independent variables. These formulas generally tend to be more accurate for large n , and for larger $\min(p_r, q_r)$ [with $\text{Cov}(X'_r, X'_s)$ for larger $\min(p_r, p_s, q_r, q_s)$]. David (1981) and Arnold and Balakrishnan (1989) provide detailed discussions on bounds and approximations for moments of order statistics.

If the distribution of X is such that $\Pr[X < x]$ is a function of only $(x - \theta)/\phi$ so that θ and $\phi (> 0)$ are location and scale parameters, then it is easy to see that $Z = (X - \theta)/\phi$ has a distribution that does not depend on θ or ϕ . Denoting the order statistics corresponding to independent random variables Z_1, Z_2, \dots, Z_n , each distributed as Z , by $Z'_{1:n}, Z'_{2:n}, \dots, Z'_{n:n}$ it is easy to see that

$$E[X'_{r:n}] = \theta + \phi E[Z'_{r:n}], \quad (12.24a)$$

and further that

$$\begin{aligned} \text{Var}(X'_{r:n}) &= \phi^2 \text{Var}(Z'_{r:n}), \\ \text{Cov}(X'_{r:n}, X'_{s:n}) &= \phi^2 \text{Cov}(Z'_{r:n}, Z'_{s:n}). \end{aligned} \quad (12.24b)$$

Hence it is possible to obtain best linear unbiased estimators of θ and ϕ , based on the order statistics $X'_{1:n}, X'_{2:n}, \dots, X'_{n:n}$, by minimizing the quadratic form:

$$\sum_r \sum_s c_{rs} (X'_{r:n} - \theta - \phi E[Z'_{r:n}]) (X'_{s:n} - \theta - \phi E[Z'_{s:n}]),$$

where the matrix (c_{rs}) is the inverse of the matrix of variances and covariances of the $Z'_{r:n}$'s [Lloyd (1952)].

In later chapters a number of results obtained by this method will be presented. The method is of particular value when not all the $X'_{r:n}$'s are used. For example, when data are censored (as described in Chapter 1, Section B10), not all the order statistics are available. Even if they were available, we would want to use only a limited number based on robustness considerations. It is useful, in such cases, to know which sets of a fixed number of order statistics will minimize the variance of the best linear unbiased estimator of θ or ϕ (or perhaps some function of these parameters). Exact calculation is usually tedious, but approximate calculation, using only the first terms of formulas (12.23a), (12.23b) is less troublesome.

In using these results, it is desirable to bear in mind that (1) there may be nonlinear estimators that are (in some sense) more accurate, (2) "best" is defined in terms of variance which is not always appropriate, and (3) the constraint of unbiasedness may exclude some good estimators. However, it

does appear that the best linear unbiased estimators of location and scale parameters, based on order statistics, usually offer accuracy close to the utmost attainable from the data.

Bennett (1952) developed a general method for determining "asymptotically efficient linear unbiased estimators." These are estimators of the form

$$L_n = \sum_{j=1}^n J\left(\frac{j}{n+1}\right) X'_{j:n} \quad (12.25)$$

where $J(\cdot)$ is a "well-behaved" function; that is, the limiting distribution of $\sqrt{n}(L_n - \theta)$ is normal with expected value zero. Bennett's thesis is not easily available. The following results are quoted from Chernoff, Gastwirth, and Johns (1967) who have also demonstrated the asymptotic normality (as $n \rightarrow \infty$) of these estimators.

Relatively simple formulas for $J(\cdot)$ are available for the special case when the parameters θ_1, θ_2 are location and scale parameters so that (for each unordered X)

$$\Pr[X \leq x] = g\left(\frac{x - \theta_1}{\theta_2}\right), \quad \theta_2 > 0. \quad (12.26)$$

The corresponding density function is $\theta_2^{-1}g'[(x - \theta_1)/\theta_2]$, and the Fisher information matrix is

$$\begin{pmatrix} I_{11} & I_{12} \\ I_{21} & I_{22} \end{pmatrix} = \begin{pmatrix} \int_{-\infty}^{\infty} \frac{dL_1}{dy} g(y) dy & \int_{-\infty}^{\infty} \frac{dL_2}{dy} g(y) dy \\ \int_{-\infty}^{\infty} y \frac{dL_1}{dy} g(y) dy & \int_{-\infty}^{\infty} y \frac{dL_2}{dy} g(y) dy \end{pmatrix} \theta_2^{-2}, \quad (12.27)$$

where

$$L_1(y) = -\frac{g'(y)}{g(y)},$$

$$L_2(y) = -1 - \frac{yg'(y)}{g(y)}$$

[Note that $I_{11} = I_{22}$ provided that $g''(y)$ exists and that $\lim_{y \rightarrow \pm\infty} yg'(y) = 0$.] Then for estimating θ_1 , with θ_2 known, we can use

$$J(u) = I_{11}^{-1}L'_1(F^{-1}(u)). \quad (12.28)$$

To make the estimator unbiased, $I_{11}^{-1}I_{12}\theta_2$ must be subtracted. For estimating θ_2 with θ_1 known, we can use

$$J(u) = I_{22}^{-1}L'_2(F^{-1}(u)).$$

To make the estimator unbiased, $I_{22}^{-1}I_{12}\theta_1$ must be subtracted.

If neither θ_1 nor θ_2 is known, then for estimating θ_1 ,

$$J(u) = I^{11}L'_1(F^{-1}(u)) + I^{12}L'_2(F^{-1}(u))$$

and for estimating θ_2 ,

$$J(u) = I^{12}L'_1(F^{-1}(u)) + I^{22}L'_2(F^{-1}(u)),$$

where

$$\begin{pmatrix} I^{11} & I^{12} \\ I^{12} & I^{22} \end{pmatrix}$$

is the inverse of the matrix I . These estimators are unbiased. Chernoff, Gastwirth, and Johns (1967) also obtain formulas to use when the data are censored. Balakrishnan and Cohen (1991) discuss this, and related methods of estimation, in considerable detail.

The limiting distributions of order statistics as n tends to infinity have been studied by a number of writers. It is not difficult to establish that if $r - n\omega$ tends to zero as n tends to infinity, the limiting distribution of $n(X'_{r:n} - X_\omega)$ (where $\Pr\{X \leq X_\omega\} = \omega$) is normal with expected value zero and standard deviation $\sqrt{\omega(1-\omega)/p(X_\omega)}$. However, other limiting distributions are possible. Wu (1966) has shown that a lognormal limiting distribution may be obtained.

Books by Galambos (1987), Resnick (1987), and Leadbetter, Lindgren, and Rootzén (1983) include discussions of asymptotic results for extreme order statistics, while those by Shorack and Wellner (1986) and Serfling (1980) have dealt with central order statistics and linear functions of order statistics. Reiss (1989) has discussed convergence results for all order statistics. Recently Arnold, Balakrishnan, and Nagaraja (1992) have presented a useful summary of many of these developments on the asymptotic theory of order statistics.

Chan (1967) has shown that the distribution function is characterized by either of the sets of values $\{E[X'_{1:n}]\}$ or $\{E[X'_{n:n}]\}$ (for all n) provided that the expected value of the distribution is finite. Many characterization results involving order statistics are reviewed in Galambos and Kotz (1978) and Arnold, Balakrishnan, and Nagaraja (1992).

3 CALCULUS OF PROBABILITY DENSITY FUNCTIONS

The reader may have noted that many of the results of the preceding section were expressed in terms of probability density functions. Although these are only auxiliary quantities — actual probabilities being the items of real importance — they are convenient in the analysis of continuous distributions. In this section we briefly describe techniques for working with probability density functions that will be employed in later chapters. More detailed discussions, and proofs, can be found in textbooks; see, for example, Mood, Graybill, and Boes (1974), Bickel and Doksum (1977), Hogg and Craig (1978), Dudewicz and Mishra (1988), and Casella and Berger (1990).

If X_1, X_2, \dots, X_n are independent random variables with probability density functions $p_{X_1}(x_1), p_{X_2}(x_2), \dots, p_{X_n}(x_n)$, then the joint probability density function may be taken as

$$p_{X_1, X_2, \dots, X_n}(x_1, x_2, \dots, x_n) = \prod_{j=1}^n p_{X_j}(x_j). \quad (12.29)$$

If the variables are not independent, conditional probability density functions must be used. Then in place of (12.29) we have

$$p(x_1, x_2, \dots, x_n) = p(x_1)p(x_2|x_1)p(x_3|x_1, x_2) \dots p(x_n|x_1, x_2, \dots, x_{n-1}).^* \quad (12.30)$$

Of course (12.30) includes (12.29), since, if X_1, \dots, X_n are a mutually independent set of variables, then

$$\begin{aligned} p(x_2|x_1) &= p(x_2), \\ p(x_3|x_1, x_2) &= p(x_3) \dots \end{aligned}$$

If $p(x_1, \dots, x_n)$ is known, then the joint probability density function of any subset of n random variables can be obtained by repeated use of the formula

$$\int_{-\infty}^{\infty} p(x_1, \dots, x_n) dx_p = p(x_1, \dots, x_{p-1}, x_{p+1}, \dots, x_n). \quad (12.31)$$

To find the joint distribution of n functions of X_1, \dots, X_n (statistics) when $T_1 \equiv T_1(X_1, \dots, X_n), \dots, T_n \equiv T_n(X_1, \dots, X_n)$ and the transformation from (X_1, \dots, X_n) to (T_1, \dots, T_n) is one to one, then the formula

$$p_{T_1, \dots, T_n}(t_1, \dots, t_n) = p_{X_1, \dots, X_n}(x_1(t), \dots, x_n(t)) \left| \frac{\partial(x_1, \dots, x_n)}{\partial(t_1, \dots, t_n)} \right| \quad (12.32)$$

*In the remainder of this and succeeding sections of this chapter, subscripts following p will often be omitted for convenience. In succeeding chapters the subscripts will usually appear.

may be used [t_1, \dots, t_n and x_1, \dots, x_n are related in the same way as T_1, \dots, T_n and X_1, \dots, X_n ; $x_j(t)$ means that x_j is expressed in terms of t_1, \dots, t_n and $\partial(x_1, \dots, x_n)/\partial(t_1, \dots, t_n)$ is the Jacobian of (x_1, \dots, x_n) with respect to (t_1, \dots, t_n) in that it is a determinant of n rows and n columns with the element in the i th row and the j th column equal to $\partial x_i/\partial t_j$].

If the transformation is not one to one, the simple formula (12.32) cannot be used. In special cases, however, straightforward modifications of (12.32) can be employed. For example, if k different sets of values of the x 's produce the same set of values of the t 's, it may be possible to split up the transformation into k separate transformations. Then (12.32) is applied to each, and the results added together.

Having obtained the joint distribution of T_1, T_2, \dots, T_n , the joint distribution of any subset thereof can be obtained by using (12.21) repeatedly. The conditional distribution of X_1 , given X_2, \dots, X_n is sometimes called the array distribution of X_1 (given X_2, \dots, X_n). The expected value of this conditional distribution (a function of X_2, \dots, X_n) is called the regression of X_1 on X_2, \dots, X_n . The variance is called the array variance (of X_1 , given X_2, \dots, X_n); if it does not depend on X_2, \dots, X_n , the variation is said to be homoscedastic.

4 SYSTEMS OF DISTRIBUTIONS

Some families of distributions have been constructed to provide approximations to as wide a variety of observed distributions as possible. Such families are often called systems of distributions, or, more often, systems of frequency curves. Although theoretical arguments may indicate the relevance of a particular system, their value should be judged primarily on practical, *ad hoc* considerations. Particular requirements are ease of computation and facility of algebraic manipulation. Such requirements make it desirable to use as few parameters as is possible in defining an individual member of the system. How few we may use, without prejudicing the variety of distributions included, is a major criterion in judging the utility of systems of distributions.

For most practical purposes it is sufficient to use four parameters. There is no doubt that at least three parameters are needed; for some purposes this is enough. Inclusion of a fourth parameter does produce noticeable improvement, but it is doubtful whether the improvement obtained by including a fifth or sixth parameter is commensurate with the extra labor involved. Here we will describe some systems of frequency curves. Among these systems there should be at least one that suffices for practical needs and possibilities in most situations.

4.1 Pearson System

Between 1890 and 1895 **Pearson (1895)** designed a system whereby for every member the probability density function $p(x)$ satisfies a differential equation

of form

$$\frac{1}{p} \frac{dp}{dx} = - \frac{a + x}{c_0 + c_1x + c_2x^2}. \quad (12.33)$$

The shape of the distribution depends on the values of the parameters a , c_0 , c_1 , and c_2 . If $-a$ is not a root of the equation

$$c_0 + c_1x + c_2x^2 = 0,$$

p is finite when $x = -a$ and dp/dx is zero when $x = -a$. The slope (dp/dx) is also zero when $p = 0$. But, if $x \neq -a$ and $p \neq 0$, then $dp(x)/dx \neq 0$. Since the conditions $p(x) \geq 0$ and

$$\int_{-\infty}^{\infty} p(x) dx = 1$$

must be satisfied, it follows from (12.33) that $p(x)$ must tend to zero as x tends to infinity, and likewise must dp/dx . This may not be true of formal solutions of (12.33). In such cases the condition $p(x) \geq 0$ is not satisfied, and it is necessary to restrict the range of values of x to those for which $p(x) > 0$ and to assign the value $p(x) = 0$ when x is outside this range.

The shape of the curve representing the probability density function varies considerably with a , c_0 , c_1 , and c_2 . **Pearson** classified the different shapes into a number of types. We will give a **resumé** of his classification. We follow his system of numbering because it is well-established, but it does not have a clear systematic basis.

The form of solution of (12.33) evidently depends on the nature of the roots of the equation

$$c_0 + c_1x + c_2x^2 = 0, \quad (12.34)$$

and the various types correspond to these different forms of solution. We first note that if $c_1 = c_2 = 0$, equation (12.33) becomes

$$\frac{d \log p(x)}{dx} = - \frac{x + a}{c_0},$$

whence

$$p(x) = K \exp \left[- \frac{(x + a)^2}{2c_0} \right],$$

where K is a constant, chosen to make

$$\int_{-\infty}^{\infty} p(x) dx = 1.$$

It is clear that c_0 must be positive and that $K = \sqrt{2\pi c_0}$. As a result the corresponding distribution is normal with expected value $-a$ and standard deviation $\sqrt{c_0}$. The next chapter is devoted to this distribution.

The normal curve is not assigned to particular type. It is in fact a limiting distribution of all types. From now on we will suppose that the origin of the scale of X has been chosen so that $E[X] = 0$.

Type I corresponds to both roots of (12.33) being real, and of opposite signs. Denoting the roots by a_1, a_2 , with

$$a_1 < 0 < a_2,$$

we have

$$c_0 + c_1x + c_2x^2 = -c_2(x - a_1)(a_2 - x).$$

Equation (12.33) can be written

$$\frac{1}{p} \frac{dp}{dx} = \frac{a + x}{(x - a_1)(a_2 - x)}$$

the solution of which is

$$p(x) = K(x - a_1)^{m_1}(a_2 - x)^{m_2}, \quad (12.35)$$

with

$$m_1 = \frac{a + a_1}{c_2(a_2 - a_1)},$$

$$m_2 = -\frac{a + a_2}{c_2(a_2 - a_1)}$$

For both $x - a_1$ and $a_2 - x$ to be positive, we must have $a_1 < x < a_2$, so we limit the range of variation to these values of x . Equation (12.35) can represent a proper probability density function provided $m_1 > -1$ and $m_2 > -1$. This is a general form of beta distribution, which will be discussed further in Chapter 25. Here we briefly note a few points relating to the function $p(x)$.

The limiting value of $p(x)$, as x tends to a_1 , is zero or infinite depending on whether m_j is positive or negative (for $j = 1, 2$). If m_1 and m_2 have the same sign, $p(x)$ has a single mode or **antimode** (according as the m 's are

positive or negative, respectively). Type I distributions can be subdivided according to the appearance of the graph of $p(x)$ against x . Thus we have

Type I(U): if $m_1 < 0$ and $m_2 < 0$.

Type I(J): if $m_1 < 0$ and $m_2 > 0$, or if $m_1 > 0$ and $m_2 < 0$.

If m_j is zero, then $p(x)$ tends to a nonzero limit as x tends to a_j ($j = 1$ or 2).

The symmetrical form of (12.35), with $m_1 = m_2$, is called a Type II distribution. If the common value is negative, the distribution is U-shaped, which is sometimes described as Type III(U). Type III corresponds to the case $c_2 = 0$ (and $c_1 \neq 0$). In this case (12.33) becomes

$$\frac{d \log p(x)}{dx} = -\frac{x+a}{c_0+c_1x} = -\frac{1}{c_1} - \frac{a-c_0/c_1}{c_0+c_1x},$$

whence

$$p(x) = K(c_0+c_1x)^m \exp\left(\frac{-x}{c_1}\right), \quad (12.36)$$

with $m = c_1^{-1}(c_0c_1^{-1} - a)$. If $c_1 > 0$, we take the range of x as $x > -c_0/c_1$; if $c_1 < 0$, the range is taken to be $x < -c_0/c_1$. Type III distributions are gamma *distributions* and are discussed further in Chapter 17.

Type IV distributions correspond to the case in which the equation

$$c_0 + c_1x + c_2x^2 = 0$$

does not have real roots. Then we use the identity

$$c_0 + c_1x + c_2x^2 = C_0 + c_2(x + C_1)^2,$$

with $C_0 = c_0 - \frac{1}{4}c_1^2c_2^{-1}$, $C_1 = \frac{1}{2}c_1c_2^{-1}$. We write (12.33) as

$$\frac{d \log p(x)}{dx} = \frac{-(x+C_1) - (a-C_0)}{C_0 + c_2(x+C_1)^2}.$$

From this it follows that

$$p(x) = K \left[C_0 + c_2(x + C_1)^2 \right]^{-(2c_2)^{-1}} \exp \left[-\frac{a - C_0}{\sqrt{c_2 C_0}} \tan^{-1} \frac{x + C_1}{\sqrt{C_0/c_2}} \right]. \quad (12.37)$$

(Note that since $c_0 + c_1x + c_2x^2 = 0$ has no real roots, $c_1^2 < 4c_0c_2$, and so $c_2C_0 = c_0c_2 - \frac{1}{4}c_1^2$ is positive.)

Since no common statistical distributions are of Type IV form, it will not be discussed in a later chapter, but we devote a little space here to this type. Formula (12.37) leads to intractable mathematics if one attempts to calculate values of the cumulative distribution function. As we will see later, it is possible to express the parameters a , c_0 , c_1 , and c_2 in terms of the first four moments of the distribution, so it is possible to fit by equating actual and fitted moments. Fitting Type IV by maximum likelihood is very difficult (with unknown accuracy in finite-sized samples) and rarely attempted.

The tables in **Pearson** and **Hartley** (1972) give standardized quantiles (percentiles) of **Pearson** system distributions to four decimal places for $\sqrt{\beta_1} = 0.0(0.1)2.0$ and for β_2 increasing by intervals of 0.2. With some interpolation these tables can provide approximate values of the cumulative distribution function, without the need to evaluate K (for Type IV). To evaluate K for Type IV, special tables must be used or a special quadrature of $K^{-1}p(x)$ [according to (12.37)] carried out.

Amos and Daniel (1971) and Bouver and Bargmann (1974) provide more extensive tables of quantiles, to four and five decimal places, respectively. Also Bouver (1973) gives values of the cdf for Type IV distributions, to nine decimal places.

Bowman and Shenton (1979a, b) obtained rational fraction approximations to percentile points of standardized **Pearson** distributions. Davis and Stephens (1983) utilized these approximations to construct a computer algorithm to determine approximate 0.01, 0.025, 0.05, 0.10, 0.25, 0.50, 0.75, 0.90, 0.95, 0.975, and 0.99 percentiles, for $0 \leq |\sqrt{\beta_1}| \leq 2$ and values of β_2 (between 1.5 and 15.8) depending on $\sqrt{\beta_1}$ and the percentile being evaluated.

On account of the technical difficulties associated with the use of Type IV distributions, efforts have been made to find other distributions with simpler mathematical forms and with circumstances close enough to Type IV distributions to replace them. More information on this point will be given later in this chapter.

Approximations for the cdfs of Type IV distributions, especially aimed at accuracy in the tails of the distributions, have been developed by **Woodward** (1976) and **Skates** (1993). **Woodward** (1976), taking the pdf in the form

$$p_X(x) = K_1 \left(1 + \frac{x^2}{a^2}\right)^{-m} \exp\left\{-k \tan^{-1}\left(\frac{x}{a}\right)\right\}, \quad (12.37)'$$

obtained the approximation

$$F_X(x) \doteq 1 - K_1 a^2 \left(1 + \frac{x^2}{a^2}\right)^{-m+1} \frac{\exp\{-k \tan^{-1}(x/a)\}}{2mx + ak}. \quad (12.38)$$

Skates (1993), using techniques for approximating integrals developed by Reid and Skates (1986) and Barndorff-Nielsen (1990), formulated the pdf as

$$p_X(x) = K_2 \left\{ 1 + \frac{1 + \rho^2}{\nu} \left(x + \rho \sqrt{\frac{\nu}{1 + \rho^2}} \right) \right\}^{-(\nu+1)/2} \\ \times \exp \left[\nu \rho \tan^{-1} \left(\left(x + \rho \sqrt{\frac{\nu}{1 + \rho^2}} \right) \sqrt{\frac{1 + \rho^2}{\nu}} \right) \right], \quad (12.39)$$

which can be obtained from (12.37)' by putting

$$C_0 = \frac{\nu}{(\nu + 1)(1 + \rho^2)},$$

$$C_1 = \rho \sqrt{\frac{\nu}{1 + \rho^2}},$$

$$C_2 = (\nu + 1)^{-1},$$

$$\rho = \frac{\rho}{\nu + 1} \sqrt{\frac{\nu}{1 + \rho^2}}.$$

He derived a sequence of "secant approximations," whose initial approximation is

$$F_X(x) \doteq \Phi(r\sqrt{\nu}) - \phi(r\sqrt{\nu}) \left\{ \frac{1}{x} \sqrt{1 + (x + \rho)^2} - \frac{1}{r} \right\} \frac{1}{\sqrt{\nu}} \quad (12.40)$$

with

$$r^2 = \log \left\{ \frac{1 + (x + \rho)^2}{1 + \rho} \right\} - 2\rho \{ \tan^{-1}(x + \rho) - \tan^{-1} \rho \},$$

and also an approximation based on Barndorff-Nielsen's (1990) analysis,

$$F_X(x) \doteq \Phi \left(r\sqrt{\nu} - \frac{1}{r\sqrt{\nu}} \log \left[\frac{r}{x} \sqrt{1 + (x + \rho)^2} \right] \right). \quad (12.41)$$

Type V corresponds to the case where $c_0 + c_1x + c_2x^2$ is a perfect square ($c_1^2 = 4c_0c_2$). Equation (12.33) can be rewritten

$$\begin{aligned}\frac{d \log p(x)}{dx} &= -\frac{x+a}{c_2(x+C_1)^2} \\ &= -\frac{1}{c_2(x+C_1)} - \frac{a-C_1}{c_2(x+C_1)^2},\end{aligned}$$

whence

$$p(x) = K(x+C_1)^{-1/c_2} \exp\left[\frac{a-C_1}{c_2(x+C_1)}\right]. \quad (12.42)$$

If $(a-C_1)/c_2 < 0$, then $x > -C_1$; if $(a-C_1)/c_2 > 0$, then $x < -C_1$. [The inverse Gaussian distribution (Chapter 15) belongs to this family.] If $a = C_1$ and $|c_2| < 1$, then we have the special case

$$p(x) = K(x+C_1)^{-1/c_2},$$

which is sometimes called Type VIII and Type IX provided that $c_2 > 0$ or $c_2 < 0$. From (12.42) it can be seen that $(x+C_1)^{-1}$ has a **Type III** distribution.

Type VI corresponds to the case when the roots of $c_0 + c_1x + c_2x^2 = 0$ are real and of the same sign. If they are both negative (e.g., $a, < a, < 0$), then an analysis similar to that leading to equation (12.35) can be carried out, with the result written in the form

$$p(x) = K(x-a_1)^{m_1}(x-a_2)^{m_2}. \quad (12.43)$$

Since the expected value is greater than a , it is clear that the range of variation of x must be $x > a$. [Formula (12.43) can represent a proper probability density function provided that $m_2 < -1$ and $m_1 + m_2 < 0.1$.

Finally, Type VII corresponds to the case where $c_1 = a = 0$, $c_0 > 0$, and $c_2 > 0$. In this case equation (12.33) becomes

$$\frac{d \log p(x)}{dx} = -\frac{x}{c_0 + c_2x^2},$$

whence

$$p(x) = K(c_0 + c_2x^2)^{-(2c_2)^{-1}} \quad (12.44)$$

A particularly important distribution belonging to this family is the (central) t distribution, **which will** be discussed further in Chapter 28. Distribution

(12.44) can be obtained by a simple multiplicative transformation from a t distribution with "degrees of freedom" (possibly fractional) equal to $c_2^{-1} - 1$.

The parameters a , c_0 , c_1 , and c_2 in (12.33) can be expressed in terms of the moments of the distribution. Equation (12.33) may be written (after multiplying both sides by x^r)

$$x^r(c_0 + c_1 + c_2 x^2) \frac{dp(x)}{d(x)} + x^r(a + x)p(x) = 0. \quad (12.45)$$

Integrating both sides of (12.45) between $-\infty$ and $+\infty$, and assuming that $x^r p(x) \rightarrow 0$ as $x \rightarrow \pm\infty$ for $r \leq 5$, we obtain the equation

$$-rc_0\mu'_{r-1} + [-(r+1)c_1 + a]\mu'_r + [-(r+2)c_2 + 1]\mu'_{r+1} = 0. \quad (12.46)$$

Putting $r = 0, 1, 2, 3$ in (12.46), and noting that $\mu'_0 = 1$ and (in the present context) $\mu'_{-1} = 0$, we obtain four simultaneous linear equations for a , c_0 , c_1 , and c_2 with coefficients which are functions of μ'_1 , μ'_2 , μ'_3 , and μ'_4 . The expected value of the variable can always be arranged (as we have done above) to be zero. If this be done, then $\mu'_1 = 0$ and $\mu'_r = \mu_r$ for $r \geq 2$. The formulas for a , c_0 , c_1 , and c_2 are then

$$c_0 = (4\beta_2 - 3\beta_1)(10\beta_2 - 12\beta_1 - 18)^{-1}\mu_2, \quad (12.47a)$$

$$a = c_1 = \sqrt{\beta_1}(\beta_2 + 3)(10\beta_2 - 12\beta_1 - 18)^{-1}\sqrt{\mu_2}, \quad (12.47b)$$

$$\begin{aligned} c_2 &= (2\mu_4\mu_2 - 3\mu_3^2 - 6\mu_2^3)(10\mu_4\mu_2 - 12\mu_3^2 - 18\mu_2^3)^{-1} \\ &= (2\beta_2 - 3\beta_1 - 6)(10\beta_2 - 12\beta_1 - 18)^{-1} \end{aligned} \quad (12.47c)$$

From the definitions of the various types of distributions, it is clear that equations (12.47) yield

$$\text{Type I: } \kappa = \frac{1}{4}c_1^2(c_0c_2)^{-1} = \frac{1}{4}\beta_1(\beta_2 + 3)^2(4\beta_2 - 3\beta_1)^{-1}(2\beta_2 - 3\beta_1 - 6)^{-1} < 0.$$

$$\text{Type II: } \beta_1 = 0, \beta_2 < 3.$$

$$\text{Type III: } 2\beta_2 - 3\beta_1 - 6 = 0.$$

$$\text{Type IV: } 0 < \kappa < 1.$$

$$\text{Type V: } \kappa = 1.$$

$$\text{Type VI: } \kappa > 1.$$

$$\text{Type VII: } \beta_1 = 0, \beta_2 > 3.$$

The division of the (β_1, β_2) plane among the various types is shown in Figure 12.2. (Note that it is impossible to have $\beta_2 - \beta_1 - 1 < 0$.)

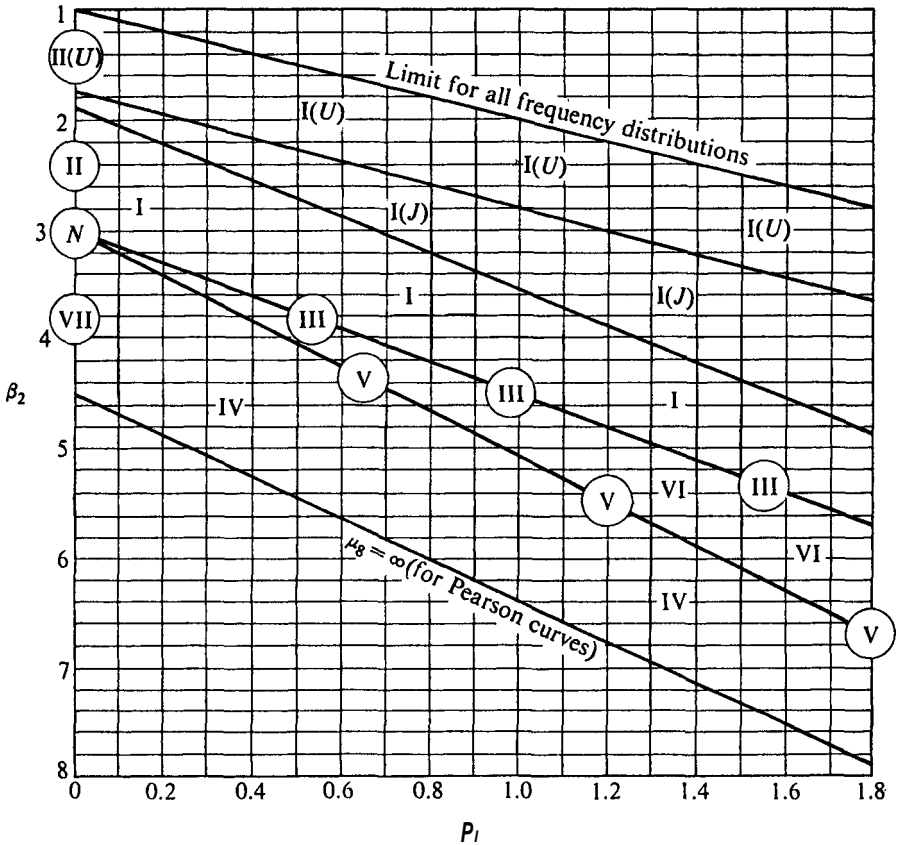


Figure 12.2 A Chart Relating the Type of Pearson Frequency Curve to the Values of β_1, β_2

The upside-down presentation of this figure is in accordance with well-established convention. Note that only Types I, VI, and IV correspond to areas in the (β_1, β_2) diagram. The remaining types correspond to lines and are sometimes called *transition* types. Other forms of diagrams have been proposed by Boetti (1964) and Craig (1936). The latter uses $(2\beta_2 - 3\beta_1 - 6)/(\beta_2 + 3)$ in place of β_2 for one axis.

Examples of fitting **Pearson** curves to numerical data are given in Elderton and Johnson (1969). Computer programs for producing values of random variables having **Pearson** type distributions have been described by Cooper et al. (1965). We conclude this subsection by noting a few general properties of **Pearson** type distributions.

Glänzel (1991) has shown that if $E[X^2]$ is finite, and $E[X|X \geq x]$ and $E[X^2|X \geq x]$ are differentiable functions of x , the distribution of X belongs to the **Pearson** system if

$$E[X^2|X \geq x] = L_1(x)E[X|X \geq x] + L_2(x)$$

density function. If $p(x)$ is a probability density function with cumulants $\kappa_1, \kappa_2, \dots$, then the function

$$g(x) = \exp \left[\sum_{j=1}^{\infty} \varepsilon_j \left\{ \frac{(-D)^j}{j!} \right\} \right] p(x) \quad (12.51)$$

will have cumulants $\kappa_1 + \varepsilon_1, \kappa_2 + \varepsilon_2, \dots$. It is necessary to explain the meaning of (12.51) rather carefully. The operator

$$\exp \left[\sum_{j=1}^{\infty} \varepsilon_j \left\{ \frac{(-D)^j}{j!} \right\} \right]$$

is to be understood in the sense described in Chapter 1. That is, the exponential must be formally expanded as

$$\sum_{i=0}^{\infty} \frac{\left[\sum_{j=1}^{\infty} \varepsilon_j \left\{ \frac{(-D)^j}{j!} \right\} \right]^i}{i!}$$

and then applied to $p(x)$. [As in Chapter 1, Section A4, D is the differentiation operator and $D^j p(x) = d^j p(x)/dx^j$.] It should be clearly understood that $g(x)$ may not satisfy the condition $g(x) \geq 0$ for all x . Note that the cumulants of $g(x)$ are defined as coefficients of $t^r/r!$ in the expansion of

$$\log \left[\int_{-\infty}^{\infty} e^{tx} g(x) dx \right]$$

whether or not $g(x) \geq 0$.

Despite this limitation it is often possible to obtain useful approximate representation of a distribution with known moments (and known cumulants) in terms of a known pdf $p(x)$. By far the most commonly used initial family of distributions is the normal distribution. The representations arising from this choice of initial distribution are called *Gram-Charlier* series. From (12.51) we find (formally)

$$\begin{aligned} g(x) = & p(x) - \varepsilon_1 D p(x) + \frac{1}{2} (\varepsilon_1^2 + \varepsilon_2) D^2 p(x) \\ & - \frac{1}{6} (\varepsilon_1^3 + 3\varepsilon_1 \varepsilon_2 + \varepsilon_3) D^3 p(x) \\ & + \frac{1}{24} (\varepsilon_1^4 + 6\varepsilon_1^2 \varepsilon_2 + 4\varepsilon_1 \varepsilon_3 + \varepsilon_4) D^4 p(x) + \dots \quad (12.52) \end{aligned}$$

For the approximation to the cumulative distribution function, we have

$$\int_{-\infty}^x g(t) dt = \int_{-\infty}^x p(t) dt - \varepsilon_1 p(x) + \frac{1}{2}(\varepsilon_1^2 + \varepsilon_2) Dp(x) + \dots \quad (12.53)$$

In many cases [including the case when $p(x)$ is a normal probability density function]

$$D^j p(x) = P_j(x) p(x),$$

where $P_j(x)$ is a polynomial of degree j in x . Then (12.52) can be written in the form

$$g(x) = \left[1 - \varepsilon_1 P_1(x) + \frac{1}{2}(\varepsilon_1^2 + \varepsilon_2) P_2(x) - \frac{1}{6}(\varepsilon_1^3 + 3\varepsilon_1 \varepsilon_2 + \varepsilon_3) P_3(x) + \frac{1}{24}(\varepsilon_1^4 + 6\varepsilon_1^2 \varepsilon_2 + 4\varepsilon_1 \varepsilon_3 + \varepsilon_4) P_4(x) - \dots \right] p(x) \quad (12.52)'$$

with a corresponding form for (12.53).

If the expected values and standard deviations of $p(x)$ and $g(x)$ have been made to agree, then $\varepsilon_1 = \varepsilon_2 = 0$, and (12.52)' becomes

$$g(x) = \left[1 - \frac{1}{6} \varepsilon_3 P_3(x) + \frac{1}{24} \varepsilon_4 P_4(x) - \dots \right] p(x) \quad (12.54)$$

and also

$$\int_{-\infty}^x g(t) dt = \int_{-\infty}^x p(t) dt - \left[\frac{1}{6} \varepsilon_3 P_2(x) - \frac{1}{24} \varepsilon_4 P_3(x) + \dots \right] p(x), \quad (12.55)$$

assuming that $P_j(x)p(x) \rightarrow 0$ at the extremes of the range of variation of x . A common way of ensuring this agreement in the expected value and the standard deviation is to use standardized variables and to choose $p(x)$ so that the corresponding distribution is standardized. If desired, the actual expected value and standard deviation can be restored by an appropriate linear transformation.

Suppose that we use a standardized variable. In taking $p(x) = (\sqrt{2\pi})^{-1} e^{-x^2/2}$ (normal), we have $(-1)^j P_j(x)$ as the **Hermite** polynomial $H_j(x)$ described in Chapter I. Then, since $\kappa_r = 0$ when r is greater than 2 for the normal distribution, $\varepsilon_3, \varepsilon_4, \dots$, are equal to the corresponding cumulants of the distribution that we want to approximate. Further, since this function

is standardized, we have

$$\begin{aligned}\varepsilon_3 &= \alpha_3 = \sqrt{\beta_1}, \\ \varepsilon_4 &= \alpha_4 - 3 = \beta_2 - 3,\end{aligned}$$

where the shape factors refer to this distribution. Thus we have

$$g(x) = \left[1 + \frac{1}{6}\sqrt{\beta_1}H_3(x) + \frac{1}{24}(\beta_2 - 3)H_4(x) + \dots \right] (\sqrt{2\pi})^{-1} e^{-x^2/2}, \quad (12.56)$$

and by integrating both sides of (12.56), we obtain

$$\begin{aligned}\int_{-\infty}^x g(t) dt &= \Phi(x) - \left[-\frac{1}{6}\sqrt{\beta_1}H_2(x) + \frac{1}{24}(\beta_2 - 3)H_3(x) + \dots \right] \phi(x) \\ &= \Phi(x) - \frac{1}{6}\sqrt{\beta_1}(x^2 - 1)\phi(x) \\ &\quad - \frac{1}{24}(\beta_2 - 3)(x^3 - 3x)\phi(x) + \dots,\end{aligned} \quad (12.57)$$

where

$$\begin{aligned}\Phi(x) &= (\sqrt{2\pi})^{-1} \int_{-\infty}^x e^{-t^2/2} dt, \\ \phi(x) &= (\sqrt{2\pi})^{-1} e^{-x^2/2}.\end{aligned} \quad (12.58)$$

Equations (12.56) and (12.57) are known as Gram-Charlier expansions (1905); some earlier writers refer to them as Bruns-Charlier expansions (1906). In these expansions the terms occur in sequence determined by the successive derivatives of $\phi(x)$. This is not necessarily in decreasing order of importance, and a different ordering is sometimes used. The ordering is based on the fact that for a sum of n independent, identically distributed standardized random variables, the r th cumulant is proportional to $n^{1-r/2}$ ($r \geq 2$). This means that, in our notation, ε_r is $n^{1-r/2}$. Collecting terms of equal order in $n^{-1/2}$, and rearranging in ascending order, gives an Edgeworth expansion [Edgeworth (1896, 1907)] whose leading terms are

$$g(x) = \left[1 + \frac{1}{6}\sqrt{\beta_1}H_3(x) + \frac{1}{24}(\beta_2 - 3)H_4(x) + \frac{1}{72}\beta_1H_6(x) + \dots \right] \phi(x) \quad (12.59)$$

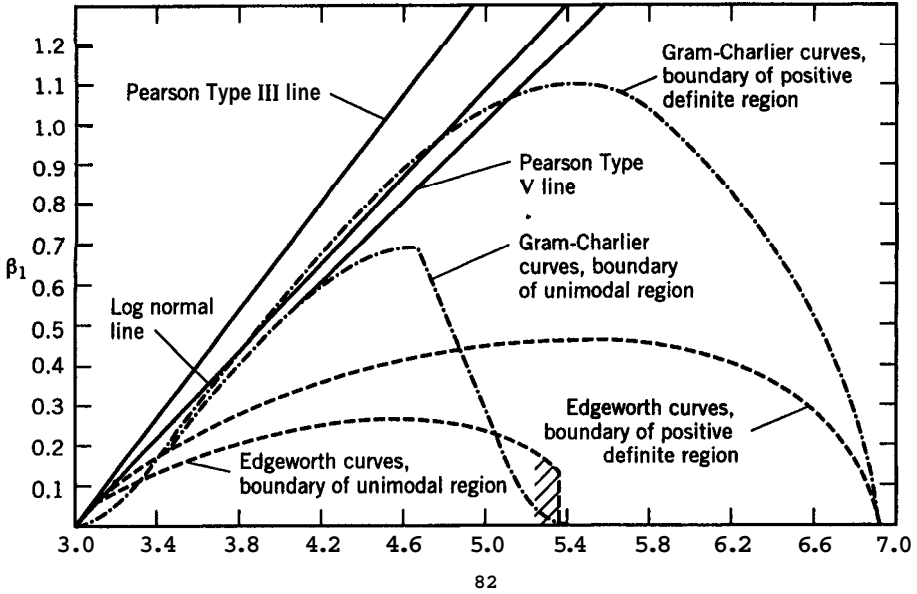


Figure 12.3 β_1, β_2 Plane Showing Regions of Unimodal Curves and Regions of Curves Composed Entirely of Nonnegative Ordinates

from which we obtain

$$\int_{-\infty}^x g(t) dt = \Phi(x) - \frac{1}{6}\sqrt{\beta_1}(x^2 - 1)\phi(x) - \frac{1}{24}(\beta_2 - 3)(x^3 - 3x)\phi(x) - \frac{1}{72}\beta_1(x^5 - 10x^3 + 15x)\phi(x) + \dots \tag{12.59}'$$

As we noted at the beginning of this subsection, the mathematical expression obtained by applying a cumulant modifying function will not, in general, represent a proper probability density function because there are many intervals throughout which it is negative. This is also true when only a finite number of terms of the expansion is used. Figure 12.3 presents the results of an investigation by Barton and Dennis (1952) and shows the regions in the (β_1, β_2) plane where the expressions (12.56) and (12.59) are never negative. The shaded region should be excluded from the Edgeworth **unimodal** region, as was shown by Draper and Tierney (1972). [See also Balitskaya and Zolotuhina (1988).]

Figure 12.3 also shows the region where the curves corresponding to (12.56) and (12.59) are unimodal. Multimodality in expansions like (12.56) or (12.59), fitted to empirical data, often indicates an unnecessary fidelity to more or less accidental features of the data, in the form of "humps" in the

tails. This kind of phenomenon is more likely to be encountered as more terms are used in the expansion.

In most applications only the first four moments are used, and the following terminating expressions are used:

$$g(x) = \left[1 + \frac{1}{6} \sqrt{\beta_1} (x^3 - 3x) + \frac{1}{24} (\beta_2 - 3)(x^4 - 6x^2 + 3) \right] \phi(x)$$

(Gram-Charlier), (12.60)

$$g(x) = \left[1 + \frac{1}{6} \sqrt{\beta_1} (x^3 - 3x) + \frac{1}{24} (\beta_2 - 3)(x^4 - 6x^2 + 3) + \frac{1}{72} \beta_1 (x^6 - 15x^4 + 45x^2 - 15) \right] \phi(x) \quad (\text{Edgeworth}). \quad (12.61)$$

Note that the Edgeworth has no general theoretical superiority over the Gram-Charlier expansion—it depends on a particular assumption about the orders of magnitude of successive cumulants which may, or may not, be a good approximation to actual conditions.

Although the expansions (12.60) and (12.61) terminate, and so the general theory at the beginning of this paragraph does not apply, it can be seen, from the orthogonality (with normal weight function) of **Hermite** polynomials that they are functions with the correct values for the first four moments, and that they also satisfy the condition $\int_{-\infty}^{\infty} g(x) dx = 1$. Since

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} |x| x^j e^{-x^2/2} dx = 0 \quad \text{for } j \text{ odd,}$$

and for j even

$$\begin{aligned} \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} |x| x^j e^{-x^2/2} dx &= \sqrt{\frac{2}{\pi}} \int_0^{\infty} x^{j+1} e^{-x^2/2} dx \\ &= \sqrt{\frac{2}{\pi}} 2^{(j+1)/2-1/2} \int_0^{\infty} t^{j/2} e^{-t} dt, \end{aligned}$$

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} x |x|^j e^{-x^2/2} dx = 2^{j/2} \left(\frac{1}{2} j \right)! \quad (j \text{ even}),$$

it follows that for the Gram-Charlier (finite term) distribution as given by (12.45) the mean deviation is

$$\sqrt{\frac{2}{\pi}} \left[1 - \frac{1}{24}(\beta_2 - 3) \right] = \sqrt{\frac{2}{\pi}} \frac{27 - \beta_2}{24}.$$

This is also the ratio of mean deviation to standard deviation for this Gram-Charlier expansion, with general values for the expected value and variance. Note that for $\beta_2 > 27$ the mean deviation is negative. This is because the probability density function is negative for some values of x .

However, for $1 < \beta_2 < 7$,

$$\frac{5}{6} \sqrt{\frac{2}{\pi}} < \frac{\text{Mean deviation}}{\text{Standard deviation}} < \frac{13}{12} \sqrt{\frac{2}{\pi}}.$$

Similar results can be obtained for the Edgeworth expansion (12.61). For this, **Bhattacharjee (1965)** and **Singh (1967)** have obtained the distributions of extreme values and ranges, and they have given numerical values for expected values and variances in random samples of size up to 12. **Subrahmaniam (1966)** has obtained the distributions of linear functions of independent sample values, and of sample variance for random samples for this distribution.

It is possible to derive expansions of Gram-Charlier form by arguments similar to those used in deriving certain central limit theorems (Chapter 13). **Cramér (1928)** gives a general discussion; **Longuet-Higgins (1964)** gives an analysis from a physicist's point of view.

Some theoretical results of **Bol'shev (1963)** are relevant here. Starting from the normalizing transformation

$$y(x) = \Phi^{-1}[\text{Pr}[S \leq x]] \quad (12.62)$$

one can expand the argument $\text{Pr}[S \leq x]$ about $\Phi(x)$, as a power series in $\text{Pr}[S \leq x] - \Phi(x)$. If this difference, in turn, be expanded as a power series in x , then (12.62) gives a power series (in x) expression for $y(x)$. [See also equation (12.21) et *seq.* of this chapter.]

In the particular case where $S \equiv S_n$ is the standardized sum of n independent identically distributed variables X_1, X_2, \dots, X_n with finite expected value ξ and standard deviation σ , respectively (and finite cumulants of all orders) [i.e., $S_n = (n\sigma^2)^{-1/2} \sum_{j=1}^n (X_j - \xi)$], there is an expansion

$$\text{Pr}[S_n \leq x] - \Phi(x) = Q(x), \quad (12.63)$$

where $Q(x)$ is a polynomial with coefficient depending on the common

moment ratios of each X_i . Inserting (12.62) in (12.63), we obtain

$$y(x) = x + \sum P_{3j-1}(x)n^{-j/2} + O(n^{-(r-2)/2}), \quad (12.64)$$

with

$$P_2(x) = \frac{1}{6}\sqrt{\beta_1}(x^2 - 1),$$

$$P_5(x) = \frac{1}{36}\beta_1(4x^3 - 7x) - \frac{1}{24}(\beta_2 - 3)(x^3 - 3x).$$

Bol'shev shows that of all functions $u(x, n)$ satisfying the conditions that (1) $\partial^{r-2}u/\partial x^{r-2}$ exists and is continuous with respect to n on the line $n = 0$ and (2) $\partial u/\partial x$ exists in a domain

$$|x| < Cn^{-(r-2)}(r-1), \quad C > 0, r \geq 3,$$

the only one for which

$$\Pr[u(x, n) \leq u_0] = \phi(u_0) + O(n^{-(r-2)/2})$$

is the function given by (12.64). Bol'shev has applied this result in a number of special cases.

It will be appreciated that it is not essential that $p(x)$ in (12.52) must be a normal probability density function. In particular, if $p(x)$ is a standard gamma probability density function, expansions in terms of Laguerre polynomials are obtained. Such expansions have been discussed by **Khamis** (1958) and applied to approximate the distribution of noncentral F (Chapter 30) by **Tiku** (1965). If $p(x)$ is a standard beta distribution, expansions in terms of Jacobi polynomials are obtained, but these have not been much used.

Woods and Posten (1968) have made a systematic study of the use of Fourier series expansions in calculating cumulative distribution functions. Their methods are based on the following theorem: If X is a random variable with $F_X(x) = 0, 1$ for $x < 0, x > 1$, respectively, then for $0 \leq x \leq 1$,

$$F_X(x) = 1 - \theta\pi^{-1} - \sum_{j=1}^{\infty} b_j \sin j\theta, \quad (12.65)$$

where

$$\theta = \cos^{-1}(2x - 1)$$

and

$$b_j = 2(j\pi)^{-1}E[\cos(j \cos^{-1}(2X - 1))].$$

(The function of which the expected value is to be taken is the j th Chebyshev polynomial $T_j(x)$; see Chapter 1, Section A1.)

Woods and Posten also use a generalized form of this theorem which expresses $F_X(x)$ in terms, of any conveniently chosen "distribution function" $G(x)$, with $G(x) = 0, 1$ for $x < 0, x > 1$, respectively. For $0 \leq x \leq 1$,

$$F_X(x) = G(x) - \sum_{j=1}^w d_j \sin j\theta, \quad (12.66)$$

with

$$d_j = b_j - 2(j\pi)^{-1} \int_0^1 T_j(x) dG(x).$$

Appropriate choice of $G(x)$ —usually close to $F_X(x)$ —can increase the rate of convergence of the infinite series, though the d 's are not so easily computed as the b 's. There are similar results for the case when $F_X(x) = 0, 1$ for $x < -1, x > 1$.

Computer programs based on these theorems are given in Woods and Posten (1968) for evaluating the cumulative distribution and percentage points of the beta, F and chi-square distributions (Chapters 25, 27, and 18, respectively) and of the noncentral forms of these distributions (Chapters 30 and 29). In Chapter 25 (Section 6) some further details are given in regard to the application of these series to the beta distributions.

A book by Hall (1992) contains an excellent exposition of Edgeworth expansions and their properties. It includes the use of *tilted* Edgeworth expansions, designed for use when greater accuracy is required in certain parts (e.g., in upper or lower tails) of the distribution.

43 Transformed Distributions

If the distribution of a random variable X is such that a simple explicit function $f(X)$ has a well-known distribution, it becomes possible to use the results of research on the latter—including published tables—in studying the former distribution. The best known of such distributions is the *lognormal* distribution (Chapter 14) where $\log(X - \xi)$ has a normal distribution. Other well-known families of distributions correspond to cases in which $(X - \xi)^c$ or $e^{-(X-\xi)}$ have exponential distributions [Type II (or Weibull) and Type III extreme value distributions, respectively; see Chapters 21 and 22].

Edgeworth (1916, 1917) considered the possibility of polynomial transformations to normality. To make sure the **transformation** is monotonic, it is necessary to impose restrictions on the coefficients in the polynomial. This analysis is rather complicated and this kind of transformation is not often used at present.

Plotting on probability paper* will indicate the form of the transformation. One of the earliest papers on this method is **Kameda (1928)**. Further references include Flapper (1967) and Chambers and Fowlkes (1966). Sets of "model plots" of quantiles of various distributions against those of the unit normal distribution contained in the latter reference can be helpful in deciding on suitable transformations.

By analogy with the **Pearson** system of distributions, it would be convenient if a simple transformation to a normally distributed variable could be found such that, for any possible pair of values $\sqrt{\beta_1}, \beta_2$ there is just one member of the corresponding family of distributions. No such single simple transformation is available, but Johnson (1949, 1954) and Tadikamalla and Johnson (1982, 1989) have described sets of three such transformations which, when combined, do provide one distribution corresponding to each pair of values $\sqrt{\beta_1}$ and β_2 . We now describe the sets presented in 1949 in some detail.

One of the three transformations is simply

$$Z = \gamma + \delta \log(X - \xi), \quad X \geq \xi, \quad (12.67a)$$

which corresponds to the family of lognormal distributions. The others are

$$Z = \gamma + \delta \log\left\{\frac{X - \xi}{\xi + \lambda - X}\right\}, \quad \xi \leq X \leq \xi + \lambda, \quad (12.67b)$$

$$Z = \gamma + \delta \sinh^{-1}\left\{\frac{X - \xi}{\lambda}\right\}. \quad (12.67c)$$

The distribution of Z is, in each case, unit normal. The symbols γ , δ , ξ , and λ represent parameters. The value of λ must be positive, and we conventionally make the sign of δ positive also.

The range of variation of X in (12.67b) is bounded and the corresponding family of distributions is denoted by S_B ; in (12.67c) the range is unbounded, and the symbol S_U is used. For lognormal distributions the range is bounded below (if $\delta < 0$, it would be bounded above).

It is clear that the shapes of the distribution of X depends only on the parameters γ and δ (δ only, for lognormal). Writing $Y = (X - \xi)/\lambda$, we have

$$Z = \gamma' + \delta \log Y, \quad \text{for lognormal } (\gamma' = \gamma - \delta \log \lambda), \quad (12.68a)$$

$$Z = \gamma + \delta \log\left\{\frac{Y}{1 - Y}\right\}, \quad \text{for } S_B, \quad (12.68b)$$

$$Z = \gamma + \delta \sinh^{-1} Y, \quad \text{for } S_U, \quad (12.68c)$$

*Probability paper is graph paper designed so that a plot of the cumulative frequency against the variable value would give a linear relation for a specified distribution—often the normal distribution.

and Y must have a distribution of the same shape as X . The moments of Y in (12.68a) are given in Chapter 14.

For S_B , from (12.68b),

$$\mu'_r(Y) = (\sqrt{2\pi})^{-1} \int_{-\infty}^{\infty} [1 + e^{-(z-\gamma)/\delta}]^{-r} e^{-z^2/2} dz.$$

Although it is possible to give explicit expressions for $\mu'_r(Y)$ (not involving integral signs) [see Johnson (1949), equations (56) and (57)], they are very complicated.

It is interesting to note that for S_B distributions,

$$\frac{\partial \mu'_r}{\partial \gamma} = \frac{r}{\delta} (\mu'_{r+1} - \mu'_r), \tag{12.69a}$$

$$\frac{\partial \mu'_r}{\partial \delta} = \frac{r}{\delta^3} (\gamma\delta - r)(\mu'_r - \mu'_{r+1}) + \frac{r(r+1)}{\delta^3} (\mu'_{r+1} - \mu'_{r+2}). \tag{12.69b}$$

For S_s , however, we obtain from (12.68a),

$$\mu'_r(Y) = (\sqrt{2\pi})^{-1} 2^{-r} \int_{-\infty}^{\infty} [e^{(z-\gamma)/\delta} - e^{-(z-\gamma)/\delta}]^r e^{-z^2/2} dz \tag{12.70}$$

and this can be evaluated in a straightforward manner, yielding the following values for the expected value, and lower central moments of Y :

$$\mu'_1(Y) = \omega^{1/2} \sinh R, \tag{12.71a}$$

$$\mu_2(Y) = \frac{1}{2}(\omega - 1)(\omega \cosh 2\Omega + 1), \tag{12.71b}$$

$$\mu_3(Y) = -\frac{1}{4}\omega^{1/2}(\omega - 1)^2\{\omega(\omega + 2)\sinh 3\Omega + 3\sinh \Omega\}, \tag{12.71c}$$

$$\begin{aligned} \mu_4(Y) = \frac{1}{8}(\omega - 1)^2\{\omega^2(\omega^4 + 2\omega^3 + 3\omega^2 - 3)\cosh 4\Omega + 4\omega^2(\omega + 2) \\ \times \cosh 2\Omega + 3(2\omega + 1)\}, \tag{12.71d} \end{aligned}$$

where $\omega = \exp(\delta^{-2})$, $\Omega = \gamma/\delta$. Note that $\omega > 1$ and that μ_3 , so $\alpha_3 (= \sqrt{\beta_1})$ has the *opposite* sign to γ . For $\gamma = 0$, the shape factors (for both X and Y) are

$$\alpha_3^2 = \beta_1 = 0,$$

$$\alpha_4 = \beta_2 = \frac{1}{2}(\omega^4 + 2\omega^2 + 3).$$

As γ increases both β_1 and β_2 increase, and the (β_1, β_2) point approaches the point with coordinates $[(\omega - 1)(\omega + 2)^2, \omega^4 + 2\omega^3 + 3\omega^2 - 3]$ as $\gamma \rightarrow \infty$. **The** latter point is on the "lognormal line" (see Chapter 14). It corresponds to a lognormal distribution defined by (12.67a).

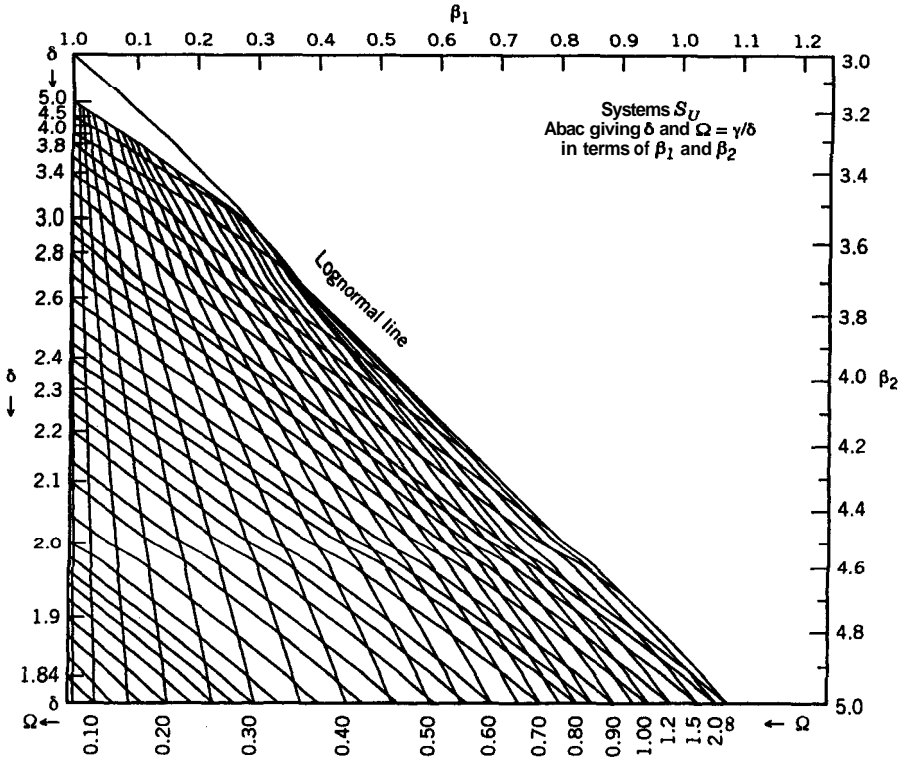


Figure 12.4 Abac for S_U

The variation of (β_1, β_2) with γ and δ is shown diagrammatically in Figure 12.4. This figure can be used to obtain approximate values of γ and δ , for given β_1 and β_2 (note that the sign of γ must be opposite to that of $\sqrt{\beta_1}$; see above). More accurate values can be obtained using tables in Johnson (1965), possibly combined with methods of iterative calculation described in that reference. Methods of fitting based on order statistics have been described by Mage (1982), Slifker and Shapiro (1980), and Wheeler (1980). Siekierski (1992) contains a useful comparative study of methods of fitting.

It can be seen from Figure 12.4 (and proved analytically) that for any (β_1, β_2) point "below" the lognormal line, there is an appropriate S_U distribution. Similarly for any possible point "above" the lognormal line there is an appropriate S_B distribution. In fact the lognormal, S_U and S_B families (or systems) cover the whole possible (β_1, β_2) plane uniquely—namely there is just one appropriate distribution corresponding to each (β_1, β_2) point. The normal distribution, corresponding to the point $(0, 3)$, has to be considered as the limiting form of all three families as $\delta \rightarrow \infty$.

Some typical probability density functions belonging to the S_B and S_U families are shown in Figures 12.5a-f (S_B) and 12.6a-c (S_U) [taken from

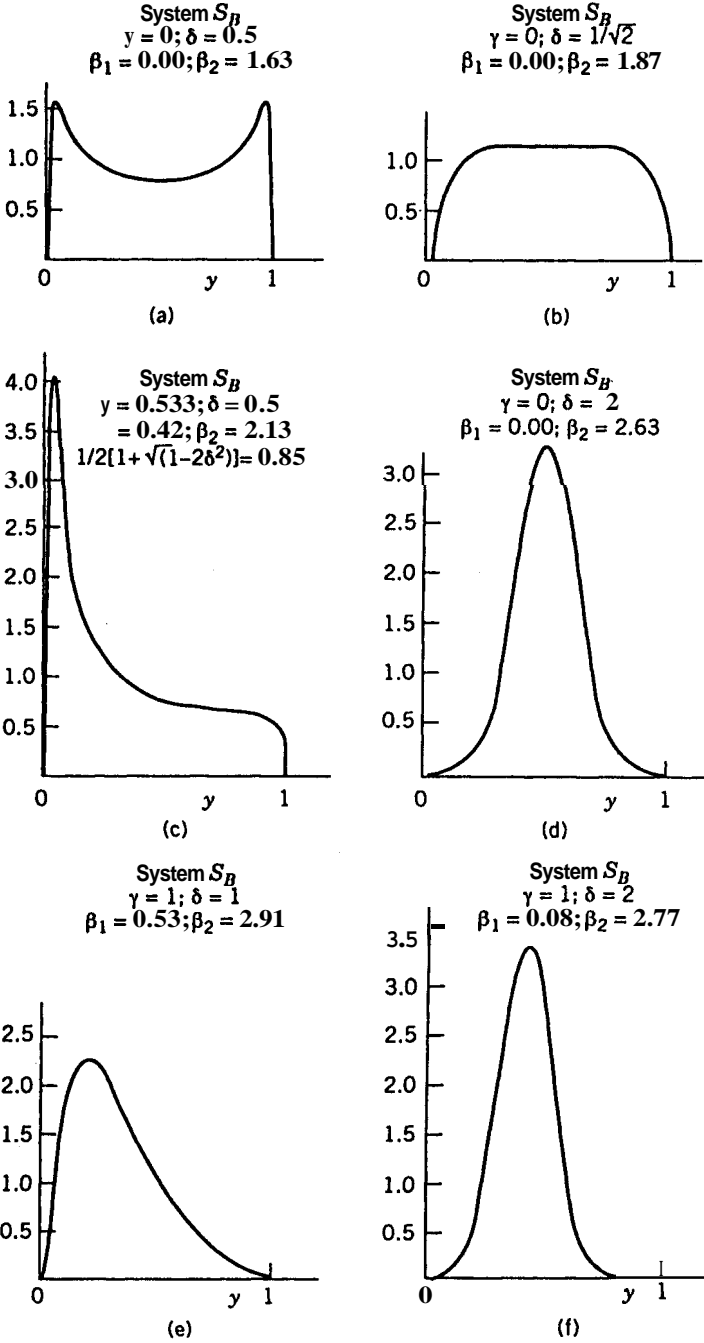


Figure 12.5 System S_B Density Functions

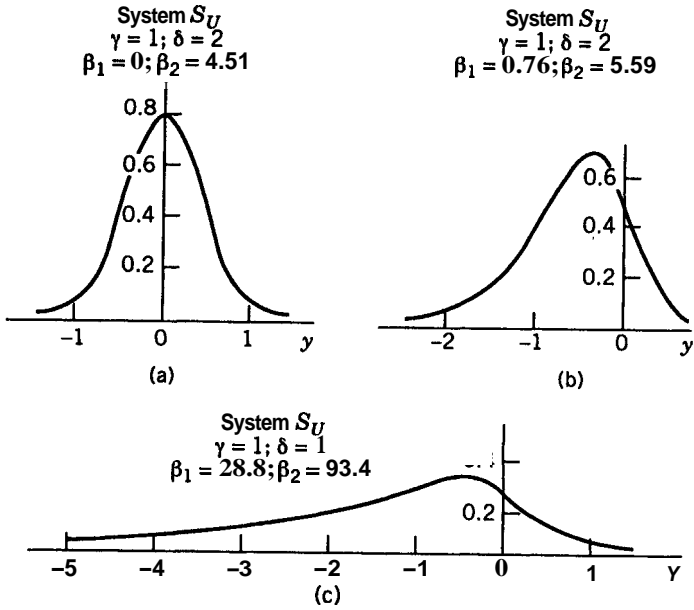


Figure 12.6 System S_U Density Functions

Johnson (1949)]. All S_U curves are unimodal; S_B curves may be unimodal, or they may have two modes, with an **antimode** between them. The latter case occurs if

$$\delta < 1/\sqrt{2},$$

$$|\gamma| < \delta^{-1} \sqrt{1 - 2\delta^2} - 2\delta \tanh^{-1} \sqrt{1 - 2\delta^2}. \quad (12.72)$$

There are transition cases in which one mode and the **antimode** coalesce into a point of inflection (see Figures 12.5a, c). If $\gamma = 0$ and $S = 1/\sqrt{2}$ (Figure 12.5b), a flat-topped distribution is obtained.

For all S_B and S_U (and also lognormal) distributions there is "high contact" at the extremities of the range of variation. That is to say, not only does the probability density function tend to zero as the extremity is approached, but so do all derivatives. (This applies as $Y \rightarrow \pm\infty$, as well as when the extremities are finite.) This property is not shared by all Pearson system distributions.

Numerical comparisons of the cumulative distribution functions of the Pearson Type IV and S_U distributions corresponding to the same pair of values of β_1 and β_2 indicate remarkably close agreement. Distributions of either system may often be used in place of their counterpart in the other system with low risk of errors of practical importance being incurred. Agreement is poorest in the lower tails for large β_1 and/or β_2 . Rieck and

Nedelman (1991) introduce a sort of reverse S'_{UJ} system, wherein X is distributed as a linear function of $\sinh^{-1}((Z - \gamma)/\delta)$, with Z having a unit normal distribution. Thus

$$Z = \gamma + \delta \sinh\left(\frac{X - \xi}{\lambda}\right). \quad (12.73)$$

Analogous sets of three transformations, with Z [in equations (12.68)] having (1) a standard Laplace distribution (S'_L, S'_B, S'_{UJ}) or (2) a standard logistic distribution (L_L, L_s, L_{UJ}) have been described by Johnson (1954) and Tadikamalla and Johnson (1982), respectively. These two sets possess similar properties to S_L, S_s, S_s . Among these properties are the following:

1. They cover the (β_1, β_2) plane uniquely with $S'_B(L_B)$ "above" and $S'_{UJ}(L_{UJ})$ "below" the dividing log-Laplace (log-logistic) line.
2. The S'_B and L_s curves are bimodal for (β_1, β_2) "above" a line in the $S'_B(L_B)$ area, while all the S'_{UJ} and L_s curves are unimodal.

Transformations of a standard uniform variable U whose pdf is

$$p_U(u) = 1, \quad 0 < u < 1$$

(see Chapter 26) have the useful feature that it is very easy to simulate observed values.

Tukey lambda distributions [Hastings et al. (1947); Tukey (1962)] are defined by the transformation

$$X = \frac{aU^\lambda - (1 - U)^\lambda}{\lambda}, \quad a > 0, \lambda \neq 0; \quad -\lambda^{-1} \leq X \leq \lambda^{-1} \text{ for } \lambda > 0, \quad (12.74a)$$

with the transitional $\lambda = 0$ transformation

$$X = \log\left\{\frac{U^a}{1 - U}\right\}, \quad a > 0. \quad (12.74b)$$

Transformations (12.74a) and (12.74b) are each monotonic increasing, so if $\lambda \neq 0$,

$$x = \frac{au^\lambda - (1 - u)^\lambda}{\lambda},$$

then

$$F_X(x) = u,$$

since $F_U(u) = u$, $0 \leq u \leq 1$. Also $F_X(X)$ has a standard uniform distribution, so the transformations (12.74a) and (12.74b) can be regarded as expressions for X corresponding to a specified value F of $F_X(x)$. Expressed differently,

$$x(F) = x = \frac{aF^\lambda - (1 - F)^\lambda}{\lambda}, \quad a > 0, \lambda \neq 0, \quad (12.74a)'$$

and

$$X = \log \left\{ \frac{U^a}{1 - U} \right\}, \quad a > 0. \quad (12.74b)'$$

Originally attention was mainly directed at the symmetrical Tukey lambda distributions $a = 1$, defined by

$$X = \frac{U^\lambda - (1 - U)^\lambda}{\lambda}, \quad \lambda \neq 0, \quad (12.75a)$$

and

$$X = \log \left(\frac{U}{1 - U} \right) \quad (\text{corresponding to } \lambda \rightarrow 0). \quad (12.75b)$$

The lower quartile, median and upper quartile for (12.74a) are obtained by putting $U = \frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$, which yields

$$(a - 3^\lambda)(4^\lambda \lambda)^{-1}, \quad (a - 1)(2^\lambda \lambda)^{-1} \quad \text{and} \quad (3^\lambda - 1)(4^\lambda \lambda)^{-1},$$

respectively. The value of Galton's skewness index

$$\frac{\text{Lower quartile} + \text{Upper quartile} - 2(\text{Median})}{\text{Upper quartile} - \text{Lower quartile}}$$

is given by

$$\frac{a - 1}{a + 1} \frac{3^\lambda - 2^{\lambda+1} + 1}{3^\lambda - 1} \quad (12.76)$$

For (12.74a) the r th moment about zero of X is

$$\begin{aligned} \mu'_r(X) &= \frac{1}{\lambda^r} \int_0^1 \{au^\lambda - (1 - u)^\lambda\}^r du \\ &= \frac{1}{\lambda^r} \sum_{j=0}^r (-1)^j \binom{r}{j} a^{r-j} B(\lambda(r - j) + 1, \lambda j + 1). \end{aligned} \quad (12.77)$$

In particular, the expected value and variance are

$$E[X] = \lambda^{-1}(\lambda + 1)^{-1}(a - 1) \quad (12.78a)$$

and

$$\text{Var}(X) = (\lambda + 1)^{-1}(2\lambda + 1)^{-1}(a^2 + 1) - 2\lambda^{-2}\{B(\lambda + 1, \lambda + 1) - (\lambda + 1)^{-2}\}a. \quad (12.78b)$$

Joiner and Rosenblatt (1971) provide a detailed analysis for the **symmetrical** distributions (12.75a). They point out that although explicit formulas for the pdf of X are not generally available, the values $A = 1$ and $A = 2$ both correspond to uniform distributions for X [over range $(-1, 1)$, $(-\frac{1}{2}, \frac{1}{2})$, respectively]. Also, for appropriate values of A , very good approximations to normal and t distributions (Chapter 13) can be obtained. They suggest that $A = 0.135$ for normal approximation. (Of course location and scale parameters can be introduced to give any required expected value and standard deviation.) The least possible value of β_2 is 1.75 (**approx.**). For any value greater than this, there are *two* possible values of A . Thus for $\beta_2 = 3$ (as for a normal distribution) the values of A are 0.135 (as suggested above) and *also* 5.2. The two corresponding pdf's (standardized to have expected value zero and standard deviation 1) are shown in Figure 12.7 [taken from Joiner and Rosenblatt (1971)]. The pdf's of X are slightly U-shaped for $1 < A < 2$; they are unimodal for $A < 1$ or $A > 2$.

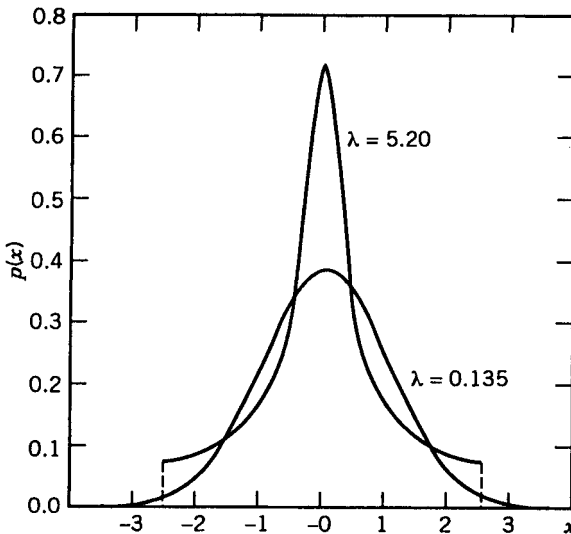


Figure 12.7 Probability Density Functions for Standardized Lambda Distributions, Each Having $\beta_2 = 3.00$ (and $\beta_1 = 0$)

Ramberg (1975) deals with distributions defined by a slight modification of (12.74a), namely

$$X = \lambda_1 + \frac{aU^{\lambda_3} - (1 - U)^{\lambda_3}}{\lambda_2}. \quad (12.74c)$$

He shows that the (β_1, β_2) points cover the whole plane except those "above" a line joining the uniform (0, 1.8) and exponential (4, 9) points [in the **Pearson Type I** (beta) area]. He gives tables of values of A , A_1 , and A_2 , producing specified values for β_1 and β_2 for a standardized variable.

Skew distributions for X can be obtained in other ways than by putting $a \neq 1$ in (12.74a). Johnson and Kotz (1973) replace U in (12.75a) by T , where T has a standard beta (θ, ϕ) distribution. The resulting pdf of X is

$$p_X(x) = \{B(\theta, \phi)\}^{-1} \{t(x)\}^{\theta-1} \{1 - t(x)\}^{\phi-1} \times \left[\{t(x)\}^{\lambda-1} + \{1 - t(x)\}^{\lambda-1} \right]^{-1}, \quad (12.79)$$

where $t(x)$ satisfies the equation

$$x = \frac{\{t(x)\}^\lambda - \{1 - t(x)\}^\lambda}{\lambda} \quad (12.80)$$

In general there is no explicit formula for $p_X(x)$, as we have already noted. The r th moment about zero is

$$\mu'_r(X) = \{B(\theta, \phi)\}^{-1} \lambda^{-r} \sum_{j=0}^r \binom{r}{j} (-1)^j B(\theta + (r - j)\lambda, \phi + j\lambda). \quad (12.81)$$

Clearly $p_X(x) \rightarrow 0$ or ∞ at the extremes of the range of variation of X , according as $p_T(t) \rightarrow 0$ or ∞ , for $A > 1$.

We now consider the variation in shape of the distribution of X with changes in A , the parameters θ and ϕ having fixed values. Since $X - (1 - X) = 2X - 1 = X^2 - (1 - X)^2$, we see that the values of $\sqrt{\beta_1}$ and β_2 must be the same for $A = 1$ and $A = 2$. In each one of these two cases we have a beta distribution with the same parameters, though different range, as that of the original variables. By virtue of the continuity of the function involved, β_2 must take a maximum or minimum value for some value of A between 1 and 2. It is in fact a minimum when $\theta = \phi$, but can be a maximum when $\theta \neq \phi$, and occurs for a value of A in a remarkably narrow range about $A = 1.45$; see Table 12.1 for a few examples. By considering neighboring loci of $(\sqrt{\beta_1}, \beta_2)$ for varying A , with slightly different values of θ and ϕ it can be seen that at

Table 12.1 Values of A Giving Maximum or Minimum β_2

θ	ϕ	λ	$\sqrt{\beta_1}$	β_2	θ	ϕ	λ	$\sqrt{\beta_1}$	β_2
0.5	0.5	1.44	0	1.469"	2	2	1.46	0	2.086"
0.5	1.0	1.47	0.662	2.134"	2	5	1.48	0.661	2.944
0.5	2.0	1.44	1.318	3.987	2	10	1.46	1.035	4.090
0.5	5.0	1.43	2.109	8.171	2	15	1.44	1.195	4.752
0.5	10.0	1.41	2.549	11.69	5	5	1.48	0	2.489"
1	1	1.45	0	1.753	5	10	1.51	0.380	2.836
1	2	1.44	0.604	2.401	5	15	1.48	0.551	3.155
1	5	1.45	1.299	4.549	10	10	1.49	0	2.705^a
1	10	1.43	1.688	6.573	10	15	1.48	0.179	2.804"

"Minimum.

least for some values of $\sqrt{\beta_1}$ and β_2 , there will be more than one set of values (θ, ϕ, A) giving these values for the shape parameters.

This might be expected, since there are three parameters available to give two specified values $\sqrt{\beta_1}$ and β_2 . Another way of looking at the situation is to consider what happens when A is fixed, but θ and ϕ vary. It is known that for $A = 1$, the region between the boundary $\beta_2 - (\sqrt{\beta_1})^2 - 1 = 0$, and the Type III line $2\beta_2 - 3(\sqrt{\beta_1})^2 - 6 = 0$ is covered. For $A > 0$, generally, the region covered is that between the line $\beta_2 - (\sqrt{\beta_1})^2 - 1 = 0$, and the line [Johnson and Kotz (1972)] corresponding to (Type III variable)! The latter is approached as $\phi \rightarrow \infty$, with θ remaining constant.

From (12.79) we see that $dp_X(x)/dx = 0$ if

$$y^{\lambda-1} = \frac{1 - \lambda y + (\phi y - \theta)}{y - \lambda - (\phi y - \theta)} = g(y), \text{ say,} \tag{12.82}$$

where $y = t(x)\{1 - t(x)\}^{-1}$. If $\theta = \phi = 1$, we find that $g(y) = y$. Then the only possible modal values are $y = 0, 1$, or ∞ [i.e., $t(x) = 0, \frac{1}{2}$ or 1 corresponding to $x = -\lambda, 0$, or A].

For $A < 1 < \min(\theta, \phi)$, $g(y)$ increases from 0 to ∞ as y increases from $(\theta - 1)/(\phi - A)$ to $(\theta - \lambda)/(\phi - 1)$, while $y^{\lambda-1}$ decreases as u increases. Equation (12.82) thus has just one root, since for y outside this range $g(y)$ is negative, and so the distribution of X is unimodal.

A similar situation, in reverse, holds if $1 < A < \min(\theta, \phi)$. If $\phi < \min(1, A)$ and $\theta > \max(1, A)$, then $g(y)$ is always negative for $u > 0$, and (12.82) has no solution. In this case, since $\theta > 1$ and $\phi < 1$, $p_X(x) \rightarrow 0$ as $y \rightarrow -1$ and $\rightarrow \infty$ as $y \rightarrow 1$. The density function of X is J-shaped, as is that of T . Related results hold similarly if $\phi > \max(1, A)$ and $\theta < \min(1, A)$. For $\phi > 1$ and $\theta > 1$, $p_Y(y) = 0$ at $t = 0$ or 1; hence, the slope of $p_X(x)$ is also zero at these points.

An interesting special case corresponds to $A = \theta + \phi - 1$. Then (12.82) becomes

$$y = \left(\frac{\theta - 1}{\phi - 1} \right)^{(\theta + \phi - 2)^{-1}} \quad (12.83)$$

In the symmetrical case $\theta = \phi$, (12.82) is satisfied by $y^{\lambda-1} = 1$, whence $t = \frac{1}{2}$ and the corresponding modal value for X is 0 , as is to be expected. The distribution can, however, be bimodal, with **antimode** at 0 . This is so, for example, if $A > 1$ and $\theta = \phi < \frac{1}{2}(\lambda^2 - A + 2)$. Moments of order statistics are easily obtained. Joiner and Rosenblatt (1971) give formulas for the r th moment of X'_i and for the expected value and variance of the range in random samples of size n .

Other systems that include asymmetric distributions are

$$X = \begin{cases} -\lambda_1(\lambda_2 - U)^{\lambda_3}, & \lambda_2 \geq U, \\ \lambda_1(U - \lambda_2)^{\lambda_3}, & \lambda_2 \leq U \end{cases} \quad (12.84)$$

[Schmeiser and Deutsch (1977), quoted by Butterworth (1987)],

$$X = U^{\lambda_1} - (1 - U)^{\lambda_2} \quad (\lambda_1 \neq \lambda_2) \quad (12.85)$$

[**Ramberg** and Schmeiser (1974); **Ramberg et al.** (1979)]. As in all cases, location and scale parameters can be introduced to give desired values for expectation and variance. Transformation (12.84) has the attractive feature that it has a simple explicit inverse.

Lam, Bowman, and Shenton (1980) discuss (12.85). They note, as did Joiner and Rosenblatt (1971) for the symmetrical distribution, that the equations for A , and A , obtained by requiring $\sqrt{\beta_1}$ and β_2 to have specified values may not have unique solutions. Figure 12.8, taken from Lam, Bowman, and Shenton (1980), indicates loci of constant $\sqrt{\beta_1}$ and of constant β_2 as functions of A , and λ_1/λ_2 . This paper also includes comparisons of 1%, 5%, 95%, and 99% points for standardized curves of various systems with common values $\sqrt{\beta_1}, \beta_1$, indicating quite close agreement. Similar more extensive comparisons are available in several other papers [e.g., **Pearson**, Johnson, and Burr (1979)]. The closeness of results is often due to the fact that the different systems can have similar features of smoothness that increase comparability beyond that to be expected from just equality of first four moments. Mallows (1956) provides an interesting study of these possibilities (see also Chapter 33).

Another system of this kind, ascribed to H. A. Thomas by Hosking (1986), quoting Houghton (1978), is defined by the relation

$$X = \xi + \left(\frac{\alpha}{\beta} \right) \{1 - (1 - U)^\beta\} - \left(\frac{\gamma}{\delta} \right) \{1 - (1 - U)^{-\delta}\}. \quad (12.86)$$

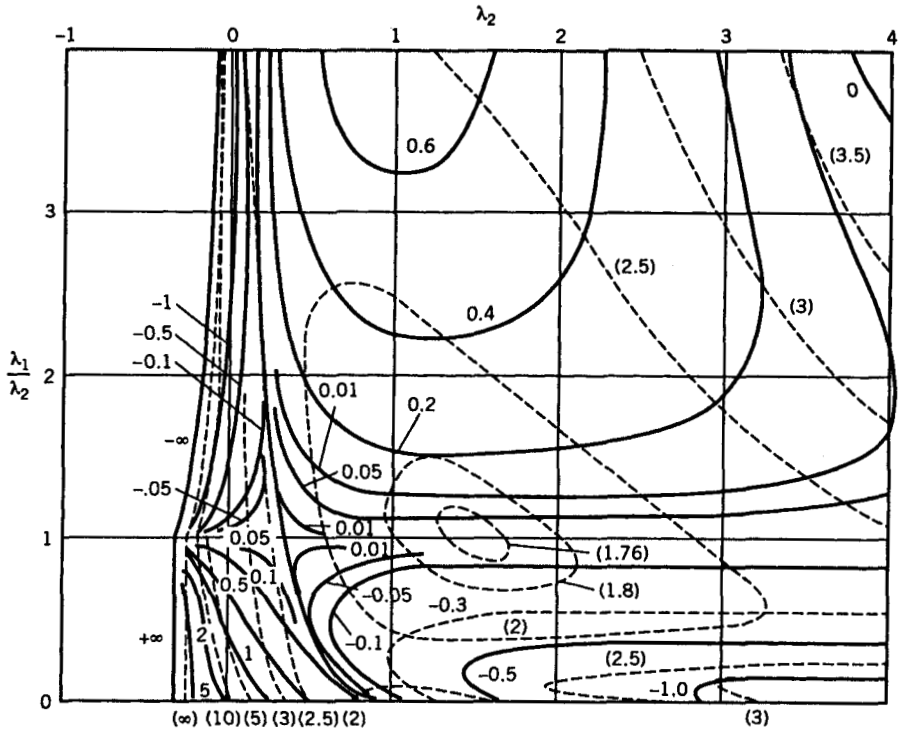


Figure 12.8 Contours of $\sqrt{\beta_1}$ and β_2 for Distribution (12.85). ——— constant $\sqrt{\beta_1}$
 - - - - - constant β_2

Essentially $X = \phi(1 - U)^{-\delta} - \theta(1 - U)^\beta + k$ with $4 = \gamma/\delta$, $\delta = \alpha/\beta$; $k = \xi + \theta - \phi$.

If α , β , γ , and δ are each positive, X is already a monotonic increasing function of U . Since (12.86) is unchanged if α and γ , and β and $-\delta$ are interchanged, it can be assumed, without loss of generality, that $\beta + \delta \geq 0$. The following further conditions ensure uniqueness of the relation between X and U [i.e., equation (12.86) has only one solution]:

1. Either $\beta + \delta > 0$, or $\beta = \gamma = \delta = 0$.
2. If $\alpha = 0$, then $\beta = 0$.
3. If $\gamma = 0$, then $\delta = 0$.
4. $\gamma \geq 0$.
5. $\alpha + \gamma \geq 0$.

These distributions have been used in hydrology to model flood and stream flow data. They are called *Wakeby* distributions.

The range of variation of X is from ξ up to infinity if $\delta \geq 0$ and $\gamma > 0$. If either $\delta < 0$ or $\gamma = 0$, the range is finite, from ξ to $\xi + \alpha/\beta - \gamma/\delta$

(= $\xi + \theta - \phi$). The pdf $p(x)$ of X is related to the cdf $F(x)$ by the formula

$$\begin{aligned}
 p(x) &= [\alpha\{1 - F(x)\}^{\beta-1} + \gamma\{1 - F(x)\}^{-\delta-1}]^{-1} \\
 &= \{1 - F(x)\}^{\delta+1}(\alpha t + \gamma)^{-1}
 \end{aligned}
 \tag{12.87}$$

with

$$t = \{1 - F(x)\}^{\beta+\delta}$$

As $x \rightarrow \xi$,

$$p(x) \rightarrow \begin{cases} \infty & \text{if } \alpha + \gamma = 0, \\ (\alpha + \gamma)^{-1} & \text{if } \alpha + \gamma > 0. \end{cases}$$

As $x \rightarrow \infty$,

$$p(x) \sim \begin{cases} \gamma^{1/\delta}(\delta x)^{-1-1/\delta} & \text{if } \delta > 0, \\ \gamma^{-1} \exp\left(\frac{-x}{\gamma}\right) & \text{if } \delta = 0, \gamma > 0. \end{cases}
 \tag{12.88a}$$

If $\delta < 0$ so that the range is from ξ to $\omega = \xi + \theta - \phi$, then as $x \rightarrow \omega$,

$$p(x) \sim (-\delta^{-1})(-\theta)^{\delta-1}(\omega - x)^{-\delta^{-1}-1} \tag{12.88b}$$

Pdf's of some Wakeby distributions are shown in Figures 12.9, for parameter values shown below ($\xi = 0$ in all cases):

Pdf Number	α	β	γ	δ	Pdf Number	α	β	γ	δ
1	30	20			9	5			
2	1	5	1	0.3	10	0.5	5	1	-0.8
3	1	2			11	0.01			
4	1	0.5			12	-0.5			
5	10	10			13	5			
6	1	3	1		14	0.5	10		
7	1	2		-0.3	15	0.01		1	-1.1
8	1	1	3		16	-0.5	5		
					17	-0.9	1.12	10	
					18	-1.1	1.11	1.11	

The fact that the distributions have three disposable shape parameters (plus location and scale parameters) gives the system considerable flexibility. See also generalized Pareto distributions (Chapter 20, Section 8).

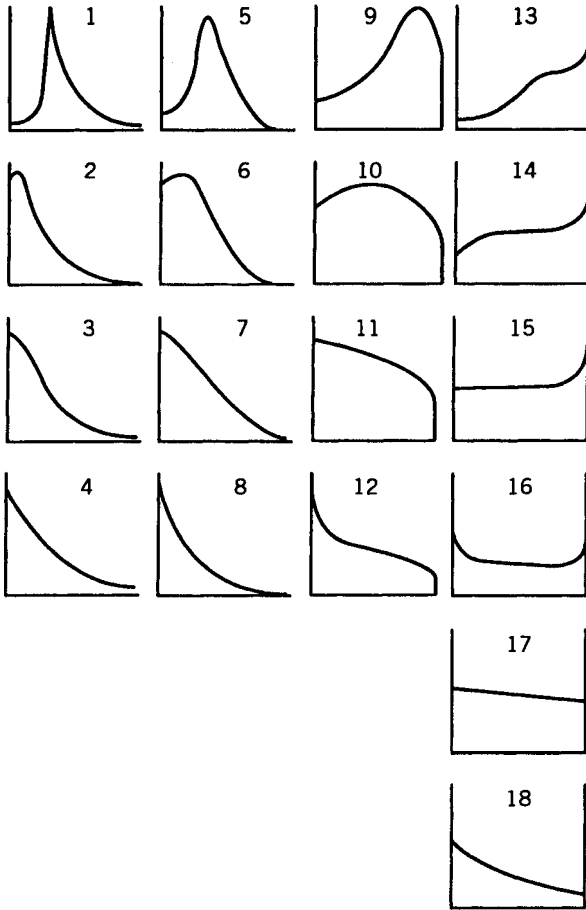


Figure 12.9 Wakeby Probability Density Functions

Hoaglin (1984) describes the *Tukey g- and h-system* obtained by the transformations

$$X = \begin{cases} \xi + \lambda g^{-1} \exp(\frac{1}{2}hZ^2 + gZ - 1), & g \neq 0, \\ \xi + \lambda Z \exp(\frac{1}{2}hZ^2), & g = 0, \end{cases} \quad (12.89)$$

where Z is a unit normal variable. This system covers a large part of the (β_1, β_2) diagram, excluding some symmetrical U-shaped distributions.

Combining the Pearson and Tukey lines of approach, Voit (1992) defines a system of *S-distributions* by the differential equation

$$p(x) = \frac{dF(x)}{dx} = \alpha \left[\{F(x)\}^g - \{F(x)\}^h \right] \quad (12.90)$$

(1983) have discussed the distribution of the kurtosis statistic b_2 based on normal samples. Owen (1980) has presented a valuable table giving formulas for various integrals related to the normal distribution. Some additions to this table have been made by Chou (1981).

Recently, for the U.S. population of men and women aged 17–84 years, Brainard and Burmaster (1992) showed that the normal distribution fits the marginal histograms of height (in cells representing 1-in. intervals) for both genders. Further, they demonstrated that the bivariate histogram for men is fit well by the bivariate normal distribution between the height and the natural logarithm of weight (in cells representing 10-lb intervals).

4 ORDER STATISTICS

Let $X'_1 \leq X'_2 \leq \dots \leq X'_n$ be the order statistics obtained from a random sample of size n from the standard normal distribution (13.4). Then the density of X'_r ($1 \leq r \leq n$) is

$$p_{X'_r}(x) = \frac{n!}{(r-1)!(n-r)!} \{\Phi(x)\}^{r-1} \{1-\Phi(x)\}^{n-r} Z(x),$$

$$-\infty < x < \infty, \quad (13.19)$$

and the joint density of X'_r and X'_s ($1 \leq r < s \leq n$) is

$$p_{X'_r, X'_s}(x, y)$$

$$= \frac{n!}{(r-1)!(s-r-1)!(n-s)!} \{\Phi(x)\}^{r-1} \{\Phi(y) - \Phi(x)\}^{s-r-1}$$

$$\times \{1 - \Phi(y)\}^{n-s} Z(x)Z(y), \quad -\infty < x < y < \infty. \quad (13.20)$$

From (13.19) and (13.20), the single and the product moments of order statistics may be derived. Derivations of these quantities explicitly in terms of some elementary functions have been attempted by numerous authors, including Jones (1948), Godwin (1949a), Ruben (1954, 1956), Watanabe et al. (1957, 1958), Bose and Gupta (1959), and David (1963). These authors have been successful in their attempts at least for small sample sizes. By adopting a differential equation approach and using the characterizing differential equation (of the standard normal density function) $Z^{(1)}(x) = dZ(x)/dx = -xZ(x)$, Bose and Gupta (1959) have shown, for example, that when $n = 2$,

$$E[X'_2] = -E[X'_1] = \frac{1}{\sqrt{\pi}};$$

There are three parameters α , g , and h in (12.90). A fourth (location) parameter ξ is introduced by the condition

$$F(0) = F_X(\xi).$$

a is a scale parameter; g and h determine the shape. This system includes a few standard distributions—notably logistic distributions ($g = 1$, $h = 2$)—and gives good approximations to many others. It is especially well suited for computational work.

The condition $p(x) \geq 0$ requires that $g < h$ [if $g = h$, we have $p(x) = 0$ for all x] and $a \neq 0$. Voit (1992) notes that the distribution of X is symmetric about zero if

$$\{F(x)\}^g - \{F(x)\}^h = \{1 - F(x)\}^g - \{1 - F(x)\}^h \quad \text{for all } x,$$

$$\{F(x)\}^g - \{1 - F(x)\}^g = \{F(x)\}^h - \{1 - F(x)\}^h \quad \text{for all } F(x)$$

in $[0, 1]$, which leads to $g = 1$, $h = 2$ (logistic). [Equation clearly holds if $F(x) = \frac{1}{2}$ at the median of X but not, in general, for other values of x .]

At a mode, with $dp(x)/dx = 0$, we have

$$gp(x)\{F(x)\}^{g-1} = hp(x)\{F(x)\}^{h-1}.$$

So, if $p(x) \neq 0$,

$$g\{F(x)\}^{g-1} = h\{F(x)\}^{h-1}. \quad (12.91)$$

Since $\{F(x)\}^{g-h}$ is a monotonic function of $F(x)$, there is a single mode, at $F^{-1}((g/h)^{1/(h-g)})$.

Pdfs of three \hat{S} -distributions are shown in Figure 12.10, taken from Voit (1992).

Power transformations have generally been the subject of several studies. We will encounter some special cases in later chapters including power transformations of gamma and Pareto variables (generalized gamma and generalized Pareto) in Chapters 17 and 20, respectively. For power transformations to normality, Box and Cox (1964) is a standard reference, though there are several others. They discussed transformations of the form

$$Y = \begin{cases} \frac{X^\lambda - 1}{\lambda}, & \lambda \neq 0, \\ \log X, & \lambda = 0. \end{cases} \quad (12.92)$$

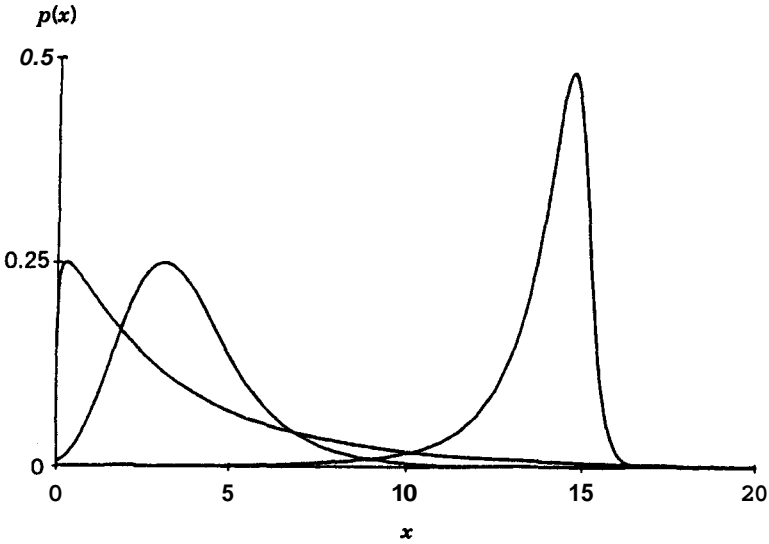


Figure 12.10 Densities of Three S-Distributions. From left to right: $g = 0.25, h = 0.5; g = 0.75, h = 1.5; g = 1.2, h = 5$. In all three cases $\alpha = 1$ and $F(0) = 0.01$.

(The $A = 0$ of course leads to lognormal distributions; see Chapter 14.) This approach is limited to variables X that have support excluding negative values. In particular, X cannot have a normal distribution. Attempts at overcoming this constraint include papers by Moore (1957) and Goto, Inoue, and Tsuchiya (1983, 1987).

Moore (1957) approached the problem by seeking to find numbers $r, m,$ and c such that

$$Z = \frac{X^r - m}{c}$$

is approximately normal, with a very small probability that Z is negative (i.e., m/c is large).

Goto, Matsubara, and Tsuchiya (1983) define a power-normal distribution having pdf,

$$\frac{x^\lambda}{\Phi(\text{sgn}(\lambda)|\lambda m + 1|/\lambda\sigma)} \phi\left(\frac{x^\lambda - 1 - \lambda\mu}{\lambda}\right), \quad \lambda \neq 0, \quad (12.93)$$

where

$$\Phi(u) = (\sqrt{2\pi})^{-1} \int_{-\infty}^u \exp(-\frac{1}{2}t^2) dt;$$

$$\phi(u) = \Phi'(u) = (\sqrt{2\pi})^{-1} \exp(-\frac{1}{2}u^2).$$

4.4 Bessel Function Distributions

McKay (1932) described a system of distributions that would provide (at least) one distribution corresponding to any pair of values (β_1, β_2) for which $(\beta_2 - 3)/\beta_1 > 1.5$ (i.e., "below" the Type III line). In fact for the narrow strip

$$1.5 < \frac{\beta_2 - 3}{\beta_1} \leq 1.57735, \quad (12.94)$$

there are *three* possible distributions of this system corresponding to a single (β_1, β_2) point. Although most of the formulas presented below were derived by McKay, we will first mention a possible genesis of the system constructed by Bhattacharyya (1942). The distributions can in fact be obtained as distributions of $X_1\sigma_1^2 \pm X_2\sigma_2^2$ where X_1, X_2 are mutually independent random variables, each distributed as χ^2 with ν degrees of freedom (see Chapter 18).

The distribution of $Y = X_1\sigma_1^2 + X_2\sigma_2^2$ is the first of McKay's forms. It has probability density function

$$p(y) = \frac{|1 - c^2|^{m+1/2}|y|^m}{\pi^{1/2}2^m b^{m+1}\Gamma(m + \frac{1}{2})} e^{-cy/b} I_m\left(\left|\frac{y}{b}\right|\right), \quad y > 0, \quad (12.95)$$

with

$$\begin{aligned} b &= 4\sigma_1^2\sigma_2^2(\sigma_1^2 - \sigma_2^2)^{-1}, \\ c &= (\sigma_1^2 + \sigma_2^2)(\sigma_1^2 - \sigma_2^2)^{-1} > 1, \\ m &= 2\nu + 1. \end{aligned}$$

The distribution of $Z = X_1\sigma_1^2 - X_2\sigma_2^2$ is the second of McKay's forms. It has probability density function

$$p_Z(z) = \frac{|1 - c^2|^{m+1/2}|y|^m}{\pi^{1/2}2^m b^{m+1}\Gamma(m + \frac{1}{2})} e^{-cz/b} K_m\left(\left|\frac{z}{b}\right|\right), \quad (12.96)$$

with

$$\begin{aligned} b &= 4\sigma_1^2\sigma_2^2(\sigma_1^2 + \sigma_2^2)^{-1}, \\ c &= -(\sigma_1^2 - \sigma_2^2)(\sigma_1^2 + \sigma_2^2)^{-1}, \quad |c| < 1, \\ m &= 2\nu + 1. \end{aligned}$$

In (12.95) and (12.96), $I_m(\cdot)$ and $K_m(\cdot)$ are modified Bessel functions (of the first and second kind, respectively) of order m (see Chapter 1, Section 3).

when $n = 3$,

$$E[X'_3] = -E[X'_1] = \frac{3}{2\sqrt{\pi}}, \quad E[X'_2] = 0;$$

when $n = 4$,

$$E[X'_4] = -E[X'_1] = \frac{6}{\pi\sqrt{\pi}} \tan^{-1} \sqrt{2},$$

$$E[X'_3] = -E[X'_2] = \frac{6}{\sqrt{\pi}} - \frac{18}{\pi\sqrt{\pi}} \tan^{-1} \sqrt{2};$$

and when $n = 5$,

$$E[X'_5] = -E[X'_1] = \frac{15}{\pi\sqrt{\pi}} \tan^{-1} \sqrt{2} - \frac{5}{2\sqrt{\pi}},$$

$$E[X'_4] = -E[X'_2] = \frac{10}{\sqrt{\pi}} - \frac{30}{\pi\sqrt{\pi}} \tan^{-1} \sqrt{2}, \quad E[X'_3] = 0.$$

This method, however, fails to give explicit expressions in terms of elementary functions for expected values of order statistics in samples of size 6 or more. It is of interest to mention that Ruben (1954), who has shown that the single moments of order statistics can be expressed as linear functions of the contents of certain hyperspherical simplices, noted that for dimension greater than three these contents cannot be expressed in terms of elementary functions. This possibly explains why the method of Bose and Gupta fails at sample size 6. Renner (1976) has discussed the evaluation of expected values by means of power series for sample sizes six and seven.

Similar explicit formulas may be derived for the product moments of order statistics from small sample sizes. First, it is clear that when $n = 2$,

$$E[X'_1 X'_2] = E[X_1 X_2] = E[X_1] E[X_2] = 0.$$

Following the differential equation approach, it can be shown that when $n = 3$,

$$E[X'_1 X'_2] = E[X'_2 X'_3] = \frac{\sqrt{3}}{2\pi}, \quad E[X'_1 X'_3] = -\frac{\sqrt{3}}{\pi},$$

For both kinds of distributions (12.95) and (12.96) the moment-generating function is

$$\left[(1 - c^2) \{ 1 - (c - tb)^2 \}^{-1} \right]^{m+1/2}$$

(with of course appropriate values of b and c , depending on which kind of distribution is being considered).

It follows that the r th cumulant is

$$\kappa_r = (r - 1)! (m + \frac{1}{2}) b^r (c^2 - 1)^{-r} [(c - 1)^r + (c + 1)^r]. \quad (12.97)$$

(This can be established directly from **Bhattacharyya's** approach.) In particular

$$\begin{aligned} \mu'_1 &= (2m + 1)bc(c^2 - 1)^{-1}, \\ \mu_2 &= (2m + 1)b^2(c^2 + 1)(c^2 - 1)^{-2}, \\ \beta_1 &= 4c^2(c^2 + 3)^2(2m + 1)^{-1}(c^2 + 1)^{-3}, \\ \beta_2 &= 3 + 6(c^4 + 6c^2 + 1)(2m + 1)^{-1}(c^2 + 1)^{-2}. \end{aligned} \quad (12.98)$$

$\sqrt{\beta_1}$ has the opposite sign to c . From the last two equations of (12.98) it can be shown that

$$2c^2(c^2 + 3)^2 \left(\frac{\beta_2 - 3}{\beta_1} \right) - 3(c^2 + 1)(c^4 + 6c^2 + 1) = 0. \quad (12.99)$$

Regarded as a cubic equation in c^2 , (12.99) has a single positive root for

$$\frac{\beta_2 - 3}{\beta_1} > 1.57735,$$

and three positive roots for $(\beta_2 - 3)/\beta_1 > 1.5$. [The three positive roots are given by McKay (1932) to 5 significant figures for $(\beta_2 - 3)/\beta_1 = 1.502(0.002)1.576$.] For the region between the line

$$\beta_2 - 1.57735\beta_1 - 3 = 0 \quad (12.100)$$

(termed the *Bessel line* by McKay) and the axis of β_2 there is a unique "Bessel distribution" corresponding to any given (β_1, β_2) point. Figure 12.11 [taken from Bhattacharyya (1942)] shows how the values of m and c^2 vary over this region, which was called the K-region by McKay [because only distributions of form (12.96) can be used here]. This diagram also shows how

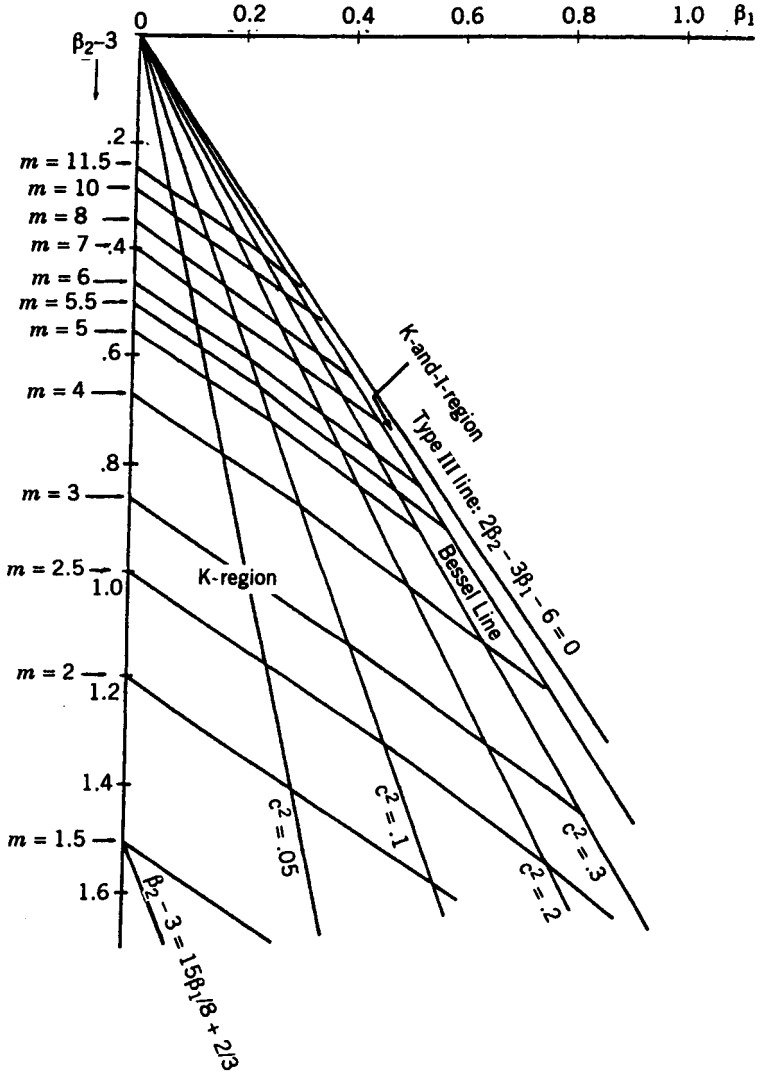


Figure 12.11 Bessel Distribution Regions in (β_1, β_2) Plane

narrow is the **K and I region**, where there are two distributions of form (12.95) and one of form (12.96) for each pair of values (β_1, β_2) .

It would seem that the **K-form** (12.96) is likely to be more generally useful than the **I-form** (12.95). Indeed, it has been suggested that (12.96) would lead to less troublesome computation than the **Pearson Type IV** distributions that have the same (β_1, β_2) values. However, the **I-form** (12.95) has been used [Bose (1938)] for graduating an observed frequency distribution. Also the

family of **I-distributions** include the noncentral χ^2 distributions [see **Laha** (1953) and Chapter 29] and the distribution of the **Mahalanobis** D^2 -statistic. A generalization of the K-form, with probability density function proportional to $|z|^{m'} K_m(|z/b|)$, $m' \neq m$, has been studied by **Sastry** (1948).

McNolty (1967) has described the application of Bessel function **I-distributions** to the distributions of signal or noise in output processed by a radar receiver under various sets of conditions. This paper contains interesting accounts of how the Bessel distribution might be expected to arise in each case. **McLeish** (1982) suggests the family of symmetrical distributions (of T) generated by $T = G^{1/2}Z$, where G has a gamma ($\alpha, 2$) distribution (see Chapter 17) and Z is a unit normal variable, independent of G , as "robust alternatives" to the normal distribution, in the sense of possessing robust maximum likelihood estimators. The resulting distribution has pdf,

$$p_T(t) = g(t) = \frac{1}{\sqrt{\pi} \Gamma(\alpha)} \left(\frac{|t|}{2} \right)^{\alpha-1/2} K_{\alpha-1/2}(t).$$

If α is an integer, we have

$$g_\alpha(t) = \frac{e^{-|t|}}{2^{2\alpha-1}} \sum_{j=0}^{\alpha-1} \binom{2\alpha-1-j}{\alpha-1} \frac{|2t|^j}{j!}.$$

Location and scale parameters may be introduced in the usual way. **McLeish** (1982) notes that this distribution was defined by **Pearson**, **Jeffery**, and **Elderton** (1929) and studied in **Pearson**, **Stouffer**, and **David** (1932), and that a more general family with pdf,

$$p_T(t) = (1 - a^2)^\alpha e^{at} g_\alpha(t)$$

is "closely" related to **McKay's** Bessel-function distributions.

45 Miscellaneous

Burr (1942) has suggested a number of forms of cumulative distribution function that might be useful for purposes of graduation. In choosing one of these forms of distribution, the principal aim is to facilitate the mathematical analysis to which it is to be subjected, while attaining a reasonable approximation.

The forms for the cumulative distribution function ($F_Y(y)$) listed by **Burr** are shown below (the first corresponds to a uniform distribution and is

included because it is in the original list):

- (I) y for $0 < y < 1$.
- (II) $(e^{-y} + 1)^{-k}$.
- (III) $(y^{-c} + 1)^{-k}$ for $0 < y$.
- (IV) $[(c - y)/y]^{1/c} + 1]^{-k}$ for $0 < y < c$.
- (V) $(ce^{-\tan y} + 1)^{-k}$ for $-\pi/2 < y < \pi/2$.
- (VI) $(ce^{-k \sinh y} + 1)^{-k}$.
- (VII) $2^{-k}(1 + \tanh y)^k$.
- (VIII) $[(2/\pi)\tan^{-1} e^y]^k$.
- (IX) $1 - 2/[c\{(1 + e^y)^k - 1\} + 2]$.
- (X) $(1 - e^{-y^2})^k$ for $0 < y$.
- (XI) $[y - (1/2\pi)\sin 2\pi y]^k$ for $0 < y < 1$.
- (XII) $1 - (1 + y^c)^{-k}$ for $0 < y$.

Here k and c are positive parameters. Setting $y = (x - \xi)/\lambda$, we can introduce two extra parameters.

Burr (1942) devoted special attention to the family (XII) of distributions. The probability density function of $Z = Y^c$ is

$$k(1 + z)^{-(k+1)}, \quad z > 0. \quad (12.101)$$

and the r th moment of X is

$$E[Z^{r/c}] = kB \left(\frac{r}{c} + 1, k - \frac{r}{c} \right), \quad r < ck \quad (12.102)$$

Burr gives, for $c = 1(1)10$ and $k = 1(1)11$, tables of mean and standard deviation to 5 decimal places, and of $\sqrt{\beta_1}$ and β_2 to 3 decimal places or 4 significant figures. In Burr (1968) and Burr and Cislak (1968) there is further discussion of properties of this family, with special reference to the distributions of sample median and range. There is a thorough analysis of Type XII distributions in Rodriguez (1977). [See also Voda (1982).] Wingo (1993) has discussed the maximum likelihood estimation of the parameters of Type XII distributions based on progressively censored samples.

It should be noticed that it is possible to relate some of the above forms of distribution by simple transformations. Thus (III) can be obtained from (II) by replacing y by $c \log y$. Fry (1993) has recently provided a detailed survey of the univariate and multivariate Burr distributions.

Mielke's (1973) *kappa* distributions have cdf's of form

$$\left\{ 1 - (1 + y^{\alpha\theta})^{-1} \right\}^{1/\alpha}. \quad (12.103)$$

Fattorini and Lemmi (1979) describe applications and provide graphs of some pdfs. Ferreri (1964) has described a system of distributions with probability density functions of form

$$p_X(x) = \sqrt{b} [G(-\frac{1}{2}, a)]^{-1} [\exp\{a + b(x - \xi)^2\} + c]^{-1}, \quad c = \pm 1, \quad (12.104)$$

where

$$G(p, a) = \Gamma(p + 1) \sum_{j=1}^{\infty} (-c)^{j-1} e^{-ja} j^{-(p+1)}.$$

This distribution depends on four parameters a , b , c , and ξ . The r th absolute moment about ξ (the mean) is

$$b^{-r/2} \frac{G(\frac{1}{2}(r-1), a)}{G(-\frac{1}{2}, a)}. \quad (12.105)$$

For $c = 1$, $\beta_2 < 3$; for $c = -1$, $\beta_2 > 3$. As a increases, the distribution approaches normality.

Among other systems of distributions we note those described by Toranzos (1952) and Laha (1961). Toranzos describes a class of bell-shaped frequency distributions with probability density functions of form

$$(\text{Constant}) \cdot x^c \exp\left[-\frac{1}{2}(\alpha + \beta x)^2\right], \quad x > 0. \quad (12.106)$$

Laha considers distributions for which there is a standard form having characteristic function $(1 + |t|^\alpha)^{-1}$ for some value of α in range $0 < \alpha \leq 2$. This distribution, known as the Linnik distribution, is discussed in Chapter 24.

There are some very broad classes of distributions, including most of the common distributions. We will not devote much attention to these, as we are concerned more with properties of specific distributions than with broad classification. The exponential-type class includes all density functions that can be written in the form

$$p(x) = \exp[A(x)B(\theta) + C(x) + D(\theta)], \quad (12.107)$$

where $A(\cdot)$, $B(\cdot)$, $C(\cdot)$, and $D(\cdot)$ are arbitrary functions. This class was recognized nearly simultaneously by Darmois (1935) and Koopman (1936) (as the form taken by the density function if a single sufficient statistic for θ exists, given values of n independent identically distributed random variables). It is often called the Darmois-Koopman (or *Koopman-Darmois*) class. A subclass of these distributions, still very broad, is thoroughly discussed in Morris (1983).

An even broader class is that of the **Pólya-type** distributions, introduced by **Karlin** (1957). A frequency function $\Lambda(x)$ is said to be a **Pólya-type** frequency function if for every positive integer n and every pair of sets of increasing numbers $x_1 < x_2 < \dots < x_n, y_1 < y_2 < \dots < y_n$, the determinant $\|\Lambda(x_i - y_k)\| \geq 0$. A characterization of **Pólya-type** frequency functions by means of the structure of their characteristic functions was given by **Lukacs** (1968).

Mathai and **Saxena** (1966) have pointed out that the formula for the density function

$$p_X(x) = \frac{da^{c/d}\Gamma(\alpha)\Gamma(\beta)\Gamma(r-c/d)}{\Gamma(c/d)\Gamma(r)\Gamma(\alpha-c/d)\Gamma(\beta-c/d)} x^{c-1} {}_2F_1(\alpha, \beta; r; -ax^d) \quad (12.108)$$

(with $x > 0, c > 0, \alpha - c/d > 0, \beta - c/d > 0$) and the limiting form obtained by letting a tend to infinity, and a to zero in such a way that a^a tends to a' :

$$p_X(x) = \frac{da'^{c/d}\Gamma(\beta)\Gamma(r-c/d)}{\Gamma(c/d)\Gamma(r)\Gamma(\beta-c/d)} x^{c-1} {}_1F_1(\beta; r; -a'x^d) \quad (12.109)$$

can be made to represent a considerable variety of commonly used distributions by appropriate choice of values for the parameters; the confluent hypergeometric functions ${}_2F_1$ and ${}_1F_1$ are defined in Chapter 1, Sections A6 and A7, respectively.

The class of stable distributions has very considerable importance in probability theory, though statistical applications appear to be rather limited. Nevertheless, **Mandelbrot** (1963) and **Fama** (1965) have applied stable laws to stock market data, though this application was criticized by **Nicklin** and **Paulson** (1975). See also **Fielitz** and **Smith** (1972), and, more recently, **Akgiray**, **Booth**, and **Loistl** (1989). **Holtmark** (1919) applied them to modeling electrical fields; see also **DuMouchel** (1973). Informally speaking, a location scale family is stable if the convolution of two distributions belonging to the family also belongs to the family. More formally if the pdf of X_i is

$$\frac{1}{\sigma_i} f\left(\frac{x - \theta_i}{\sigma_i}\right), \quad i = 1, 2,$$

and X_1 and X_2 are independent, then the pdf of $(X_1 + X_2)$ is of form $f[(x - \theta)/\sigma]/\sigma$ for some θ and σ .

An alternative definition [**Monrad** and **Stout** (1988)] is that if X, X_1, \dots, X_n are i.i.d. and there exist constants $a, > 0$ and b such that $\sum_{j=1}^n X_j/a_n - b$ has the same distribution as X , the common distribution is stable (excluding the case of degenerate one-point distributions).

All stable distributions have characteristic functions (Chapter 1, Section B8) of form

$$\varphi_x(t) = \exp[i\mu t - c|t|^\alpha \{1 + i\beta \operatorname{sgn}(t)\omega(|t|, a)\}], \quad (12.110)$$

where

$$\omega(|t|, \alpha) = \begin{cases} \tan(\frac{1}{2}\pi\alpha), & \alpha \neq 1, \\ 2n^{-1} \log(t), & \alpha = 1, \end{cases}$$

and $i = \sqrt{-1}$ ($0 < a \leq 2$; $-1 \leq \beta \leq 1$). μ is a location parameter and c is a scale parameter. If $c = 0$, the distribution is degenerate. The shape of the pdf is determined by the parameters a and β . The latter is a skewness parameter. If $\beta = 0$, the distribution is symmetric. When $\beta = 0$,

$\alpha = 2$ gives normal distributions (Chapter 13) for any value of β ,

$a = 1$ gives Cauchy distributions (Chapter 16),

$a = \frac{1}{2}$ gives distributions with the same shape as $(\chi^2 \text{ with } 1 \text{ degree of freedom})^{-1}$, a special case of **Pearson Type III** (Section 4.2).

For other values of a (and/or $\beta \neq 0$) we do not have simple expressions for the pdfs. There are a few special cases [Zolotarev (1954)]:

$$a = \frac{1}{3}, \quad \beta = 1 \quad (\text{the Macdonald distribution})$$

$$\left. \begin{array}{l} a = \frac{2}{3}, \quad \beta = 0 \text{ or } 1 \\ a = \frac{3}{2}, \quad \beta = 1 \end{array} \right\} \quad (\text{in terms of Whittaker functions})$$

[Kropac (1982) has a discussion of distributions involving Macdonald functions.]

There are explicit formulas for the pdfs of standardized stable distributions as convergent series, although they are rather complicated. For $0 < \alpha < 1$,

$$p_X(x) = \frac{1}{\pi x} \sum_{j=1}^{\infty} \frac{(-1)^{j-1} \Gamma(j\alpha + 1)}{j!} \frac{\sin[j\{\frac{1}{2}\pi\alpha - \tan^{-1}(\beta \tan \frac{1}{2}\pi\alpha)\}]}{x^{j\alpha} (1 + \beta^2 \tan^2 \frac{1}{2}\pi\alpha)^{j/2}} \quad (12.111a)$$

For $1 < a \leq 2$,

$$p_X(x) = \frac{1}{\pi x} \sum_{j=1}^{\infty} \frac{(-1)^{j-1} \Gamma(j\alpha_{-1} + 1)}{j!} x^j \left(1 + \beta^2 \tan^2 \frac{1}{2} \pi \alpha \right)^{j/(2\alpha)} \quad (12.111b)$$

Chernin and Ibragimov (1959) have shown that all stable pdf's are unimodal.

Figures 12.12a-c show pdfs of stable distributions for $a = 0.5, 1.0$, and 1.5 each for various values of β , taken from Holt and Crow (1973), which further contains figures and tables of the pdf to 4 decimal places, for

$$\alpha = 0.25(0.25)1.75,$$

$$\beta = -1.00(0.25)1.00,$$

$$x = 0.000(0.001)0.010(0.01)2.00(0.1)M(1)M^*(5 \text{ or } 10);$$

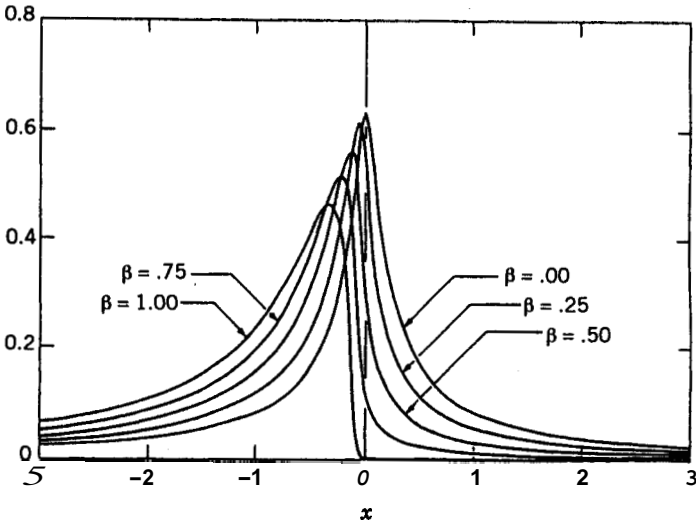
the values of M, M^* were chosen to allow for easy interpolation out to value 0.0001 for the pdf.

Tables of the cdf [to four decimal places, when $x = 0.05(0.05)1.00(0.1)2.0(0.2)4.0(0.4)6.0(1)8, 10, 15, 20$] and percentile points [to 3 decimal places, with $p = 0.52(0.02)0.94(0.01)0.97(0.005)0.995, 0.9975$] for *symmetric* stable distributions ($\beta = 0$) with $a = 1.0(0.1)1.9, 1.95, 2.0$ had already been given by Fama and Roll (1968). Soon after Holt and Crow (1973), additional tables of the cdfs of standardized symmetric distributions were given by Worsdale (1975). Included were values for $a = 0.6(0.1)2.0$ with $x = 0(0.05)3.00$, and also with $\log_e x = 0.40(0.05)2.50$. Values were given to five decimal places, though there is a warning of possible round-off error in the fourth place.

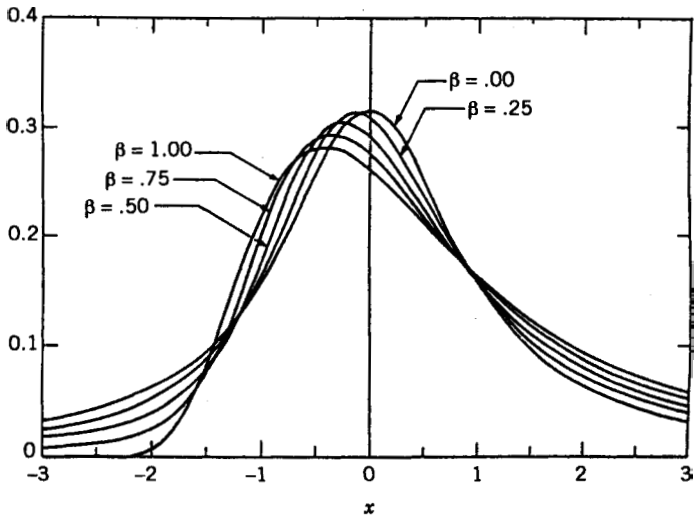
Tables calculated by Worsdale's method, for $a = 1.0(0.1)1.9, 1.95, 2.0$ and $x = 0.00(0.05)1.00(0.1)2.0(0.2)4.0(0.4)6.0, 7, 8, 10, 15, 20$ are presented in Panton (1992). There has been some reluctance to include tables for smaller values of a , presumably associated with the somewhat unusual shapes of the corresponding distributions, already becoming apparent in Figure 12.12a (where $a = 0.5$).

Properties of symmetric stable distributions have been studied by Gawronski (1984) and Nagaer and Shkol'nik (1989). Gawronski (1984) showed that all stable densities are "bell-shaped"—that is, $p_X(x)$ is infinitely differentiable (for x real), and $d^k p_X(x)/dx^k$ has exactly k zeros (all simple) on the support of the distribution varying with a and chosen so as to make interpolation feasible. An unusual feature is that for $a \neq 1$, the heavier tail is in the negative direction (negative skewness in the ordinary sense) for $\beta > 0$, and conversely for $\beta < 0$; the situation is reversed for $a = 1$. (See Figure 12.12b).

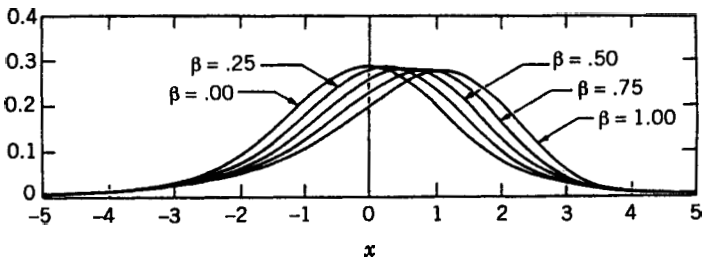
de Haan and Resnick (1980) presented a simple asymptotic estimate for the index of a stable distribution. Saniga, Pfaffenberger, and Hayya (1975)



(a) when $\alpha = 0.5$



(b) when $\alpha = 1.0$



(c) when $\alpha = 1.5$

Figure 12.12 Stable Probability Density Functions. In (b) note the reversal of location of heavier tail from that for $\alpha \neq 1$.

discussed small-sample properties of the maximum likelihood estimator of the index α by means of Monte Carlo simulations. These authors also examined the power of various goodness-of-fit tests for stable versus normal and normal versus stable distributions.

Barndorff-Nielsen (1978) observed that from observational data, plots of log (frequency) against value of the variable will often show approximately hyperbolic formula. This implied that the pdf would be of form

$$\left\{2\sqrt{1 + \alpha^2} K_1(\zeta)\right\}^{-1} \exp\left[\sqrt{(1 + \alpha^2)(1 + x^2)} - \alpha x\right], \quad (12.112)$$

where $\zeta < 0$ and $K_1(\zeta)$ is the Bessel function (Chapter 1, Section A5). Location and scale parameters, θ and a , respectively, can be introduced, making four parameters in all. Equation (12.112) defines the hyperbolic **system** of distributions. Barndorff-Nielsen and **Blaesild** (1983) give a succinct account of this system. The expected value for (12.112) is

$$E[X] = \frac{\alpha K_2(\zeta)}{K_1(\zeta)}, \quad (12.113a)$$

and the variance is

$$\text{Var}(X) = \zeta^{-1} \left\{ \frac{K_2(\zeta)}{K_1(\zeta)} \right\} + \frac{\alpha^2 \{K_3(\zeta)K_1(\zeta) - K_2^2(\zeta)\}}{K_1^2(\zeta)}. \quad (12.113b)$$

Sargan pdf's [Goldfield and Quandt (1981), ascribed to D. **Sargan**] are of form

$$\frac{1}{2} \left\{ \sum_{j=0}^p (j! \beta_j)^{-1} \right\} e^{-\alpha|x|} \sum_{j=0}^p \beta_j \alpha^j |x|^j, \quad \beta_0 = 1; \alpha > 0, \beta_j \geq 1. \quad (12.114)$$

This is a p -order **Sargan** density. The distributions are symmetrical about zero. Goldfield and Quandt (1981) recommend (12.114) as a viable alternative to normal distributions in econometric modeling. For $p = 0$ we have **Laplace** distributions (Chapter 24). Missiakoulis (1983) notes that the pdf of the arithmetic mean of $p + 1$ independent **Laplace** variables is a p -order **Sargan** density, and he discusses the choice of order when fitting a **Sargan** distribution. Tse (1987) also considers this question and indicates a preference for higher orders than those recommended by Missiakoulis (1983).

Azzalini (1985) noted that if X and Y are independent random variables, each having a pdf symmetric about zero, then for any A ,

$$\frac{1}{2} = \Pr[X - \lambda Y < 0] = \int_{-\infty}^{\infty} p_Y(y) F_X(\lambda y) dy.$$

Hence $2p_Y(y)F_X(\lambda y)$ is a pdf. Taking X and Y each to be unit normal variables, we obtain Azzalini's "skew-normal" class of distributions, with pdf's,

$$2\phi(x)\Phi(\lambda x). \quad (12.115)$$

These distributions have a single parameter A . ($A = 0$ gives a unit normal distribution.) Location and scale parameters can be added, in the usual way. It is interesting to note that if X has pdf (12.115), then X^2 is distributed as χ^2 with one degree of freedom (for all values of A).

To increase coverage of the (β_1, β_2) plane Azzalini (1985) introduced a further parameter, ξ , and defined densities

$$p_X(x|\lambda, \xi) = \frac{\phi(x)\Phi(\lambda x + \xi)}{\Phi\{\xi(1 + \lambda^2)^{-1/2}\}} \quad (12.116)$$

Henze (1986) showed that if X_1 and X_2 are independent standard normal variables ($N(0, 1)$), then

$$X = (1 + \lambda^2)^{-1/2} \{\lambda|X_1| + X_2\}$$

has pdf (12.115). Also, extending Azzalini's original approach, he showed that the distribution of X_2 , conditional on $X_1 < AX_2 + \xi$ has pdf (12.116).

Mallows (1983) constructed a system of distributions that would cover the whole (β_1, β_2) plane in a smooth manner, without the sharp transitions of the Pearson and Johnson systems. The system is defined as distributions of the random variable

$$X = \xi + \lambda(\psi Y_w + \theta Z_\alpha), \quad (12.117)$$

where ξ , A , ψ , w , θ , and α are parameters, Y_w and Z_α are mutually independent, Y_w is a continuous variable with pdf

$$\{R(w)\}^{-1}(1 + y^2)^{-1}\phi(\omega y),$$

with $R(\omega) = \{1 - \Phi(\omega)\}/\{\phi(\omega)\}$ (Mills's ratio; see Chapter 13). Z_α is a two-point Bernoulli variable with

$$\Pr\left[Z_\alpha = \sqrt{\left(\frac{1-\alpha}{\alpha}\right)}\right] = \alpha,$$

$$\Pr\left[Z_\alpha = -\sqrt{\left(\frac{\alpha}{1-\alpha}\right)}\right] = 1 - \alpha.$$

$[E[Z_\alpha] = 0, \text{Var}(Z_\alpha) = 1, \mu_3(Z_\alpha) = \{\alpha(1-\alpha)\}^{-2}(1-2\alpha), \text{ and } \mu_4(Z_\alpha) = \{\alpha(1-\alpha)\}^{-1} - 3.]$

Although there are six parameters in (12.117), the scale factor (λ) is redundant. Mallows suggested fitting by the first four moments, introducing the relationship

$$\{\beta_2(Y_\omega) - \beta_2(X)\}\{\beta_2(Y_\omega) - 3\} = 2\beta_1(X). \quad (12.118)$$

From (12.118) the value of

$$\beta_2(Y_\omega) = \frac{1}{\omega^3 R(\omega) [\{\omega R(\omega)\}^{-1}]^2} - \frac{1}{\{\omega R(\omega)\}^{-1} - 1}, \quad (12.119)$$

and hence of w , is determined. Then θ is determined from

$$\beta_2(X) = \theta^{-2}\beta_1(X) + \theta^4 + 6\theta^2(1 - \theta^2) + \beta_2(Y_\omega)(1 - \theta^2)^2. \quad (12.120)$$

Finally, the values

$$\psi = \left\{ (1 - \theta^2) [\omega R(\omega)]^{-1} - 1 \right\}^{1/2} \quad (12.121)$$

and

$$\alpha = \frac{1}{2} \left[1 - \left\{ \beta_1(X) (\beta_2(X))^{-1} + 4\theta^6 \right\}^{1/2} \right] \quad (12.122)$$

are calculated.

The standard slash distribution is the distribution of the ratio of a unit normal variable to an independent standard uniform (0, 1) variable. Its pdf is

$$p(x) = \begin{cases} \frac{\{\phi(0) - \phi(x)\}}{x^2}, & x \neq 0, \\ \frac{1}{2}\phi(0), & x = 0, \end{cases} \tag{12.123}$$

where $\phi(x) = (\sqrt{2\pi})^{-1} \exp(-\frac{1}{2}x^2)$. Equation (12.123) is mainly of use in simulation studies. General slash distributions can be obtained by replacing the unit normal variable by a general normal $N(\xi, \sigma^2)$ random variable. Properties of this family of distributions have been discussed by Rogers and Tukey (1972) and Mosteller and Tukey (1977). Their applications to robustness studies through Monte Carlo simulations have been well illustrated by Andrews et al. (1972) and Gross (1973). The maximum likelihood estimation of location and scale parameters for this family has been described by Kafadar (1973).

Albert, Delampady, and Polasek (1991) have proposed the use of an *extended-power family* of distributions in robustness studies. These are symmetric distributions with pdf,

$$p_X(x) = K\theta^{1/2} \exp\left[-\frac{1}{2}c\lambda^{-1}\left\{\left(1 + \frac{\theta}{c-1}(x - \xi)^2\right)^\lambda - 1\right\}\right],$$

$$\lambda, \theta > 0; c > 1, \tag{12.124a}$$

where K depends on c and A but not on θ . For $\lambda = 0$,

$$p_X(x) = K\theta^{1/2} \exp\left[-\frac{1}{2}c \log\left\{1 + \frac{\theta}{c-1}(x - \xi)^2\right\}\right] \tag{12.124b}$$

is suggested. This is a Cauchy distribution (Chapter 16), since the right hand side of (12.124b) can be written as

$$K\theta^{1/2}\left\{1 + \frac{\theta}{c-1}(x - \xi)^2\right\}^{-c/2}$$

5 CORNISH-FISHER EXPANSIONS

If any distribution is fitted by making the first s moments of the fitted and actual distributions agree, it is, in principle, possible to calculate quantiles of

the fitted distribution and to regard these as approximations to the corresponding quantiles of the actual distribution. In fact the fitted quantiles are functions of the s fitted moments. So we have estimators of the actual quantiles which are functions of these s moments.

Usually these functions are very complicated and not easily expressible in explicit form. However, in the case of the Gram-Charlier and Edgeworth expansions, described in Section 4.2, it is possible to obtain explicit expansions for standardized quantiles as functions of corresponding quantiles of the unit normal distributions. In these expansions the terms are polynomial functions of the appropriate unit normal quantile, with coefficients that are functions of the moment-ratios of the distribution. We now outline the method of derivation of these expansions, using an argument propounded by Cornish and Fisher (1937). [The argument has been reformulated in Fisher and Cornish (1960) and extended by Finney (1963).]

From (12.51) we have formally

$$\int_{-\infty}^x g(t) dt = D^{-1} \exp \left[\sum_{j=1}^{\infty} \frac{\varepsilon_j (-D)^j}{j!} \right] p(x), \quad (12.125)$$

and if $p(x) = \phi(x) = (\sqrt{2\pi})^{-1} e^{-x^2/2}$, then $D^j p(x) = (-1)^j H^j(x) \phi(x)$. Now suppose that X_α and U_α are defined by

$$\int_{-\infty}^{X_\alpha} g(x) dx = a = \int_{-\infty}^{U_\alpha} \phi(x) dx.$$

Using the expansion (12.125)

$$\int_{-\infty}^{X_\alpha} \phi(x) dx + \left[\sum_{i=0}^{\infty} D^{-1} \frac{\left\{ \sum_{j=1}^{\infty} \varepsilon_j (-D)^j / j! \right\}^i}{i!} \right] \phi(X_\alpha) = \int_{-\infty}^{U_\alpha} \phi(x) dx. \quad (12.126)$$

We now expand the right-hand side as

$$\begin{aligned} \int_{-\infty}^{U_\alpha} \phi(x) dx &= \int_0^{X_\alpha} \phi(x) dx + \sum_{j=0}^{\infty} \left\{ \frac{(U_\alpha - X_\alpha)^j}{j!} \right\} D^j \phi(X_\alpha) \\ &= \int_0^{X_\alpha} \phi(x) dx + \sum_{j=1}^{\infty} \left\{ \frac{(X_\alpha - U_\alpha)^j}{j!} \right\} H_j(X_\alpha) \phi(X_\alpha). \end{aligned} \quad (12.127)$$

Inserting this in (12.126) gives the *identity*

$$\left[\sum_{i=0}^{\infty} D^{-1} \frac{\left\{ \sum_{j=1}^{\infty} \varepsilon_j (-D)^j / j! \right\}^i}{i!} \right] \phi(X_\alpha) = \left[\sum_{j=1}^{\infty} \left\{ \frac{(X_\alpha - U_\alpha)^j}{j!} \right\} H_j(X_\alpha) \right] \phi(X_\alpha). \tag{12.128}$$

Expanding the left-hand side and dividing both sides by $\phi(X_\alpha)$ gives an identity, of polynomial form, between $(X_\alpha - U_\alpha)$ and X_α . By straightforward, though tedious, algebra it is possible to rearrange (12.118) to obtain either U_α as a function of X_α [i.e., $U_\alpha = U(X_\alpha)$] or X_α as a function of U_α [i.e., $X_\alpha = X(U_\alpha)$].

Cornish and Fisher (1937) gave detailed formulas for $U(X_\alpha)$ and $X(U_\alpha)$, and they extended these in Fisher and Cornish (1960). They collected terms according to Edgeworth's system (see Section 4.3). Based on their formula we have (to order n^{-1} if κ_r is of order $n^{1-r/2}$ with the distribution **standardized**)

$$\begin{aligned} X(U_\alpha) = & U_\alpha + \frac{1}{6}(U_\alpha^2 - 1)\kappa_3 \\ & + \frac{1}{24}(U_\alpha^3 - 3U_\alpha)\kappa_4 - \frac{1}{36}(2U_\alpha^3 - 5U_\alpha)\kappa_3^2 \\ & + \frac{1}{120}(U_\alpha^4 - 6U_\alpha^2 + 3)\kappa_5 - \frac{1}{24}(U_\alpha^4 - 5U_\alpha^2 + 2)\kappa_3\kappa_4 \\ & + \frac{1}{324}(12U_\alpha^4 - 53U_\alpha^2 + 17)\kappa_3^3 \\ & + \frac{1}{720}(U_\alpha^5 - 10U_\alpha^3 + 15U_\alpha)\kappa_6 \\ & - \frac{1}{180}(2U_\alpha^5 - 17U_\alpha^3 + 21U_\alpha)\kappa_3\kappa_5 \\ & - \frac{1}{384}(3U_\alpha^5 - 24U_\alpha^3 + 29U_\alpha)\kappa_4^2 \\ & + \frac{1}{288}(14U_\alpha^5 - 103U_\alpha^3 + 107U_\alpha)\kappa_3^2\kappa_4 \\ & - \frac{1}{7776}(252U_\alpha^5 - 1688U_\alpha^3 + 1511U_\alpha)\kappa_3^4 + \dots \end{aligned} \tag{12.129}$$

Also

$$\begin{aligned}
 U(X_\alpha) = & X_\alpha - \frac{1}{6}(X_\alpha^2 - 1)\kappa_3 \\
 & - \frac{1}{24}(X_\alpha^3 - 3X_\alpha)\kappa_4 + \frac{1}{36}(4X_\alpha^3 - 7X_\alpha)\kappa_3^2 \\
 & - \frac{1}{120}(X_\alpha^4 - 6X_\alpha^2 + 3)\kappa_5 + \frac{1}{144}(11X_\alpha^4 - 42X_\alpha^2 + 15)\kappa_3\kappa_4 \\
 & - \frac{1}{648}(69X_\alpha^4 - 187X_\alpha^2 + 52)\kappa_3^3 \\
 & - \frac{1}{720}(X_\alpha^5 - 10X_\alpha^3 + 15X_\alpha)\kappa_6 \tag{12.130} \\
 & + \frac{1}{360}(7X_\alpha^5 - 48X_\alpha^3 + 51X_\alpha)\kappa_3\kappa_5 \\
 & + \frac{1}{384}(5X_\alpha^5 - 32X_\alpha^3 + 35X_\alpha)\kappa_4^2 \\
 & - \frac{1}{864}(111X_\alpha^5 - 547X_\alpha^3 + 456X_\alpha)\kappa_3^2\kappa_4 \\
 & + \frac{1}{7776}(948X_\alpha^5 - 3628X_\alpha^3 + 2473X_\alpha)\kappa_3^4 + \dots
 \end{aligned}$$

The formulas given in the 1937 and 1960 papers include terms adjusting the mean and variance. In formulas (12.129) and (12.130), however, it has been assumed that the distribution to be fitted has been standardized, so no correction is needed.

Numerical values of the coefficients in formula (12.129) of Fisher and Cornish (1960) are given to 5 decimal places for $\alpha = 0.5, 0.75, 0.9, 0.95, 0.975, 0.99, 0.995, 0.999, \text{ and } 0.9995$. This paper also gives the values of the first seven **Hermite** polynomials, to 12 decimal places, for the same values of α . It is especially to be noted that the functional forms $U(\cdot)$ and $X(\cdot)$ *do not* depend on the value of α . The function $U(X)$ may be regarded as a *normalizing transformation* of the random variable X . The function $X(\cdot)$ expresses the quantiles of the (standardized) distribution of X as a function of corresponding quantiles of the unit normal distribution.

In practice only a finite number of terms of the expansions $U(\cdot)$ or $X(\cdot)$ are used. It is important to recognize that the results obtained are not equivalent to those obtained by retaining a similar number (or indeed any specified number) of terms in the Gram-Charlier expansions. They may be (in

favorable cases) good approximations to the quantiles of the "distributions" represented by the complete expansions.

Even though the Cornish-Fisher expansions are directly related to the Edgeworth form of distribution, there is a difference in the way these two are used. It is unusual to use moments higher than the fourth in fitting an Edgeworth (or Gram-Charlier) expansion. This is partly because the possibility of negative values (and multimodality) becomes more serious as further terms are added and partly because, with observed data, estimation of higher moments is often of low accuracy. Cornish-Fisher expansions, on the other hand, are more usually applied to theoretically determined distributions (with known moments), and it is quite usual to use moments of order as high as six, or even greater.

As Finney (1963) has pointed out, it would be possible to obtain analogues of Cornish-Fisher expansions by operating on Laguerre series (or other) forms of distribution in the same way as described (for Edgeworth series) at the beginning of this section. Use of Cornish-Fisher expansions to calculate percentiles of **Pearson** distributions has been reported by Bowman and Shenton (1979a, b) and Davenport and Herring (1979). Modifications of the expansion have been described by **McCune (1977)**. Lee and Lin (1992) present a computer program for extending the Cornish-Fisher expansion to terms of order n^{-9} . (It can be adjusted to give any required order, provided the computer has sufficient capacity.) They note that the expansion is ultimately divergent and suggests, as a practical stopping rule, that the odd order and even order series of terms be considered separately, and that the summation be terminated immediately before either series increases in absolute value.

6 NOTE ON CHARACTERIZATIONS

Characterizations of specific distributions will be described at appropriate places in the text. However, the two following types of characterization, which apply to all distributions in this volume, will not usually be mentioned individually, since this would lead to tautological repetition.

If X_1, \dots, X_n are i.i.d., their common distribution is determined by

1. that of their sum, or, a fortiori their arithmetic mean (\bar{X}), or
2. that of any one order statistic $X'_{r:n}$ (the r th smallest of the X 's).

In case 1, which applies to all distributions (continuous or discrete), the common characteristic function is equal to the $(1/n)$ th power of that of the sum and thus determines the common distribution. In case 2 for absolutely

continuous distributions, the cdf of $X'_{r:n}$ is

$$F_{X'_{r:n}}(x) = I_{F(x)}(r, n - r + 1), \quad (12.131)$$

where $F(x)$ is the common cdf of X_1, \dots, X_n , and $I_p(a, b)$ is the incomplete beta function ratio (Chapter 1, Section 5). The right-hand side of (12.131) is a monotonic-increasing function of $F(x)$ and so determines $F(x)$, given $F_{X'_{r:n}}(x)$. [See Johnson and Kotz (1990).]

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CHAPTER 13

Normal Distributions

1 DEFINITION AND TABLES

A random variable X is *normally* distributed if it has the probability density function:

$$\frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x - \xi}{\sigma}\right)^2\right], \quad \sigma > 0. \quad (13.1)$$

The probability density function of $U = (X - \xi)/\sigma$ is

$$p_U(u) = (\sqrt{2\pi})^{-1} \exp(-\frac{1}{2}u^2), \quad (13.2)$$

which does not depend on the parameters ξ, σ . This is called the *standard form* of normal distribution. (It is also the *standardized form*.) The random variable U is called a *standard*, or *unit*, normal variable.

Since

$$\Pr[X \leq x] = \Pr\left[U \leq \frac{x - \xi}{\sigma}\right], \quad (13.3)$$

such probabilities can be evaluated from tables of the cumulative distribution function of U , which is

$$\Phi(u) = \Pr[U \leq u] = (\sqrt{2\pi})^{-1} \int_{-\infty}^u e^{-x^2/2} dx. \quad (13.4)$$

The notation $\Phi(\cdot)$ is widely used, so it will be used in this book. Further it is convenient to have a systematic notation for the quantiles of the distribution of U . We use the system defined by

$$\Phi(U_\alpha) = \alpha$$

so that $U_{1-\alpha}$ is the upper $100\alpha\%$ point, and $U_\alpha (= -U_{1-\alpha})$ is the lower $100\alpha\%$ point of the distribution.

There are other forms of notation that are much less frequently encountered in statistical work. The parameter in (13.1) is sometimes replaced by the *precision* modulus

$$h = (\sigma\sqrt{2})^{-1}.$$

Other functions are

$$\operatorname{erf}(x) = 2\pi^{-1/2} \int_0^x e^{-t^2} dt = 2\Phi(x\sqrt{2}) - 1, \quad (13.5)$$

$$\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$$

(erf is the error function, or Cramp function, and erfc the error function complement). Other names for the distribution are second law of *Laplace*, *Laplace*, Gaussian, Laplace-Gauss, de Moivre; $\Phi(\cdot)$ is also called the Laplace-Gauss integral, or simply the probability integral, and $\operatorname{erf}(\cdot)$ is also known by this last name and is sometimes called the error integral.

Tables relating to the unit normal distribution are a necessary ingredient of any textbook in statistical theory or its applications. This is because for many decades the normal distribution held a central position in statistics. As pointed out, tables of the unit normal distribution suffice for calculations relating to all normal distributions. Some care is necessary in using these tables; for example, putting

$$(\sqrt{2\pi})^{-1} e^{-x^2/2} = Z(x), \quad (13.6)$$

it is necessary to remember the multiplier σ^{-1} in

$$(\sqrt{2\pi}\sigma)^{-1} \exp\left[-\frac{1}{2}\left\{\frac{x-\xi}{\sigma}\right\}^2\right] = \sigma^{-1}Z\left(\frac{x-\xi}{\sigma}\right). \quad (13.7)$$

But no real difficulties are presented by the extended use of tables of the unit normal distribution. [The symbols $\varphi(x)$, $\phi(x)$ are often used in place of $Z(x)$.]

In most of the tables only positive values of the variable are given. This is all that is necessary, since

$$Z(x) = Z(-x) \quad \text{and} \quad \Phi(x) = 1 - \Phi(-x). \quad (13.8)$$

Here we give a list of only the more easily available tables. Fuller lists are given in the National Bureau of Standards (1952) (up to 1952) and **Green-**

wood and **Hartley (1962)** (up to 1958). The functions most often tabulated are $\Phi(x)$, $Z(x)$, and U_α , but there are many variants for special uses.

Pearson and Hartley (1948) give tables based on values originally computed by Sheppard (1903, 1907). These contain

1. $\Phi(x)$ and $Z(x)$ to 7 decimal places for $x = 0.00(0.01)4.50$; and to 10 decimal places for $x = 4.50(0.01)6.00$.
2. U_α to 4 decimal places for $a = 0.501(0.001)0.980(0.0001)0.9999$.
3. $Z(U_\alpha)$ to 5 decimal places for $a = 0.500(0.001)0.999$.

Pearson and Hartley (1970) have also provided these tables.

Fisher and Yates (1963) give U_α to 6 decimal places for $a = 0.505(0.005)0.995$, and to 5 decimal places for $1 - a = 0.0'1$ [$r = 2(1)8$]. These tables include values of "probits"—($5 + U_\alpha$)—to 4 decimal places for $a = 0.001(0.001)0.980(0.0001)0.9999$ and of $Z(u)$ to 4 decimal places for $u = 0.00(0.01)3.00(0.1)3.9$.

Owen (1962) gives $Z(x)$ and $\Phi(x)$ to 6 decimal places, $Z^{(1)}(x)$, $Z^{(2)}(x)$, $Z^{(3)}(x)$, and $\{1 - \Phi(x)\}/Z(x)$ to 5 decimal places, and $\Phi(x)/Z(x)$ to 4 decimal places, for $x = 0.00(0.01)3.99$; also $\{1 - \Phi(x)\}$ to 5 significance figures for $x = 3.0(0.1)6.0(0.2)10.0(1)20(10)100(25)200(50)500$, and U_α and $Z(U_\alpha)$ to 5 decimal places for $a = 0.500(0.001)0.900(0.005)0.990$.

Kelley (1948) gives U_α to 8 decimal places for $a = 0.5000(0.0001)0.9999$. Hald (1952) gives $Z(x)$ and $\Phi(x)$ to 4 significant figures for

$$x = \pm 0.00(0.01)4.99,$$

and probits ($5 + U_\alpha$) to 3 decimal places for

$$\alpha = 0.0001(0.0001)0.0250(0.001)0.9750(0.0001)0.9999.$$

We next describe some tables containing larger number of decimal places, useful for special calculations.

In Zelen and Severo (1964) there are tables of $Z(x)$, $\Phi(x)$ and $Z^{(1)}(x)$ to 15 decimal places, $Z^{(2)}(x)$ to 10, and $Z^{(r)}(x)$ ($r = 3, 4, 5, 6$) to 8 decimal places for $x = 0.00(0.02)3.00$. For the values $x = 3.00(0.05)5.00$, $\Phi(x)$ is given to 10 decimal places, $Z(x)$ to 10 significant figures, and $Z^{(r)}(x)$ ($r = 2, \dots, 6$) to 8 significant figures. A further table gives $Z^{(r)}(x)$ ($r = 7, \dots, 12$) to 8 significant figures for $x = 0.0(0.1)5.0$. There are also tables [based on Kelley (1948)] of U_α and $Z(U_\alpha)$ to 5 decimal places for $a = 0.500(0.001)0.99$, and of U_α to 5 decimal places for $a = 0.9750(0.0001)0.9999$.

In the National Bureau of Standards tables (1953) there are given tables of $Z(x)$ and $2\Phi(x) - 1$ [$= \operatorname{erf}(x/\sqrt{2})$] to 15 decimal places for $x = 0(0.0001)1.0000(0.001)7.800$; and also of $2[1 - \Phi(x)]$ to 7 significant figures for $x = 6.00(0.01)10.00$.

Table 13.1 Percentile Points of Normal Distribution, as Standardized Deviates (Values of U_α)

α	U_α
0.5	0.000000
0.6	0.253347
0.7	0.524401
0.75	0.674490 ^a
0.8	0.841621
0.9	1.281552
0.95	1.644854
0.975	1.959964
0.99	2.326348
0.995	2.575829
0.9975	2.807034
0.999	3.090232

^aThe value of $U_{0.75}$ ($= 0.6745$), the upper quartile of the unit normal distribution, is occasionally called the *probable error* of the distribution, though this nomenclature is seldom used at present. The probable error of distribution (1) is, of course, $U_{0.75}\sigma$.

There are many other publications containing various forms of tables of the normal distribution. Further tables of special functions associated with the normal distribution are used in connection with **probit** analysis. There is no need for extensive tables of the normal distribution to be given here. We confine ourselves, in Table 13.1, to a few commonly used values of U_α .

Tables of random unit normal deviates (representing values of a random variable having a unit normal distribution) have been constructed from tables of random numbers (representing values of a random variable having a discrete rectangular distribution over the integers 0–9). In 1948 Wold (1948) published a set of 25,000 random unit normal deviates (to 3 decimal places), based on Kendall and Babington Smith's (1942) tables of random numbers. A set of 10,400 random unit normal deviates (also to 3 decimal places), based on **Tippett's (1927)** table of random numbers, was published by Sengupta and Bhattacharya (1958). These replaced an earlier set of tables, first appearing in 1936 [Mahalanobis et al. (1934)] which were found to contain a number of errors.

A set of 100,000 random unit normal deviates, to 3 decimal places, based on the first half-million random numbers produced in 1947, was published by **RAND (1955)**. In Buslenko et al. (1966) there is a table of **1000** random unit normal deviates, to 4 decimal places. These were calculated from the values of five independent random variables R_1, \dots, R_5 each randomly distributed

over the range 0 to 1 (see Chapter 26), using the formulas

$$U = X - 0.01(3X - X^3),$$

where

$$X = \frac{1}{\sqrt{5}} \sum_{j=1}^5 \sqrt{3} (2R_j - 1).$$

[This formula was suggested by **Bol'shev (1959)**. Note that $\sqrt{3}(2R_j - 1)$ has a *standardized* rectangular distribution.]

2 HISTORICAL REMARKS

Because of the importance of the normal distribution, considerable attention has been paid to its historical development. The earliest workers regarded the distribution only as a convenient approximation to the binomial distribution. At the beginning of the nineteenth century appreciation of its broader theoretical importance spread with the work of **Laplace** and Gauss. The normal distribution became widely and uncritically accepted as the basis of much practical statistical work, particularly in astronomy. Around the beginning of the present century, a more critical spirit developed with more attention being paid to systems of "skew (nonnormal) frequency curves" (see Chapter 12). This critical spirit has persisted, but it is offset by developments in both theory and practice. The normal distribution has a unique position in probability theory, and it can be used as an approximation to other distributions. In practice, "normal theory" can frequently be applied, with small risk of serious error, when substantially nonnormal distributions correspond more closely to observed values. This allows us to take advantage of the elegant nature and extensive supporting numerical tables of normal theory.

The earliest published derivation of the normal distribution (as an approximation to a binomial distribution) seems to be that in a pamphlet of de Moivre dated 12 November 1733. This pamphlet was in Latin; in 1738 de Moivre published an English translation, with some additions. [See also Archibald (1926) and Daw (1966).]

In 1774 **Laplace** obtained the normal distribution as an approximation to hypergeometric distribution, and four years later he advocated tabulation of the probability integral [$\Phi(x)$, in our notation]. The work of Gauss in 1809 and 1816 established techniques based on the normal distribution, which became standard methods used during the nineteenth century.

Most theoretical arguments for the use of the normal distribution are based on forms of *central limit theorems*. These theorems state conditions under which the distribution of standardized sums of random variables tends

to a unit normal distribution as the number of variables in the sum increases, that is, with conditions sufficient to ensure an asymptotic unit normal distribution. Gauss's (1816) derivation of the normal distribution, as the resultant of a large number of additive independent errors, may be regarded as one of the earliest results of this kind.

Formal rigorous mathematical discussion of central limit theorems (for independent random variables) may be said to start with the work of Lyapunov (1900). A useful theorem associated with his name states that if X_1, X_2, \dots, X_n are independent, identically distributed random variables with finite mean and standard deviation then the distribution of the standardized sum

$$\frac{\sum_{j=1}^n X_j - nE[X]}{\sqrt{n \text{Var}(X)}}$$

tends to the unit normal distribution as n tends to infinity. Lyapunov also obtained an upper bound for the magnitude of the difference between the cumulative distribution functions of the standardized sum and the unit normal. This upper bound was of the form $Cn^{-1/2} \log n$, where C is a constant depending on the variances and third moments of the X_i 's. It has subsequently been considerably improved by Cramér (1928), Berry (1941), Esseen (1942), Zahl (1966), and Zolotarev (1967). For the case when the variables $\{X_i\}$ are identically distributed the upper bound obtained by Zolotarev (1967) is

$$0.82 \left(\frac{\nu_3}{\sigma^3} \right) n^{-1/2}$$

where

$$\sigma^2 = \text{Var}(X_i),$$

$$\nu_3 = E[|X_i - E[X_i]|^3].$$

This result was an improvement on an earlier result of Wallace (1959) [correcting a result of Berry (1941)]. Zahl (1966) has shown that the upper bound

$$0.65 \left(\frac{\nu_3}{\sigma^3} \right) n^{-1/2}$$

can be obtained, provided $\nu_3/\sigma^3 \geq 3/\sqrt{2} = 2.22$.

It can be shown by consideration of particular cases that the upper bound must be at least

$$C \left(\frac{\nu_3}{\sigma^3} \right) n^{-1/2},$$

with

$$C = \frac{\sqrt{13}}{6\sqrt{2\pi}} = 0.40974.$$

Zolotarev (1967) has shown that if the variance and absolute third central moment of X_j are σ_j^2, ν_{3j} , respectively ($j = 1, 2, \dots, n$), then an upper bound for the magnitude of the difference between cumulative distribution functions is

$$0.9051 \left(\sum_{j=1}^n \nu_{3j} \right) \left(\sum_{j=1}^n \sigma_j^2 \right)^{-3/2}$$

For the general case of independent (but not necessarily identically distributed) variables, Lindeberg (1922) showed that putting $\text{Var}(X_i) = \sigma_i^2$ and

$$\sigma_{(n)}^2 = \sum_{i=1}^n \sigma_i^2,$$

if

$$\lim_{n \rightarrow \infty} \sigma_{(n)}^{-2} \sum_{i=1}^n \left(\Pr\{|X_i - E[X_i]| \geq t\sigma_{(n)}\} \right. \\ \left. \times E\left[\{X_i - E[X_i]\}^2 \mid |X_i - E[X_i]| \geq t\sigma_{(n)}\right] \right) = 0$$

for all $t > 0$, the distribution of the standardized sum

$$\sigma_{(n)}^{-1} \sum_{i=1}^n (X_i - E[X_i])$$

tends to the unit normal distribution as n tends to infinity. The necessity of Lindeberg's condition was established by Feller (1935). Since then attention has moved to consideration of conditions under which a limiting normal distribution applies to sums of nonindependent random variables. An account of some such conditions can be found in a book by Loève (1963).

A comprehensive account of the central limit theorem and related problems (up to the early 1950s) has been given by Gnedenko and Kolmogorov

(1954). Multidimensional extensions of central limit theorems have been investigated by Bergstrom (1945), Esseen (1958), Sadikova (1966), and Sazanov (1967) among others.

Porter (1985), while discussing the historical details of the concepts of variation and error in Quetelet's statistics, has brought out the vital role that the normal distribution plays in the mathematics of society. Wilf (1988) has commented briefly on the general quest for normality. Read (1985) has provided a fine review of the various important developments on the normal distribution. Stigler (1982) has proposed a new standard for the normal distribution.

As one would expect, there has been a phenomenal development on various aspects of the normal distribution. Consequently several books and monographs have appeared dealing specifically with inference, characterizations, tolerance limits, prediction, goodness-of-fit, and so on. It is therefore neither feasible nor necessary to discuss all these developments in detail. Fortunately there is a handbook prepared by Patel and Read (1981) available on the distribution; the second edition of this book is currently under preparation. We are hopeful and confident that this volume will provide a comprehensive treatment to the distribution, and hence we have concentrated on adding only those results that are primarily of distributional nature (rather than specific inferential aspect). We refer the readers to the above-mentioned handbook and other books/monographs (listed for specific topics) for an elaborate discussion.

3 MOMENTS AND OTHER PROPERTIES

If U has the unit normal distribution, then, since the distribution is symmetrical about $U = 0$,

$$E[U] = 0, \quad (13.9)$$

and so

$$\mu_r = \mu'_r = E(U^r) = (\sqrt{2\pi})^{-1} \int_{-\infty}^{\infty} x^r e^{-x^2/2} dx. \quad (13.10)$$

If r is odd,

$$\mu_r = 0.$$

If r is even,

$$\begin{aligned}
 \mu_r &= (\sqrt{2/\pi}) \int_0^\infty x^r e^{-x^2/2} dx \\
 &= (\sqrt{2/\pi}) 2^{(r+1)/2} \int_0^\infty t^{(r-1)/2} e^{-t} dt \\
 &= 2^{r/2} \Gamma(\frac{1}{2}(r+1)) / \sqrt{\pi} \\
 &= (r-1)(r-3) \dots 3 \cdot 1.
 \end{aligned} \tag{13.11}$$

Hence

$$\begin{aligned}
 \text{Var}(U) &= \mu_2 = 1, \\
 \alpha_3(U) &= 0, \\
 \beta_2(U) &= \alpha_4(U) = 3.
 \end{aligned}$$

This, as pointed out in Section 1, reveals that the unit normal is also the standardized normal distribution. If X has the general normal distribution (13.1), then

$$X = \xi + \sigma U, \tag{13.12}$$

where U is a unit normal variable.

Some normal probability density functions are shown in Figure 13.1. The nine curves shown correspond to all possible combinations of $\xi = -1, 0, 1$ and $a = \frac{1}{2}, 1, 2$. The curve in the center represents the unit normal distribution ($\xi = 0, a = 1$). The distribution is symmetrical about $X = \xi$; the probability density function has points of inflexion at $X = \xi \pm a$. The distribution is unimodal with mode at $X = \xi$ (which is also the median of the distribution). The modal value of the probability density function is $(\sqrt{2\pi})^{-1} = 0.3979$.

The moment generating function of $X (= \xi + \sigma U)$ is

$$E[e^{tX}] = e^{t\xi + (t^2\sigma^2/2)} \tag{13.13}$$

and the characteristic function is $e^{it\xi - (t^2\sigma^2/2)}$. For all $r > 2$, the cumulants κ_r are zero. This property characterizes normal distributions.

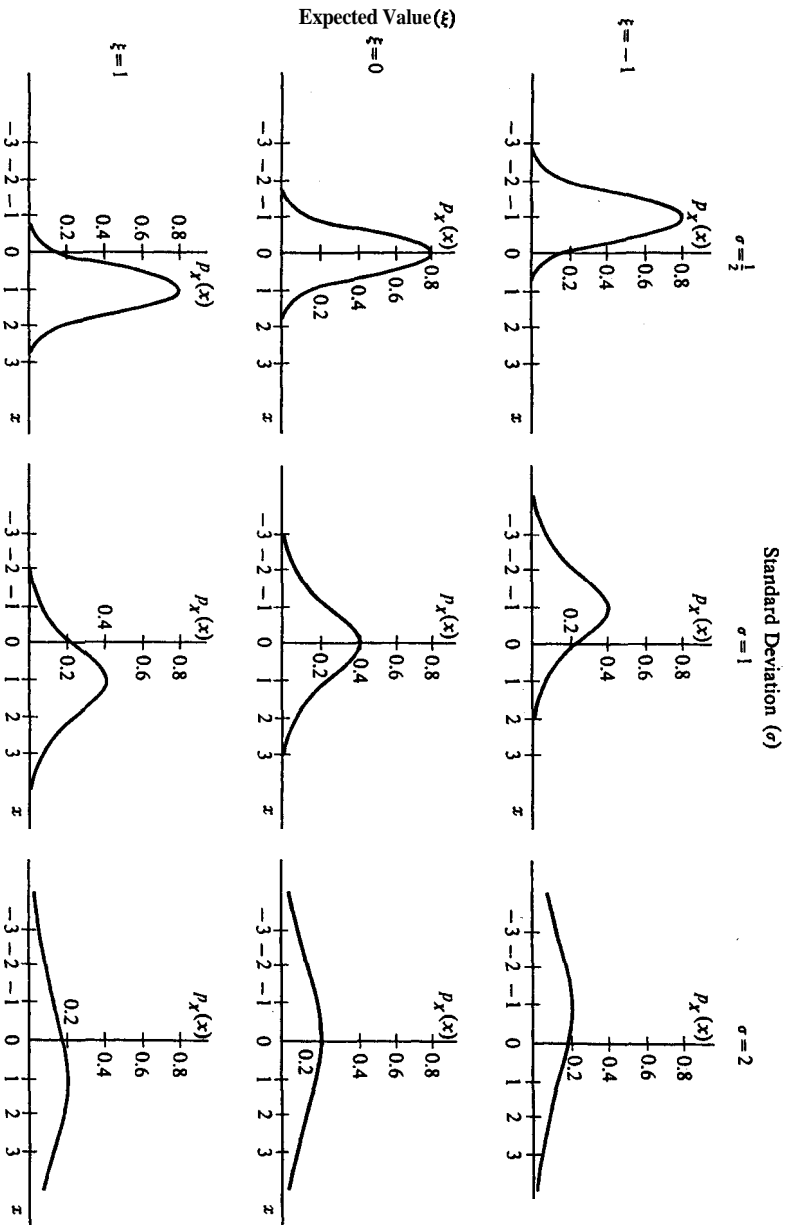


Figure 13.1 Normal Density Functions

The mean deviation of X is $\sigma\sqrt{2/\pi} = 0.798\sigma$. For all normal distributions

$$\frac{\text{Mean deviation}}{\text{Standard deviation}} = \sqrt{\frac{2}{\pi}} = 0.798. \tag{13.14}$$

The information-generating function of X is

$$(\sqrt{2\pi}\sigma)^{-u} \left(\frac{\sqrt{2\pi}\sigma}{\sqrt{u}} \right) = (\sqrt{2\pi}\sigma)^{-(u-1)} u^{-1/2}. \tag{13.15}$$

The entropy is

$$\log(\sqrt{2\pi}\sigma) + \frac{1}{2}. \tag{13.16}$$

It is of some interest to note that the probability density function (13.1) can be expressed in the numerical form

$$0.3979(0.6065)^{[(x-\xi)/\sigma]^2}. \tag{13.17}$$

The derivatives of the function $Z(\cdot)$ are also of some interest. They are used, for example, in the Gram-Charlier expansion (see Chapter 12). We have already discussed them in Chapter 1, and Section 1 of Chapter 12 contains some references to tables of their numerical values.

If X_1, X_2, \dots, X_n are independent, normally distributed random variables, then any linear function of these variables is also normally distributed. It is of interest to note that if X_1 and X_2 are independent, and each is normally distributed with zero expected value, then $X_1 X_2 (X_1^2 + X_2^2)^{-1/2}$ is also normally distributed. If further $\text{var}(X_1) = \text{var}(X_2)$, then $(X_1^2 - X_2^2)/(X_1^2 + X_2^2)$ is also normally distributed [Shepp (1964)].

If X_1, X_2, \dots, X_n are independent random variables each distributed as (13.1), then by applying the transformation

$$\begin{cases} X_1 = \bar{X} + (1 \cdot 2)^{-1/2} U_2 \sigma + (2 \cdot 3)^{-1/2} U_3 \sigma + \dots + [(n-1)n]^{-1/2} U_n \sigma, \\ X_2 = \bar{X} - (1 \cdot 2)^{-1/2} U_2 \sigma + (2 \cdot 3)^{-1/2} U_3 \sigma + \dots + [(n-1)n]^{-1/2} U_n \sigma, \\ X_3 = \bar{X} \qquad \qquad \qquad - 2(2 \cdot 3)^{-1/2} U_3 \sigma + \dots + [(n-1)n]^{-1/2} U_n \sigma, \\ \vdots \\ X_n = \bar{X} \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad - (n-1)[(n-1)n]^{-1/2} U_n \sigma, \end{cases} \tag{13.18}$$

it can be shown that

- $\bar{X} (= n^{-1} \sum_{j=1}^n X_j)$ has a normal distribution with expected value ξ and standard deviation σ/\sqrt{n} .

2. Each U_j ($j = 2, \dots, n$) is a unit normal variable.
3. \bar{X}, U_2, \dots, U_n are a mutually independent set of variables, and hence
4. $\sum_{j=1}^n (X_j - \bar{X})^2 = \sigma^2 \sum_{j=2}^n U_j^2$ is distributed as $\sigma^2 (\chi^2$ with $(n - 1)$ degrees of freedom).

This last result was obtained by Helmert in 1875–76. The transformation (13.18) is called Helmert's transformation.

Since any function

$$g(X_1 - \bar{x}, \dots, X_n - \bar{X})$$

of the deviations $\{X_j - \bar{X}\}$ alone is a function of $\{U_j\}$ alone, we further note that by (13.18) and by property 3,

5. \bar{X} and any function $g(X_1 - \bar{X}, \dots, X_n - \bar{X})$ are mutually independent.

This result is helpful in calculating moments and distributions of statistics such as $\bar{X}[\text{Range}(X_1, \dots, X_n)]^{-1}$; $\bar{X}[n^{-1} \sum_{j=1}^n |X_j - \bar{X}|]^{-1}$. It can also be shown that

6. $\sum_{j=1}^n (X_j - \bar{X})^2$ and any function of the ratios

$$\left\{ (X_i - \bar{X}) \left[\sum_{j=1}^n (X_j - \bar{X})^2 \right]^{-1/2} \right\}$$

are mutually independent.

Zehna (1991) has recently given a simple proof for the result that \bar{X} and S^2 are statistically independent. Bondesson (1981) discussed a normal sample with given sample mean and variance. Szekely (1985) established the multiplicative infinite divisibility of a standard normal distribution, while Chernoff (1981) presented an inequality involving the normal distribution function. Berg (1988) showed that the distribution of the cube (or, indeed, any odd power) of a normal random variable is not determined by its moments.

Hawkins (1975) has made a comment on the computation of noncentral t and normal integrals. Hawkins and Wixley (1986) have made some observations on the transformation of chi-squared variables to the normal distribution (see also Chapter 18). Aroian, Taneja, and Cornwell (1978) have derived the mathematical forms of the distribution of the product of two normal variables, while Cornwell, Aroian, and Taneja (1977) have discussed the numerical evaluation of that distribution. Hayya, Armstrong, and Gressis (1975) have considered the distribution of the ratio of two normal variables. Karhunen and Narula (1989) have similarly derived the distribution of the ratio of the absolute values of two normal variables. Anscombe and Glynn

and when $n = 4$,

$$E[X'_1 X'_2] = E[X'_3 X'_4] = \frac{\sqrt{3}}{\pi}, \quad E[X'_2 X'_3] = \frac{\sqrt{3}}{\pi}(2 - \sqrt{3}),$$

$$E[X'_1 X'_3] = E[X'_2 X'_4] = -\frac{\sqrt{3}}{\pi}(2 - \sqrt{3}), \quad E[X'_1 X'_4] = -\frac{3}{\pi}.$$

A general approach, given by **Godwin (1949a)**, is to express the product moments in terms of integrals of the form

$$J_n = \int_0^\infty \cdots \int_0^\infty e^{-Q(x_1, \dots, x_n)} dx_1 \cdots dx_n, \quad (13.21)$$

where $Q(x_1, \dots, x_n)$ is a quadratic form in the x_i 's. For $n = 1, 2, 3$, J_n can be expressed explicitly in terms of elementary functions as follows:

$$n = 1, \quad Q(x_1) = a_{11}x_1^2, \quad J_1 = \frac{i\sqrt{n}}{2a_{11}},$$

$$n = 2, \quad Q(x_1, x_2) = a_{11}x_1^2 + a_{22}x_2^2 + 2a_{12}x_1x_2,$$

$$J_2 = \frac{1}{\sqrt{\Delta_2}} \left\{ \frac{\pi}{2} - \tan^{-1} \left(\frac{a_{12}}{\sqrt{\Delta_2}} \right) \right\},$$

where

$$\Delta_2 = \begin{vmatrix} a_{11} & a_{12} \\ a_{12} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}^2;$$

$$n = 3, \quad Q(x_1, x_2, x_3)$$

$$= a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + 2a_{12}x_1x_2 + 2a_{13}x_1x_3 + 2a_{23}x_2x_3,$$

$$J_3 = \frac{\sqrt{\pi}}{4\sqrt{\Delta_3}} \left\{ \frac{\pi}{2} + \tan^{-1} \left(\frac{a_{12}a_{13} - a_{11}a_{23}}{\sqrt{a_{11}\Delta_3}} \right) + \tan^{-1} \left(\frac{a_{12}a_{23} - a_{13}a_{22}}{\sqrt{a_{22}\Delta_3}} \right) \right.$$

$$\left. + \tan^{-1} \left(\frac{a_{13}a_{23} - a_{12}a_{33}}{\sqrt{a_{33}\Delta_3}} \right) \right\},$$

where

$$\Delta_3 = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{vmatrix} \\ = a_{11}a_{22}a_{33} - a_{11}a_{23}^2 - a_{22}a_{13}^2 - a_{33}a_{12}^2 + 2a_{12}a_{13}a_{23}.$$

The values of means of order statistics have been tabulated to five decimal places by Harter (1961a) for $n = 2(1)100(25)250(50)400$, and also by Harter (1970) for some more choices of n . The mean and variance of the i th quasi-range have been tabulated by Harter (1959) for n up to 100. Tippett (1925) has computed the expected value of the sample range for $n \leq 1000$, while Harter (1960) presented tables of the mean, variance, and the coefficients of skewness and kurtosis for $n \leq 100$. Teichroew (1956) has presented tables of means and product moments of order statistics for sample sizes up to 20. By making use of Teichroew's tables, Sarhan and Greenberg (1962) have tabulated the variances and covariances of order statistics (to 10 decimal places) for $n \leq 20$. These tables have been extended by Tietjen et al. (1977) for sample sizes up to 50. The values of the mean and standard deviation of order statistics prepared by Yamauti (1972) for sample sizes up to 50 are contained in the tables of Tietjen et al. (1977). For the largest order statistic X'_n , Ruben (1954) has tabulated the first ten moments for $n \leq 50$ and Borenus (1965) has presented the first two moments for $n \leq 120$. Parrish (1992a, b) has presented tables of means, variances and covariances of order statistics (up to 25 decimal places) for some selected sample sizes up to 50. Miyakawa, Tamiya, and Kotani (1985a) have discussed the numerical evaluation of moments of order statistics through an orthogonal inverse expansion. Öztürk and Aly (1991) have proposed some simple approximations for the moments of order statistics.

Royston (1982) has given an algorithm for computing the expected values of normal order statistics. This algorithm will compute and present the exact values for sample sizes up to 1000 and will also present an approximate value for the quantity for larger sample sizes [see Koeniger (1983) for an additional remark on this algorithm]. Balakrishnan (1984) has presented an algorithm, based on an orthogonal inverse expansion, to approximate the sum of squares of normal scores, namely $S = \sum_{i=1}^n \{E[X'_i]\}^2$. This quantity arises often in nonparametric statistics. Dansie (1986) described the normal order statistics as permutation probability models, while Nelson (1983) discussed the usefulness of normal scores as a transformation.

For the standard normal distribution, an interesting property satisfied by order statistics is that

$$\sum_{j=1}^n E[X'_i X'_j] = \sum_{j=1}^n \text{Cov}(X'_i, X'_j) = 1, \quad i = n. \quad (13.22)$$

That is, every row (or column) of the product-moment matrix or the variance-covariance matrix adds up to 1. This follows easily from the fact that \bar{X} and $X'_i - \bar{X}$ are statistically independent. Some relationships between moments of order statistics have also been established by various authors, and almost all of them have been derived by exploiting the characterizing differential equation $Z^{(1)}(x) = -xZ(x)$. For example, Govindarajulu (1963) has shown that for $1 \leq i \leq n$,

$$E[X_i'^2] = 1 + n \binom{n-1}{i-1} \sum_{j=0}^{n-i} (-1)^j \binom{n-1}{i+j} \frac{-}{i+j} E[X'_{1:i+j} X'_{2:i+j}]. \quad (13.23)$$

If we set $i = n$ in (13.23), we obtain the relation

$$E[X_1'^2] = E[X_n'^2] = 1 + E[X_1' X_2']. \quad (13.24)$$

The results in (13.22), (13.23), and (13.24) have been used for checking the computation of the product moments. Furthermore Davis and Stephens (1977, 1978) have applied (13.22) and (13.24) to improve the David-Johnson approximation of the variance-covariance matrix (see Chapter 12). Reference may also be made to Shea and Scallan (1988) for further remarks in this regard.

By noting that the condition $Z^{(1)}(x) = -xZ(x)$ is satisfied by both the standard normal and the half-normal (see Section 10) distributions, Joshi and Balakrishnan (1981) established the following results satisfied by order statistics from both these distributions:

$$\sum_{j=i}^n E[X_i' X_j'] = 1 + \sum_{j=i}^n E[X_{i-1}' X_j'] \quad \text{for } 1 \leq i \leq n, \quad (13.25)$$

$$\sum_{j=i+1}^n E[X_i' X_j'] = \sum_{j=i+1}^n E[X_j'^2] - (n-i) \quad \text{for } 1 \leq i \leq n-1, \quad (13.26)$$

$$\sum_{j=1}^n E[X_i' X_j'] = 1 + nE[X'_{1:1}]E[X'_{i-1:n-1}] \quad \text{for } 1 \leq i \leq n, \quad (13.27)$$

and

$$\sum_{j=1}^n \text{Cov}(X_i', X_j') = 1 - (n-i+1)E[X'_{1:1}]\{E[X_i'] - E[X'_{i-1}]\} \quad \text{for } 1 \leq i \leq n. \quad (13.28)$$

Joshi and Balakrishnan (1981) have used these relations to derive a convenient expression for the variance of the selection differential or reach statistic, defined as $A_k = \bar{X}_k - \bar{X}$, where \bar{X}_k is the average of the k largest order statistics, X'_{n-k+1}, \dots, X'_n . For example, Joshi and Balakrishnan (1981) have shown that

$$E[\bar{X}_k^2] = \frac{1}{k^2} \sum_{i=n-k+1}^n (2i - 2n + 2k - 1) E[X_i'^2] - \frac{k-1}{k}. \quad (13.29)$$

Consequently the mean and variance of \bar{X}_k (and hence of A_k) can be determined from the first two raw moments of X'_i alone. These quantities have been tabulated for sample sizes up to 50 by Joshi and Balakrishnan (1981). Some properties of \bar{X}_k have also been discussed by Schaeffer, van Vleck, and Velasco (1970) and Burrows (1972, 1975). In particular, they observed that $k \text{Var}(\bar{X}_k)$ remains almost constant for the selected fraction k/n . While Schaeffer, van Vleck, and Velasco (1970) tabulated the values of $k \text{Var}(\bar{X}_k)$ for $n \leq 20$ and all choices of k , Burrows (1972, 1975) provided approximations to $E[\bar{X}_k]$ and $k \text{Var}(\bar{X}_k)$ for large values of n . But, Joshi and Balakrishnan (1981) have pointed out that Burrows' approximation for $k \text{Var}(\bar{X}_k)$ is not satisfactory for small values of k even when n is 50, and that the approximation improves when k increases. The statistic A_k is related to Murphy's test statistic for outliers; for details, see Hawkins (1980) and Barnett and Lewis (1994).

The cumulative distribution function of the extreme X'_n was tabulated by Tippett (1925) for $n = 3, 5, 10, 20, 30, 50, 100(100)1000$. Percentage points for $n \leq 30$ were given by Pearson and Hartley (1970), and the cumulative distribution function of X'_n was tabulated by Pearson and Hartley (1972), to 7 decimal places, for $n = 3(1)25(5)60, 100(100)1000$ and for x in steps of 0.1. Gupta (1961) and Govindarajulu and Hubacker (1964) have presented percentage points of all order statistics for $n < 10$ and $n \leq 30$, respectively. Eisenhart, Deming, and Martin (1963) have tabulated percentage points of the sample median. Pearson and Hartley (1942, 1970) have provided tables for the distribution function of the sample range $X'_n - X'_1$. Harter and Clemm (1959) have given extensive tables of the cumulative distribution function (to 8 decimal places) and also of the percentage points (to 6 decimal places) of the range for $n = 2(1)20(2)40(10)100$ and the argument in steps of 0.01, and 23 different percentage points for each n , respectively. Besides reproducing these tables, Harter (1970) has presented tables of the probability density function of the sample range (to 8 decimal places) for n up to 16 and the argument in steps of 0.01. The cumulative distribution function of the i th quasi-range, $X'_{n-i+1} - X'_i$, is presented by Harter (1970) to 8 decimal places for $n = 2(1)20(2)40(10)100, i = 1, 2, \dots, 9$, and the argument in steps of 0.05. Harter (1970) has also presented tables of corresponding percentage

points to 6 decimal places. Currie (1980) has discussed the distribution of the studentized range. An algorithm for calculating the probability integral of the sample range has been presented by **Barnard** (1978); see El Lozy (1982) for some additional remarks on this computational algorithm.

David, Kennedy, and Knight (1977) have provided tables of means, variances, and covariances of order statistics arising from a standard normal sample with one outlier. These values are presented for all n up to 20, for the two cases: (1) location-outlier, the outlier being $N(\lambda, 1)$ for $\lambda = 0(0.5)3, 4$; and (2) scale-outlier, the outlier being $N(0, \tau^2)$ for $\tau = 0.5, 2, 3, 4$. These tables have since been used in many robustness studies because they can be utilized to determine exactly the bias and the mean square error of any linear estimator when there is a single outlier present in the sample.

In addition to the numerous tables listed here, there are also several tables pertaining tests for outliers. The recently published third edition of **Barnett and Lewis** (1994) provides a complete list of all the available tables.

5 RECORD VALUES

Let $X_{U(1)}, X_{U(2)}, \dots$ be the upper record values arising from a sequence $\{X_j\}$ of i.i.d. standard normal variables. That is, with $T_0 = 0$ and

$$T_n = \min\{j : j > T_{n-1}, X_j > X_{T_{n-1}}\}$$

denoting the upper record times, the record value sequence $\{X_{U(n)}\}_{n=1}^{\infty}$ is defined by $X_{U(n)} = X_{T_{n-1}}$, $n = 1, 2, \dots$. Then the density of $X_{U(n)}$ is

$$p_{X_{U(n)}}(x) = \frac{1}{(n-1)!} \{-\log(1 - \Phi(x))\}^{n-1} Z(x), \quad -\infty < x < \infty, \quad (13.30)$$

and the joint density of $X_{U(m)}$ and $X_{U(n)}$ is given by

$$\begin{aligned} p_{X_{U(m)}, X_{U(n)}}(x, y) &= \frac{1}{(m-1)!(n-m-1)!} \{-\log(1 - \Phi(x))\}^{m-1} \frac{Z(x)}{1 - \Phi(x)} \\ &\quad \times \{-\log(1 - \Phi(y)) + \log(1 - \Phi(x))\}^{n-m-1} Z(y), \\ &\quad -\infty < x < y < \infty, 1 \leq m < n. \end{aligned} \quad (13.31)$$

From (13.30) and (13.31), Houchens (1984) and Balakrishnan and Chan (1994) have determined (by numerical methods) the values of $E[X_{U(n)}]$, $\text{Var}(X_{U(n)})$, and $\text{Cov}(X_{U(m)}, X_{U(n)})$. By making use of these values, these

authors have also derived the best linear unbiased estimators of ξ and σ based on the first n upper record values. Balakrishnan and Chan (1994) have also discussed the prediction of a future record and a test for spuriousity of a current record value. They have also established that

$$E[X_{U(n-1)}X_{U(n)}] = E[X_{U(n)}^2] - 1 \quad \text{for } n \geq 2, \quad (13.32)$$

and consequently that

$$\begin{aligned} \text{Cov}(X_{U(n-1)}, X_{U(n)}) \\ = \text{Var}(X_{U(n)}) + E[X_{U(n)}]\{E[X_{U(n)}] - E[X_{U(n-1)}]\} - 1. \end{aligned} \quad (13.33)$$

Suppose that $X_{L(1)}, X_{L(2)}, \dots$, denote the lower record values arising from a sequence $\{X_j\}$ of i.i.d. standard normal variables; that is, with $T_0^* = 1$ and

$$T_n^* = \min\{j : j > T_{n-1}^*, X_j < X_{T_{n-1}^*}\}$$

denoting the lower record times, the lower record value sequence $\{X_{L(n)}\}_{n=1}^{\infty}$ is defined by $X_{L(n)} = X_{T_{n-1}^*}$, $n = 1, 2, \dots$. Then, due to the symmetry of the standard normal distribution, it may be easily observed that

$$\begin{aligned} X_{L(n)} &\stackrel{d}{=} -X_{U(n)}, \\ (X_{L(m)}, X_{L(n)}) &\stackrel{d}{=} (-X_{U(m)}, -X_{U(n)}). \end{aligned}$$

With this property, moments of the lower record values (and inference based on the lower record values) can be easily obtained from the corresponding results for the upper record values.

6 CHARACTERIZATIONS

We first summarize normal characterizations presented in the first edition of this book [Johnson and Kotz (1970)]. In all cases X_1, \dots, X_n are i.i.d. random variables, unless explicitly stated otherwise.

1. $\bar{X} = n^{-1}\sum_{j=1}^n X_j$ has a normal distribution. [See Chapter 12, Section 6. Janson (1988) expresses this in the form $d^k \phi_X(t)/dt^k|_{t=0} = 0$ for all $k > 2$, where $\phi_X(t)$ is the characteristic function of the common distribution of the X's.]

A more sophisticated characterization based on properties of \bar{X} is due to Fieger (1971). If the distribution of the X's belongs to a location family, with $F_X(x) = g(x - \theta)$, if $E[|X_i|]$ is finite, and if \bar{X} is the best translation invariant estimator of θ for any convex loss function

$W(\theta^*, 6) = W(|\theta^* - \theta|)$ with $W(u) \geq W(0)$ for all u , then the common distribution is normal.

2. \bar{X} and $g(\{X_i - X_j, i \neq j\})$ mutually independent, given one of three conditions:
 - a. $g(\cdot) = \sum_{j=1}^n (X_j - \bar{X})^2 (= nS)$. [Lukacs (1942); weakened to \bar{X} and S which have joint pdf of form $h(\bar{X}, S)S^{n-2}$, with $\partial h/\partial \bar{X}$ and $\partial h/\partial S$ existing, by Kaplansky (1943).]
 - b. $g(\cdot)$ is a k -statistic [i.e., $g(\cdot)$ is a polynomial in the X 's and $E[g(\cdot)] = \kappa_r$, which is the r th cumulant of the common distribution of the X 's for some integer $r > 2$]. [Basu and Laha (1954); Lukacs (1955). See also Geary (1936) and Kawata and Sakamoto (1949).]
 - c. $g(\cdot) = 0$ if and only if $X_j = \bar{X}$ for all j ; and

$$g(c\bar{X}) = |c|g(\bar{X})$$

[Paskevich (1958), Rao (1958), Zinger (1958)].

3. Conditions on conditional expected values:
 - a. $E[\bar{X}|\{X_i - X_j, i \neq j\}] = E[\bar{X}]$ (for $n > 2$) [Kagan, Linnik, and Rao (1965, 1973)]. Note that for $n = 3$, this condition is satisfied by any symmetric distribution with finite expected value. Rao (1967) extended this condition to

$$E[X_i|X_j - \bar{X}] = E[\bar{X}] \quad \text{for all } i \neq j.$$

- b. The common distribution has zero mean and finite variance, and there exist $(n - 1)$ linearly independent statistics $Y_j = \sum_{i=1}^n a_{ji} X_i$ ($j = 1, \dots, n - 1$) such that

$$E\left[Y_j \sum_i b_i X_i\right] = 0 \quad \text{for a } j = 1, \dots, n - 1 \quad (13.34)$$

and some $\{b_j\}$ ($\{a_{j1}, \dots, a_{jn}\}$ not all zero). Kagan, Linnik, and Rao (1973, p. 156) improve this result by requiring only $j = 1$ in (13.34) and not finite variance, but restricted to $n \geq 3$. [Cacoullos (1967b)].

- c. $\sum_{j=1}^n a_j b_j = 0$, where $a_j \neq 0$ ($j = 1, \dots, n$), $\{b_j\}$ are not all zero, and

$$E\left[\left(\sum_{j=1}^n b_j X_j\right)^2 \middle| \sum_{j=1}^n a_j X_j\right] = E\left[\left(\sum_{j=1}^n b_j X_j\right)^2\right]$$

[Cacoullos (1967a)].

4. Conditions based on identity of distributions:
- $\sum_{j=1}^n a_j X_j$ ($a_j \neq 0$, $j = 1, \dots, n$) and each X_i ($i = 1, \dots, n$) for some (a.) [Shimizu (1962), referring to Linnik (1952)].
 - $\sum_{j=1}^n a_j X_j$ and $\sum_{j=1}^n b_j X_j$, where $a_j b_j \neq 0$ (for all j), and $\{b_j\}$ is not just a rearrangement of (a.), provided the common distribution has finite moments of all order [Marcinkiewicz (1939)]. [Linnik (1952) showed that this result is not valid if some moments are infinite.]
 - ($n = 2$) of X_1 and $(X_1 + X_2)/\sqrt{2}$ [Pólya (1923), referred to by Bryc (1990)].
5. Characterizations based on order statistics [Govindarajulu (1966)]:
- Provided the common distribution has a finite variance, the condition

$$E[X_n'^2 - X_{n-1}'X_n'] = \sigma^2$$

ensure that the common distribution is either normal (with variance σ^2) or truncated (from above) normal.

- If the expected value of the common distribution is zero, the condition

$$nE[X_j'\bar{X}] = \sigma^2, \quad j = 1, \dots, n; \quad n \geq 2, \quad (13.35)$$

ensures that the common distribution is normal. [Note that if it be assumed that the common distribution has zero probability for negative values, condition (13.35) ensures that it is half-normal (see Section 10).]

6. Conditions based on distributions of specific statistics:
- $\sum_{j=1}^n X_j^2$ and $\{X_i^2/(\sum_{j=1}^n X_j^2)\}$ ($i = 1, \dots, n$) are mutually independent [Tamhankar (1967)].
 - The distribution of $\sum_{j=1}^n (X_j + a_j)^2$ depends on the parameters $\{a_j\}$ only through $\sum_{j=1}^n a_j^2$ [Kagan and Shalayevskii (1967)].
 - Provided that $a_j b_j \neq 0$ ($j = 1, \dots, n$), $\sum_{j=1}^n a_j X_j$ and $\sum_{j=1}^n b_j X_j$ are mutually independent for some $\{a_j, b_j\}$. [Darnois (1951), Skitovich (1953). The result is known as the *Darnois-Skitovich* theorem. Another proof was given by Tranquilli (1968).]

This condition and the following one do not require assumption of finite variance—or indeed, identity of distributions of X_1, \dots, X_n —though mutual independence is still a necessary property.

- Extending condition 1 to cases of not necessarily identically distributed variables, if $(X_1 + X_2)$ has a normal distribution, so do each

of X_1 and X_2 . [Cramér (1936), extended to $n > 2$ random variables by Lukacs (1956).]

- e. If each X_j is distributed symmetrically about zero, the condition that the statistics

$$Y_j = \sqrt{j-1} X_j / \left\{ \sum_{i=1}^{j-1} X_i^2 \right\}^{1/2}, \quad j = 2, \dots, n,$$

are mutually independent and distributed as t with $j - 1$ degrees of freedom ($j = 2, \dots, n$) is necessary and sufficient to ensure that each X_j has the same normal distribution [Kotlarski (1966)].

Books by Kagan, Linnik, and Rao (1973) and Mathai and Pederzoli (1977), as well as a survey by Kotz (1974), provide a useful, and reasonably adequate, basis for more mathematically inclined readers desiring to understand derivations of the above results. Ghurye and Olkin (1973) include a clear exposition of the work of Pólya (1923) and Linnik (1953), and they illustrate the application of Linnik's results.

In the two decades following publication of the first edition of this book, there has been substantial growth in literature on characterizations, in which characterization of normal distributions has played a prominent part. In fact, to some extent, characterization of normal distributions has become a branch of mathematics, with emphasis on functional equations and characteristic functions but with only limited impact on applied statistics. We are unable to provide a comprehensive, or even fully representative, account due in part to space restriction but also to our feeling that a sizable proportion of the more recent results are of little value in applied work. Exploitation of earlier results has not occurred to the extent that one might have expected, or hoped for. This is true even for results of type 2 above (p. 101).

A possible exception is the following characterization initially due to Csorgo and Seshadri (1971) and Csorgo, Seshadri, and Yalovsky (1975). It was used to develop tests of normality. An early version is as follows: Given X_1, \dots, X_n ($n = 2k + 3, k \geq 2$) which are i.i.d. with expected value ξ and variance σ^2 , and

$$Z_j = \frac{\sum_{i=1}^j X_i - jX_j}{\sqrt{j(j+1)}} \quad j = 1, \dots, n-1, \tag{13.36}$$

$$Z_n = \sum_{i=1}^n X_i,$$

and given

$$Y_g = Z_{2g-1}^2 + Z_{2g}^2, \quad g = 1, \dots, k+1 = \frac{1}{2}(n-1),$$

and the statistics

$$Y_r^* = \frac{\sum_{g=1}^r Y_g}{\sum_{g=1}^{k+1} Y_g}, \quad r = 1, 2, \dots, k,$$

which have the joint distribution of order statistics for k mutually independent standard uniform variables, then the common distribution of X_1, \dots, X_n is normal.

A parallel result, applicable for $n = 2k$, if $E[X_j] = \xi$ is known, and it can be assumed that the common distribution is symmetrical, is that if the statistics

$$Y_r'^* = \frac{\sum_{g=1}^r Y_g'}{\sum_{g=1}^k Y_g'}, \quad r = 1, 2, \dots, k-1,$$

where $Y_g' = (X_{2g-1} - \xi)^2 + (X_{2g} - \xi)^2$ ($g = 1, \dots, k$) have the joint distribution of order statistics for $k-1$ mutually independent standard uniform variables, the common distribution of the X 's is normal. Further extensions have been obtained in later work.

A typical result of this class due to Pakshirajan and Mohan (1971), which states that if X_1, X_2 , and X_3 are mutually independent random variables each symmetric about zero, with cdf continuous at 0 (i.e., $\Pr[X_j = 0] = 0$), then the joint characteristic function of the ratios X_1/X_3 and X_2/X_3 is $\exp(-\sqrt{t_1^2 + t_2^2})$ if and only if the X 's have a common normal distribution with zero expected value. However, as noted in the first edition (p. 53), the distribution of the ratio X_1/X_2 of two i.i.d. variables does not characterize a normal distribution [Fox (1965)].

Bryc (1990) has extended Pólya's (1923) result (4c above) as follows: If X_1 and X_2 are i.i.d. random variables with finite variance such that, for some α and $\beta (> 0)$, $(\alpha + \beta X_1)$ and $(X_1 + X_2)$ have identical distributions, then X_1 has a normal distribution.

A further generalization [Wesolowski (1990)] is this: If X_1, \dots, X_n ($n \geq 2$) are square integrable random variables and $\{a_1, \dots, a_n\}$ are real numbers with $a_i \neq -1, 0$, or 1 and X_1 and $\sum_{j=1}^n a_j X_j$ have identical distributions, then X_1 has a normal distribution [compare 3a; Shimizu (1962) requires a similar condition for each X_i]. Arnold and Isaacson (1978) give a simpler proof. See also Lukacs and Laha (1964), who relaxed the condition of square integrability.

Kagan, Linnik, and Rao (1973) contains some extensions and refinements of results already mentioned. These include

1. If X_1, \dots, X_n are i.i.d. and

$$\sum_{j=1}^n a_j X_j \left(\sum_{j=1}^n a_j^2 = 1 \right) \quad \text{and} \quad \left(\sum_{j=1}^n a_j X_j \right)^2$$

are mutually independent, the X 's are normally distributed (pp. 105-106) (cf. 2a).

2. If X_1, \dots, X_n ($n \geq 3$) are mutually independent, with $E[X_i] = 0$, if

$$L_i - \sum_{j=1}^n a_{ij} X_j, \quad i = 1, \dots, n,$$

are linearly independent, and if

$$E[L_1 | L_2, \dots, L_n] = 0,$$

then the X 's each have a normal distribution (p. 419).

3. If X_1, \dots, X_n are mutually independent and $\{a_j\}, \{b_j\}$ are nonzero real numbers satisfying the conditions

$$\begin{aligned} a_j, b_j &\neq 0 && \text{for all } j, \\ a_j b_j^{-1} + a_k b_k^{-1} &\neq 0 && \text{for all } j \neq k, \end{aligned}$$

then each X_j has a normal (possibly degenerate) distribution provided that the conditional distribution of $\sum_{j=1}^n a_j X_j$ and $\sum_{j=1}^n b_j X_j$ is symmetric.

We also note the following:

4. If X_1 and X_2 are i.i.d., they are unit normally distributed if and only if, for some $a_1, a_2 \neq 0$ each of $(a_1 X_1 + a_2 X_2)^2 / (a_1^2 + a_2^2)$ and $(a_1 X_1 - a_2 X_2)^2 / (a_1^2 + a_2^2)$ has a χ^2 distribution with 1 degree of freedom [Geisser (1973, pp. 492-494)].
5. Kelker and Matthes (1970) considered location-scale families. These are families with cdf of form

$$F_X(x) = \frac{1}{\sigma} g\left(\frac{x - \theta}{\sigma}\right),$$

where θ, σ are the location and scale parameters, respectively.

According to Kelker and Matthes, "Within the location and scale parameter families (\bar{X}, S) is a sufficient statistic [for (θ, σ)] if and only if the family is the normal distribution family." This is indeed correct, but Bondesson (1977) has pointed out that their proof required $F_X(x)$ to represent a continuous distribution. He amended the proof to avoid this assumption. Kelker and Matthes (1970) also showed that

- 6. If X_1, \dots, X_n are independent and nondegenerate random variables with location family cdfs $F_{X_i}(x) = g_i(x - \theta)$ ($i = 1, \dots, n$), then a necessary and sufficient condition for $\sum_{j=1}^n b_j X_j$ ($b_1, \dots, b_n \neq 0$) to be a sufficient statistic for θ is that X_i have a normal distribution with variance proportional to b_i^{-1} .
- 7. If X_1, \dots, X_n ($n = 4$) are i.i.d. and $(X_1 - X_2)/S$ is independent of (\bar{X}, S) , then the common distribution of the X 's is normal.

Braverman (1985) has obtained characterizations in terms of unconditional expected values. These include the following characterizations:

- 1. If X_1, X_2 , and X_3 are i.i.d. random variables with finite moments of odd order, and there are constants C_a such that

$$E \left[\left| \sum_{j=1}^3 a_j X_j \right|^p \right] = C_a \left(\sum_{j=1}^3 a_j^2 \right)^{p/2} \tag{13.37}$$

for all $a = (a_1, a_2, a_3)$ and all odd p , then each of the three variables has a normal distribution.

This result is not true for even integers p .

- 2. If X_1 and X_2 are i.i.d., with a symmetric common distribution, with

$$E \left[\exp(\lambda |X_j|^2) \right] < \infty \quad \text{for some } \lambda > 0$$

and

$$E[|X_j|^s] \neq 0 \quad \text{for all } s$$

real or complex, with $\text{Re } s > 0$, and

$$E[|a_1 X_1 + a_2 X_2|] = C(a_1^2 + a_2^2)^{1/2} \tag{13.38}$$

for suitable C , then the common distribution is normal.

Braverman (1989) has also shown that

- 3. If X_1 and X_2 are i.i.d. (not necessarily symmetric) and there are two odd numbers, p_1 and p_2 , such that

$$E[|a_1 X_1 + a_2 X_2|^{p_j}] = C_j (a_1^2 + a_2^2)^{p_j/2}, \quad j = 1, 2, \tag{13.39}$$

for all real a , σ , and suitable C_j , then the common distribution of the X 's is normal.

Next we present a few notes on "stability" (or "robustness") of characterizations—namely, how far small departures from exact characterization conditions can affect size of departure from the characterized form.

Defining the distance between two cdfs as

$$\delta(G(x), F(x)) = \sup_x |G(x) - F(x)|$$

Meshalkin (1968) described the two distributions as ε -coincident if $\delta(G(x), F(x)) \leq \varepsilon$, and termed a random variable X , with cdf $F_X(x)$, ε -normal if

$$\delta \left[F_X(x), \Phi \left(\frac{x - \xi}{\sigma} \right) \right] \leq \varepsilon$$

for some pair (ξ, σ) .

Sapogov (1956) showed that if X_1 and X_2 are independent, with

$$F_{X_1}(0) = \frac{1}{2},$$

$$\int_{-g(\varepsilon)}^{g(\varepsilon)} x dF_{X_1}(x) = \xi_1,$$

$$\int_{-g(\varepsilon)}^{g(\varepsilon)} x^2 dF_{X_1}(x) = \sigma_1^2 + \xi_1^2,$$

where

$$g(\varepsilon) = (-2 \log \varepsilon)^{1/2} + 1, \quad 0 < \varepsilon < 1,$$

then, if $X_1 + X_2$ is ε -normal, X_1 is $\beta(\varepsilon)$ -normal with

$$\beta(\varepsilon) = C\sigma_1^{-3}(-\log \varepsilon)^{-1/2},$$

where C is some constant (not depending on ε), because

$$\sup_x \left| F_{X_1}(x) - \Phi \left(\frac{x - \xi_1}{\sigma_1} \right) \right| < C\sigma_1^{-3}(-\log \varepsilon)^{-1/2}. \quad (13.40)$$

Using the concept of ε -independence of X_1 and X_2 , defined by

$$\left| \int_{a_j x_1 + b_j x_2 < c_j} \delta(F_{X_1, X_2}(x_1, x_2) - F_{X_1}(x_1)F_{X_2}(x_2)) dx_1 dx_2 \right| \leq \varepsilon$$

for all (a_j, b_j, c_j) , Nye (1966) showed that

1. if X_1 and X_2 are mutually independent, and $(X_1 + X_2)$ and $(X_1 - X_2)$ are ε -independent, X_1 and X_2 are both $\beta_1(\varepsilon)$ -normal,
2. if X_1, \dots, X_n are i.i.d. random variables and \bar{X} and S^2 are ε -independent, then the common distribution of the X_i 's is $\beta_2(\varepsilon)$ -normal.

Both $\beta_1(\varepsilon)$ and $\beta_2(\varepsilon)$ were of order $(-\log \varepsilon)^{-1/2}$, and so was $\beta(\varepsilon)$.

Meshalkin (1968) obtained an improved order of magnitude in the following results: If X_1 and X_2 are i.i.d., with expected value zero and variance 1, and $E[|X_i|^2]$ is bounded, then (1') ε -independence of $(X_1 + X_2)$ and $(X_1 - X_2)$ implies $\beta_3 \varepsilon^{1/2}$ -normality of the common distribution, and (2') ε -coincidence of the distribution functions of $(X_1 + X_2)/\sqrt{2}$ and X_i implies $\beta_4 \varepsilon^{1/2}$ -normality of X_1 and X_2 . The multipliers β_3 and β_4 depend on the bound of $E[|X_i|^3]$, but not on ε .

Yanushkyavichyus (1989) in his doctoral dissertation at Vilnius University provided the following stability theorem, improving on the above results: Let X_1, \dots, X_n be independent identically distributed random variables. If \bar{X} and S^2 , defined by the formulas,

$$\bar{X} = \frac{1}{n} \sum_{j=1}^n X_j,$$

$$S^2 = \frac{1}{n} \sum_{j=1}^n (X_j - \bar{X})^2, \quad n \geq 2$$

are (δ, ε) -independent [i.e., $\delta(F_{(X,Y)}, F_X F_Y) \leq \varepsilon$, where $F_{(X,Y)}(x, y) = \Pr(X < x, Y < y)$, $F_X(x) = \Pr(X < x)$], then

$$\delta(X_j, N) \leq C \left(\ln \frac{1}{\varepsilon} \right)^{-1/2} \quad (13.41)$$

[i.e., there exists a normal r.v. N , such that (13.41) is valid, where C is an absolute constant].

Yanushkyavichyus (1989) also improved on Nye (1966) and Meshalkin's result by showing that if X_1 and X_2 are independent identically distributed random variables and if $S = X_1 + X_2$ and $T = X_1 - X_2$ are $(6, \epsilon)$ -independent, then there exists a normal r.v. N , such that

$$\delta(X_j, N) \leq C\epsilon^{1/3} \left(\ln \frac{1}{\epsilon} \right)^{(2/3)\log_2 3}$$

Note that the loss of order from ϵ to $\epsilon^{1/3}$ with a logarithm factor is due to passage from the functional equations, in terms of distribution functions $F_{(S,D)}(x, y) = F_S(x)F_D(y) + r(x, y)$, $(|r(x, y)| \leq \epsilon, \text{ for all } (x, y) \in R^2)$ to a functional equation in terms of characteristic functions. Yanushkyavichyus's results do not involve any restrictions on moments or on possible degeneracy of the r.v. under consideration.

Stability in regression models was studied by Lukacs (1942) and Yanushkyavichyus (1989), among others. Yanushkyavichyus's result is as follows: Let μ be a distance defined on the space of random variables. A r.v. X (with a finite expectation $E[X]$) has (μ, ϵ) -regression on r.v. Y if

$$\mu |E[X|Y], E[X]| \leq \epsilon.$$

Yanushkyavichyus (1989) selects $\mu |Z_1, Z_2| = E|Z_1 - Z_2|$ and proves the following theorem: If X_1, X_2 are i.i.d. random variables with $E[X_j] = 0, E[X_j^2] = a^2, E[|X_j|^{2+\delta}] \leq M < \infty$ for some $\delta > 0$ and $L_1 = a_1X_1 + a_2X_2$ has (μ, ϵ) -regression on $L_2 = b_1X_1 + b_2X_2$ (and $a_1b_1 + a_2b_2 \neq 0; |b_2|, |b_1| < 1$), then there is a normal distribution $[G(x)]$ with parameter $(0, \sigma^2)$ such that

$$\sup_x |F(x) - G(x)| \leq C\sqrt{-\log \epsilon},$$

where $F(x) = \Pr[X_j \leq x]$ and C depends on M and (a_1, a_2, b_1, b_2) only.

Numerous other characterizations of normal are available in the literature. Gabovich (1974) has discussed the stability of certain characterization results. Khatri (1975a, b) has characterized the normal distribution by the constancy of regression; see Gyires (1975). Sampson (1975) has characterized the general exponential family of distributions by moment generating functions. Ruben (1974, 1975) has presented some characterizations through the distribution of the sample variance (see also Chapter 18). A characterization of normal distribution, through the general linear model, has been given by Ruben (1976). Parthasarathy (1976) characterized the normal law through the local independence of some statistics. Several weak sense analogues of characteristic properties were given by Kagan (1976). Zinger (1977) presented

a characterization through identically distributed linear statistics. Many of these characterizations have been reviewed in the book on this topic by Mathai and Pederzoli (1977).

Some characterization results were also developed based on some properties of estimators. For example, Klebanov and **Melamed** (1976) provided a characterization through properties of Bayesian estimators. Klebanov and **Melamed** (1978) also characterized the normal distribution through properties of Fisher information amount. Fieger (1976) characterized the distribution based on a homogeneous **Pitman** estimator. Bondesson (1976), by starting with the question when the sample mean is BLUE, established a characterization result. Bondesson (1974, 1975, 1978) also proved some characterizations of the normal law through properties of distributions of some statistics. In particular, in the 1978 paper Bondesson has shown that the sample variance, when properly normalized, is distributed as chi-square only for the normal distribution (also see Chapter 18). In an interesting note, **Goel** and **DeGroot** (1980) established that only normal distributions have linear posterior expectations in linear regression. **Ahmad** (1978) and Wesolowski (1987) have provided further characterizations based on regression. Bischoff, Cremers, and Fieger (1987) used the sufficiency of the least-squares estimation for characterization. Eberl (1986) has characterized the normal distribution in translation classes through properties of Bayes estimators. Stadje (1988) provided a characterization through maximum likelihood estimation. Klebanov and Neupokoeva (1990) recently proved an interesting characterization by a property of the expected values of order statistics. A characterization of the normal law in the Gauss-Markov model has been given by Stepniak (1991).

Fieger (1977) discussed transformations that characterize the normal distribution. Arnold and Isaacson (1978) presented some characterizations through the distribution of linear forms (assuming finite variance). Prakasa Rao (1979) used some identities for characterizations. Lukacs (1976, 1977, 1980) presented stability theorems for many characterizations. Some more assorted characterization results for the normal distribution are due to Talwalker (1980), Lajko (1980), Joshi (1982), Borovkov and Utev (1983), Ramasubramanian (1985), Viskov (1985), Ahsanullah and Hamedani (1988), and Ahsanullah (1990). Letac (1981) proved some interesting characterizations via the concepts of isotropy and sphericity. Findeisen (1982) has discussed Gauss's characterization of the normal distribution. Hombas (1985) has characterized the normal density function as the solution of a differential equation. Ahsanullah (1989) has used properties of linear statistics as well as chi-squared in order to characterize the normal distribution. It is important to mention that the finiteness of the variance is a critical assumption in many of the above mentioned characterization results; see Lancaster (1987) for some comments in this regard. Quite recently, Cacoullou, Papathanasiou, and Utev (1993) discussed a characterization of the normal distribution and also presented a proof of the central limit theorem connected with it.

7 APPROXIMATIONS AND ALGORITHMS

The most common use of the normal distribution is as an approximation where either normality is ascribed to a distribution in the construction of a model or a known distribution is replaced by a normal distribution with the same expected value and standard deviation. Examples of such replacement are the Fisher and Wilson-Hilferty approximations to the χ^2 -distribution (Chapter 18), the normal approximation to the (central) t-distribution (Chapter 28), and the use of normal distribution to approximate the distribution of the arithmetic mean of a number (often not very large, around 8 or more) of independent and identically distributed random variables. But now we are concerned with approximations to the normal distribution. It is possible to regard the distributions that are approximated by the normal distribution as being, themselves, approximations to normal distributions. However, they are usually more complex than the normal distribution, and we would like to study approximations that are simpler than the normal distribution.

From the point of view of replacement of a normal distribution by another distribution we note that:

1. A lognormal distribution can give a good representation of a normal distribution that has a small absolute value (say, less than 0.25) of the coefficient of variation.
2. A particular form of logistic distribution is very close to a normal distribution (see Chapter 23).
3. A form of the Weibull distribution with the shape parameter ≈ 3.25 is almost identical with the unit normal distribution (see Chapter 21).
4. Raab and Green (1961) have suggested that the distribution with probability density function

$$(2\pi)^{-1}(1 + \cos x), \quad -\pi < x < \pi, \quad (13.42)$$

can be used to replace a normal distribution. The correspondence is not very precise (see Table 13.2 comparing standardized percentile deviates of the two distributions) but will sometimes give useful analytical results. The replacement would only be used if substantial simplification in analysis were effected thereby.

The expected value and standard deviation of a random variable with distribution (13.42) are zero and $(\frac{1}{3}\pi^2 - 2)^{1/2} = 1.14$. The standardized range of the distribution $(-\pi, \pi)$ is thus from -2.77 to $+2.77$ standard deviations, and obviously the replacement gives a poor fit in the tails.

5. Bell (1962) has described even simpler approximations, using triangular distributions (Chapter 26). He pointed out that such approximations can be regarded as the second stage in a series of approximations

Table 13.2 Standardized Percentile Points of Distribution (13.42) and the Normal Distribution

Cumulative Probability	Standardized Value	
	Normal	Distribution (13.42)
0.5	0.000	0.000
0.6	0.253	0.279
0.75	0.674	0.732
0.9	1.282	1.334
0.95	1.645	1.649
0.975	1.960	1.888
0.99	2.326	2.124
β_2	3.000	2.406

by distributions of means of increasing numbers of independent rectangularly distributed variables (see the method of construction of "random normal deviates" used by Buslenko et al. (1966) described in Section 1).

Chew (1968) includes 2, 4, and 5 in a list of five possible replacements for normal distributions. The two other distributions he suggests are uniform (Chapter 26) and **Laplace** (Chapter 24). These also will be very crude approximations.

6. **Hoyt (1968)** has suggested using the distribution of the sum of three mutually independent random variables each uniformly distributed over the interval -1 to $+1$ as an approximation to the unit normal distribution. The density function is

$$\frac{1}{8}(3 - x^2) \quad \text{for } |x| \leq 1,$$

$$\frac{1}{16}(3 - |x|)^2 \quad \text{for } 1 \leq |x| \leq 3.$$

This gives an error not exceeding 0.01 in the cumulative distribution function.

7. **Steffensen (1937)** has suggested the use of the distribution of a multiple of a chi random variable (i.e., $c\chi_\nu$), with ν sufficiently large. He called this a "semi-normal" distribution.
8. A different kind of approximation has been developed in connection with calculation of the functions $\Phi(\cdot)$, $Z(\cdot)$ in computers. These approximations usually employ polynomial expressions. They give quite high accuracy, sometimes only within definite limits on the values of the variable. Outside these limits they may give quite poor approximation.

Zelen and Severo (1964) quote, among other things, the following formulas, which are based on formulas given by Hastings (1955):

$$\Phi(x) \doteq 1 - (a_1 t + a_2 t^2 + a_3 t^3) Z(x), \quad (13.43)$$

with $t = (1 + 0.33267x)^{-1}$, $a_1 = 0.4361836$, $a_2 = -0.1201676$, and $a_3 = 0.9372980$. The error in $\Phi(x)$, for $x \geq 0$, is less than 1×10^{-5} .

$$\Phi(x) \doteq 1 - \frac{1}{2}(1 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4)^{-4}, \quad (13.44)$$

with $a_1 = 0.196854$, $a_2 = 0.115194$, $a_3 = 0.000344$, and $a_4 = 0.019527$. The error in $\Phi(x)$, for $x \geq 0$, is less than 2.5×10^{-4} .

$$Z(x) \doteq (a_0 + a_2 x^2 + a_4 x^4 + a_6 x^6)^{-1}, \quad (13.45)$$

with $a_0 = 2.490895$, $a_2 = 1.466003$, $a_4 = -0.024393$, and $a_6 = 0.178257$. The error in $Z(x)$ is less than 2.7×10^{-3} .

Very accurate results can be obtained with the formula [Hart (1966)]

$$1 - \Phi(x) \doteq (x\sqrt{2\pi})^{-1} [\exp(-x^2/2)] \\ \times \left[1 - \frac{(1 + bx^2)^{1/2}}{(1 + ax^2)} \left\{ x\sqrt{\frac{\pi}{2}} \right. \right. \\ \left. \left. + \left[\frac{1}{2}\pi x^2 + \frac{(1 + bx^2)^{1/2}}{(1 + ax^2)} e^{-x^2/2} \right]^{1/2} \right\}^{-1} \right] \quad (13.46)$$

with

$$a = \frac{1}{2\pi} \left[1 + (1 + 6\pi - 2\pi^2)^{1/2} \right] = 0.212024,$$

$$b = \frac{1}{2\pi} \left[1 + (1 + 6\pi - 2\pi^2)^{1/2} \right]^2 = 0.282455.$$

For $x > 2$, Schucany and Gray (1968) have constructed the simpler formula

$$1 - \Phi(x) \doteq [(x^2 + 2)\sqrt{2\pi}]^{-1} \\ \times x \left[\exp\left(\frac{-x^2}{2}\right) \right] \frac{x^6 + 6x^4 + 14x^2 - 28}{x^6 + 5x^4 - 20x^2 - 4}, \quad (13.47)$$

which is even better than (13.46) for $x > 3$. [The proportionate error of (13.46) for $5 \leq x \leq 10$ is about 0.5×10^{-5} ; that of (13.47) decreases from 0.39×10^{-5} for $x = 5$ to 0.42×10^{-7} for $x = 10.1$

By use of rather elaborate formulas, quite remarkable accuracy can be attained. **Strecock** (1968) gives formulas for values of $\text{erf}(x)$ [see (13.5)] and of the inverse function [$\text{inverf}(y)$ where $\text{erf}(\text{inverf}(y)) = y$], correct to 22 decimal places for $|x|$ (or $|\text{inverf}(y)|$) less than 7.85.

9. Burr (1967) has considered approximations to $\Phi(x)$ of form

$$G(x) = 1 - [1 + (\alpha + \beta x)^c]^{-k}.$$

He suggests taking $a = 0.644693$, $\beta = 0.161984$, $c = 4.874$, and $k = -6.158$. An even better approximation is obtained by using

$$H(x) = \frac{1}{2}[G(x) + 1 - G(-x)],$$

which is a symmetrical function of x . The discrepancy $|H(x) - \Phi(x)|$ reaches its maximum value of about 0.00046 when $x \doteq \pm 0.6$.

10. **McGillivray** and Kaller (1966) have considered the discrepancy between $\Phi(x)$ and $\Phi(x) + a_{2r}Z(x)H_{2r-1}(x)$, where $H_{2r-1}(x)$ is the **Hermite** polynomial of order $2r - 1$ and a_{2r} is a constant chosen so that $1 + a_{2r}H_{2r}(x)$ cannot be negative. This means that a_{2r} must be between zero and

$$A_{2r} = \left| \inf_x H_{2r}(x) \right|^{-1}.$$

The second function $\Phi(x) + a_{2r}Z(x)H_{2r-1}(x)$ is the cumulative distribution function of a symmetrical distribution having the first r even central moments (and of course all odd moments), the same as those for a unit normal distribution. The discrepancy cannot exceed

$$A_{2r} \sup_x \{Z(x)|H_{2r-1}(x)|\}.$$

The values of this quantity, for $r = 2, 3$, and 4 are 0.10, 0.03, and 0.005, respectively. [Of course other distributions with the same (zero) odd central moments and first r even central moments *might* have greater discrepancies, but these results do give a useful idea of the accuracy obtained by equating moments.]

11. Riffenburgh (1967) has suggested that a symmetrical truncated unit normal distribution be approximated by the density function

$$\frac{\frac{1}{2}(Z(x) - Z(c))}{\Phi(c) - \frac{1}{2} - cZ(c)}, \quad -c \leq x \leq c,$$

where $-c, c$ are the points of truncation. Use of this approximation is recommended only when c exceeds 1 (preferably $c \geq 1.5$). Tables of the variance (to 3 decimal places) of the approximate distribution are given by Riffenburgh (1967) for $c = 0.8(0.1)1.2(0.05)4.00$, and also of $\Pr[X \leq x] - \frac{1}{2}$ (to 4 decimal places) for $c = 1.2(0.1)3.0$ and x at intervals of 0.05. (Riffenburgh has also developed test procedures based on this distribution.)

We now discuss some bound on the value of $\Phi(x)$. Various inequalities for Mills's ratio can also be interpreted as bounds for $\Phi(x)$ or $Z(x)$. Using a simple geometrical argument (based on the joint distribution of two independent unit normal variables) it can be shown that

$$\frac{1}{2} \left[1 + (1 - e^{-x^2/2})^{1/2} \right] \leq \Phi(x) \leq \frac{1}{2} \left[1 + (1 - e^{-x^2})^{1/2} \right] \quad (13.48)$$

[e.g., see D'Ortenzio (1965)]. By a refinement of the argument, on the left-hand side of (13.48), $(1 - e^{-x^2/2})$ can be replaced by

$$1 - e^{-x^2/2} + (2\pi^{-1} - \frac{1}{2})^2 e^{-x^2},$$

and on the right-hand side, $(1 - e^{-x^2})$ can be replaced by

$$1 - e^{-x^2} - (1 - 2\pi^{-1})^2 e^{-x^2}.$$

The approximation

$$\Phi(x) \doteq \frac{1}{2} \left[1 + \left\{ 1 - \exp\left(\frac{-2x^2}{\pi}\right) \right\}^{1/2} \right] \quad (13.49)$$

was obtained by Pólya (1945). This has a maximum error of 0.003, when $x = 1.6$. Cadwell (1951) modified (13.49) to

$$\Phi(x) \doteq \frac{1}{2} \left[1 + \left\{ 1 - \exp\left(-2\pi^{-1}x^2 - \frac{2}{3}\pi^{-2}(\pi - 3)x^4\right) \right\}^{1/2} \right]. \quad (13.50)$$

Over the range $0 < x < 3.5$, the maximum error of (13.50) is 0.0007, when $x = 2.5$. Formula (13.50) should not be used for large values of x . **Cadwell** suggested, on empirical grounds, the addition of the terms

$$-0.0005x^6 + 0.00002x^8$$

to the exponent in (13.50). This reduces the maximum error to 0.00005.

Carta (1975) developed approximations, similar to that of **Hastings** in (13.44), of the form

$$\Phi(x) \doteq 1 - \frac{1}{2}(a_1 + a_2x + \cdots + a_nx^{n-1})^{-2q}, \quad \text{for } x \geq 0. \quad (13.51)$$

Note the added flexibility of a variable first coefficient, as opposed to the fixed value of 1 in (13.44). For different choices of n and q , **Carta** (1975) has presented the coefficients a_i 's that yield the minimum absolute error. For example, from **Carta's** table, we have the coefficients corresponding to $n = 6$ and $q = 4$ as

$$\begin{aligned} &0.9999998582, \quad 0.0487385796, \quad 0.02109811045, \\ &0.003372948927, \quad -0.00005172897742, \quad 0.00008569579420. \end{aligned}$$

The absolute error for this approximation (for all $x \geq 0$) is less than 1.2×10^{-6} . Note that in this case (and also for some other choices of n, q), the leading coefficient is very nearly 1 [as in (13.44)]. **Carta** also has presented similar approximations for x restricted in the intervals $[0, 3.091]$, $[0, 4.001]$, and $[0, 5.20]$.

Badhe (1976) presented the following approximation which is easily implementable on a hand calculator:

$$\Phi(x) \doteq 1 - \frac{Z(x)}{x} \left[1 - \frac{1}{Y} \left(1 + \frac{1}{Y} \left\{ 7 + \frac{1}{Y} \left[55 + \frac{1}{Y} \left(445 + \frac{3745Q_1(x)}{Y} \right) \right] \right\} \right) \right], \quad (13.52)$$

where $Y = x^2 + 10$ and

$$Q_1(x) = 8.5(x^2 - 0.4284639753x^{-2} + 1.240964109)^{-1} + 1.$$

Badhe (1976) has pointed out that the approximation in (13.52) is good when $x > 4$, but certainly not suitable when $x \leq 2$. For the case where $x \leq 2$, **Badhe** has presented a seventh degree polynomial approximation (obtained

by Chebyshev economization) given by

$$\Phi(x) \doteq \frac{1}{2} + x\{a + Y[b + Y\{c + Y\{d + Y\{e + Y\{f + Y\{g + hY\}\}\}\}\}\}], \quad (13.53)$$

where

$$\begin{aligned} Y &= x^2/32, \\ a &= 0.3989422784, \\ b &= -2.127690079, \\ c &= 10.2125662121, \\ d &= -38.8830314909, \\ e &= 120.2836370787, \\ f &= -303.2973153419, \\ g &= 575.073131917, \\ h &= -603.9068092058. \end{aligned}$$

The maximum absolute error for this approximation, for $x \in [0, 2]$, is 0.2×10^{-8} .

By making use of the **Hermite** expansion

$$\sqrt{2\pi} \int_0^x Z(t) dt = 2e^{-x^2/8} \sum_{n=0}^{\infty} \frac{1}{(2n+1)!} (x/2)^{2n+1} H_{2n}(x/2), \quad (13.54)$$

where $H_n(x)$ is the n th **Hermite** polynomial, and the known recurrence relation

$$H_{n+1}(x) = xH_n(x) - nH_{n-1}(x) \quad \text{for } n = 1, 2, \dots,$$

with $H_0(x) \equiv 1$ and $H_1(x) = x$, Kerridge and Cook (1976) suggested using the series

$$\sqrt{2\pi} \int_0^x Z(t) dt = xe^{-x^2/8} \sum_{n=0}^{\infty} \frac{1}{2n+1} \theta_{2n}(x/2) \quad (13.55)$$

for computing $\Phi(x)$ on a computer. In (13.55), $\theta_n(x) = x^n H_n(x)/n!$, which is easily computed using the recurrence relation

$$\theta_{n+1} = \frac{x^2(\theta_n - \theta_{n-1})}{n+1}, \quad n = 1, 2, \dots$$

Beasley and Springer (1977) have provided an algorithm for computing the percentage point x_p , for a specified value of p , such that

$$p = \int_{-\infty}^{x_p} Z(t) dt.$$

Their Fortran subroutine replaces p by $q = p - \frac{1}{2}$ and then compares $|q|$ with 0.42; if $|q| \leq 0.42$, x_p is determined by a rational approximation

$$x_p = \frac{qA(q^2)}{B(q^2)}, \quad (13.56)$$

where A and B are polynomials of degrees 3 and 4, respectively, while if $|q| > 0.42$ an auxiliary variable, $r = \{\ln(\frac{1}{2} - |q|)\}^{1/2}$ is first formed and then x_p as

$$x_p = \pm \frac{C(r)}{D(r)}, \quad (13.57)$$

where C and D are polynomials of degrees 3 and 2, respectively, the sign being taken that of q . See also an earlier algorithm given by Odeh and Evans (1974).

Page (1977) considered simple approximations of the form

$$\Phi(x) \doteq \frac{e^{2y}}{1 + e^{2y}}, \quad (13.58)$$

where $y = a_1 x(1 + a_2 x^2)$, and determined $a_1 = 0.7988$ and $a_2 = 0.04417$ to provide an approximation with maximum error 0.14×10^{-3} . Page has also presented a similar simple approximation for the percentage point that gives two decimal accuracy.

Derenzo (1977) provided an approximation to the unit normal cdf as

$$\Phi(x) = 1 - \frac{1}{2} \exp\left\{-\frac{(83x + 351)x + 562}{(703/x) + 165}\right\}, \quad x > 0, \quad (13.59)$$

with a maximum absolute error of 0.042% for $x \in (0, 5.5]$. Another approximation that Derenzo presented is

$$\Phi(x) \doteq 1 - \frac{1}{\sqrt{2\pi}x} \exp\left(-\frac{x^2}{2} - \frac{0.94}{x^2}\right) \quad (13.60)$$

with a maximum absolute error of 0.040% for $x \geq 5.5$. Derenzo (1977) also provided an approximation for the percentage point x_p (for a given p) as

$$x_p \doteq \left\{ \frac{[(4y + 100)y + 205]y^2}{[(2y + 56)y + 192]y + 131} \right\}^{1/2}, \quad (13.61)$$

where $y = -\log(1 - p/2)$, with a maximum absolute error of 1.3×10^{-4} for $x \in (0, 5.2)$. For $x \in [5.2, 22.6)$, Derenzo has given the approximation

$$x_p \doteq \left\{ \frac{[(2y + 280)y + 572]y}{(y + 144)y + 603} \right\}^{1/2} \quad (13.62)$$

with a maximum absolute error of 4×10^{-4} .

Some more simple (but not necessarily more accurate for all x) approximations for the cumulative distribution function $\Phi(x)$ have been given by Parsonson (1978), Easingwood (1979), Heard (1979), Martynov (1981), Monahan (1981), Allasia and Giordano (1982), Hawkes (1982), Fearn (1983), Edgeman (1988), and Abernathy (1988). Pugh (1989) has made a survey of many of the algorithms available for computing the cdf $\Phi(x)$.

Moran (1980), by slightly modifying a formula of Strecock (1968) given for the error function, came up with the approximation

$$\Phi(x) \doteq \frac{1}{2} + \frac{1}{\pi} \sum_{n=0}^{12} \left(n + \frac{1}{2}\right)^{-1} e^{-(n+(1/2))^2/9} \sin\left\{\frac{\sqrt{2}}{3}\left(n + \frac{1}{2}\right)x\right\}. \quad (13.63)$$

Compared to the 38-term approximation given by Strecock, this approximation is simpler to use and is also accurate to nine decimal places for $|x| \leq 7$.

Shore (1982), by using a "betalike" cumulative distribution $G(x)$ [with $G(-\infty) = 0$, $G(\infty) = 1$, $G(0) = \frac{1}{2}$, and

$$\frac{dG}{dx} = \begin{cases} cG^{k_1}(1-G)^{k_2}, & 0 \leq G \leq \frac{1}{2}, \\ c(1-G)^{k_1}G^{k_2}, & \frac{1}{2} \leq G \leq 1, \end{cases}$$

where $k_1 > 0$] to approximate $\Phi(x)$, derived the following three approximations for the percentage point x_p :

$$x_p \doteq -5.5310 \left\{ \left(\frac{1-p}{p} \right)^{0.1193} - 1 \right\}, \quad p > \frac{1}{2}, \quad (13.64)$$

$$x_p \doteq -0.4115 \left\{ \frac{1-p}{p} + \ln\left(\frac{1-p}{p}\right) - 1 \right\}, \quad p \geq \frac{1}{2}, \quad (13.65)$$

$$x_p \doteq -a \ln\left(\frac{1-p}{p}\right) + b, \quad p \geq \frac{1}{2}, \quad (13.66)$$

where a and b should satisfy

$$b = [1 - 1.3682a^2]^{1/2} - 1.3862a$$

or its approximate simpler form $b = 1.3086 - 2.3735a$ (which is easier to use when a value of a is sought that gives the best fit for any desired range of x).

The approximation in (13.64) is the most accurate of the three with a maximum absolute difference of **0.0073 (0.5%)** for $0 \leq x \neq 2.3$. It is interesting to note that for $b = 0$, we have $a = 0.5513 = \sqrt{3}/\pi$, in which case the simple approximation in (13.66) becomes the logistic approximation (with location parameter 0 and shape parameter $\sqrt{3}/\pi$); see Chapter 23. For $-0.5 \leq x \leq 2.2$, the best approximation of (13.66) is with $a = 0.495$ and $b = 0.1337$; for $x > 2.2$, the best approximation is obtained with $a = 0.4506$ and $b = 0.2252$.

Shore (1982) has also obtained a good approximation for the standard normal pdf as

$$\begin{aligned} Z(x) &\doteq 1.4184(1-p)^{0.8632} p, \\ p &= \Phi(x) \geq \frac{1}{2}. \end{aligned} \quad (13.67)$$

This approximation immediately yields an approximation for the Mills's ratio (hazard rate—see Chapter 33, Section 2) as

$$\frac{Z(x)}{1 - \Phi(x)} \doteq \begin{cases} [1.4184p^{0.8632}]^{-1}, & p \leq \frac{1}{2}, \\ [1.4184(1-p)^{-0.1368} p]^{-1}, & p \geq \frac{1}{2}. \end{cases} \quad (13.68)$$

Shore has also discussed the accuracy of this approximation.

Shah (1985) suggested the following approximation for $\Phi(x) - \frac{1}{2}$, $x \geq 0$:

$$\begin{cases} \frac{x(4.4 - x)}{10}, & 0 \leq x \leq 2.2 \\ 0.49, & 2.2 < x < 2.6 \\ 0.50, & x \geq 2.6. \end{cases} \quad (13.69)$$

Even though this approximation is simple to use, it is clear from (13.69) that it is not designed to approximate right tail areas for $x \geq 2.6$. For this reason Norton (1989) proposed the approximations for $1 - \Phi(x)$ as

$$\frac{1}{2}e^{-(x^2+x)/2}, \quad 0 \leq x \leq 2.6, \quad (13.70)$$

$$\frac{1}{2}e^{-(x^2+1.2x^{0.8})/2}, \quad 0 \leq x \leq 2.7, \quad (13.71)$$

$$Z(x)/x, \quad x > 2.7. \quad (13.72)$$

A number of comments and criticisms have been made on these approximations given by Norton; see Hoaglin (1989), Pratt (1989), Cox (1989), Shore

(1990), Sharp (1990), Revfeim (1990), and McConnell (1990), and also the replies to these comments by Norton (1990a, b).

Schonfelder (1978) discussed further on Chebyshev expansions for the error and related functions, including $\Phi(x)$. Hamaker (1978) presented simple approximations for the cdf $\Phi(x)$ as well as for the percentage point x_p . Lin (1988) discussed alternatives to Hamaker's approximations. Schmeiser (1979) gave easy approximations for the percentage point x_p that could be used on hand calculators. Bailey (1981) proposed alternatives to Hastings's approximation to x_p . Lew (1981) presented an approximation to $\Phi(x)$ with simple coefficients. Wichura (1988) and Guirguis (1991) have discussed approximations to the percentage point x_p . While Heffernan (1988) gave a simple formula for the cdf $\Phi(x)$, Lin (1989) presented approximations for the normal tail probability as well as its inverse which are easy to use even on a hand calculator. Lin (1990) has also proposed a simpler logistic approximation to $\Phi(x)$ and to x_p [also see the comment after (13.66)]. Even though all these approximations are quick and easy to use, their relative accuracies may vary dramatically, and therefore their use should be adjudged for the particular situation one intends to use. The modern personal computer with its great power and memory does make some of the work (if not all) unnecessary, as the following remarks indicate.

Fleming (1989) has advocated the use of numerical integration for approximating $\Phi(x)$, for it can be easily demonstrated using a spreadsheet program and a personal computer. For example, $\Phi(x)$ can be computed using Lotus 1-2-3 by approximating the area under the standard normal pdf $Z(x)$. Fleming (1989) has noted that a rectangular integration gives results accurate to four decimal places for $0 \leq x \leq 3$, with the interval width being taken as 0.01. As he has pointed out, other methods of integration (like the trapezoidal rule, Simpson's rule, Newton's three-eighths rule) are also easily adaptable and will be even more accurate in evaluating $\Phi(x)$. When a powerful personal computer with a spreadsheet program is available, it should be put to use rather than relying on simple-to-use approximations.

A mechanical method of drawing a normal probability density curve has been described by Edwards (1963). *Normal probability paper* is graph paper with a natural scale in the horizontal (abscissa) direction, while the distances on the vertical (ordinate) scale are proportional to the corresponding normal deviates. The vertical scale is usually marked in percentages. Thus 50% correspond to the horizontal axis, 25% and 75% are at distances 0.6745 below and above this line, 5% and 95% are at distances 1.9600 below and above this line, and so on (see Figure 13.2). Barnett (1976) has discussed convenient probability plotting positions, while Nelson (1976) has elaborated the construction of normal probability paper. Recently Nelson (1989) put forward a stabilized normal probability plotting technique; Rouncefield (1990), among many others, explained how one could use the normal probability paper to assess the validity of the assumption of normal distribution for a sample.

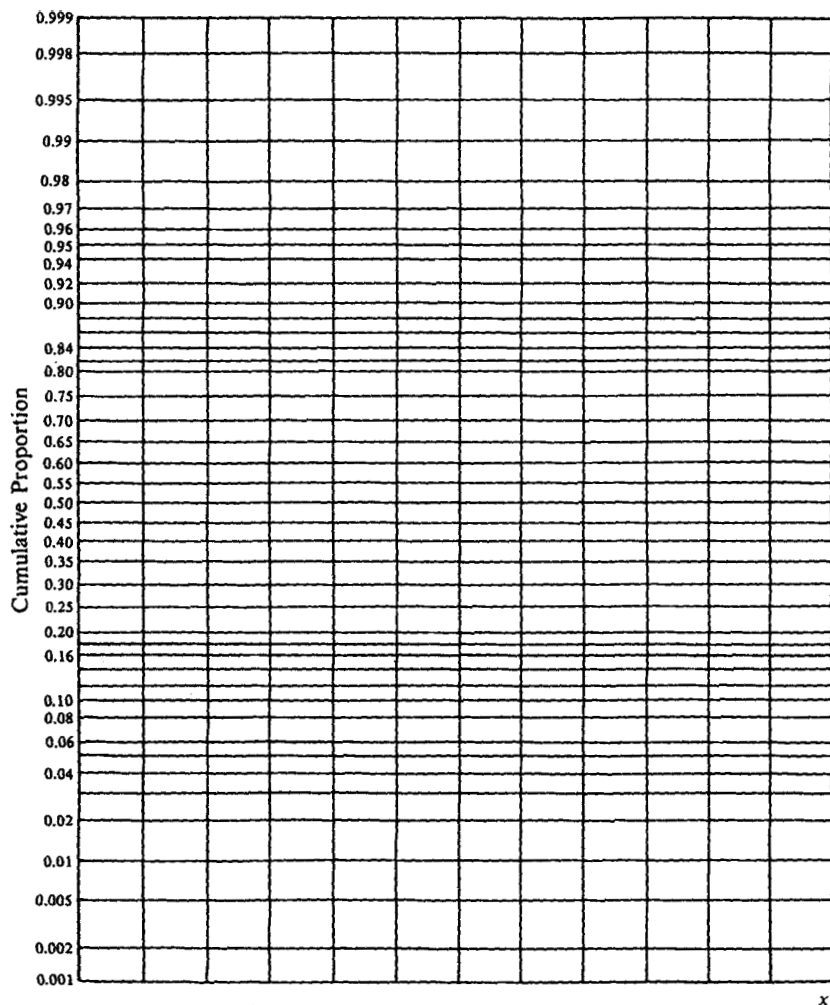


Figure 13.2 Normal Probability Paper

If X has the distribution (13.1) and $\Pr[X \leq x]$ is plotted (as the ordinate) against x (as the abscissa), then a straight line is obtained. The slope of this line is σ^{-1} and its intercept on the horizontal axis is at $x = \xi$. If observed frequencies of the events $(X \leq x)$ are used in place of the actual probabilities, an approximately straight-line plot may be expected. A straight line fitted to these observed points gives estimates of σ and ξ . Such graphical methods of estimation can give good practical accuracy,

If the horizontal scale is logarithmic, we have *lognormal probability paper* (see Chapter 14). *Half-normal probability paper* is simply normal probability paper with negative abscissas omitted. It is used in connection with analysis of variance techniques developed by Daniel (1959).

8 ESTIMATION

The theory of estimation of ξ and σ has been fully worked out. To facilitate comprehension, this section is divided into four subsections. Subsections 8.1 through 8.3 describe techniques primarily appropriate to a complete sample (though some apply also to censored data) corresponding to values of n independent random variables each having distribution (13.1). Subsection 8.4 describes techniques suitable when the data have been censored by omission of certain order statistics. (Truncated normal distributions will be discussed in Section 10.) Subsection 8.5 lists various **books/monographs** available on specific topics relating to inference for the normal distribution.

The variety of applicable methods can be bewildering. To judge rapidly between them, it is necessary to bear in mind accuracy, sensitivity to variations from normality, and ease of calculation. The relative importance of these factors varies with circumstance, but they should always be taken into account. As mentioned earlier in Section 2, there are numerous volumes available on specific topics relating to inference for the normal distribution (as listed in Section 8.5). This is understandable of course, due to the volume of literature. Because of the availability of all these volumes and the upcoming revised edition of "Handbook of the Normal Distribution" by Patel and Read, we only present briefly the recent developments, referring the readers to appropriate volumes for a comprehensive treatment of the topic of interest.

8.1 Estimation of ξ

The arithmetic mean $\bar{X} = n^{-1} \sum_{j=1}^n X_j$ and the mean square deviation $S^2 = n^{-1} \sum_{j=1}^n (X_j - \bar{X})^2$ are jointly sufficient for ξ and σ , and \bar{X} is sufficient for ξ alone. For most practical purposes \bar{X} is the best estimator for ξ , whether or not σ is known. It is the maximum likelihood estimator and is unbiased.

The only circumstances under which this estimator would not be used are (1) when not all observations are available (as will be discussed more fully in Section 8.4), or (2) when the accuracy of some values (**e.g.**, outlying values) is doubtful. In either case estimation may be based on a central block of order statistics. As an extreme case (when n is odd), a single order statistic, the median, may be used to estimate ξ . This is an unbiased estimator of ξ , and has standard deviation approximately equal to

$$\frac{1}{2} \pi \sigma^2 n^{-1} = 1.5708 \sigma^2 n^{-1}$$

compared with

$$\text{Var}(\bar{X}) = \sigma^2 n^{-1}.$$

The efficiency of the median, relative to \bar{X} , is thus approximately

$$100 \times (1.5708)^{-1}\% = 63.7\%.$$

Alternatively, the j th *Winsorized* mean

$$\tilde{\xi}_{(j)} = n^{-1} \left[jX'_{j+1} + \sum_{i=j+1}^{n-j} X'_i + jX'_{n-j} \right] \quad (13.73)$$

may be used ($j < [(n-1)/2]$). It can be seen that $\tilde{\xi}_{(j)}$ is obtained by replacing each of X'_1, X'_2, \dots, X'_j by X'_{j+1} and X'_{n-j+1}, \dots, X'_n by X'_{n-j} . This is also an unbiased estimator of ξ . It is interesting to note that Chernoff, Gastwirth, and Johns (1967) obtain a formula of the type (13.73), if only $X'_{j+1}, \dots, X'_{n-j}$ are available, with the multipliers (j) of X'_{j+1} and X'_{n-j} replaced by

$$a = \frac{[Z(U_\varepsilon)]^2 \varepsilon^{-1} + U_\varepsilon Z(U_\varepsilon)}{1 - 2\varepsilon + 2U_\varepsilon Z(U_\varepsilon) + 2[Z(U_\varepsilon)]^2 \varepsilon^{-1}},$$

where $\varepsilon = j/(n+1)$, and n^{-1} replaced by $(n - 2j + 2a)^{-1}$. In fact a is slightly less than j .

Rather than replace the values of extreme observations by more central values, we can simply omit them. The resulting unbiased estimator of ξ is the j th trimmed mean

$$\tilde{\xi}'_{(j)} = (n - 2j)^{-1} \sum_{i=j+1}^{n-j} X'_i. \quad (13.74)$$

Some relative efficiencies of $\tilde{\xi}'_{(j)}$, compared with \bar{X} , are shown in Table 13.3. (For efficiencies of $\tilde{\xi}_{(j)}$, see Table 13.9.)

Table 13.3 Efficiency of Trimmed Means, Relative to \bar{X}

n	j	Relative Efficiency
		of $\tilde{\xi}'_{(j)}$ (%)
5	2	69
10	2	89
10	3	81
15	2	92
15	4	83
15	6	73

It is apparent that the Winsorized mean $\tilde{\xi}_{(j)}$ is more efficient than $\tilde{\xi}'_{(j)}$. In fact, compared with the best linear unbiased estimator using the same order statistics, its efficiency never falls below 99.9% for $n \leq 20$ [Sarhan and Greenberg (1962)]. Meeden (1976) has pointed out a special property of linear estimates of ξ , while Mehran (1975) has derived relationships between the **UMVUEs** of the mean and median of a function of a normal distribution.

Knowledge of σ is of no help in calculating point estimators of ξ . It is, however, used in calculating the standard deviations of such estimators and in constructing confidence intervals for ξ . If σ is known, $100(1 - \alpha)\%$ confidence limits for ξ are

$$\bar{X} \pm \frac{U_{1-\alpha/2}\sigma}{\sqrt{n}}. \quad (13.75)$$

Although the similar formulas

$$\begin{aligned} \tilde{\xi}_{(j)} \pm U_{1-\alpha/2} \sqrt{\text{Var}(\tilde{\xi}_{(j)})}, \\ \tilde{\xi}'_{(j)} \pm U_{1-\alpha/2} \sqrt{\text{Var}(\tilde{\xi}'_{(j)})} \end{aligned} \quad (13.76)$$

do not give exact limits (since $\tilde{\xi}_{(j)}$, $\tilde{\xi}'_{(j)}$ do not have normal distributions), they give limits that are useful provided that n is not too small (e.g., $n \geq 15$).

If σ is not known, the above formulas cannot be used. It is natural to replace σ by an estimator of σ . If the sample size is large and a good (efficient) estimator of σ is used, this can be done with little serious effect on the confidence coefficient. The "estimator" of σ most often employed is

$$(1 - n^{-1})^{-1/2} S = \left[(n - 1)^{-1} \sum_{j=1}^n (X_j - \bar{X})^2 \right]^{1/2},$$

although this is not an unbiased estimator of σ . If this estimator is used, then $U_{1-\alpha/2}$ in (13.75) should be replaced by $t_{n-1, 1-\alpha/2}$, the upper $50\alpha\%$ point of the t distribution with $(n - 1)$ degrees of freedom (see Chapter 28). The effect of replacement of σ by $(1 - n^{-1})^{-1/2} S$ in formulas (13.76) is not so clear, but there should be comparable increase in the multiplying factor $U_{1-\alpha/2}$.

It can be shown (see Section 3) that \bar{X} and any function of the deviations $\{X_j - \bar{X}\}$, only, are mutually independent. This facilitates computation of percentage points of distributions of statistics of form

$$\frac{\sqrt{n}(\bar{X} - \xi)/\sigma}{f(X_1 - \bar{X}, \dots, X_n - \bar{X})} = T_{(f)},$$

say, with various functions $f(X_1 - \bar{X}, \dots, X_n - \bar{X})$ in the denominator, subject to the restrictions that $f(\cdot)$ is positive with probability one and that

$$f(ay_1, ay_2, \dots, ay_n) = af(y_1, y_2, \dots, y_n)$$

for any $a \geq 0$. For example, we might have

$$\begin{aligned} f(X_1 - \bar{X}, \dots, X_n - \bar{X}) &= \text{range} \\ &= \max(X_1 - \bar{X}, \dots, X_n - \bar{X}) \\ &\quad - \min(X_1 - \bar{X}, \dots, X_n - \bar{X}) \\ &= W \end{aligned}$$

or

$$\begin{aligned} f(X_1 - \bar{X}, \dots, X_n - \bar{X}) &= \text{mean deviation} \\ &= n^{-1} \sum_{j=1}^n |X_j - \bar{X}| \\ &= M. \end{aligned}$$

Indeed, any of the estimators of σ to be described in Section 8.2 might be used as $f(\cdot)$.

Under the conditions stated, the distribution of $\sigma^{-1}f(X_1 - \bar{X}, \dots, X_n - \bar{X})$ does not depend on σ . The distribution of $T_{(f)}$ therefore does not depend on ξ or σ . As a result it is possible, in principle, to construct tables of percentage points $T_{(f), \alpha}$ of this distribution, defined by $f(\cdot)$ and α alone. The relation

$$\Pr \left[T_{(f), \alpha_1} < \frac{\sqrt{n}(\bar{X} - \xi)/\sigma}{f(X_1 - \bar{X}, \dots, X_n - \bar{X})} < T_{(f), 1-\alpha_2} | \xi, \sigma \right] = 1 - (\alpha_1 + \alpha_2)$$

can be arranged to show that the limits

$$\begin{aligned} \bar{X} - \frac{\sigma T_{(f), \alpha_1} f(X_1 - \bar{X}, \dots, X_n - \bar{X})}{\sqrt{n}}, \\ \bar{X} - \frac{\sigma T_{(f), 1-\alpha_2} f(X_1 - \bar{X}, \dots, X_n - \bar{X})}{\sqrt{n}}, \end{aligned} \tag{13.77}$$

form a $100(1 - \alpha_1 - \alpha_2)\%$ confidence interval for ξ .

To calculate such limits it is necessary to have tables of percentage points of the distribution of $T_{(f)}$, among which the following are available:

For $f(\cdot) = (1 - n^{-1})^{-1/2}S$, as described in Chapter 28 (tables of distribution).

For $f(\cdot) = W$ [in Lord (1947)].

For $f(\cdot) = M$ [in Herrey (1965)].

If such tables are not available, approximations may be used, for example, the approximations to the distributions of M and W to be described in Section 8.2; alternatively, they may be determined through Monte Carlo simulations.

8.2 Estimation of σ

The maximum likelihood estimator of a (ξ not being known) is

$$S = \left[n^{-1} \sum_{j=1}^n (X_j - \bar{X})^2 \right]^{1/2}. \quad (13.78)$$

If ξ is known, the maximum likelihood estimator is

$$\left[n^{-1} \sum_{j=1}^n (X_j - \xi)^2 \right]^{1/2} = \left[S^2 + (\bar{X} - \xi)^2 \right]^{1/2}. \quad (13.79)$$

It is, however, very unusual to know ξ exactly, and we will not discuss this estimator further, except to note that neither (13.78) nor (13.79) is an unbiased estimator of a . In fact

$$\begin{aligned} E[S] &= \frac{\sigma(2/n)^{1/2}\Gamma(n/2)}{\Gamma[(n-1)/2]} \\ &= \frac{\sigma}{a_n} \end{aligned} \quad (13.80)$$

and

$$E\left[\left\{ S^2 + (\bar{X} - \xi)^2 \right\}^{1/2} \right] = \frac{\sigma(2/n)^{1/2}\Gamma[(n+1)/2]}{\Gamma(n/2)}.$$

To obtain an unbiased estimator of σ , we must multiply S by a_n . A few values of a_n are shown in Table 13.4. Values of $a'_n = a_n\sqrt{1 - n^{-1}}$, such that $a'_n E[\{(n-1)^{-1}\sum(X_j - \bar{X})^2\}^{1/2}] = \sigma$, are also shown.

Table 13.4 Multipliers a_n , a'_n Such That $E[a_n S] = \sigma = E[a'_n \sqrt{V}]$

n	a_n	a'_n
2	1.77245	1.25331
3	1.38198	1.12838
4	1.25331	1.08540
5	1.18942	1.06385
6	1.15124	1.05094
7	1.12587	1.04235
8	1.10778	1.03624
9	1.09424	1.03166
10	1.08372	1.02811

For n greater than 10, the formulas

$$a_n \doteq 1 + \frac{3}{4}(n-1)^{-1},$$

$$a'_n \doteq 1 + \frac{1}{4}(n-1)^{-1}$$

give quite good approximations.

$$V = n(n-1)^{-1}S^2 = (n-1)^{-1} \sum_{j=1}^n (X_j - \bar{X})^2 \quad (13.81)$$

is an unbiased estimator of σ^2 . Jarrett (1968) has given an interesting historical account of tables of these multiplying factors. [See also Cureton (1968) and Bolch (1968).] Note that the value of a minimizing the *mean square error* of aS^2 as an estimator of σ^2 is $(n^{-1} + 1)^{-1}$. The value of b minimizing the mean square error of bS as an estimator of σ is a'_{n+1} [Markowitz (1968)]. Iliescu and Voda (1974) have discussed the estimation of σ in detail.

The variance of the unbiased estimator, $a_n S$, of σ is

$$\text{Var}(a_n S) = [a_n^2(1 - n^{-1}) - 1]\sigma^2. \quad (13.82)$$

The variance of V is

$$\text{Var}(V) = 2(n-1)^{-1}\sigma^4. \quad (13.83)$$

Unbiased estimator of σ can also be obtained by multiplying the mean deviation (M) and the range (W) by appropriate factors (depending of course on n). The resulting unbiased estimators $b_n M$, $c_n W$ are identical with $a_n S$ for $n = 2$, and have greater variances than $a_n S$ for $n > 2$. Values of b_n

can be calculated from the simple formula $b_n = \sqrt{(\pi/2)n(n-1)^{-1}}$. Values of c , for $n = 2(1)20$ are given in **Pearson** and **Hartley** (1948).

Relative efficiencies (inverse ratio of variances) of $b_n M$, $c_n W$ and other unbiased estimators of σ compared with $a_n S$, are shown in Table 13.7 on page 136. From this table it can be seen that the estimator based on range is (slightly) more efficient than that based on mean deviation for $n = 4, 5$, but less efficient for $n \geq 6$. (For $n = 2, 3$ the two estimators give identical estimators of σ .)

The formula for b_n , quoted above, follows from

$$E[M] = \sigma \sqrt{\left(\frac{2}{\pi}\right)(1 - n^{-1})}. \quad (13.84)$$

The variance of M is

$$\text{Var}(M) = \frac{2\sigma^2}{n\pi} \left(1 - \frac{1}{n}\right) \left\{ \frac{1}{2}\pi + \sqrt{n(n-2)} - n + \sin^{-1} \frac{1}{n-1} \right\}. \quad (13.85)$$

For $n \geq 5$, a very good approximation (error no more than about 0.00001) is

$$\sigma^2 \text{Var}(M) \doteq n^{-1}(1 - 2\pi^{-1})(1 - 0.12n^{-1}). \quad (13.86)$$

Approximate formulas for the moment ratios of M are

$$\begin{aligned} \beta_1(M) &\doteq 1.05n^{-1}, \\ \beta_2(M) &= 3 + 0.91n^{-1}. \end{aligned}$$

Godwin and **Hartley** (1945) calculated a table of the probability integral of the distribution of M , giving $\text{Pr}[M \leq mu]$ to 5 decimal places for $m = 0.00(0.02)3.00$ and $n = 2(1)10$, and also multipliers M_α for percentile points such that

$$\text{Pr}[M \leq M_\alpha \sigma] = a$$

to 3 decimal places, for $n = 2(1)10$ and $a = 0.001, 0.005, 0.01, 0.025, 0.05, 0.1, 0.9, 0.95, 0.975, 0.99, 0.995, \text{ and } 0.999$. For $n = 10$ there are also given approximate values calculated from the formula

$$M_\alpha \doteq E\left[\frac{M}{\sigma}\right] + U_\alpha \left(\sqrt{\text{Var}\left(\frac{M}{\sigma}\right)} \right). \quad (13.87)$$

Although the upper and lower 2.5%, 5% and 10% values are not too inaccurate, approximation is poor for the more extreme values. A better

approximation was obtained by **Cadwell (1953)**, by regarding $(M/\sigma)^{1.8}$ as having (approximately) a $c\chi_\nu^2$ distribution with

$$\log c = -\log 2 - 1.8 \left[\log \left(\frac{5}{9} + \frac{\nu}{2} \right) - \log \Gamma \left(\frac{\nu}{2} \right) - \frac{1}{2} \log \left\{ \left(\frac{2}{\pi} \right) (1 - n^{-1}) \right\} \right], \quad (13.88)$$

$$\nu = \nu_0 + 0.196 - 0.159\nu_0^{-1},$$

$$\nu_0 = \frac{0.617[E[M]]^2}{\text{Var}(M)}.$$

The approximation was obtained by first finding values of A , c , and ν to make $(M/\sigma)^A$ and $c\chi_\nu^2$ have the same first three moments. The values of course depend on n ; they are shown in Table 13.5 [based on **Cadwell (1953)**]. This table also gives the results of similar calculations for the range W . It can be seen that for M , the values of A do not vary much, once n exceeds 5, say. An "average" value of 1.8 was chosen; the values of ν and c were then adjusted to make the first **two** moments of $(M/\sigma)^{1.8}$ and $c\chi_\nu^2$ agree. It might

Table 13.5 Values of ν , A , and $\log c$ Such That First Three Moments of $(T/\sigma)^A$ and $c\chi_\nu^2$ Agree

n	T = Range			T = Mean Deviation		
	ν	A	$\log_{10} c$	ν	A	$\log_{10} c$
2	1.00	2.00	0.3010	1.00	2.00	$\bar{1}.6990$
3	2.05	1.96	0.2368	2.05	1.96	$\bar{1}.4234$
4	3.20	1.90	0.1547	3.35	1.84	$\bar{1}.2370$
5	4.5	1.83	0.0607	4.6	1.80	$\bar{1}.1149$
6	6.0	1.75	$\bar{1}.9588$	5.9	1.77	$\bar{2}.0177$
7	7.7	1.67	$\bar{1}.8574$	7.2	1.74	$\bar{2}.9388$
8	9.5	1.60	$\bar{1}.7685$	8.4	1.74	$\bar{2}.8765$
9	12.0	1.51	$\bar{1}.6457$	9.6	1.74	$\bar{2}.8222$
10	14.0	1.46	$\bar{1}.5785$	11.0	1.72	$\bar{2}.7674$
12	19.0	1.36	$\bar{1}.4252$	13.0	1.74	$\bar{2}.6964$
14	26.0	1.24	$\bar{1}.2479$	16.0	1.70	$\bar{2}.6126$
16	34.0	1.14	$\bar{1}.0964$	18.0	1.72	$\bar{2}.5617$
18	46.0	1.03	$\bar{2}.9142$	21.0	1.70	$\bar{2}.4988$
20	60.0	0.94	$\bar{2}.7569$	23.0	1.71	$\bar{2}.5491$

be thought that $A = 1.7$ would have been a better choice, but the chosen value of $A (= 1.8)$ does give closer approximation for smaller values of n , without affecting the accuracy too severely for larger values of n .

In the same paper **Cadwell** discussed approximations to the distributions of the arithmetic mean of a number (k) of (independent) (M/σ) 's or (W/σ) 's. He also considered the distributions of the ratios

$$\frac{\max_j(M_j)}{\min_j(M_j)} \quad \text{and} \quad \frac{\max_j(W_j)}{\min_j(W_j)},$$

which are analogous to the ratios of maximum to minimum of a number of independent mean square deviations $(S_1^2, S_2^2, \dots, S_k^2)$, each based on the same number of observed values. **Cadwell** gives tables of approximate upper 5% and 1% points of these statistics for $n = 3(1)10$ and $k = 2(1)12$ (for the 5% points, $n = 12, 15, 20, 30, 60$ are also included for the mean deviation ratio, and $n = 12, 15, 20$ for the range ratio). Similar tables for the statistics

$$\frac{\max_j(S_j^2)}{\min_j(S_j^2)}$$

are given by **Pearson and Hartley (1948)**. They also provide some useful tables of values connected with the distribution of (M/σ) , including the expected value, variance, β_1 , and β_2 for $n = 2(1)20, 30, 60$, and the upper and lower 0.1, 0.5, 2.5, 5, and 10 percentage points for $n = 2(1)10$.

Among the few simple exact results concerning the distribution of range, we note the following:

$$\text{For } n = 2, E[W] = 2\sigma/\sqrt{\pi}; \text{Var}(W) = 2\sigma^2(1 - 2\pi^{-1}).$$

$$\text{For } n = 3, E[W] = 3\sigma/\sqrt{\pi}; \text{Var}(W) = \sigma^2[2 - (9 - 3\sqrt{3})\pi^{-1}].$$

$$\text{For } n = 4, E[W] = (3\sigma/\sqrt{\pi})(1 + 2\pi^{-1} \sin^{-1}(\frac{1}{3})).$$

Godwin (1949a) gives a number of other exact values of first and second moments.

Subsequently, quite extensive tables of the distribution and moments of (W/σ) have become available. A historical survey (up to 1960) of these tables has been given by **Harter (1960)**, who also provided tables of percentage point multipliers, W_α , to 6 decimal places for $n = 2(1)20(2)40(10)100$ and $\alpha = 0.0001, 0.0005, 0.001, 0.005, 0.01, 0.025, 0.05, 0.1(0.1)0.9, 0.95, 0.975, 0.99, 0.995, 0.999, 0.9995, \text{ and } 0.9999$. There are also tables of the expected value, variance, and β_1 and β_2 of (W/σ) to 8 (or more) significant figures for $n = 2(1)100$ in **Harter (1960)**. **Pearson and Hartley (1948)** give tables of $\text{Pr}[W \leq w\sigma]$ to 4 decimal places for $n = 2(1)20$ and $w = 0.00(0.05)7.25$. They also give the upper and lower 0.1, 0.5, 2.5, 5, and 10 percentage points of the

distribution of (W/σ) to 2 decimal places, and expected value and variance (5 decimal places), β_1 (4 decimal places), and β_2 (3 decimal places) for $n = 2(1)20, 30$, and 60 . More elaborate tables are also available in this context, and some numerical algorithms have also been developed; see Section 4 for details.

From Table 13.5 it can be seen that a single value of A might not be found such that $(W/\sigma)^A$ is well approximated by a distribution of $c\chi_\nu^2$ (for suitably chosen c and ν) for a range of values of $n \leq 20$. **Pearson (1952)** and **Cox (1949)** have investigated this kind of approximation in some detail. From their investigations it appears that for smaller values of n (e.g., $n \leq 8$), an approximation of the form $c\chi_\nu$ is preferable (indeed, it is exact for $n = 2$); an approximation of the form $c\chi_\nu^2$ is better for larger values of n .

Using tables of percentage points of (M/σ) , (W/σ) , and χ^2 (see Chapter 18), it is possible to construct confidence intervals for σ by rewriting the equation

$$\Pr\left[T_{\alpha_1}\sigma < T < T_{1-\alpha_2}\sigma \mid \sigma\right] = 1 - \alpha_1 - \alpha_2$$

in the form

$$\Pr\left[\frac{T}{T_{1-\alpha_2}} < \sigma < \frac{T}{T_{\alpha_1}} \mid \sigma\right] = 1 - \alpha_1 - \alpha_2, \quad (13.89)$$

which shows that $(T/T_{1-\alpha_2}, T/T_{\alpha_1})$ is a $100(1 - \alpha_1 - \alpha_2)\%$ confidence interval for σ . Here T can be replaced by M , W , or $\sqrt{n}S$, and T_α by $(M/\sigma)_\alpha$, $(W/\sigma)_\alpha$, or $\sqrt{n}\chi_{n-1, \alpha}$, respectively.

The maximum likelihood estimator S of σ (like its unbiased counterpart $a_n S$) is not a linear function of the observed values of X_1, X_2, \dots, X_n . It is, however, possible to construct a best linear unbiased estimator of σ , using the order statistics X'_1, X'_2, \dots, X'_n . Such estimators (using all the sample values) are of form

$$D = \sum_{j=1}^{[n/2]} \alpha_j (X'_{n-j+1} - X'_j). \quad (13.90)$$

Values of α_j have been calculated for $n = 2(1)20$; they have been published in Sarhan and Greenberg (1962). Balakrishnan (1990) has presented similar tables for $n = 21(1)30(5)40$. The efficiency of D relative to $a_n S$ is always greater than 98%. Although this is very satisfactory, these estimators are not used often because it is just as easy to calculate $a_n S$ if all values are to be used, and this does not require such extensive auxiliary tables. If a linear estimator is desired (e.g., to reduce effects of inaccurate outlying observations), there are other linear estimators, nearly as efficient as D , but with simpler formulas for the coefficients.

We take especial note of *Gini's* mean difference

$$G = \binom{n}{2}^{-1} \sum_{i < j}^n \sum_{i < j}^n |X_i - X_j|$$

$$= \frac{4}{n(n-1)} \sum_{j=1}^{\lfloor n/2 \rfloor} \left\{ \frac{1}{2}(n+1) - j \right\} (X'_{n-j+1} - X'_j). \quad (13.91)$$

We have

$$E[G] = \left(\frac{2}{\sqrt{\pi}} \right) \sigma,$$

$$\text{Var}[G] = 4[n(n-1)]^{-1} \left[\frac{1}{3}(n+1) + 2\pi^{-1}(n-2)\sqrt{3} \right. \\ \left. - 2\pi^{-1}(2n-3) \right] \sigma^2.$$

The statistic $\frac{1}{2}\sqrt{\pi}G$ is an unbiased estimator of σ . The first three lines of Table 13.7 [taken from Nair (1949)] show the efficiencies of $M\sqrt{\pi}/2$, $\frac{1}{2}\sqrt{\pi}G$ and D, the best linear unbiased estimator of σ , for $n = 2(1)10$. It can be seen that $\frac{1}{2}\sqrt{\pi}G$ is very nearly as efficient as D. As n tends to infinity, the efficiency of $\frac{1}{2}\sqrt{\pi}G$, relative to $a_n S$, tends to

$$\left(\frac{2}{3} + 4\sqrt{3} - 8 \right)^{-1} = 97.8\%.$$

The asymptotically efficient estimator obtained by the method of Chernoff, Gastwirth, and Johns (1967) (see Section 2 of Chapter 12) is obtained by putting α_j in (13.90) equal to $U_{j/(n+1)}$ for all j .

We also mention an estimator of σ suggested by Gupta (1952) as an approximation to D. This is obtained by replacing the coefficients α_j in (13.90) by

$$a_j = \frac{E[U'_{n-j+1}]}{\sum_{j=1}^n \{E[U'_j]\}^2}, \quad (13.92)$$

where $U'_1 \leq U'_2 \leq \dots \leq U'_n$ are order statistics corresponding to n independen-

dent unit normal variables so that the estimator is

$$D' = \frac{\sum_{j=1}^n X_j E[U_j']}{\sum_{j=1}^n \{E[U_j']\}^2}. \quad (13.93)$$

For large n this estimator is very nearly the same as the asymptotically efficient estimator just described. Shapiro and Wilk (1965) described estimators similar to D' , except that the ratio of α' , to the remaining α' 's is modified.

In view of the accuracy attainable with $\frac{1}{2}\sqrt{\pi}G$, it does not seem necessary to consider the use of D' . However, we note an estimator proposed by Mead (1966) which is based on the same general idea as Gupta's estimator and may be convenient to apply in special circumstances (e.g., using certain kinds of rapid measuring apparatus). Suppose that the number of observations (n) is a multiple of m , say, km . The data are then sorted into k groups so that the m least values are in the first group, the next m least values in the second group, and so on; the last group consists of the m greatest values. If the unit normal distribution is truncated between u_{i-1} and u_i ($> u_{i-1}$), then (see Section 10.1) the expected value of the truncated distribution is

$$\lambda_{(i)} = \frac{Z(u_i) - Z(u_{i-1})}{\Phi(u_i) - \Phi(u_{i-1})}.$$

Mead's estimator is then

$$\frac{\sum_{i=1}^k \lambda_{(i)} [\text{Mean of the } i\text{th group}]}{\sum_{i=1}^k \lambda_{(i)}^2}, \quad (13.94)$$

with

$$u_0 = -\infty,$$

$$u_i = U_{i/k}, \quad i = 1, \dots, (k-1),$$

$$u_k = \infty.$$

(Note that $\Phi(u_i) - \Phi(u_{i-1}) = k^{-1}$ for all i .) Denoting the mean of the i th group by \bar{Y}_i , the estimators are as follows: for $k = 2$, $0.62666 (\bar{Y}_2 - \bar{Y}_1)$; for $k = 3$, $0.45838 (\bar{Y}_3 - \bar{Y}_1)$; for $k = 4$, $0.36927 (\bar{Y}_4 - \bar{Y}_1) + 0.09431 (\bar{Y}_3 - \bar{Y}_2)$; for $k = 5$, $0.31213 (\bar{Y}_5 - \bar{Y}_1) + 0.11860 (\bar{Y}_4 - \bar{Y}_2)$; and for $k = 6$, $0.27177 (\bar{Y}_6 - \bar{Y}_1) + 0.12373 (\bar{Y}_5 - \bar{Y}_2) + 0.03844 (\bar{Y}_4 - \bar{Y}_3)$. Mead obtained these

values for the asymptotic efficiency of this estimator (n large) relative to $a_n S$:

k	2	3	4	5	6
Asymptotic Efficiency (%)	87.6	93.3	95.6	96.8	97.8

Yet another class of linear estimators has been studied by Oderfeld and Pleszczyńska (1961) and Pleszczyńska (1965). These are linear functions of the order statistics Y'_1, \dots, Y'_n corresponding to the random variables $Y_j = |X_j - \bar{X}|$. These authors estimated the values of the coefficients in

$$\sum_{j=1}^n \alpha_j Y'_j$$

on an empirical basis, using result of sampling experiments. In the first paper the only value used for n was 5, and the suggested estimator was

$$-0.065Y'_1 + 0.150Y'_2 + 0.175Y'_3 + 0.312Y'_4 + 0.405Y'_5.$$

In the second paper the smallest absolute deviate was omitted (i.e., a , taken equal to zero). Coefficients (α_j) were estimated for $n = 3(1)10$. In all cases the largest coefficient was α_n , indicating the relative importance of extreme observations in estimating σ . These estimators appear (from empirical evidence) to have quite high (over 95%) efficiencies relative to $a_n S$, though they are no higher than, for example, estimators based on Gini's mean difference.

For $n \leq 10$ (at least) there are even simple unbiased estimators of σ that are not much less efficient than $\frac{1}{2}\sqrt{\pi} G$ or D . These are based on the thickened ranges

$$J_{(r)} = \sum_{j=1}^r (X'_{n-j+1} - X'_j) \tag{13.95}$$

[Jones (1946)]. Values of the multiplying factor to be applied to $J_{(2)}$ to make it an unbiased estimator of σ are shown in Table 13.6 [taken from Jones (1946)]. Relative efficiencies of these estimators (compared with $a_n S$) are also shown in Table 13.7. It can be seen that if $J_{(1)}$ ($\equiv W$) be used for $n \geq 1$ and $J_{(2)}$ for $6 \leq n \leq 10$, the relative efficiency never falls below 98%.

For large n Prescott (1968) has given the approximate formulas

$$E[J_{(r)}] = \frac{2r\sigma Z(U_p)}{p},$$

$$\text{Var}(J_{(r)}) = \frac{2r^2\sigma^2}{np^2} [p + \{pU_p - Z(U_p)\}\{(1 - 2p)U_p + 2Z(U_p)\}],$$

Table 13.8 Unbiased Estimators of α

n	Estimator	Efficiency (%) Relative to $a_n S$
11	$0.1608(W + W_{(2)} + W_{(4)})$	96.7
12	$0.1524(W + W_{(2)} + W_{(4)})$	97.2
13	$0.1456(W + W_{(2)} + W_{(4)})$	97.5
14	$0.1399(W + W_{(2)} + W_{(4)})$	97.7
15	$0.1352(W + W_{(2)} + W_{(4)})$	97.7
16	$0.1311(W + W_{(2)} + W_{(4)})$	97.5
17	$0.1050(W + W_{(2)} + W_{(3)} + W_{(5)})$	97.8
18	$0.1020(W + W_{(2)} + W_{(3)} + W_{(5)})$	97.8
19	$0.09939(W + W_{(2)} + W_{(3)} + W_{(5)})$	97.9
20	$0.10446(W + W_{(2)} + W_{(4)} + W_{(6)})$	98.0

sometimes called the j th quasi-range, occasionally the j th subrange. Evidently

$$J_{(r)} = \sum_{j=1}^r W_{(j)} \quad (\text{and } W_{(1)} \equiv W). \quad (13.97)$$

Dixon found that for $n \leq 10$ the most efficient estimators of form (13.96) are those based on the range ($W \equiv W_{(1)}$), or thickened range $J_{(2)}$ just described. For $n = 11 - 20$ he obtained the most efficient unbiased estimators [in the class (13.96)] given in Table 13.8. The efficiencies compare quite well with those of D , though they are not generally as high as those of Gini's mean difference.

Note that those unbiased linear estimators which are optimal (in various restricted classes) give large relative weight to the extreme observations. [Even S , which appears to be symmetrical, can be regarded (very roughly) as using weights proportional to the absolute magnitude of deviation from the sample mean.] Although we have obtained high efficiencies with these estimators, the calculations are all based on the complete validity of the normal distribution as applied to the data. Distributions of extreme order statistics are likely to be especially sensitive to departures from normality, and it is sometimes more important to guard against this possibility than to squeeze the last drop of formal "efficiency" from the data.

The simplest method of this kind uses only a single pair of symmetrically placed order statistics, in the form of a quasi-range, giving an estimator

$$\beta_r W_{(r)} = \beta_r (X'_{n-r+1} - X'_r).$$

For n large it is best to take $r \doteq 0.069n$. The efficiency (relative to $a_n S$) of the corresponding unbiased estimator of \mathbf{a} is about 65% [Pearson (1920)]. [For estimating ξ by a statistic of form

$$\beta_{r/2}(X'_{n-r+1} + X'_r),$$

the best choice is $r \doteq 0.270n$, and the efficiency is about 67%.]

Kulldorff (1963, 1964) has studied the construction of estimators of this kind in some detail. He found that if estimators of form

$$\sum_{i=1}^k \beta_{r_i} W_{(r_i)} \quad (13.98)$$

were considered, quite good results could be obtained by taking β_{r_i} proportional to i , giving estimators of form

$$\gamma \sum_{i=1}^k i W_{(r_i)}. \quad (13.99)$$

For $k = 2$ Kulldorff found that the best values of r_1 and r_2 [subject to an estimator of form (13.99) being used] to take are $0.0235n$ and $0.1279n$, respectively, with $\gamma = 0.1174$; for $k = 3$ optimal values are $r_1 = 0.0115n$, $r_2 = 0.0567n$, and $r_3 = 0.1704n$, with $\gamma = 0.0603$. The corresponding relative efficiencies are approximately 82% for $k = 2$ and 89% for $k = 3$. Note that these results apply to "large" samples (large values of n) and cannot be expected to apply when $n \leq 20$, as in the discussion of other estimators.

Using the large-sample approximations, Eisenberger and Posner (1965) have constructed "best linear unbiased estimators" of mean and standard deviation using only a fixed number (k) of quantiles, and excluding quantiles more extreme than 1 and 99%, or 2.5 and 97.5%, for $k = 2(2)20$. They also give (for the same values of k) pairs of linear estimators minimizing

(Variance of estimator of mean)

+ λ (Variance of estimator of standard deviation)

for $A = 1, 2$, and 3 . Formulas appropriate for censored samples (described in Section 8.4) can also be used for complete samples if certain observed values must be ignored.

Ogawa (1976) has commented on the optimal spacing of the systematic statistics for the estimation of normal parameters. Ogawa (1977) later presented optimal spacings for the simultaneous estimation of ξ and \mathbf{a} based on selected two sample quantiles. Cheng (1980) discussed the asymptotic best linear unbiased estimator of ξ from a censored sample. Fattorini (1978) gave percentile estimators for ξ and \mathbf{a} , while Cheng and Ling (1983) discussed the

best linear unbiased estimators based on incomplete samples. Miyakawa, Tamiya, and Kotani (1985b) addressed the question of whether optimal spacings (in the case of small samples) for the estimation of ξ and σ should be symmetric. Balakrishnan and Cohen (1991) have presented a detailed account of the optimal linear estimation problem.

For the linear estimators based on order statistics (apart from those based on W alone) there are no easily available tables of percentage points. Such tables would be needed to construct confidence intervals for σ by rearranging the relation

$$\Pr[T_{\alpha_1}\sigma < T < T_{1-\alpha_2}\sigma | \sigma] = 1 - \alpha_1 - \alpha_2$$

in the form

$$\Pr\left[\frac{T}{T_{1-\alpha_2}} < \sigma < \frac{T}{T_{\alpha_1}} \mid \sigma\right] = 1 - \alpha_1 - \alpha_2$$

[see (13.89)]. Even for those cases where such tables are available (M and W) only symmetrical intervals (with $\mathbf{a}_r = \mathbf{a}_s$) are practically useful. Except in connection with intervals based on S , no attempt has been made to construct shortest confidence intervals for σ . Nair (1947) suggested calculation of upper and lower 1% and 5% points of the distribution of the second thickened range $J_{(2)}$, but such tables have not been published. In many cases an approximation using a distribution of the form of that of a multiple of a chi random variable ($c\chi_\nu$) (Chapter 18) may give results that are not seriously inaccurate for practical purposes.

8.3 Estimation of Functions of ξ and σ

Certain functions of both ξ and σ are sometimes the primary target of statistical estimation. Among these we particularly note the $100\alpha\%$ percentile point ($\xi + U_\alpha\sigma$) and the proportion (of population) less than a fixed number x ,

$$P_x = (\sqrt{2\pi}\sigma)^{-1} \int_{-\infty}^{(x-\xi)/\sigma} e^{-u^2/2} du. \quad (13.100)$$

These quantities may be estimated by general methods, not using the special form of distribution. However, when the validity of the assumption of normality has been clearly established, it is to be expected that more accurate estimates can be obtained by using this knowledge of the form of distribution.

Evidently, if $\hat{\xi}'$, $\hat{\sigma}'$ are any unbiased estimators of ξ , σ , respectively, then $(\hat{\xi}' + U_\alpha\hat{\sigma}')$ is an unbiased estimator of $\xi + U_\alpha\sigma$. If \bar{X} is used as the estimator of ξ and if $\hat{\sigma}'$ is any of the unbiased estimators of σ described in

Section 8.2, then, since \bar{X} and $\hat{\sigma}'$ are independent,

$$\text{Var}(\bar{X} + U_\alpha \hat{\sigma}') = \sigma^2 n^{-1} + U_\alpha^2 \text{Var}(\hat{\sigma}'). \quad (13.101)$$

Combination of \bar{X} with the best linear unbiased estimator of σ (or one of the other, nearly as efficient, linear estimators of σ) will give a good linear estimator of $\xi + U_\alpha \sigma$.

If $a_n S$ is used as an estimator of σ , the distribution of the estimator $(\bar{X} + U_\alpha a_n S)$ may be evaluated in the following way:

$$\begin{aligned} \Pr[\bar{X} + U_\alpha a_n S \leq K] &= \Pr\left[\left(\xi + \frac{U\sigma}{\sqrt{n}}\right) + \left(\frac{U_\alpha a_n \sigma}{\sqrt{n}}\right) \chi_{n-1} \leq K\right] \\ &= \Pr\left[\left\{U + \frac{\sqrt{n}(\xi - K)}{\sigma}\right\} \left(\frac{\chi_{n-1}}{\sqrt{n-1}}\right)^{-1} \leq -U_\alpha a_n \sqrt{n-1}\right] \\ &= \Pr\left[t'_{n-1}\left(\frac{\sqrt{n}(\xi - K)}{\sigma}\right) \leq -U_\alpha a_n \sqrt{n-1}\right], \end{aligned} \quad (13.102)$$

where $t'_{n-1}(\lambda)$ denotes a noncentral t variable (see Chapter 31) with $n - 1$ degrees of freedom and a noncentrality parameter λ .

If other estimators of σ are used, approximate results of similar form can be obtained by approximating the distribution of $\hat{\sigma}'$ by that of $c\chi_\nu$, with suitable values of c and ν . It will usually be troublesome to assess the accuracy of these approximations. If effects of unreliable outlying observations are to be specially avoided, then estimators of ξ and σ not using such observations may be used. However, if the reason for this precaution is that lack of normality is suspected, it is doubtful that $\xi + U_\alpha \sigma$ should be estimated at all.

Coming now to the estimation of quantities like

$$\Pr[X \leq x] = (\sqrt{2\pi})^{-1} \int_{-\infty}^{(x-\xi)/\sigma} e^{-u^2/2} du,$$

it is clear that the maximum likelihood estimator is obtained by replacing ξ by \bar{X} , and σ by S . The resulting estimator is, in general, biased. (It is unbiased if it so happens that $x = \xi$.)

To obtain the minimum variance unbiased estimator, the Blackwell-Rao theorem may be used. The estimator

$$T = \begin{cases} 1 & \text{if } X_1 \leq x, \\ 0 & \text{if } X_1 > x \end{cases} \quad (13.103)$$

is an unbiased estimator of $\Pr[X \leq x]$ and \bar{X} and S are jointly complete sufficient statistics for ξ and \mathbf{a} . Hence the minimum variance unbiased estimator of $\Pr[X \leq x]$ is

$$\begin{aligned} E[T|\bar{X}, S] &= \Pr[X_1 \leq x|\bar{X}, S] \\ &= \Pr\left[\frac{X_1 - \bar{X}}{S} \leq \frac{x - \bar{X}}{S} \mid \bar{X}, S\right]. \end{aligned}$$

Since the conditional distribution of $(X_1 - \bar{X})/S$ is independent of both \bar{X} and S , it is the same as the unconditional distribution of $(X_1 - \bar{X})/S$. Making an orthogonal transformation with one new variable $\sqrt{n/(n-1)}(X_1 - \bar{X})$, and one equal to $\sqrt{n}\bar{X}$, it can be seen that $(X_1 - \bar{X})/S$ is distributed symmetrically about zero as the signed square root of $(n-1)$ times a beta variable with parameters $\frac{1}{2}, \frac{n}{2} - 1$ (see Chapter 25). Hence the minimum variance unbiased estimator of $\Pr[X \leq x]$ is

$$\begin{cases} \left[B\left(\frac{1}{2}, \frac{n}{2} - 1\right) \right]^{-1} \int_{-1}^{(x-\bar{X})/(S\sqrt{n-1})} (1-v^2)^{(n-4)/2} dv & \text{for } |x - \bar{X}| \leq S\sqrt{n-1}, \\ 0 & \text{for } x < \bar{X} - S\sqrt{n-1}, \\ 1 & \text{for } x > \bar{X} + S\sqrt{n-1}. \end{cases} \quad (13.104)$$

(Numerical evaluation can be effected using tables of the incomplete beta function, as described in Chapter 25.)

At this point we note that if X_{n+1} is independent of, and has the same distribution as each X_j , $(X_{n+1} - \bar{X})/S$ is distributed as $[(n+1)/(n-1)]^{1/2}$ times t with $n-1$ degrees of freedom. Hence the interval

$$\left(\bar{X} + t_{n-1, \alpha_1} \left[\frac{n+1}{n-1} \right]^{1/2} S, \bar{X} + t_{n-1, 1-\alpha_2} \left[\frac{n+1}{n-1} \right]^{1/2} S \right)$$

contains on average a proportion $1 - \alpha_1 - \alpha_2$ of the population values. It is thus a form of tolerance interval for the normal distribution. Unlike the tolerance intervals described in Chapter 12, the construction of this interval

makes use of knowledge of the form of population distribution. It cannot be used for other populations without the possibility of introducing bias.

Wald and Wolfowitz (1946) have shown that a good approximation to tolerance limits, such that there is a probability equal to $1 - \alpha$ that the limits include at least a specified proportion γ of the population, is

$$\bar{X} \pm \frac{\lambda_\gamma \sqrt{n} S}{\chi_{n-1, \alpha}}, \quad (13.105)$$

where λ_γ satisfies the equation

$$\Phi(n^{-1/2} + \lambda_\gamma) - \Phi(n^{-1/2} - \lambda_\gamma) = \gamma.$$

The construction of exact one-sided tolerance limits can be simply effected, using the noncentral t distribution (see Chapter 31). We note that the population proportion less than $(\bar{X} + kS)$ is

$$\Phi\left(\frac{\bar{X} + kS - \xi}{\sigma}\right),$$

and this is at least γ if

$$\frac{\bar{X} + kS - \xi}{\sigma} \geq U_\gamma.$$

This inequality can be rearranged in the form

$$\frac{\sqrt{n} \{(\bar{X} - \xi)/\sigma\} - \sqrt{n} U_\gamma}{\sqrt{n} (S/\sigma)/\sqrt{n-1}} \geq -k\sqrt{n-1}. \quad (13.106)$$

The statistic on the left-hand side of (13.106) has a noncentral t distribution with $(n - 1)$ degrees of freedom and noncentrality parameter $(-\sqrt{n} U_\gamma)$. In order that the probability that at least a proportion γ of the population is less than $(\bar{X} + kS)$, should be equal to $(1 - \alpha)$, we make $(-k\sqrt{n-1})$ equal to the lower $100\alpha\%$ point of the noncentral t distribution, i.e.

$$k = \frac{-t'_{n-1, \alpha}(-\sqrt{n} U_\gamma)}{\sqrt{n-1}} \quad (13.107)$$

Nelson (1977) has discussed tolerance factors for the normal distribution. Odeh and Owen (1980) have presented elaborate tables of normal tolerance limits. Gerisch, Struck, and Wilke (1987) determined one-sided tolerance limit factors in the case of censored samples through Monte Carlo simula-

tions. Mee (1988) discussed the estimation of the percentage of a normal distribution lying outside a specified interval. Eberhardt, Mee, and Reeve (1989) determined factors for exact two-sided tolerance limits for the normal distribution.

Sometimes it is desired to estimate the mean square error $(\xi - \xi_0)^2 + \sigma^2$, where ξ_0 is a specified number. The mean square

$$n^{-1} \sum_{j=1}^n (X_j - \xi_0)^2$$

is an unbiased estimator of this quantity. It is distributed as

$$n^{-1}\sigma^2 \times \left(\begin{array}{l} \text{Noncentral } \chi^2 \text{ with} \\ n \text{ degrees of freedom and} \\ \text{noncentrality parameter} \\ n(\xi - \xi_0)^2/\sigma^2 \end{array} \right)$$

(see Chapter 29) and has variance

$$2n^{-2}\sigma^4 \left[n + \frac{2n(\xi - \xi_0)^2}{\sigma^2} \right] = 2n^{-1}\sigma^4 \left[1 + \frac{2(\xi - \xi_0)^2}{\sigma^2} \right].$$

A natural estimate of the coefficient of variation (σ/ξ) is the ratio $a_n S/\bar{X}$, or more generally $a'_n S/\bar{X}$, with a' being suitably chosen. Since the expected value of S/\bar{X} is infinite, it is not possible to obtain an unbiased estimator of this form. We can, however, construct an approximate confidence interval for σ/ξ . We will suppose that $\Pr[\bar{X} < 0]$ can be neglected (i.e., σ/ξ sufficiently small—less than $\frac{1}{4}$, say). Then, since \bar{X}/S is distributed as $(n-1)^{-1/2}$ times noncentral t with $n-1$ degrees of freedom and noncentrality parameter $\sqrt{n}\xi/\sigma$, it follows that (in the notation of Chapter 31)

$$\Pr \left[t'_{n-1, \alpha_1} \left(\frac{\sqrt{n}\xi}{\sigma} \right) \leq \frac{\sqrt{n-1}\bar{X}}{S} \leq t'_{n-1, 1-\alpha_2} \left(\frac{\sqrt{n}\xi}{\sigma} \right) \right] = 1 - \alpha_1 - \alpha_2$$

or

$$\Pr \left[n^{-1/2} g_{1-\alpha_2} \left(\frac{\sqrt{n-1}\bar{X}}{S} \right) \leq \frac{\xi}{\sigma} \leq n^{-1/2} g_{\alpha_1} \left(\frac{\sqrt{n-1}\bar{X}}{S} \right) \right] \doteq 1 - \alpha_1 - \alpha_2, \quad (13.108)$$

where $g_\alpha(z)$ is the solution (for g) of the equation

$$t'_{n-1,\alpha}(g) = z \quad (13.109)$$

(assuming that \bar{X} is not too small). Assuming now that $\xi > 0$, (13.108) can be rewritten

$$\Pr \left[\sqrt{n} / g_{\alpha_1} \left(\frac{\sqrt{n-1}\bar{X}}{S} \right) < \frac{\sigma}{\xi} < \sqrt{n} / g_{1-\alpha_2} \left(\frac{\sqrt{n-1}\bar{X}}{S} \right) \right] \doteq 1 - \alpha_1 - \alpha_2.$$

It is necessary to use tables of the noncentral t distribution (see Chapter 31, Section 7) to calculate even these approximate limits.

More easily calculable, but rather rough, approximate limits are obtained from the formula

$$\begin{aligned} \text{Lower limit} &= V \left[1 - n^{-1/2} U_{\alpha_2} \sqrt{\frac{1}{2} + V^2} \right]^{-1}, \\ \text{Upper limit} &= V \left[1 - n^{-1/2} U_{1-\alpha_1} \sqrt{\frac{1}{2} + V^2} \right]^{-1}, \end{aligned} \quad (13.110)$$

where $V = S/\bar{X}$. These are based on the assumption that $(S - k\bar{X})$ is approximately normally distributed with expected value $(a - k\xi)$ and variance $n^{-1}\sigma^2(1 + \frac{1}{2}k^2)$ so that (since $\xi \gg a$)

$$\Pr \left[\frac{S}{\bar{X}} < k \right] \doteq \Phi \left(\sqrt{\frac{n}{1 + \frac{1}{2}k^2}} \left\{ 1 - \frac{k\xi}{\sigma} \right\} \right),$$

that is, $\sqrt{n/(1 + \frac{1}{2}V^2)} (1 - V\xi/\sigma)$ has approximately a unit normal distribution. A similar argument indicates that if X_1, X_2 are independent normal random variables and $E[X_j] = \xi_j$, $\text{Var}(X_j) = \sigma_j^2$ ($j = 1, 2$) with $\xi_2 \gg \sigma_2$, then putting $X_1/X_2 = R$, the distribution of

$$\frac{R\xi_2 - \xi_1}{(R^2\sigma_2^2 + \sigma_1^2)^{1/2}}$$

is approximately unit normal.

Koopmans, Owen, and Rosenblatt (1964) have pointed out that if the distribution of each of the independent variables is *lognormal* (see Chapter 14), then construction of exact confidence intervals for the coefficient of variation is straightforward. Since it is possible to approximate a normal distribution quite closely by a lognormal distribution (see Chapter 14, Section 3), it is likely that the same formulas will give good results for normal variables (though they will not of course give exactly specified values for

confidence coefficients). The (**approximate**) confidence limits, in terms of the original variables X_1, \dots, X_n obtained by this method, are

$$\left[\exp \left\{ \frac{\sum_{j=1}^n (\log X_j - \overline{\log X})^2}{\chi_{n-1, 1-\alpha_1}^2} \right\} - 1 \right]^{1/2} \tag{13.111}$$

and

$$\left[\exp \left\{ \frac{\sum_{j=1}^n (\log X_j - \overline{\log X})^2}{\chi_{n-1, \alpha_2}^2} \right\} - 1 \right]^{1/2},$$

where $\overline{\log X} = n^{-1} \sum_{j=1}^n \log X_j$.

The cumulative distribution function of the r th quasi-range for random samples from a unit normal distribution is [Jones et al. (1969)]

$$F_{W(r)}(w) = \sum_{i=0}^r \frac{n^{(2r-i+1)}}{r!(r-i)!} \sum_{j=0}^{r-i} \sum_{k=0}^{n-2r+i-1} (-1)^{n-2r+i-1-j+k} P, \quad w > 0,$$

where

$$P = \binom{r-i}{j} \binom{n-2r+i-1}{k} \Pr \left[\bigcap_{l=1}^{n-r+i+j-1} \left(Y_l \leq \frac{\delta_{j+h-l} w}{\sqrt{2}} \right) \right]$$

and $\delta_h = 0, 1$ for $h < 0, \geq 0$, respectively; the Y 's are standardized **multi-normal** variables (Chapter 35) with all correlations equal to $\frac{1}{2}$.

Estimates for the reliability function of the normal distribution has been considered by Hurt (1980). **Sinha** (1985) has discussed **Bayes's** estimations of the reliability function.

Owen and Hua (1977) have presented tables of confidence limits on the tail area of the normal distribution. Fertig and Mann (1977) have discussed one-sided prediction intervals for at least p out of m future observations. Nelson and Schmee (1981) have given prediction limits for the last failure time of a normal sample from early failures. Lingappaiah (1983) has discussed prediction problems in normal samples. Along the lines of Fertig and Mann (1977), Chou and Owen (1986) have studied one-sided simultaneous lower prediction intervals for 1 future samples from a normal distribution. **Whitmore** (1986) has made some interesting comments on the prediction limits for a single normal observation. Odeh (1989a) has developed simultaneous two-sided prediction intervals to contain at least 1 out of k future means. Similarly Odeh (1989b) has also discussed simultaneous one-sided prediction intervals to contain all of k future means.

8.4 Estimation from Censored Data

We will consider situations in which the r_1 least, and r_2 greatest, observations are censored (i.e., not recorded) leaving only $X'_{r_1+1}, \dots, X'_{n-r_2}$. Best linear unbiased estimators, based on these order statistics, are particularly useful in these circumstances, since the maximum likelihood estimators of ξ and σ are much more difficult to calculate than they are for complete samples. We will, first, discuss maximum likelihood estimators and then possible approximations.

The joint probability density function of $X'_{r_1+1}, \dots, X'_{n-r_2}$ is

$$p(x_{r_1+1}, \dots, x_{n-r_2}) = \frac{n!}{r_1!r_2!} \left[\Phi\left(\frac{x_{r_1+1} - \xi}{\sigma}\right) \right]^{r_1} \left[1 - \Phi\left(\frac{x_{n-r_2} - \xi}{\sigma}\right) \right]^{r_2} \quad (13.112)$$

$$\times \sigma^{-(n-r_1-r_2)} \prod_{j=r_1+1}^{n-r_2} Z\left(\frac{x_j - \xi}{\sigma}\right).$$

The maximum likelihood estimators $\hat{\xi}, \hat{\sigma}$ of ξ, σ , respectively satisfy the following equations [using the notation $\hat{U}'_j = (X'_j - \hat{\xi})/\hat{\sigma}$]:

$$r_1 \left[-\frac{Z(\hat{U}'_{r_1+1})}{\Phi(\hat{U}'_{r_1+1})} \right] + \sum_{j=r_1+1}^{n-r_2} \hat{U}'_j + r_2 \left[\frac{Z(\hat{U}'_{n-r_2})}{1 - \Phi(\hat{U}'_{n-r_2})} \right] = 0, \quad (13.113)$$

$$r_1 \left[1 - \frac{\hat{U}'_{r_1+1} Z(\hat{U}'_{r_1+1})}{\Phi(\hat{U}'_{r_1+1})} \right] + \sum_{j=r_1+1}^{n-r_2} \hat{U}'_j{}^2 + r_2 \left[1 + \frac{\hat{U}'_{n-r_2} Z(\hat{U}'_{n-r_2})}{1 - \Phi(\hat{U}'_{n-r_2})} \right] = n. \quad (13.114)$$

From equations (13.115) below it can be seen that in (13.113) the censored "observations" are replaced by the expected value of the appropriate tail of the normal distribution truncated at X'_{r_1+1} or X'_{n-r_2} , as the case may be, and that in (13.114) the squared standardized deviates of these "observations"

are replaced by the corresponding expected values for the tails. With this in mind, we obtain approximate solutions of equations (13.113) and (13.114) by replacing $(X'_{r_1+1} - \hat{\xi})/\hat{\sigma}$ and $(X'_{n-r_2} - \hat{\xi})/\hat{\sigma}$ by U_{α_1} and $U_{1-\alpha_2}$, respectively (except in the summations) with $\alpha_j = (r_j + 1)/(n + 1)$ for $j = 1, 2$. By introducing the following notation for the moments of the tails (of singly truncated normal distributions, Section 10),

$$\begin{aligned} -\frac{Z(U_{\alpha})}{\Phi(U_{\alpha})} &= \mu'_{1,(\alpha-)}, & \frac{Z(U_{\alpha})}{1-\Phi(U_{\alpha})} &= \mu'_{1,(\alpha+)}, \\ 1 - \frac{U_{\alpha}Z(U_{\alpha})}{\Phi(U_{\alpha})} &= \mu'_{2,(\alpha-)}, & 1 + \frac{U_{\alpha}Z(U_{\alpha})}{1-\Phi(U_{\alpha})} &= \mu'_{2,(\alpha+)}, \end{aligned} \quad (13.115)$$

we obtain the approximate equations

$$\bar{X}' + (n - r_1 - r_2)^{-1}(r_1\mu'_{1,(\alpha_1-)} + r_2\mu'_{1,(1-\alpha_2+)})\hat{\sigma} \doteq \hat{\xi}, \quad (13.116)$$

$$\begin{aligned} &\left[\sum_{j=r_1+1}^{n-r_2} (X'_j - \bar{X}')^2 \right] \left[n - r_1\mu'_{2,(\alpha_1-)} - r_2\mu'_{2,(1-\alpha_2+)} \right. \\ &\quad \left. - (n - r_1 - r_2)^{-1}(r_1\mu'_{1,(\alpha_1-)} + r_2\mu'_{1,(1-\alpha_2+)})^2 \right]^{-1} = \hat{\sigma}^2, \quad (13.117) \end{aligned}$$

with $\bar{X}' = (n - r_1 - r_2)^{-1} \sum_{j=r_1+1}^{n-r_2} X'_j$. Values of $\mu'_{1,\alpha_{\pm}}$ and $\mu'_{2,\alpha_{\pm}}$ can be obtained from tables mentioned in Section 1 [also in Harter and Moore (1966)].

Having obtained first approximations to $\hat{\xi}$ and $\hat{\sigma}$ from (13.116) and (13.117), these can be used to calculate new values of $\mu'_{j,\pm\alpha}$, now using $(X'_{r_1+1} - \hat{\xi})/\hat{\sigma}$ and $(X'_{n-r_2} - \hat{\xi})/\hat{\sigma}$ in place of U_{α_1} and $U_{1-\alpha_2}$, respectively. Then (13.113) and (13.114) give new **approximations** to $\hat{\xi}$, $\hat{\sigma}$, and so on. Cohen (1957) has given a chart that may be used in the solution of (13.113) and (13.114).

Approximations (for large values of n) to the variances and covariance of $\hat{\xi}$ and $\hat{\sigma}$ are the same as for the corresponding truncated distributions, with truncation points corresponding to $\alpha_j = r_j/n$ ($j = 1, 2$). Some numerical values are given in Section 10. Detailed discussions of these developments and corresponding tables and graphs may be found in the volumes of Harter (1970), Nelson (1982), Schneider (1986), Cohen and Whitten (1988), Cohen (1991), and Balakrishnan and Cohen (1991). Although solution of the maximum likelihood equations is practicable if the techniques described above or variants thereof are used, it is often convenient to use simpler estimating formulas.

Making the further approximation $r_j/n \doteq \Phi(U_{\alpha_j})$ ($j = 1, 2$), equations (13.116) and (13.117) can be written

$$\bar{X}' + \hat{\sigma} [Z(U_{1-\alpha_2}) - Z(U_{\alpha_1})][1 - \alpha_1 - \alpha_2]^{-1} = \hat{\xi}, \quad (13.118)$$

$$\left[n^{-1} \sum_{j=r_1+1}^{n-r_2} (X'_j - \bar{X}')^2 \right] \\ \times \left[1 - \alpha_1 - \alpha_2 + U_{\alpha_1} Z(U_{\alpha_1}) - U_{1-\alpha_2} Z(U_{1-\alpha_2}) \right. \\ \left. - \{Z(U_{\alpha_1}) - Z(U_{1-\alpha_2})\}^2 (1 - \alpha_1 - \alpha_2)^{-1} \right]^{-1} = \hat{\sigma}^2. \quad (13.119)$$

Tiku (1967) has suggested that the approximate formulas

$$\frac{Z(x)}{\Phi(x)} = a_1 + b_1 x, \\ \frac{Z(x)}{1 - \Phi(x)} = a_2 + b_2 x$$

be used to simplify equations (13.113) and (13.114). (The values of $a_1, b_1, a_2,$ and b_2 are chosen to give good fits over the range $U_{\alpha_1} \leq x \leq U_{1-\alpha_2}$.) This leads to the following equations for the estimators of ξ and σ (denoted here by $\hat{\xi}', \hat{\sigma}'$):

$$\hat{\xi}' = K + LB', \\ (1 - \alpha_1 - \alpha_2) \hat{\sigma}'^2 - \{ \alpha_2 a_2 X'_{n-r_2} - \alpha_1 a_1 X'_{r_1+1} - (\alpha_2 a_2 - \alpha_1 a_1) K \} \hat{\sigma}'^2 \\ - \left\{ n^{-1} \sum_{j=r_1+1}^{n-r_2} X_j'^2 + \alpha_2 b_2 X_{n-r_2}'^2 - \alpha_1 b_1 X_{r_1+1}'^2 \right\} \\ - (1 - \alpha_1 - \alpha_2 + \alpha_2 b_2 + \alpha_1 b_1) K^2 = 0,$$

with

$$K = \frac{n^{-1} \sum_{j=r_1+1}^{n-r_2} X'_j + \alpha_2 b_2 X'_{n-r_2} - \alpha_1 b_1 X'_{r_1+1}}{[1 - \alpha_1 - \alpha_2 + \alpha_2 b_2 - \alpha_1 b_1]}$$

and

$$L = \frac{\alpha_2 a_2 - \alpha_1 a_1}{1 - \alpha_1 - \alpha_2 + \alpha_2 b_2 - \alpha_1 b_1}$$

(the quadratic in $\hat{\sigma}'$ has only one positive root).

For symmetrical censoring ($a_1 = a_2 = a$), we have $a_1 = a_2 = a$, say, and $b_2 = -b_1 = b$, leading to

$$\hat{\xi}' = \frac{n^{-1} \sum_{j=r+1}^{n-r} X_j' + ab(X_{r+1}' + X_{n-r}')}{1 - 2\alpha + 2ab}$$

and

$$(1 - 2\alpha)\hat{\sigma}'^2 - \alpha a(X_{n-r}' - X_{r+1}')\hat{\sigma}' - \left[n^{-1} \sum_{j=r+1}^{n-r} X_j'^2 + ab(X_{n-r}'^2 + X_{r+1}'^2) - (1 - 2\alpha + 2ab)K^2 \right] = 0.$$

Note that $\hat{\xi}'$ is of similar form to the Winsorized mean (13.73). Tiku gives tables to assist in obtaining good values for a and b . These simplified estimators, referred to as the modified maximum likelihood estimators, have been utilized to develop several robust inference procedures (robust to departures from normality); see Tiku, Tan, and Balakrishnan (1986).

For symmetrical censoring, the Winsorized mean (13.73) described in Section 8.1 is a natural choice as estimator of ξ . For a moderate degree of asymmetry in censoring (i.e., $|r_1 - r_2|$ small), it may be worthwhile to set aside the excess observations and use the Winsorized mean of the largest available symmetrically censored set of sample values. Table 13.9 [from

Table 13.9 Efficiency (%) of Winsorized Mean Based on $X_{j+1}', \dots, X_{n-j}'$ Relative to the Best Linear Unbiased Estimator of ξ Based on $X_j', X_{j+1}', \dots, X_{n-j}'$

$n \backslash j$	1	2	3	4	5	6
3	100.0					
4	96.2					
5	96.4	100.0				
6	96.9	96.4				
7	97.3	96.3	100.0			
8	97.7	96.7	96.7			
9	98.0	97.1	96.5	100.0		
10	98.2	97.4	96.8	97.1		
12	98.6	97.9	97.4	97.0	97.4	
14	98.8	98.3	97.9	97.5	97.1	97.6
16	99.0	98.6	98.2	97.9	97.5	97.3
18	99.1	98.8	98.5	98.2	97.9	97.6
20	99.2	98.9	98.7	98.4	98.2	98.0

Dixon (1960)] gives the efficiency of the Winsorized mean

$$\xi_{(j)} = n^{-1}[(j+1)X'_{j+1} + X'_{j+2} + \cdots + X'_{n-j-1} + (j+1)X'_{n-j}]$$

relative to the best linear unbiased estimator of ξ based on $X'_j, X'_{j+1}, \dots, X'_{n-j}$. It can be seen that the loss in efficiency from ignoring the value X'_j is trifling.

Even if one of r_1 and r_2 is zero, the Winsorized mean can still be used with little loss of efficiency. Even this can be reduced by using a modified Winsorized mean of form (for $r_1 = 0, r_2 = r$)

$$(n+a-1)^{-1}[aX'_1 + X'_2 + \cdots + (r+1)X'_{n-r}] \quad (13.120)$$

with a chosen to make this an unbiased estimator of ξ . Minimum values of the efficiency of this estimator (relative to the best linear unbiased estimator) are shown below:

r	Minimum Relative Efficiency
1	99.8%
2	99.2%
3	98.5%
4	97.7%
5	96.9%
6	96.0%

Values of a are given in Dixon (1960, table II), but they can easily be calculated from tables of expected values of ordered normal variables (see Section 4).

Estimation of σ is more seriously, and adversely, affected by omission of extreme values, than is estimation of ξ . However, there is the compensating feature that the estimates are generally less sensitive to departures from exact normality of distribution (as already noted in Section 8.2). Rhiel (1986), for example, has examined the effect of nonnormality on the use of the sample range in estimating the population standard deviation σ . The simplest estimators of σ that may be used when analyzing censored samples are those based on the *quasi-ranges*

$$W_{(j)} = X'_{n-j+1} - X'_j. \quad (13.121)$$

Dixon found that for symmetrical censoring with $r_1 = r_2 = r \leq 6$, and $n \leq 20$, estimators based on

1. $W_{(r+1)} + W_{(r+2)}$ for $r = 1, 11 \leq n \leq 15$, and $r = 2, 16 \leq n \leq 19$,
2. $W_{(r+1)} + W_{(r+3)}$ for $r = 1, 16 \leq n \leq 20$, and $r = 2, n = 20$,
3. $W_{(r+1)}$ for all other $r \leq 6, n \leq 20$,

have efficiencies relative to the best linear unbiased estimators of \mathbf{a} of at least 96.5%. A similar situation exists when $|r_1 - r_2| = 1$. Dixon also gives simple formulas for linear unbiased estimators for *single* censoring with $r_1 = 0, r_2 \leq 6, n \leq 20$, that have a minimum efficiency of 93.7% relative to the best linear unbiased estimators.

Selvin (1976) has discussed a graphical estimate of ξ based on censored samples. Custer and Pam (1976) have provided correction for bias in the maximum likelihood estimator of \mathbf{a} in a right-censored sample. Persson and Rootzen (1977) have proposed some simple and highly efficient estimators for ξ and \mathbf{a} when the available sample is Type-I censored. Healy (1978) has given a mean difference estimator of σ in the case of symmetrically censored samples; see Prescott (1979) for a similar estimator of σ in the case of asymmetrically censored samples. A linear estimator of σ has also been provided by Healy (1982) for symmetrically censored samples. Schneider (1984) presented some simple and very efficient estimators for both ξ and \mathbf{a} for censored samples; also see Schneider (1986) for a detailed discussion on various estimators of ξ and σ under censored sampling. Wolynetz (1979) has developed an algorithm for determining the maximum likelihood estimates of ξ and σ from truncated and censored data. Hill (1987) and Swan (1977) have discussed algorithms for the maximum likelihood estimation from grouped and censored data. Schader and Schmid (1984) compared some algorithms available for the computation of the maximum likelihood estimates of ξ and σ from a grouped sample. Schader and Schmid (1988) have also discussed small-sample properties of these maximum likelihood estimates from a grouped data.

Sobel and Tong (1976) have described the estimation of a normal percentile by grouping. Kabe (1976) has constructed confidence bands for the quantiles. Dyer, Keating, and Hensley (1977) have compared different point estimators of normal percentiles. Durrant (1978) has presented a nomogram for confidence limits on quantiles of the normal distribution. In continuation of the work of Dyer, Keating, and Hensley (1977), a further look at the comparison of different point estimators of normal percentiles has been given by Dyer and Keating (1979). Hassanein, Saleh, and Brown (1986) have tabulated the best linear unbiased estimators of normal quantiles for sample sizes up to 20. Oppenlander, Schmee, and Hahn (1988) have proposed some simple robust estimators of normal tail percentiles and then examined their performance.

ating pseudorandom normal observations; see Kinderman and **Ramage** (1976). In this method the normal density is represented as a mixture of densities over which a variety of acceptance–rejection methods due to Marsaglia (1964), Marsaglia and Bray (1964), and Marsaglia, **MacLaren**, and Bray (1964) are applied.

Suppose that the pdf $p(x)$ is bounded above by a function $cq(x)$, where $c > 0$ and $q(x)$ is a density function for all x . Generally $q(x)$ is taken to be an easily computable function. The "rejection method" generates pseudorandom numbers from $p(x)$ as follows:

1. Provides a pair of independent uniform $(0, 1)$ random numbers, u_1 and u_2 .
2. Provides a random number from $q(x)$ using u_1 , say, x_q .
3. Accepts x_q as a pseudorandom observation from $p(x)$ if

$$u_2 \leq \frac{p(x_q)}{cq(x_q)}.$$

4. If x_q is rejected, returns to step (1).

The constant c is to be selected as the smallest number such that $p(x) \leq cq(x)$ for all x . For example, with $p(x)$ being the standard normal density function and $q(x)$ being the **Laplace** density function (Chapter 24)

$$q(x) = \frac{\alpha}{2} e^{-\alpha|x|},$$

x_q may be generated (by inverse cdf method) as

$$x_q = \begin{cases} \frac{1}{\alpha} \log(2u_1) & \text{if } 0 < u_1 \leq \frac{1}{2}, \\ -\frac{1}{\alpha} \log\{2(1 - u_1)\} & \text{if } \frac{1}{2} < u_1 < 1. \end{cases} \quad (13.128)$$

The inequality in step 3 becomes in this case

$$\log u_2 \leq c_1 + \alpha|x_q| - \frac{x_q^2}{2}, \quad (13.129)$$

where $c_1 = \frac{1}{2} \log\{2/(\pi c^2 \alpha^2)\}$. If we consider the **Laplace** distribution with mean 0 and variance 1 , then $\alpha^2 = 2$, and in this case we have $c = e/\sqrt{\pi}$ and $c_1 = -1$. Consequently (13.129) reduces to

$$\log u_2 \leq -1 + \sqrt{2}|x_q| - \frac{x_q^2}{2} = -\frac{1}{2}(|x_q| - \sqrt{2})^2. \quad (13.130)$$

94 Ahrens–Dieter Method

From the Box–Muller transformation in (13.122) or (13.126), observe that the variables

$$C = \frac{X_2}{X_1} \quad \text{and} \quad S = X_1^2 + X_2^2 \quad (13.131)$$

are independently distributed as Cauchy and exponential with mean 2, respectively. Thence the inverse of this transformation yields

$$X_1 = \sqrt{\frac{S}{1+C^2}} \quad \text{and} \quad X_2 = C\sqrt{\frac{S}{1+C^2}}. \quad (13.132)$$

The snag in using this transformation is that the signs of the square roots are undetermined. However, as Ahrens and Dieter (1988) have pointed out, these signs must be positive and negative independently and with equal probability $\frac{1}{2}$. So X_1 may receive a random sign, and $\text{sign}(X_2)$ becomes $\text{sign}(C)$. Thus the pseudorandom standard normal observations X_1 and X_2 may be generated from (13.132) by using directly the Cauchy generator (see Chapter 16) and the exponential generator (see Chapter 19) with $S = E + E$. For this algorithm Ahrens and Dieter (1988) have pointed out that (for generating a pair of pseudorandom standard normal observations) 1.023195 is the average consumption of uniform $(0, 1)$ random variables (with 1.039921 uniform variables for the exponential algorithm and 1.006469 for the Cauchy algorithm).

Several other simulational algorithms are also available for generating normal observations. Kinderman, Monahan, and **Ramage (1975)**, Marsaglia, Ananthanarayanan, and Paul (1976), **Atkinson and Pearce (1976)**, Sakasegawa (1978), Best (1979), and Deak (1980, 1981) have all presented simple and economical methods of generating normal observations. Gates (1978) presented a modified Butler algorithm for this purpose. **Burford and Willis (1978)** carried out a comparative study of unit normal variables generated by the Box–Muller algorithm using alternative standard uniform generators. **Kronmal**, Peterson, and Hutchinson (1979) discussed the generation of normal random variables using the uniform alias-rejection mixture method. Schuster (1983) made some comments on the method of generating normal variates by summing three uniforms. Dagpunar (1988) has presented a method of generating random variates from the tail of a normal distribution. Dagpunar (1987) has also given a nomogram to enable the manual sampling of random variates from a normal distribution.

Generating a normal sample with given sample mean and variance has been considered by **Pullin (1979)**, Marsaglia (1980), and Jones (1985).

10 RELATED DISTRIBUTIONS

In Section 8 we provided references for the distributions of arithmetic mean, median, variance, range, mean deviation, and so on, in "random samples from normal populations." Many chapters of this volume discuss other distributions related to the normal distribution. In the present section we will confine ourselves to discussion of *truncated* normal distributions and *mixtures* of normal distributions, together with some brief references to some other distributions related to the normal.

10.1 Truncated Normal Distributions

A random variable X has a *doubly truncated* normal distribution if its probability density function is

$$\begin{aligned} & \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\xi)^2/2\sigma^2} \left[\frac{1}{\sqrt{2\pi}\sigma} \int_A^B e^{-(t-\xi)^2/2\sigma^2} dt \right]^{-1} \\ & = \sigma^{-1} Z\left(\frac{x-\xi}{\sigma}\right) \left[\Phi\left(\frac{B-\xi}{\sigma}\right) - \Phi\left(\frac{A-\xi}{\sigma}\right) \right]^{-1}, \quad A \leq x \leq B. \end{aligned} \quad (13.133)$$

The *lower* and *upper truncation points* are A, B , respectively; the *degrees of truncation* are $\Phi((A-\xi)/\sigma)$ (from below) and $1 - \Phi((B-\xi)/\sigma)$ (from above). If A is replaced by $-\infty$, or B by ∞ , the distribution is *singly truncated* from *above*, or *below*, respectively. More elaborate forms of truncation (e.g., omission of a number of intervals of X) will not be considered here.

Some typical doubly and singly truncated normal probability density functions are shown in Figure 13.3. These are classified according to the degrees of truncation. It can be seen that when the truncations are large, the distribution bears little resemblance to a normal distribution. It is indeed more like a rectangular or trapezoidal distribution (Chapter 26). The case $A = \xi, B = \infty$ produces a *half-normal* distribution. This is actually the distribution of $\xi + \sigma|U|$ where U is a unit normal variable. We will discuss, in detail, only doubly truncated normal distributions. Treatment of singly truncated normal distributions follows on similar lines.

The expected value of X [from (13.133)] is given by

$$E[X] = \xi + \frac{Z((A-\xi)/\sigma) - Z((B-\xi)/\sigma)}{\Phi((B-\xi)/\sigma) - \Phi((A-\xi)/\sigma)} \sigma, \quad (13.134)$$

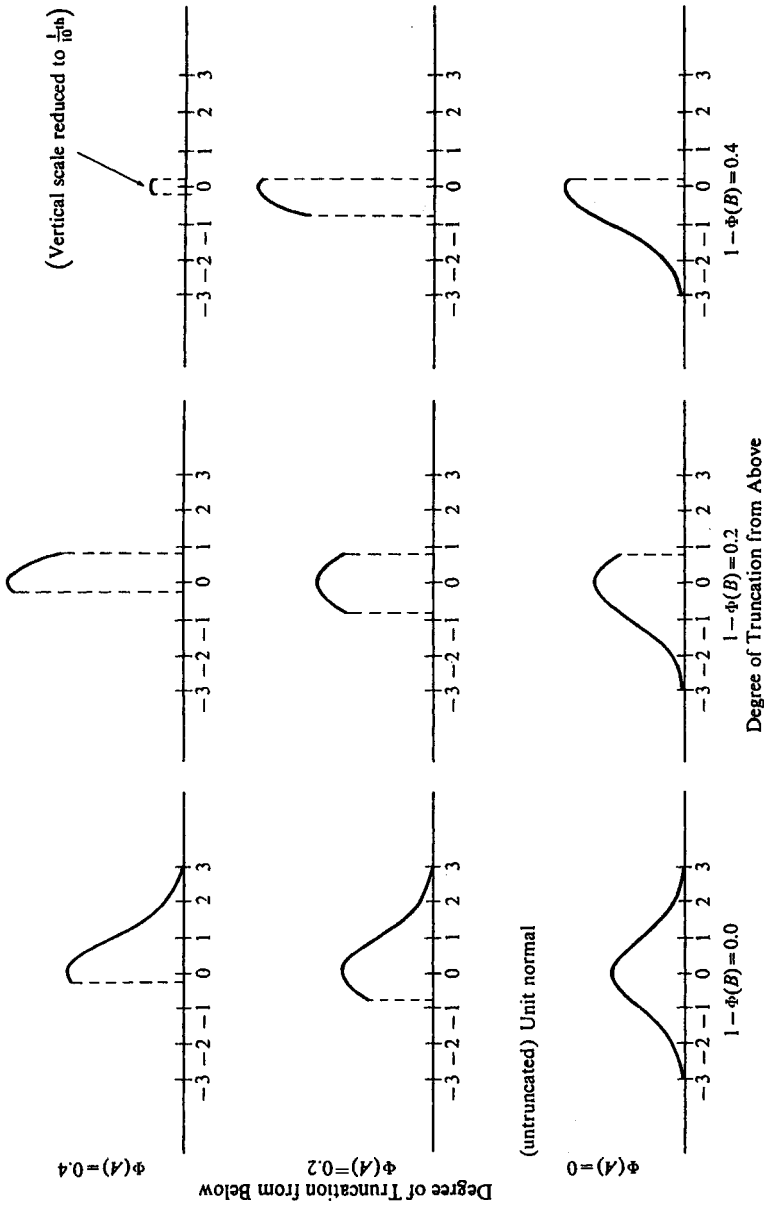


Figure 13.3 Density Functions of Some Truncated Unit Normal Distributions, Points of Truncation, $A < B$

and the variance of X by

$$\begin{aligned} \text{Var}(X) &= \left[1 + \frac{((A - \xi)/\sigma)Z((A - \xi)/\sigma) - ((B - \xi)/\sigma)Z((B - \xi)/\sigma)}{\Phi((B - \xi)/\sigma) - \Phi((A - \xi)/\sigma)} \right. \\ &\quad \left. - \left\{ \frac{Z((A - \xi)/\sigma) - Z((B - \xi)/\sigma)}{\Phi((B - \xi)/\sigma) - \Phi((A - \xi)/\sigma)} \right\}^2 \right] \sigma^2. \quad (13.135) \end{aligned}$$

Note that if $A - \xi = -(B - \xi) = -\delta\sigma$, then

$$\begin{cases} E[X] = \xi, \\ \text{Var}(X) = \left[1 - \frac{2\delta Z(\delta)}{2\Phi(\delta) - 1} \right] \sigma^2. \end{cases} \quad (13.136)$$

The mean deviation of X is

$$\begin{aligned} &2 \left[Z(J) - Z\left(\frac{B - \xi}{\sigma}\right) - \left\{ \Phi\left(\frac{B - \xi}{\sigma}\right) - \Phi(J) \right\} J \right] \\ & \times \left[\Phi\left(\frac{B - \xi}{\sigma}\right) - \Phi\left(\frac{A - \xi}{\sigma}\right) \right]^{-1}, \quad (13.137) \end{aligned}$$

where

$$J = \frac{Z((A - \xi)/\sigma) - Z((B - \xi)/\sigma)}{\Phi((B - \xi)/\sigma) - \Phi((A - \xi)/\sigma)}.$$

Some values of $E[X]$, $\sqrt{\text{Var}(X)}$ and the ratio of the mean deviation to the standard deviation are given in Table 13.10.

The moments of the truncated distribution can also be expressed in terms of the Hh functions [Fisher (1930)] defined by

$$Hh_n(y) = (n!)^{-1} \int_y^\infty (t - y)^n e^{-t^2/2} dt. \quad (13.138)$$

(Note that $Hh_n(y) = \int_y^\infty Hh_{n-1}(t) dt$; $Hh_0(y) = \sqrt{2\pi}(1 - \Phi(y))$; $Hh_{-1}(y) = e^{-y^2/2}$.)

Sugiura and Gomi (1985) have given Pearson diagrams (of the coefficients of skewness and kurtosis) for the truncated normal distributions. Nakamura (1980) has discussed the moments of positively truncated normal distribution. Hall (1979) has also derived inverse moments for a class of truncated normal distributions..

Table 13.10 Expected Value, Standard Deviation, and (Mean Deviation) / (Standard Deviation) for Truncated Normal Distributions

Degrees of Truncation		[-ξ + (Expected Value)] × σ ⁻¹	(Standard Deviation) × σ ⁻¹	(Mean Deviation)/ (Standard Deviation)
$q_1 = \Phi\left(\frac{A - \xi}{\sigma}\right)$ (Below)	$q_2 = 1 - \Phi\left(\frac{B - \xi}{\sigma}\right)$ (Above)			
0	0.1	-0.195	0.844	0.814
0	0.2	-0.350	0.764	0.812
0	0.3	-0.497	0.702	0.809
0	0.4	-0.644	0.650	0.805
0	0.5	-0.798	0.603	0.801
0	0.6	-0.966	0.558	0.795
0	0.7	-1.159	0.514	0.791
0	0.8	-1.400	0.468	0.785
0	0.9	-1.755	0.411	0.777
0.1	0.1	0.000	0.662	0.844
0.1	0.2	-0.149	0.566	0.850
0.1	0.3	-0.287	0.489	0.853
0.1	0.4	-0.422	0.420	0.854
0.1	0.5	-0.559	0.355	0.856
0.2	0.2	0.000	0.463	0.856
0.2	0.3	-0.135	0.382	0.859
0.2	0.4	-0.266	0.309	0.861
0.2	0.5	-0.397	0.239	0.863
0.3	0.3	0.000	0.297	0.862
0.3	0.4	-0.129	0.222	0.864
0.3	0.5	-0.256	0.151	0.865
0.4	0.4	0.000	0.146	0.865
0.4	0.5	-0.126	0.073	0.866

The values of A and B are usually known, at least fairly closely. If A and B are known, the maximum likelihood estimation of ξ and σ is equivalent to estimation by equating first and second sample and population moments. The equations satisfied by the estimators $\hat{\xi}$ and $\hat{\sigma}$ are similar in form to those for censored samples, with X'_{r_1+1}, X_{-r_2} replaced by A, B, respectively, and with the multipliers $r_1 n^{-1}, r_2 n^{-1}$ replaced by the degrees of truncation $\Phi((A - \xi)/\sigma), 1 - \Phi((B - \xi)/\sigma)$, respectively.

Harter and Moore (1966) have given a table of asymptotic variances of, and correlation between, $\hat{\xi}$ and $\hat{\sigma}$ (for large n). Table 13.11 is based on their figures and includes the asymptotic variance of the maximum likelihood estimator of ξ when σ is known and of σ when ξ is known. If $\Phi((A - \xi)/\sigma)$ is greater than $[1 - \Phi((B - \xi)/\sigma)]$, the variable X can be replaced by -X,

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Table 13.11 Asymptotic Values of $n \times (\text{Variance}) / \sigma^2$ for Maximum Likelihood Estimators

Proportions Censored		ξ and σ Unknown			σ Known	ξ Known
$\Phi\left(\frac{A - \xi}{\sigma}\right)$	$1 - \Phi\left(\frac{B - \xi}{\sigma}\right)$	Variance of		Correlation between	Variance of	Variance of
		$\hat{\xi}$	$\hat{\sigma}$	$\hat{\xi}, \hat{\sigma}$	$\hat{\xi}$	$\hat{\sigma}$
0.0	0.0	1.00	0.50	0.000	1.00	0.50
0.0	0.1	1.02	0.59	0.053	1.02	0.58
0.0	0.2	1.06	0.69	0.125	1.05	0.68
0.0	0.3	1.14	0.82	0.214	1.09	0.78
0.0	0.4	1.27	0.99	0.320	1.14	0.89
0.0	0.5	1.52	1.24	0.441	1.22	1.00
0.0	0.6	1.99	1.62	0.572	1.34	1.09
0.0	0.7	3.02	2.25	0.700	1.53	1.14
0.0	0.8	5.78	3.54	0.822	1.87	1.15
0.0	0.9	17.79	7.51	0.918	2.78	1.18
0.1	0.1	1.04	0.70	0.000	1.04	0.70
0.1	0.2	1.07	0.85	0.075	1.06	0.84
0.1	0.3	1.14	1.04	0.172	1.11	1.01
0.1	0.4	1.27	1.32	0.293	1.17	1.20
0.1	0.5	1.54	1.74	0.417	1.25	1.41
0.1	0.6	2.13	2.46	0.597	1.37	1.58
0.1	0.7	3.67	3.95	0.757	1.57	1.69
0.1	0.8	9.77	8.66	0.896	1.94	1.71
0.2	0.2	1.10	1.05	0.000	1.10	1.05
0.2	0.3	1.15	1.34	0.103	1.14	1.32
0.2	0.4	1.28	1.78	0.239	1.20	1.68
0.2	0.5	1.56	2.54	0.413	1.29	2.10
0.2	0.6	2.30	4.09	0.618	1.42	2.53
0.2	0.7	5.18	8.93	0.827	1.64	2.82
0.3	0.3	1.19	1.79	0.000	1.19	1.80
0.3	0.4	1.29	2.57	0.150	1.26	2.51
0.3	0.5	1.57	4.16	0.368	1.35	3.59
0.3	0.6	2.69	9.04	0.665	1.50	5.04
0.4	0.4	1.33	4.17	0.000	1.33	4.17
0.4	0.5	1.57	9.09	0.286	1.44	8.35

ξ by $-\xi$, A by $-B$ and B by $-A$, then $\Phi((-B + \xi)/\sigma)$ will be less than $[1 - \Phi((-A + \xi)/\sigma)]$, and the tables may be applied.

The tables by Harter and Moore (1966) give 6 decimal places. Earlier tables by Gupta (1952) give the first three columns to 5 decimal places for singly truncated distributions ($A = -\infty$ and so $\Phi((A - \xi)/\sigma) = 0$), for $\Phi((B - \xi)/\sigma) = 0.05(0.05)0.95(0.01)0.99$. The values given in these tables also give the asymptotic variances for estimators of ξ and σ from singly and doubly censored sets of independent identically distributed normal variables.

They are, however, only asymptotic values, and some care is needed in using them when the sample size n is not large (e.g., less than 50).

Sampling experiments [Harter and Moore (1966)] with $n = 10$ and $n = 20$ have indicated that there is a negative bias in both $\hat{\xi}$ and $\hat{\sigma}$ that increases with the degree of truncation. For a moderate degree of truncation (or censoring) knowledge of either parameter does not result in much reduction of variance of the estimator of other parameter. Occasionally, the points of truncation (A and B) are not known and must be estimated from the data, as well as ξ and σ . With sufficiently large samples it will probably be good enough to take A equal to a value slightly less than the least observed value, and B slightly larger than the greatest observed value, but sometimes more elaborate methods may be needed.

The maximum likelihood estimation of the four parameters A , B , ξ , and σ has been described by Cohen (1950a). An estimation using the first four moments has been described by Shah and Jaiswal (1966). There are marked similarities between the equations obtained by the two methods. Cohen gives tables of auxiliary quantities useful in solving the maximum likelihood equations. These tables have been extended by Lifsey (1965).

Cohen (1950b) also has described how the parameters ξ and σ can be estimated when there is a single truncation (i.e., $A = -\infty$ or $B = \infty$), using the first three sample moments. As the point of truncation is supposed known, it is not really necessary to use the third moment. However, by introducing the third moment, simple explicit formulas are obtained. Supposing that $B = \infty$ (i.e., left truncation only), the estimators of ξ and σ^2 are

$$\begin{cases} A - (2m_1'^2 - m_2')^{-1}(2m_1'm_2' - m_3'), \\ (2m_1'^2 - m_2')^{-1}(m_1'm_3' - m_2'^2), \end{cases} \quad (13.139)$$

respectively, where m_r' is the r th sample moment about the point of truncation A . Cohen found that the asymptotic efficiency of these estimators (relative to maximum likelihood estimators) is never less than 77% for ξ , 72% for σ^2 . For very small or very large degrees of truncation the efficiencies are greater.

The use of the third moment may be expected to introduce unnecessary inaccuracies. Pearson and Lee (1908) gave formulas from which estimators can be obtained, equating only first and second sample and population moments; the estimators are also maximum likelihood estimators. The equations for the estimators $\hat{\xi}$, $\hat{\sigma}$ are (again assuming $B = \infty$)

$$\hat{\sigma} = \left(\frac{Z(\hat{\delta})}{1 - \Phi(\hat{\delta})} - \hat{\delta} \right)^{-1} \bar{X}, \quad (13.140)$$

$$\left(\frac{\hat{\sigma}}{\bar{X}} \right) \left(\frac{\hat{\sigma}}{\bar{X}} - \hat{\delta} \right) = \frac{1}{n\bar{X}^2} \sum_{j=1}^n X_j^2, \quad (13.141)$$

where $\delta = (A - \hat{\xi})/\hat{\sigma}$ (= estimate of lower truncation point as a standardized deviate) and $\bar{X} = n^{-1}\sum_{j=1}^n X_j$. Using (13.140), (13.141) can be solved for δ , and then $\hat{\sigma}$ is calculated from (13.140).

Cohen and **Woodward** (1953) give tables of the functions

$$Y(\delta) = \left(\frac{Z(\delta)}{1 - \Phi(\delta)} - \delta \right)^{-1},$$

$$\frac{1}{2}Y(\delta)[Y(\delta) - \delta]$$

[to 8 significant figures for $\delta = -4.0(0.1)3.0$ to aid in the solution of (13.140) and (13.141)]. Since (13.141) can be written in the form

$$\frac{1}{2n\bar{X}^2} \sum_{j=1}^n X_j^2 = \frac{1}{2}Y(\hat{\delta})[Y(\hat{\delta}) - \hat{\delta}],$$

inverse interpolation suffices to determine δ , and then the table of $Y(\delta)$ is used to calculate $\hat{\sigma}$.

Crain (1979) has discussed further the estimation of parameters of a truncated normal distribution. Chiu and **Leung** (1981) have presented a graphical method of estimating the parameters, and Mittal and Dahiya (1987) and Hegde and Dahiya (1989) have provided further discussions on the estimation of parameters from a doubly truncated normal distribution. Detailed discussions on the estimation of parameters from truncated normal distributions may be found in the volumes by Harter (1970), Schneider (1986), Cohen and **Whitten** (1988), Cohen (1991), and **Balakrishnan** and Cohen (1991).

DePriest (1983) has used the singly truncated normal distribution to analyze satellite data. Levedahl (1989) has found an application for the truncated normal distribution in evaluating the effect of commodity donation programs. Ord and **Bagchi** (1983) have suggested the truncated normal-gamma mixture as a distribution for lead time demand.

Distributions of functions of truncated normal variables cannot usually be expressed in mathematically elegant forms. In Francis (1946) there are some tables (calculated by Campbell) of the distribution of the sums of n independent identically distributed truncated normal variables. The tables are not extensive, but they do give a useful idea of the effects of truncation on the distribution of arithmetic means, even for nonnormal distributions. Values of the cumulative distribution, to 4 decimal places, are given for values of the argument at intervals of 0.1, and for $n = 2$ and 4.

As an example of special problems that can sometimes arise, we mention the derivation of the distribution of the sum of two independent random variables, one normal and the other truncated normal. This has been discussed in Weinstein (1964).

10.2 Mixtures

Compound normal distributions are formed by ascribing a distribution to one, or both, of the parameters ξ, σ in (13.1). There are two distinct kinds of distributions: those obtained by treating ξ and/or σ as continuous random variables are of methodological and theoretical interest, while when (ξ, σ) takes only a finite (usually small) number of possible values, the fitting of corresponding distributions is usually regarded as the "dissection" of a heterogeneous population into more homogeneous "parts."

Using the notation introduced in Chapter 8, we remark that the distribution*

$$\text{Normal}(\xi, \sigma) \underset{\xi}{\wedge} \text{Normal}(\mu, \sigma')$$

is also a normal distribution, with expected value μ and standard deviation $\sqrt{\sigma^2 + \sigma'^2}$. This can be demonstrated by direct integration, or simply by regarding the compound distribution as that of $(\mu + U'\sigma') + U\sigma$, where U, U' are independent unit normal variables.

It can also be shown that

$$\text{Normal}(\xi, \sigma) \underset{\sigma^{-2}}{\wedge} \text{Gamma}(c\chi_\nu^2)$$

is equivalent to a **Pearson** Type VII distribution (Chapter 12, Section 4.1). In fact

$$\begin{aligned} & (2c)^{-\nu/2} \left[\Gamma\left(\frac{\nu}{2}\right) \right]^{-1} \int_0^\infty [\sqrt{2\pi}\sigma]^{-1} (\sigma^{-2})^{(\nu/2)-1} \\ & \quad \times \exp\left[-(2c\sigma^2)^{-1} - (2\sigma^2)^{-1}(x - \xi)^2\right] d\sigma^{-2} \quad (13.142) \\ & = \frac{c^{1/2}}{B(1/2, \nu/2)} \left[1 + \frac{(x - \xi)^2}{c} \right]^{-(\nu+1)/2} \end{aligned}$$

(It may be noted that the distribution ascribed to σ^{-2} is of a kind sometimes called *fiducial*, which is obtained by formal inversion of the statement " V is distributed as $\chi_\nu^2 \sigma^2$ " to become " σ^{-2} is distributed as $V^{-1} \chi_\nu^2$.")

Teichroew (1957) has studied the distribution

$$\text{Normal}(0, \sigma^2) \underset{\sigma^2}{\wedge} \text{Gamma}(c\chi_\nu^2).$$

*In the notation introduced in Chapter 8, ξ is a random variable.

The distribution has a complicated form, although its characteristic function is simply $(1 + ct^2)^{-\nu/2}$.

The distribution

$$\text{Normal}(\xi, a) \wedge_{\xi} \text{Rectangular}$$

has been studied by **Bhattacharjee et al. (1963)**. Clow, Hansen, and **McNolty (1974)** have considered this distribution as the distribution for the pulse-plus-stationary Gaussian noise (under a constant amplitude).

Coming now to mixtures of a finite number (k) of normal components, a general form for the probability density function is

$$\sum_{i=1}^k \omega_i (\sqrt{2\pi} \sigma_i)^{-1} \exp \left[-\frac{1}{2} \left\{ \frac{(x - \xi_i)^2}{\sigma_i^2} \right\} \right]. \quad (13.143)$$

The quantities w_1, w_2, \dots, w_k ($0 < w_i; \sum_{i=1}^k w_i = 1$) are called the weights of the component normal distributions. We will consider in detail only the case $k = 2$. With increasing number of components the general case rapidly becomes extremely complicated, though simplifications (e.g., supposing all σ_i 's to be equal) can sometimes be used to render the analysis more manageable.

With $k = 2$, and ξ_1 and ξ_2 sufficiently different, it is possible for (13.143) to represent bimodal distributions [**Helguero (1904)**; **Prasad (1955)**; **Teichroew (1957)**]. A systematic study of conditions under which this is so has been made by **Eisenberger (1964)** [see also **Wessels (1964)**]. He summarizes his results as follows:

1. If

$$(\xi_1 - \xi_2)^2 < \frac{27\sigma_1^2\sigma_2^2}{4(\sigma_1^2 + \sigma_2^2)},$$

the distribution cannot be bimodal (in particular, if $\xi_1 = \xi_2$).

2. If

$$(\xi_1 - \xi_2)^2 > \frac{8\sigma_1^2\sigma_2^2}{\sigma_1^2 + \sigma_2^2},$$

there are values of ω_1 and ω_2 ($= 1 - \omega_1$) for which the distribution is bimodal.

3. For any set of values ξ_1, ξ_2, a , and σ_2 there are values of ω_1 and ω_2 for which the distribution is unimodal. (This is fairly evident, on considering that if $\omega_1 = 0$ or $\omega_1 = 1$, a normal distribution, which is unimodal, is obtained.)

Tables of moments of (13.143) with $k = 2$ [(standard deviation) σ^{-1} , a , and $(a, -3)$ to 3 decimal places for $\omega_2/\omega_1 = 0.1, 0.9$, and 1.0 ; $\sigma_2/\sigma_1 = 1.0(0.5)3.0$ and $(\xi_2 - \xi_1)/\sigma_1 = 0.0(0.5)3.0$] have been given by Linders (1930). If ω_1 is nearly 1, and so ω_t (for $t > 1$) is small, the mixture distribution (13.143) is sometimes called a contaminated normal distribution [Tukey (1949)]. It has been used as a model to assess tests for rejection of outlying observations obtained in samples from a supposedly normal distribution, and also in robustness studies for various inference procedures.

In the general case (13.143), the r th moment of X about zero is

$$\begin{aligned}\mu'_r(X) &= \sum_{t=1}^k E[X^r | \xi_t, \sigma_t] = \sum_{t=1}^k E[(\xi_t + U\sigma_t)^r] \\ &= \sum_{j=0}^{[r/2]} \binom{r}{2j} E[U^{2j}] \sum_{t=1}^k \xi_t^{r-2j} \sigma_t^{2j},\end{aligned}\quad (13.144)$$

where U is a unit normal variable (remember that $E[U^j] = 0$ if j is odd).

Suppose that k is equal to 2, and that we want to estimate the 5 parameters ω_1 ($= 1 - \omega_2$), ξ_1 , ξ_2 , σ_1 , and σ_2 by the method of moments. Five moments will be needed. From the equations

$$\begin{aligned}\mu'_1 &= \omega_1 \xi_1 + (1 - \omega_1) \xi_2, \\ \mu'_2 &= \omega_1 (\xi_1^2 + \sigma_1^2) + (1 - \omega_1) (\xi_2^2 + \sigma_2^2), \\ \mu'_3 &= \sum_{t=1}^2 \omega_t (\xi_t^3 + 3\xi_t \sigma_t^2), \\ \mu'_4 &= \sum_{t=1}^2 \omega_t (\xi_t^4 + 6\xi_t^2 \sigma_t^2 + 3\sigma_t^4), \\ \mu'_5 &= \sum_{t=1}^2 \omega_t (\xi_t^5 + 10\xi_t^3 \sigma_t^2 + 15\xi_t \sigma_t^4),\end{aligned}\quad (13.145)$$

we try to find values for ω_1 , ξ_1 , ξ_2 , a , and a .

This problem was considered by Pearson in 1894. Subsequently a number of improvements have been effected [e.g., Charlier and Wicksell (1924); Helguero (1905)]. Papers by Molenaar (1968) and Cohen (1967) give a useful account of this work. The following summary is based on information in these papers.

Putting $\theta_j = \xi_j - \mu'_1$ ($j = 1, 2$) the central moments μ_2 , μ_3 , μ_4 , and μ_5 are obtained from (13.145) by replacing ξ_t by θ_t ($t = 1, 2$). From the resulting equations can be derived an equation of ninth degree for $\phi = \theta_1 \theta_2$:

$$\sum_{j=0}^9 a_j \phi^j = 0, \quad (13.146)$$

where

$$\begin{aligned}
 a_0 &= -24\mu_3^6, \\
 a_1 &= -96\mu_3^4\kappa_4, \\
 a_2 &= -63\mu_3^2\kappa_4^2 - 72\mu_3^3\kappa_5, \\
 a_3 &= 288\mu_3^4 - 108\mu_3\kappa_4\kappa_5 + 27\kappa_4^3, \\
 a_4 &= 444\mu_3^2\kappa_4 - 18\kappa_5^2, \\
 a_5 &= 90\kappa_4^2 + 72\mu_3\kappa_5, \\
 a_6 &= 36\mu_3^2, \\
 a_7 &= 84\kappa_4, \\
 a_8 &= 0, \\
 a_9 &= 24,
 \end{aligned}$$

with

$$\begin{aligned}
 \kappa_4 &= \mu_4 - 3\mu_2^2, \\
 \kappa_5 &= \mu_5 - 10\mu_2\mu_3.
 \end{aligned}$$

In application, values of μ_r are replaced by sample values of these moments.

Since equation (13.146) might have as many as nine roots, there may be difficulty in choosing the "right" root. Since μ'_1 lies between ξ_1 and ξ_2 , it follows (unless $\xi_1 = \xi_2$) that θ_1 and θ_2 are of opposite signs, and so $\phi = \theta_1\theta_2 < 0$. Hence only negative roots of (13.146) need be considered. For ease of computation the following method appears to be convenient.

If the value of $4' = \theta_1 + \theta_2$ is known then ϕ is a negative root of the cubic equation

$$6\phi^3 - 2\phi'^2\phi^2 + (3\kappa_4 - 4\phi'\mu_3)\phi + \mu_3^2 = 0, \quad (13.147)$$

and this equation has only one such root. Using ϕ' , and the value of 4 obtained from (13.147), values of θ_1 and θ_2 can be determined, and from these ξ_1, ξ_2 are estimated as

$$\xi_j = \bar{X} + \theta_j, \quad j = 1, 2 \quad (13.148)$$

(\bar{X} being the sample mean), and ω_1 as

$$\omega_1 = \frac{\theta_2}{\theta_2 - \theta_1}. \quad (13.149)$$

Finally, we have

$$\sigma_j^2 = \frac{1}{3}\theta_j \left(2\phi' - \frac{\mu_3}{\phi} \right) + \mu_3 - \theta_j^2, \quad j = 1, 2. \quad (13.150)$$

Using the parameter values so obtained, a value for μ_5 can be calculated such as $\mu_5(\phi')$. By inverse interpolation from a series of such values of $\mu_5(\phi')$, a value for ϕ' (and hence a set of values for all five parameters) can be estimated. [This does not exclude the possibility that more than one value of ϕ' may make $\mu_5(\phi')$ equal to the sample value, so it may still be necessary to distinguish among such values. **Pearson** (1894) suggested that the value giving closest agreement between sample and population sixth moments be chosen. It is easy, however, to think of other criteria, e.g., choosing the value giving the least value of χ^2 or some other goodness-of-fit criterion.]

In view of the likely inaccuracy in estimating the sixth central moment, it seems preferable to use the first and third absolute central moments, ν_1 (mean deviation) and ν_3 , together with the variance μ_2 . From the equations

$$\begin{aligned} \nu_1 &= [\omega_1\sigma_1 + (1 - \omega_1)\sigma_2] \sqrt{\frac{2}{\pi}}, \\ \mu_2 &= \omega_1\sigma_1^2 + (1 - \omega_1)\sigma_2^2, \\ \nu_3 &= [\omega_1\sigma_1^3 + (1 - \omega_1)\sigma_2^3] \left(2\sqrt{\frac{2}{\pi}} \right), \end{aligned} \quad (13.151)$$

we obtain σ_1, a , as roots of the equation

$$\left(\mu_2 - \frac{1}{2}\pi\nu_1^2 \right) z^2 - \left(\frac{1}{2}\sqrt{\frac{\pi}{2}}\nu_3 - \sqrt{\frac{\pi}{2}}\nu_1\mu_2 \right) z + \frac{1}{4}\pi\nu_1\nu_3 - \mu_2^2 = 0. \quad (13.152)$$

Sometimes simpler procedures can give adequate results. If the difference between the means $|\xi_1 - \xi_2|$ is large enough, then the left-hand and right-hand tails of the distribution come almost entirely from single (and different) components of the mixture. Figure 13.4 typifies such a situation, with $\xi_1 < \xi_2$ (and $\sigma_1 > \sigma_2$). In such cases a truncated normal distribution may be fitted to each tail separately (as described, for single truncation, in Section 1). This gives estimates of $\xi_1, \xi_2, a,$ and a . Finally, ω_1 is determined from the equation

$$\omega_1\xi_1 + (1 - \omega_1)\xi_2 = \bar{X}.$$

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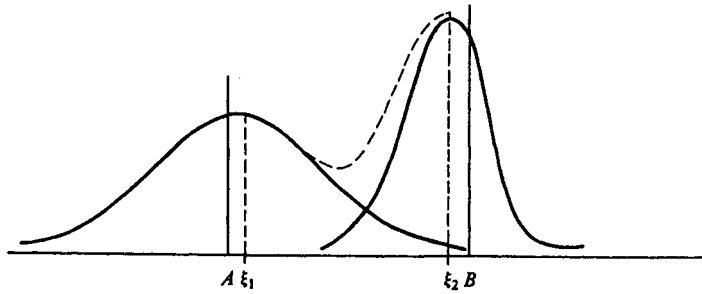


Figure 13.4 Data in the Region Below A Used for Estimation of the Component with Expected Value ξ_1 , and Data above B Used for Estimation of the Component with Expected Value ξ_2

A major difficulty in this method is the choice of points of truncation. Some check is possible by moving the points inward, toward the bulk of the distribution, so long as the estimators of ξ_j and σ_j remain "reasonably" consistent. A number of graphical methods of estimation have been developed [e.g., Harding (1949), Molenaar (1965), Taylor (1965), and **Wiechselberger** (1961)]. **Rivest** (1981) has discussed the sum of two contaminated normals.

If $\xi_1 = \xi_2$, then the distribution is symmetrical for any value of ω_1 . A symmetrical distribution is also obtained (even with $\xi_1 \neq \xi_2$) if $\sigma_1 = \sigma_2$ and $\omega_1 = \frac{1}{2}$. This can be distinguished from the symmetrical distribution obtained with $\xi_1 = \xi_2$ (and $\sigma_1 \neq \sigma_2$), since in the former case $\kappa_4 < 0$ while in the latter case $\kappa_4 > 0$. Moment estimators for the case $\xi_1 = \xi_2$ have been discussed in detail by **Agard** (1961). A maximum likelihood estimation procedure, for the case $\sigma_1 = \sigma_2$, was described by **Molenaar** (1965), who also constructed a computer program for this procedure.

Since 1970 extensive work has gone on with regard to the inference, modeling, and application aspects of the mixture-normal distributions. Books by **Titterington, Smith, and Makov** (1985) and **McLachlan and Basford** (1987) provide elaborate discussions on all these developments.

103 Other Related Distributions

If X_1 and X_2 are independent unit normal variables, and $F = (X_1/X_2)^2$, then F is distributed as $F_{1,1}$ (see Chapter 27). Equivalently, $t = X_1/X_2$ is distributed as t_1 (see Chapter 28), and so has a Cauchy distribution (see Chapter 16).

Among statistics used in testing normality are the following:

1. The sample skewness,

$$\sqrt{b_1} = \left[n^{-1} \sum_{j=1}^n (X_j - \bar{X})^2 \right]^{-3/2}$$

2. The sample kurtosis,

$$b_2 = \left[n^{-1} \sum_{j=1}^n (X_j - \bar{X})^4 \right] \left[n^{-1} \sum_{j=1}^n (X_j - \bar{X})^2 \right]^{-2}.$$

[Considerable attention has been devoted to obtaining formulas for the higher moments (up to eight) of these two statistics. See Fisher (1930), Geary (1933, 1947), Geary and Worlledge (1947), Hsu and Lawley (1940), and Wilkinson (1961). Tables of approximate percentiles are available in Pearson (1965).]

3. The ratio (sample mean deviation)/(sample standard deviation) [Geary (1935, 1936)].
4. The ratio (best linear unbiased estimator of α) \times (sample variance)⁻¹ [Shapiro and Wilk (1965)].
5. Ratios of symmetrical differences between order statistics,

$$\frac{X'_{n-r_1+1} - X'_{r_1}}{X'_{n-r_2+1} - X'_{r_2}}$$

[David and Johnson (1954)].

6. The ratio (sample range)/(sample standard deviation) [Pearson, Hartley, and David (1954); Pearson and Stephens (1964)].

As mentioned earlier in Section 8, a complete account of the goodness-of-fit tests for the normal distribution (along with detailed tables of percentage points, approximations for large samples, comparative power studies, etc.) can be had from the books by Shapiro (1986) and D'Agostino and Stephens (1986). In the construction of tests for outlying observations, distributions of the following statistics have been studied:

1. $(X'_n - \bar{X})/\sigma$, $(\bar{X} - \bar{X}'_1)/\sigma$ and the same statistics with σ replaced by the sample standard deviation [David (1956); Nair (1947); Sarhan (1954); Pearson and Chandra Sekar (1936)].
2. Ratios of order statistics of form

$$\frac{X'_r - X'_1}{X'_{r+1} - X'_1}, \frac{X'_n - X'_{n-r-1}}{X'_n - X'_{n-r}} \quad \text{for } r = 2, 3, 4, \dots$$

[Dixon (1950)].

Since 1970 the literature on outliers and related issues has expanded significantly. This is clearly evident from the third edition of Barnett and Lewis (1994). Many new tests have been proposed, their performance have been

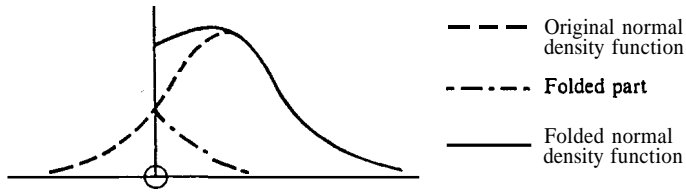


Figure 13.5 Folded Normal Distribution

evaluated, comparative studies have been carried out, and several tables have been constructed to facilitate the users. All these developments have been discussed in great detail in **Barnett** and **Lewis** (1994).

If X has a normal distribution as in (13.2), then $|X|$ is said to have a folded normal distribution. As the name suggests, the distribution can be regarded as being formed by folding the part corresponding to negative X about the vertical axis (see Figure 13.5) and then adding it to the positive part.

The folded normal distribution is identical with the distribution of

$$\sigma X \left(\begin{array}{l} \text{Noncentral } \chi \text{ with} \\ \text{one degree of freedom and} \\ \text{noncentrality parameter } (\xi/\sigma)^2 \end{array} \right),$$

and, as such, will be described in Chapter 29. If the folding is about the mean, then $\xi = 0$ and a central χ is obtained. This is also the half-normal distribution referred to earlier in this chapter (Section 10.1). **Leone**, **Nelson** and **Nottingham** (1961) and **Nelson** (1980) have discussed various properties and applications of the folded normal distribution. **Sinha** (1983) has derived Bayesian estimates for the parameters of this distribution.

In Chapter 12 we discussed Johnson's system of distributions (as three different transformations of normal random variables). **Shenton** and **Bowman** (1975) have used the S_U -distributions to examine the sample skewness and kurtosis statistics. **Hill** (1976) has given an algorithm for normal-Johnson and Johnson-normal transformations. **Olsson** (1979) has explained the fitting of Johnson's S_B and S_U systems of curves using the maximum likelihood method. **Hill** and **Wheeler** (1981) have commented on the algorithm of **Hill** (1976) and also on the fitting of Johnson curves by the method of moments; also see **Dodgson** and **Hill** (1983). The *logistic-normal* distribution, in particular, has received considerable attention from many authors. **Aitchison** and **Shen** (1980) have discussed some properties and uses of this distribution, while **Lenk** (1988) used this distribution for Bayesian and nonparametric predictive densities. **Titterton** (1989) has provided a review of the logistic-normal distribution. **Crouch** and **Spiegelman** (1990) recently considered integrals of the form $\int_{-\infty}^{\infty} f(t) e^{-t^2} dt$ and applied them to the study of logistic-normal models.

Azzalini's (1985) *skewed-normal distributions* was described in Chapter 12. This family of distributions, including the normal (when $A = 0$) and the half-normal (when $A = \infty$), has been discussed further by Azzalini (1986). Henze (1986) has provided a probabilistic representation of this family of distributions. Kotz and Johnson (1988) have provided a brief review of this distribution, while Liseo (1990) has recently discussed inferential aspects of this distribution from a Bayesian viewpoint.

A robust alternative to the normal distribution proposed by McLeish (1982) has already been pointed out in Chapter 12. Tardiff (1980) and Canal (1981) have discussed a generalized normal distribution, while Vianelli (1983) has defined families of normal and lognormal distributions of order r . Goto and Hatanaka (1985) have studied power-normal transformations. The *Sargan distribution* was introduced in Chapter 12. Kafael and Schmidt (1985) have examined the adequacy of the Sargan distribution as an approximation to the normal distribution.

When X has a $N(\xi, \sigma^2)$ distribution, then it is easily seen that $Y = 1/X$ has the density function

$$p_Y(y|\xi, \sigma) = \frac{1}{\sqrt{2\pi}\sigma y^2} e^{-((1/y) - \xi)^2 / (2\sigma^2)}. \quad (13.153)$$

Robert (1991), in generalizing the density in (13.153), has proposed the family of *generalized inverse normal distributions* with density

$$p_Y(y|\alpha, \xi, \sigma) = \frac{K(\alpha, \xi, \sigma)}{|y|^\alpha} e^{-((1/y) - \xi)^2 / (2\sigma^2)}, \quad \alpha > 1, \sigma > 0, \quad (13.154)$$

where $K(\alpha, \xi, \sigma)$ is the normalizing constant. The distribution is always bimodal, with modes at

$$y_1 = -\frac{\xi + \sqrt{\xi^2 + 4\alpha\sigma^2}}{2\alpha\sigma^2} \quad \text{and} \quad y_2 = \frac{\sqrt{\xi^2 + 4\alpha\sigma^2} - \xi}{2\alpha\sigma^2}.$$

The constant $K(\alpha, \xi, \sigma)$ can be expressed explicitly in terms of confluent hypergeometric functions. The k th moment exists only if $\alpha > k + 1$. For example, when $\alpha > 2$, the mean of the distribution is given by

$$\frac{\xi}{\sigma^2} \frac{{}_1F_1((\alpha - 1)/2; 3/2; \xi^2/2\sigma^2)}{{}_1F_1((\alpha - 1)/2; 1/2; \xi^2/2\sigma^2)}.$$

Kanji (1985) and Jones and McLachlan (1990) have considered *Laplace-normal mixture distribution* with density function

$$p(x; \xi, \sigma, \alpha, \beta) = \frac{\alpha}{2\beta} e^{-|x-\xi|/\beta} + \frac{1-\alpha}{\sqrt{2\pi}\sigma} e^{-(x-\xi)^2/(2\sigma^2)} \quad (13.155)$$

and applied the distribution to fit wind shear data.

A random variable X is said to have a circular normal distribution if its probability density function is [Kotz and Johnson (1982)]

$$p_X(x) = \frac{1}{2\pi I_0(k)} e^{k \cos(x-\theta)}, \quad 0 \leq x < 2\pi, 0 < \theta < 2\pi, \quad (13.156)$$

where $I_0(k) = \sum_{j=0}^{\infty} (k/2)^{2j} / (j!)^2$ is the modified **Bessel** function of first kind and order 0. The parameters of the distribution are θ and k ; as k increases, the distribution becomes more and more concentrated around the pole $x = \theta$. Sometimes a bivariate normal distribution with equal marginal standard deviations is also referred as a circular normal **distribution**; see Dyer (1974). In fact Dyer considered a truncated form of that distribution, discussed an estimation method for the parameters, and illustrated the method with ballistic applications.

A random variable X is said to have a lineo-normal distribution if its cdf is given by

$$F_X(x) = \sqrt{\frac{2}{\pi\sigma^2}} \int_{-\infty}^x \int_0^1 t^{1/2} e^{-y^2/(2t\sigma^2)} dt dy \quad (13.157)$$

[Kotz and Johnson (1985a)]. The distribution is symmetric about 0 and has variance $2u^2/3$. This distribution is a member of the *modified* normal distributions constructed by Romanowski. The cdf of this family is [Kotz and Johnson (1985c)]

$$F_X(x) = \frac{a+1}{\sqrt{2\pi\sigma}} \int_{-\infty}^x \int_0^1 t^{a-1/2} e^{-y^2/(2t\sigma^2)} dt dy. \quad (13.158)$$

Formula (13.158) is in fact a compound (or mixture) distribution obtained by ascribing the power function distribution with density $(a+1)t^a$, $0 \leq t \leq 1$ and $a \geq -1$, to the distribution $N(0, \sigma^2)/\sigma^2$. This distribution is also symmetric about 0, has variance $\sigma^2(a+1)/(a+2)$ and kurtosis $3(a+2)^2/\{(a+1)(a+3)\}$. The lineo-normal distribution in (13.157) is a special case of (13.158) with $a = 1$. When $a = 0$, the distribution in (13.158) is referred to as *equi-normal* distribution. When $a = \frac{1}{2}$, (13.158) is called as a *radico-normal* distribution. When $a = 2$, (13.158) is called as a *quadri-normal* distribution.

The lagged normal density function is the convolution of a normal density function and a descending exponential function, and is given by

$$q(t) = \int_{-\infty}^t p_1(\tau) p_2(t-\tau) d\tau, \quad (13.159)$$

where $p_1(x)$ is the density function of $N(\xi, \sigma^2)$ and $p_2(x)$ is the exponential density $\lambda \exp(-\lambda x)$, $x \geq 0$. The mean and variance of the density (13.159) are simply $\xi + 1/\lambda$ and $\sigma^2 + 1/\lambda^2$, respectively. A generalized lagged normal density function may similarly be defined by convoluting the normal density function with two or more exponentials. Realizing that the convolution of two or more exponentials is the generalized Erlangian distribution, the **general-**

ized lagged normal density function simply becomes the convolution of a normal density function and a generalized Erlangian density function. Davis and Kutner (1976) have applied this generalized lagged normal density function to fit indicator-dilution curves.

The *alpha distribution* has its cdf as

$$F_X(x) = \Phi\left(\alpha - \frac{\beta}{x}\right) / \Phi(\alpha), \quad \alpha, \beta > 0, \quad (13.160)$$

and pdf as

$$p_X(x) = \frac{\beta}{\sqrt{2\pi} \Phi(\alpha) x^2} e^{-(\alpha - \beta/x)^2/2}. \quad (13.161)$$

The distribution has its mode at $\beta(\sqrt{\alpha^2 + 8} - \alpha)/4$, and it moves to the left (right) as $\alpha(\beta)$ increases. This distribution has been applied to tool wear problems and has also been suggested for use in modeling lifetimes under accelerated test condition. Salvia (1985) has provided a characterization of the distribution, some other inferential results, and further pointed out the reliability application of the distribution. Note the similarity between (13.161) and the inverse normal density function (13.153). The similarity is due to the fact that (13.161) is nothing but the density function of $X = 1/Y$ when Y has a $N(\xi, \sigma^2)$, truncated to the left of 0, distribution (with $a = \xi/\sigma$ and $\beta = 1/\sigma$).

A random variable X is said to have a *two-piece normal distribution* with parameters ξ , σ_1 and σ_2 if it has its pdf,

$$p_X(x) = \begin{cases} Ae^{-(x-\xi)^2/(2\sigma_1^2)}, & x \leq \xi, \\ Ae^{-(x-\xi)^2/(2\sigma_2^2)}, & x > \xi, \end{cases} \quad (13.162)$$

where $A = \sqrt{2}(\sigma_1 + \sigma_2)^{-1}/\sqrt{\pi}$. John (1982) investigated the fitting of this distribution by the method of moments as well as the maximum likelihood method, and he discussed a number of properties of the distribution. In addition John has suggested a test of normality against a two-piece normal alternative. The distribution was originally introduced by Gibbons and Mylroie (1973) by joining two half-normal distributions; they then applied it to fit impurity profiles data in ion-implantation research. Kimber (1985) has examined this distribution further, and discussed methods of estimation and testing. Kimber has also considered the truncated two-piece normal distribution and derived maximum likelihood estimates of its three parameters. Kimber and Jeynes (1985) have applied the truncated two-piece normal distribution to an analysis of the depth measurements of arsenic implants in silicon.

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CHAPTER 14

Lognormal Distributions

1 INTRODUCTION

The idea of a transformation such that the transformed variable is normally distributed was encountered in Chapter 12. In Section 4.3 of that chapter some specific transformations were introduced. Of these the most commonly used, and the only one of sufficient importance to merit a separate chapter, is the simple logarithmic transformation.

If there is a number θ such that $Z = \log(X - \theta)$ is normally distributed, the distribution of X is said to be lognormal. For this to be the case, it is clearly necessary that X take any value exceeding θ but have zero probability of taking any value less than θ . The term "lognormal" can also be applied to the distribution of X if $\log(\theta - X)$ is normally distributed, X having zero probability of exceeding θ . However, since replacement of X by $-X$ (and θ by $-\theta$) reduces this situation to the first, we will consider only the first case.

The distribution of X can be defined by the equation

$$U = \gamma + \delta \log(X - \theta) \quad (14.1)$$

where U is a unit normal variable and γ , δ and θ are parameters. From (14.1) it follows that the probability density function of X is

$$p_X(x) = \delta [(x - \theta)\sqrt{2\pi}]^{-1} \exp\left[-\frac{1}{2}\{\gamma + \delta \log(x - \theta)\}^2\right], \quad x > \theta. \quad (14.2)$$

(We take $\delta > 0$, without loss of generality, since $-U$ has the same distribution as U .) An alternative notation replaces γ and δ by the expected value ζ and standard deviation σ of $Z = \log(X - \theta)$. The two sets of parameters are related by the equations

$$\zeta = -\frac{\gamma}{\delta}, \quad \sigma = \delta^{-1},$$

so that (14.1) becomes

$$U = \frac{\log(X - \theta) - \zeta}{\sigma}, \quad (14.1)'$$

and (14.2) becomes

$$p_X(x) = [(x - \theta)\sqrt{2\pi}\sigma]^{-1} \exp\left[-\frac{1}{2} \frac{\{\log(x - \theta) - \zeta\}^2}{\sigma^2}\right] (x > \theta). \quad (14.2)'$$

The lognormal distribution is sometimes called the *antilognormal* distribution. This name has some logical basis in that it is not the distribution of the logarithm of a normal variable (this is not even always real) but of an exponential—that is, antilogarithmic—function of such a variable. However, "lognormal" is most commonly used, and we will follow this practice. The minor variants *logarithmic*- or *logarithmico-normal* have been used, as have the names of pioneers in its development, notably *Galton* (1879) and *McAlister* (1879), *Kapteyn* (1903), *van Uven* (1917a), and *Gibrat* (1930) (see Section 2). When applied to economic data, particularly production functions, it is sometimes called the *Cobb-Douglas* distribution [e.g., *Dhrymes* (1962)].

It can be seen that a change in the value of the parameter θ affects only the location of the distribution. It does not affect the variance or the shape (or any property depending only on differences between values of the variable and its expected value). It is convenient to assign θ a particular value for ease of algebra, with the understanding that many of the results so obtained can be transferred to the more general distribution. In many applications θ is "known" to be zero (so that $\Pr[X \leq 0] = 0$ or X is a "positive random variable"). This important case has been given the name *two-parameter lognormal distribution* (parameters y , δ or ζ , a). For this distribution (14.1) becomes

$$U = \gamma + \delta \log X \quad (14.3)$$

and (14.1)' becomes

$$U = \frac{\log X - \zeta}{\sigma} \quad (14.4)$$

The general case (with θ not necessarily zero) can be called the *three-parameter lognormal distribution* (parameters y , δ , θ or ζ , a , θ).

A so-called four parameter lognormal distribution has been defined by

$$U = \gamma + \delta \log \left\{ \frac{X - \theta}{\lambda} \right\}. \quad (14.5)$$

Since (14.5) can be rewritten

$$U = \gamma' + \delta \log(X - \theta) \quad (14.5)'$$

with $\gamma' = \gamma - \delta \log \lambda$, it is really only a three-parameter lognormal that is defined by (14.1).

2 HISTORICAL REMARKS

Galton (1879) pointed out that, if X_1, X_2, \dots, X_n are independent positive random variables and

$$T_n = \prod_{j=1}^n X_j,$$

then

$$\log T_n = \sum_{j=1}^n \log X_j,$$

and if the independent random variables $\log X_j$'s are such that a central limit type of result applies, then the standardized distribution of $\log T_n$ would tend to a unit normal distribution as n tends to infinity. The limiting distribution of T_n would then be (two-parameter) lognormal. In an accompanying paper McAlister (1879) obtained expressions for the mean, median, mode, variance, and certain percentiles of the distribution.

Subsequent to this, little material was published relating to the **lognormal** distribution until 1903 when Kapteyn again considered its genesis on the lines described above. [Fechner (1897) mentioned the use of the distribution in the description of psychophysical phenomena but gave little emphasis to this topic.] Kapteyn and van Uven (1916) gave a graphical method (based on the use of sample quantiles) for estimating parameters, and in the following years there was a considerable increase in published information on the lognormal and related distributions. **Wicksell** (1917) obtained formulas for the higher moments (in a study of the distribution of ages at first marriage), while van Uven (1917a, b) considered transformations to normality from a more general point of view; **Nydell** (1919) obtained approximate formulas for the standard deviations of estimators obtained by the method of moments. Estimation from percentile points was described by Davies (1925, 1929) and tables to

facilitate estimation from sample moments were published by Yuan (1933). Unbiased estimators based on sample moments were constructed by Finney (1941).

From 1930 onward fields of application of the lognormal distribution have increased steadily. Gibrat (1930, 1931) found the distribution usefully representing the distribution of size for varied kinds of 'natural' economic units. Gibrat's "law of proportional effect" can be expressed as

$$X_j = X_{j-1}(1 + Z_j), \quad (14.6)$$

where $X_0, X_1, X_2, \dots, X_n$ is a sequence of random variables and $\{Z_j\}$ is a set of mutually independent random variables, statistically independent of $\{X_j\}$.

Formula (14.6) leads to

$$X_n = X_0 \prod_{j=1}^n (1 + Z_j).$$

For Z_j small compared to 1, we have

$$\log X_n = \log X_0 + \sum_{j=1}^n Z_j.$$

Using a multiplicative analogue to the additive central limit theorem, we arrive at the conclusion that X_n is asymptotically lognormally distributed with two parameters. Variations and extensions of Gibrat's argument have appeared in the literature. Kalecki (1945) assumed that the regression of $\log(1 + Z_j)$ on $\log X_{j-1}$ is linear, with

$$\log(1 + Z_j) = -\alpha_j \log X_{j-1} + Y_j \quad \text{with} \quad E[Y_j] = 0,$$

leading to

$$\log X_n = \log \left\{ X_0 \prod_{j=1}^n (1 - \alpha_j) + Y_1 \prod_{j=2}^n (1 - \alpha_j) + \dots + Y_{n-1} (1 - \alpha_n) + Y_n \right\}.$$

Soon after Gibrat's work, Gaddum (1933) and Bliss (1934) found that distributions of critical dose (dose just causing reaction) for a number of drugs could be represented with adequate accuracy by a (two-parameter) lognormal distribution. On the basis of these observations, a highly developed method of statistical analysis of "quantal" (all-or-none) response data has been elaborated. (The term "probit analysis" has been given to such analyses, although "probit" is often understood to apply to a special transformed value, $\Phi^{-1}(\hat{p}) + 5$, where \hat{p} is an observed proportion.)

Lognormal distributions have also been found to be applicable to distributions of particle size in naturally occurring aggregates [Hatch (1933), Hatch

and Choute (1929), and Krumbein (1936), with Bol'shev, Prohorov, and Rudinov (1963), Herdan (1960), Kalinske (1946), Kolmogorov (1941), Kottler (1950), and Wise (1952) among many others]. It is possible to give a general theoretical basis for this application on lines similar to those of Gibrat's arguments. Consider a quantity A , subjected to a large number of successive independent subdivisions, the j th resulting in a proportion X_j of the quantity surviving, so that after n divisions the surviving quantity is $AX_1X_2 \dots X_n$. If X_1, \dots, X_n are each uniformly distributed (see Chapter 26) over the interval 0 to 1, then the distribution of this quantity will be approximately lognormal. [See Halmos (1944) and Herdan (1960) for more complete accounts of this argument.]

Further applications, in agricultural, entomological, and even literary research were described by Cochran (1938), Williams (1937, 1940), Grundy (1951), Herdan (1958, 1966), and Pearce (1945). Koch (1966, 1969) discussed mechanisms that might generate lognormal distributions in a variety of biological and pharmacological situations.

This broadening of areas of practical usefulness of the distribution was followed by (and presumably associated with) renewed interest in estimation of its parameters. (Section 4 of this chapter contains technical accounts of estimation procedures.) Even in 1957 there were so many doubtful points in this regard that Aitchison and Brown (1957) devoted a substantial part of their book to discussion of problems of estimation, on account of "unresolved difficulties." Many of these difficulties, especially those concerning maximum likelihood estimation, have now been solved, or at least clarified. A recent paper [Nakamura (1991)] contains a description of construction of an adequate theoretical framework. Wu (1966) has shown that lognormal distributions can arise as limiting distributions of order statistics when order and sample size increase in certain relationships.

The book by Aitchison and Brown (1957) was very useful to us when organizing material for this chapter in the first edition. It can still be recommended for supplementary reading together with a more recent compendium on lognormal distributions, edited by Crow and Shimizu (1988), containing contributions from several experts. In revising the present chapter, we have tended to include topics which are less thoroughly covered in this compendium.

3 MOMENTS AND OTHER PROPERTIES

Most of the following discussion will be in terms of the two-parameter distribution, using (14.4) rather than (14.3). The r th moment of X about zero is

$$\mu'_r = E[X^r] = E[\exp r(\zeta + U\sigma)] = \exp(r\zeta + \frac{1}{2}r^2\sigma^2). \quad (14.7)$$

The expected value of X is

$$\mu'_1 = \exp\left(\zeta + \frac{1}{2}\sigma^2\right) = e^\zeta \omega^{1/2}, \quad (14.8a)$$

where $\omega = \exp(\sigma^2)$, and the variance is

$$\mu_2 = \mu'_2 - \mu'^2_1 = e^{2\zeta}(\omega^2 - (\omega^{1/2})^2) = e^{2\zeta}\omega(\omega - 1). \quad (14.8b)$$

The r th central moment of X [Wartmann (1956)] is

$$\begin{aligned} \mu_r &= E[(X - \mu'_1)^r] = \sum_{j=0}^r (-1)^j \binom{r}{j} \mu'_{r-j} \mu'^j_1 \\ &= \sum_{j=0}^r (-1)^j \binom{r}{j} \exp\left\{(r-j)\zeta + \frac{1}{2}(r-j)^2\sigma^2 + j\zeta + \frac{1}{2}j\sigma^2\right\} \\ &= \sum_{j=0}^r (-1)^j \binom{r}{j} \exp\left[r\zeta + \frac{1}{2}\{(r-j)^2 + j\}\sigma^2\right] \\ &= e^{r\zeta} \sum_{j=0}^r (-1)^j \binom{r}{j} \omega^{((r-j)^2 + j)/2} \\ &= \omega^{r/2} \left\{ \sum_{j=0}^r (-1)^j \binom{r}{j} \omega^{(r-j)(r-j-1)/2} \right\} e^{r\zeta}. \end{aligned} \quad (14.8c)$$

In particular

$$\mu_3 = \omega^{3/2}(\omega - 1)^2(\omega + 2)e^{3\zeta}, \quad (14.8d)$$

$$\mu_4 = \omega^2(\omega - 1)^2(\omega^4 + 2\omega^3 + 3\omega^2 - 3)e^{4\zeta}. \quad (14.8e)$$

The shape factors are

$$\alpha_3 = \sqrt{\beta_1} = (\omega - 1)^{1/2}(\omega + 2) \quad (14.9a)$$

and

$$\alpha_4 = \beta_2 = \omega^4 + 2\omega^3 + 3\omega^2 - 3. \quad (14.9b)$$

Neither of these depends on ζ . Note that $\alpha_3 > 0$ and $\alpha_4 > 3$ —that is, the distributions are positively skewed and are leptokurtic.

Equations (14.9a) and (14.9b) may be regarded as parametric equations of a curve in the (β_1, β_2) plane. This curve is called the lognormal line and is

shown in Figure 12.1 of Chapter 12, where it separates the regions for Johnson S_U and S_B distributions. The coefficient of variation is $(\omega - 1)^{1/2}$. It also does not depend on ζ . The distribution of X is unimodal; the mode is at

$$\text{Mode}(X) = \omega^{-1}e^{\zeta}. \quad (14.10)$$

From (14.4) it is clear that the value x_α , such that $\Pr\{X \leq x_\alpha\} = a$, is related to the corresponding percentile u_α of the unit normal distribution by the formula:

$$x_\alpha = \exp(\zeta + u_\alpha\sigma). \quad (14.11a)$$

In particular

$$\text{Median}(X) = x_{0.5} = e^{\zeta} \quad (\text{since } u_{0.5} = 0). \quad (14.11b)$$

Comparison of (14.8a), (14.10), and (14.11b) shows that

$$E[X] > \text{Median}(X) > \text{Mode}(X) \quad (14.12a)$$

and

$$\frac{\text{Mode}(X)}{E[X]} = \omega^{-3/2} = \left[\frac{\text{Median}(X)}{E[X]} \right]^3. \quad (14.12b)$$

The Theil coefficient is

$$E \left[\frac{X}{E[X]} \log \left\{ \frac{X}{E[X]} \right\} \right] = \frac{1}{2}\sigma^2. \quad (14.13)$$

Since the coefficient of variation is $(\omega - 1)^{1/2}$, the asymmetry index is (from (14.9a))

$$\frac{\sqrt{\beta_1}}{\text{Coefficient of variation}} = \omega + 2 = (\text{Coefficient of variation})^2 + 3. \quad (14.14)$$

In hydrological literature special attention has been devoted to relations between μ_i , $\text{Median}(X)$ and $\sqrt{\beta_1}$ [Burgess, Lettenmeier, and Bates (1975); Charbeneau (1978); Burgess and Hoshi (1978)].

The standardized $100\alpha\%$ deviate is, for example,

$$\begin{aligned} x'_\alpha &= \frac{x_\alpha - \mu'_1(X)}{\sqrt{\mu_2(X)}} \\ &= \frac{\omega^{-1/2} \exp(u_\alpha\sigma) - 1}{(\omega - 1)^{1/2}} = g(u_\alpha) \end{aligned} \quad (14.15)$$

[compare (14.11a), (14.8a) and (14.8b)]. Some values of x'_α are shown in Table 14.1.

Slifker and Shapiro (1980) have noted that for lognormal distributions

$$\frac{\{g(3u_\alpha) - g(u_\alpha)\} - \{g(-u_\alpha) - g(-3u_\alpha)\}}{\{g(u_\alpha) - g(-u_\alpha)\}^2} = 1 \quad \text{for all } a, \quad (14.16)$$

Table 14.1 Standardized $100\alpha\%$ Points (x'_α) of Lognormal Distributions ($\sigma = \delta^{-1}$)

σ	α (Upper Tail) (Lower Tail)	99.95 0.05	99.9 0.1	99.75 0.25	99.5 0.5	99 1	97.5 25	95 5	90 10	75 25	50 (Median)
0.02		3.39	3.18	2.88	2.63	2.37	1.99	1.66	1.29	0.669	
		-3.19	-3.01	-2.75	-2.52	-2.28	-1.93	-1.63	-1.27	-0.680	-0.010
0.04		3.49	3.27	2.95	2.69	2.42	2.02	1.68	1.29	0.663	
		-3.10	-2.92	-2.67	-2.46	-2.24	-1.90	-1.61	-1.27	-0.680	-0.020
0.06		3.60	3.36	3.02	2.75	2.46	2.04	1.69	1.30	0.657	
		-3.01	-2.84	-2.61	-2.41	-2.20	-1.87	-1.59	-1.26	-0.689	-0.030
0.08		3.71	3.45	3.09	2.81	2.50	2.07	1.71	1.30	0.650	
		-2.29	-2.76	-2.54	-2.36	-2.15	-1.85	-1.57	-1.25	-0.693	-0.040
0.10		3.82	3.54	3.17	2.87	2.55	2.10	1.72	1.31	0.643	
		-2.83	-2.69	-2.48	-2.30	-2.11	-1.82	-1.56	-1.24	-0.697	-0.050
0.12		3.93	3.64	3.24	2.93	2.60	2.13	1.74	1.31	0.635	
		-2.75	-2.61	-2.42	-2.25	-2.07	-1.79	-1.54	-1.23	-0.701	-0.060
0.14		4.05	3.74	3.32	2.99	2.64	2.15	1.75	1.31	0.628	
		-2.67	-2.54	-2.36	-2.20	-2.03	-1.76	-1.52	-1.23	-0.704	-0.069
0.16		4.17	3.84	3.40	3.05	2.69	2.18	1.77	1.32	0.620	
		-2.59	-2.47	-2.30	-2.15	-1.98	-1.73	-1.50	-1.22	-0.706	-0.079
0.18		4.29	3.95	3.48	3.11	2.73	2.21	1.78	1.32	0.611	
		-2.51	-2.40	-2.24	-2.10	-1.94	-1.70	-1.48	-1.21	-0.708	-0.089
0.20		4.42	4.05	3.56	3.17	2.78	2.23	1.79	1.32	0.603	
		-2.44	-2.33	-2.18	-2.05	-1.90	-1.67	-1.46	-1.14	-0.714	-0.098
0.30		5.10	4.61	3.97	3.49	3.00	2.35	1.84	1.32	0.555	
		-2.10	-2.03	-1.92	-1.82	-1.71	-1.53	-1.36	-1.14	-0.714	-0.143
0.40		5.86	5.23	4.41	3.81	3.22	2.45	1.88	1.30	0.402	
		-1.81	-1.76	-1.68	-1.61	-1.53	-1.39	-1.25	-1.07	-0.709	-0.185
0.50		6.71	5.89	4.86	4.13	3.42	2.54	1.89	1.27	0.444	
		-1.56	-1.52	-1.47	-1.42	-1.36	-1.25	-1.15	-1.00	-0.695	-0.220
1.00		11.66	9.41	6.90	5.32	3.98	2.52	1.63	0.904	0.145	
		-0.746	-0.742	-0.735	-0.728	-0.718	-0.698	-0.674	-0.634	-0.527	-0.300

and they have suggested using this as a basis for deciding whether a lognormal distribution is appropriate.

From Table 14.1 we see that as \mathbf{a} tends to zero (or δ to infinity), the standardized lognormal distribution tends to a unit normal distribution, and $x'_\alpha \rightarrow u_\alpha$. For \mathbf{a} small,

$$x'_\alpha \doteq u_\alpha + \frac{1}{2}(u_\alpha^2 - 1)\sigma + \frac{1}{12}(2u_\alpha^3 - 9u_\alpha)\sigma^2. \tag{14.17}$$

It is to be expected that

1. x'_α will change relatively slowly with σ (for σ small) if $u_\alpha^2 = 1$ (i.e., $\mathbf{a} = 0.84$ or 0.16),
2. the standardized **inter-100 α %** distance,

$$x'_\alpha - x'_{1-\alpha} \doteq 2u_\alpha + \frac{1}{6}(2u_\alpha^3 - 9u_\alpha)\sigma^2,$$

will change relatively slowly if $u_\alpha^2 = 9/2$ (i.e., $\mathbf{a} = 0.983$ or 0.017). These features also are indicated in Table 14.1. It is also clear from this table that as σ increases the lognormal distribution rapidly becomes markedly **nonnormal**. Table 14.2, which gives values of \mathbf{a} , and α_3 , also indicates how rapidly the skewness and kurtosis increase with \mathbf{a} . It is for this reason that only relatively small values of σ are used in Table 14.1.

It can be seen in Table 14.1 that for larger σ , there is a high probability density below the expected value, leading to small numerical standardized deviations. Conversely there is a long positive tail with large standardized deviations for upper percentiles. Figure 14.1 shows some typical probability density functions (standardized in each case so that the expected value is zero and the standard deviation is 1).

Table 14.2 Values of α_3 and \mathbf{a} , for Distribution (14.2)'

σ	α_3	α_4
0.1	0.30	3.16
0.2	0.61	3.68
0.3	0.95	4.64
0.4	1.32	6.26
0.5	1.75	8.90
0.6	2.26	13.27
0.7	2.89	20.79
0.8	3.69	34.37
0.9	4.75	60.41
1.0	6.18	113.94

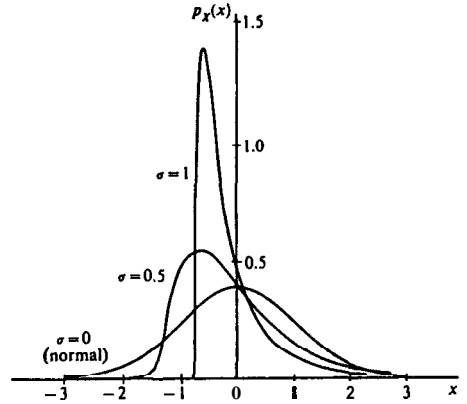


Figure 14.1 Standardized Lognormal Distribution

Wise (1952) has shown that the probability density function of the two-parameter distribution has two points of inflection at

$$x = \exp \left[\zeta - \frac{3\sigma^2}{2} \pm \sigma \sqrt{1 + \frac{1}{4}\sigma^2} \right]. \tag{14.18}$$

Just as the sum of two independent normal variables is also normally distributed, so the product of two independent (two-parameter) lognormally distributed variables is also lognormally distributed. If

$$U_j = \gamma_j + \delta_j \log X_j, \quad j = 1, 2,$$

are independent unit normal variables, then

$$\log(X_1 X_2) = \delta_1^{-1} U_1 + \delta_2^{-1} U_2 - (\gamma_1 \delta_1^{-1} + \gamma_2 \delta_2^{-1}),$$

and so

$$(\delta_1^{-2} + \delta_2^{-2})^{-1/2} [\log(X_1 X_2) + \gamma_1 \delta_1^{-1} + \gamma_2 \delta_2^{-1}]$$

is a unit normal variable. In particular, if X_1, X_2, \dots, X_n is a random sample from the distribution (14.2)' (with $\theta = 0$) so that $\log X_i$ is distributed normally with expected value ζ and variance σ^2 , then $n^{-1} \sum_{j=1}^n \log X_j = \log(G(x))$, where $G(x)$ is the sample geometric mean of X_1, \dots, X_n , is distributed normally with expected value ζ and variance σ^2/n . The sample geometric mean $G(x)$ therefore has a lognormal distribution with parameters $\zeta, n^{-1}\sigma^2$ [in (14.2)'], or $y = -\sqrt{n}\zeta/\sigma, \delta = \sqrt{n}/\sigma$.

We introduce the notation $\Lambda(\zeta, \sigma^2)$ to denote a distribution defined by (14.4) so that $X_1 X_2$ has the distribution $\Lambda(\zeta_1 + \zeta_2, \sigma_1^2 + \sigma_2^2)$ if X_j has the distribution $\Lambda(\zeta_j, \sigma_j^2)$ (for any j) and X_1, X_2 are mutually independent. Then the distribution of $a_j X_j$, where a_j is any positive constant, is

$\Lambda(\zeta_j + \log a_j, \sigma_j^2)$. Clearly, if X_1, X_2, \dots, X_k are a mutually independent set, then $\prod_{j=1}^k a_j X_j$ is distributed as $\Lambda(\sum_{j=1}^k \{\zeta_j + \log a_j\}, \sum_{j=1}^k \sigma_j^2)$.

Distributions of sums of independent random variables, each having lognormal distribution, have received special attention in the literature. These distributions are of importance in many areas of telecommunication, statistical detection problems, multihop scatter systems, and so on.

Fenton (1960) approximates the distribution of sum by a lognormal distribution with the same first two moments. Barakat (1976) considers the sum $S = \sum_{j=1}^N X_j$ of N i.i.d. X_j 's distributed as $\Lambda(\zeta, \sigma^2)$. He expresses the characteristic function of each X , in the form

$$\phi_X(t) = \frac{e^{i\sigma t}}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-y^2/2\sigma^2} e^{i\sigma t(e^y - y - 1)} e^{iyt} dy.$$

He then uses the expansion

$$\exp\{i\sigma t(e^y - y - 1)\} = \sum_{n=0}^{\infty} a_n(i\sigma t) \frac{y^n}{n!}$$

to obtain the characteristic function in the form

$$\phi_X(t) = \exp\left\{i\sigma t - \frac{1}{2}(\sigma t)^2\right\} \sum_{n=0}^{\infty} \frac{(i\sigma)^n}{n!} a_n(i\sigma t) h_n(i\sigma t). \quad (14.19)$$

Values of the coefficients $a_n(s)$ are given in Barakat's Table 1; the $h_n(x)$ are "quasi-Hermite" polynomials. The pdf is obtained by inverting (14.19) using quadrature.

The somewhat less ambitious target of obtaining the distribution of the sum of two independent lognormal variables was considered by Naus (1969). He obtained the moment-generating function of the distribution of the sum of two independent $\Lambda(0, \sigma^2)$ variables. Schwartz and Yeh (1982) consider the same problem when the two lognormal variables are not necessarily identically distributed.

The following (condensed) analysis of the problem indicates the difficulties involved: Suppose that X_j is distributed $\Lambda(\zeta_j, \sigma_j^2)$ ($j = 1, 2$) and that X_1 and X_2 are mutually independent. The joint pdf of X_1 and X_2 is

$$p_{X_1, X_2}(x_1, x_2) = \frac{1}{2\pi\sigma_1\sigma_2 x_1 x_2} \exp\left\{-\frac{1}{2} \sum_{j=1}^2 \left(\frac{\log x_j - \zeta_j}{\sigma_j}\right)^2\right\}, \quad 0 \leq x_1, x_2.$$

Changing to variables $Y_1 = X_1 + X_2$, $Y_2 = X_2$, we have the Jacobian

$$\left| \frac{\partial(X_1, X_2)}{\partial(Y_1, Y_2)} \right| = \begin{vmatrix} 1 & -1 \\ 0 & 1 \end{vmatrix} = 1,$$

and the joint pdf of Y_1 and Y_2 is

$$\frac{1}{2\pi\sigma_1\sigma_2(y_1 - y_2)y_2} \exp \left[-\frac{1}{2} \left\{ \frac{\log(y_1 - y_2) - \zeta_1}{\sigma_1} \right\}^2 - \frac{1}{2} \left(\frac{\log y_2 - \zeta_2}{\sigma_2} \right)^2 \right], \quad 0 \leq y_2 \leq y_1.$$

Hence

$$\begin{aligned} p_{Y_1}(y_1) &= \int_{-\infty}^{\infty} p_{Y_1, Y_2}(y_1, y_2) dy_2 = \int_0^{y_1} p_{Y_1, Y_2}(y_1, y_2) dy_2 \\ &= \frac{1}{2\pi\sigma_1\sigma_2} \int_0^{y_1} \frac{1}{(y_1 - y_2)y_2} \exp \left[-\frac{1}{2} \left\{ \frac{\log(y_1 - y_2) - \zeta_1}{\sigma_1} \right\}^2 - \frac{1}{2} \left(\frac{\log y_2 - \zeta_2}{\sigma_2} \right)^2 \right] dy_2. \end{aligned}$$

Setting $y_2 = y_1 t$, we obtain

$$\begin{aligned} p_{Y_1}(y_1) &= \frac{1}{2\pi\sigma_1\sigma_2 y_1} \int_0^1 \frac{1}{t(1-t)} \exp \left[-\frac{1}{2} \left\{ \frac{\log(1-t) + \log y_1 - \zeta_1}{\sigma_1} \right\}^2 - \frac{1}{2} \left(\frac{\log t + \log y_1 - \zeta_2}{\sigma_2} \right)^2 \right] dt. \end{aligned} \tag{14.20}$$

The integral in (14.20) may be evaluated by quadrature.

The preceding discussion has been limited to variables with two-parameter lognormal distributions. The extra parameter, θ in (14.2) or (14.2)' moves ("translates") the whole distribution by an amount θ in the direction of increasing X . Many properties—particularly variance and shape—remain unchanged, but the reproductive property does not hold if $\theta \neq 0$ for either X_1 or X_2 .

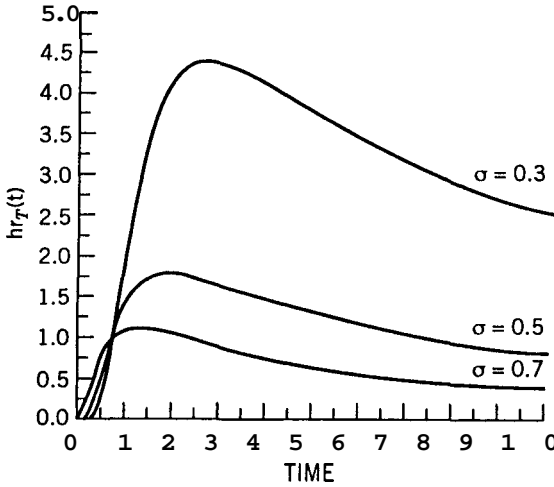


Figure 14.2 Hazard Rate of the Lognormal Distribution, with $E[\log T] = 0$; $\sigma = \text{S.D.}(\log T) = 0.3, 0.5, 0.7$

The information-generating function corresponding to (14.2) is

$$\left(\frac{\delta}{\sqrt{2\pi}}\right)^{u-1} \exp\left[\frac{1}{2}(u-1)^2(u\delta^2)^{-1} + (u-1)\frac{\gamma}{\delta}\right]. \tag{14.21}$$

The entropy is

$$\frac{1}{2} - \left(\frac{\gamma}{\delta}\right) - \log\left(\frac{\delta}{\sqrt{2\pi}}\right). \tag{14.22}$$

A recent reference for the characteristic function of $\Lambda(\zeta, \sigma^2)$ is **Leipnik** (1991). The distribution is not determined by its moments. A result of **Bondesson** (1979) is that any distribution with pdf of form

$$cx^{\beta-1}g(x), \quad \beta > 0, g(0) = 1,$$

with $g(\cdot)$ completely monotone on $(0, \infty)$, satisfying some mild regularity conditions is infinitely divisible (see Chapter 1). This result enables us to deduce that lognormal distributions are infinitely divisible.

Sweet (1990) has studied the hazard rate of lognormal distributions. Figure 14.2, taken from that paper, exhibits some of his results for $\Lambda(\zeta, \sigma^2)$. From this figure it can be seen that $h(0) = 0$ and that $h(t)$ runs to a maximum and thereafter decreases slowly to zero. The value t_M of t that maximizes $h(t)$ is

$$t_M = \exp(\zeta + z_M\sigma), \tag{14.23}$$

where $(z_M + \sigma)^{-1} = \{1 - \Phi(z_M)\}/\phi(z_M) = R(z_M)$, which is Mills's ratio (see Chapter 13).

From (14.23), $-\sigma < z_M < -\sigma + \sigma^{-1}$, and hence

$$e^{\zeta - \sigma^2} < t_M < e^{\zeta - \sigma^2 + 1}. \quad (14.24)$$

As $\sigma \rightarrow \infty$, $t_M \rightarrow \exp(\zeta - \sigma^2)$, and so for large σ ,

$$\max_t h(t) \doteq \frac{\exp(\zeta - \sigma^2/2)}{\sigma\sqrt{2\pi}}. \quad (14.25a)$$

As $\sigma \rightarrow 0$, $t_M \rightarrow \exp(\zeta - \sigma^2 + 1)$, and so for small σ ,

$$\max_t h(t) = (\sigma^2 \exp(\zeta - \sigma^2 + 1))^{-1}. \quad (14.25b)$$

4 ESTIMATION

4.1 θ Known

If the value of the parameter θ is known (it is often possible to take θ equal to zero), then estimation of the parameters ζ and σ (or γ and δ) presents few difficulties beyond those already discussed in connection with the normal distribution. In fact, by using values of $Z_i = \log(X_i - \theta)$, the problem is reduced to that of estimation of parameters of a normal distribution. Many specialized problems, such as those relating to truncated distributions or censored samples, or the use of order statistics, may be reduced to corresponding problems (already discussed in Chapter 13) for the normal distribution. Maximum likelihood estimation is exactly equivalent to maximum likelihood estimation for normal distributions, so that the maximum likelihood estimators $\hat{\zeta}, \hat{\sigma}$ for ζ and σ , respectively, are

$$\hat{\zeta} = \bar{Z}, \quad (14.26a)$$

$$\hat{\sigma} = \left[n^{-1} \sum_{j=1}^n (Z_j - \bar{Z})^2 \right]^{1/2}, \quad (14.26b)$$

where $\bar{Z} = n^{-1} \sum_{j=1}^n Z_j$ (assuming of course that X_1, X_2, \dots, X_n are independent random variables each having the same lognormal distribution with θ known).

There are a few situations where techniques appropriate to normal distributions cannot be applied directly. One is the construction of best linear unbiased estimators, using order statistics of the original variables X_j . An-

other is that where the original values $\{X_j\}$ are not available, but the data are in groups of equal width. While the results can immediately be written down in the form of grouped observations from a normal distribution, the groups appropriate to the transformed variables will not be of equal width. In such circumstances methods of the kind described in Chapter 12, Section 2, might be applied.

Sometimes it may be desired to estimate not ζ or σ but rather the expected value $\exp(\zeta + \sigma^2/2)$ and the variance $e^{\sigma^2}(e^{\sigma^2} - 1)e^{2\zeta}$ of the variable X . Since \bar{Z} and $S^2 = (n-1)^{-1}\sum_{j=1}^n (Z_j - \bar{Z})^2$ are jointly complete and sufficient statistics for ζ and σ , if σ^2 is known the UMVU estimator of $\theta_{a,b} = \exp(a\zeta + b\sigma^2)$ is

$$\hat{\theta}_u = \exp\left\{a\bar{Y} + b\sigma^2 - \frac{a^2\sigma^2}{2n}\right\}. \quad (14.27)$$

If a function $f(\bar{Z}, S^2)$ has expected value $h(\zeta, \sigma)$, it is the minimum variance unbiased estimator of $h(\zeta, \sigma)$. Finney (1941) obtained such estimators of the expected value and variance in the form of infinite series

$$M = \exp(\bar{Z})g\left(\frac{1}{2}S^2\right) \quad (14.28a)$$

$$V = \exp(2\bar{Z})\left\{g(2S^2) - g\left(\frac{(n-2)S^2}{n-1}\right)\right\}, \quad (14.28b)$$

respectively, where

$$g(t) = 1 + \frac{n-1}{n}t + \sum_{j=2}^{\infty} \frac{(n-1)^{2j-1}}{n^j(n+1)(n+3)\dots(n+2j-3)} \frac{t^j}{j!}. \quad (14.29)$$

Unfortunately, the series in (14.29) converges slowly (except for very small values of t). Finney recommends using the approximation

$$g(t) \doteq e^t \left\{1 - \frac{t(t+1)}{n} + \frac{t^2(3t^2 + 22t + 21)}{6n^2}\right\} \quad (14.30)$$

which (he states) should be safe for $n > 50$ in (14.28a) and $n > 100$ in (14.28b) provided that the coefficient of variation $[(e^{\sigma^2} - 1)^{1/2}]$ is less than 1 (corresponding to $a < 0.83$).

Finney showed that [with $\omega = \exp(\sigma^2)$]

$$n \text{Var}(M) \doteq \sigma^2 e^{2\zeta} \omega \left(1 + \frac{1}{2}\sigma^2\right), \quad (14.31a)$$

$$n \text{Var}(V) \doteq 2\sigma^2 e^{4\zeta} \omega^2 \{2(\omega - 1)^2 + \sigma^2(2\omega - 1)^2\}. \quad (14.31b)$$

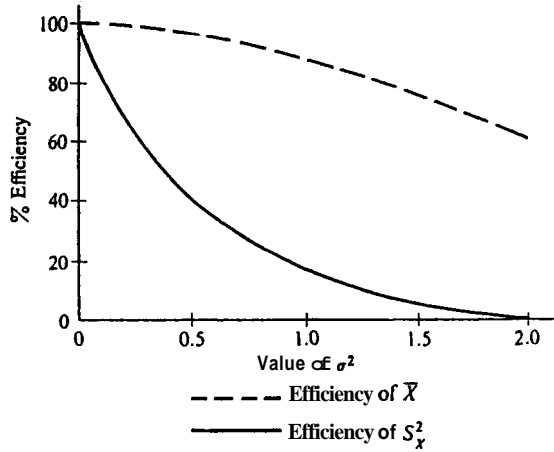


Figure 14.3 The Efficiency of \bar{X} and of S_X^2 in Large Samples

By comparison, for the unbiased estimators of the expected value and variance, \bar{X} and $S_X^2 = (n - 1)^{-1} \sum_{j=1}^n (X_j - \bar{X})^2$, respectively,

$$n \text{Var}(\bar{X}) = e^{2\zeta} \omega (\omega - 1), \tag{14.32a}$$

$$n \text{Var}(S_X^2) \doteq e^{4\zeta} \omega^2 (\omega - 1)^2 (\omega^4 + 2\omega^3 + 3\omega^2 - 4). \tag{14.32b}$$

Figure 14.3 [taken from Finney (1941)] shows approximate values of the "efficiency" ratios $100 \times \text{Var}(M)/\text{Var}(\bar{X})$ and $100 \times \text{Var}(V)/\text{Var}(S_X^2)$ as a function of σ^2 . It will be noted that while \bar{X} is reasonably efficient compared with M, considerable reduction in variance is achieved by using V in place of S_X^2 . [See also Oldham (1965).] Peters (1963) has constructed best quadratic estimators of $\log \mu'_r = r\zeta + r^2 u^2/2$, using order statistics based on $\log X_j$'s.

Confidence limits for ζ and/or α can of course be constructed from the transformed values Z_1, Z_2, \dots, Z_n using techniques in Chapter 13. In particular (when $\theta = 0$), since the coefficient of variation of X is $(e^{\sigma^2} - 1)^{1/2}$, confidence limits (with confidence coefficient $100\alpha\%$) for this quantity are $(\exp[(n - 1)S^2/\chi_{n-1, 1-\alpha/2}^2] - 1)^{1/2}$ and $(\exp[(n - 1)S^2/\chi_{n-1, \alpha/2}^2] - 1)^{1/2}$, where $\chi_{\nu, \epsilon}^2$ denotes the $100\epsilon\%$ point of the χ^2 distribution with ν degrees of freedom, to be described in Chapter 18. [See Koopmans, Owen, and Rosenblatt (1964).] Similar arguments could be used to construct confidence limits for any other monotonic function of σ , such as $\sqrt{\beta_1}$ and β_2 .

4.2 θ Unknown

Estimation problems present considerable difficulty when θ is not known. As might be expected, estimation of θ is particularly inaccurate. This parameter is a "threshold value," below which the cumulative distribution function is

Table 14.3 Percentile Points of Standardized Lognormal Distributions

σ	θ	Lower		Median	Upper	
		10%	25%		25%	10%
0.02	-49.995	-1.275	-0.680	-0.010	0.669	1.288
0.04	-24.990	-1.268	-0.685	-0.020	0.663	1.293
0.06	-16.652	-1.260	-0.689	-0.030	0.657	1.299
0.08	-12.480	-1.252	-0.693	-0.040	0.650	1.303
0.10	-9.975	-1.244	-0.697	-0.050	0.643	1.307
0.12	-8.303	-1.235	-0.700	-0.060	0.635	1.311
0.14	-7.108	-1.225	-0.703	-0.069	0.628	1.314
0.16	-6.210	-1.216	-0.706	-0.079	0.620	1.316
0.18	-5.511	-1.206	-0.708	-0.089	0.611	1.318
0.20	-4.950	-1.195	-0.710	-0.098	0.603	1.320

zero and above which it is positive. Such values are often—one might say "usually" **difficult** to estimate.

However, estimation of parameters is often not as important as estimation of probabilities—in particular, of cumulative distribution functions. Table 14.3 shows the median and upper and lower 10% and 25% points of lognormal distributions with widely differing values of θ , but with ζ and σ so chosen that each distribution is standardized (i.e., has zero expected value and unit standard deviation; see also Table 14.1).

There can be considerable variation in θ with little effect on the percentiles and little effect on values of the cumulative distribution functions for fixed values of X . Insensitivity to variation in θ is most marked for large negative values of θ . These observations and Table 14.3 should correct any feeling of depression caused by the inaccuracy of estimation of θ . Of course there can be situations where the accuracy of estimation of θ itself is a primary consideration. In these cases special techniques, both of experimentation and analysis, may be needed. These will be briefly described at the end of this section.

Maximum likelihood estimation of θ , ζ , and σ might be expected, to be attained by the following tedious, but straightforward, procedure. Since for given θ , the likelihood function is maximized by taking

$$\hat{\zeta} = \hat{\zeta}(\theta) = n^{-1} \sum_{j=1}^n \log(X_j - \theta), \quad (14.33a)$$

$$\hat{\sigma} = \hat{\sigma}(\theta) = \left[n^{-1} \sum_{j=1}^n \{ \log(X_j - \theta) - \hat{\zeta}(\theta) \}^2 \right]^{1/2}, \quad (14.33b)$$

[cf. (14.26a), (14.26b)],

one might take a sequence of values of θ , calculate the maximized likelihood corresponding to each, and then try to estimate numerically the value θ of θ by maximizing the maximized likelihood. However, Hill (1963) has shown that as θ tends to $\min(X_1, X_2, \dots, X_n)$,* the maximized likelihood tends to infinity. Formally this would seem to indicate that we should accept the "estimates": $\hat{\theta} = \min(X_1, X_2, \dots, X_n)$, $\hat{\zeta} = -\infty$, $\hat{\sigma} = \infty$. Hill resolved this difficulty by introducing a prior joint distribution for θ , ζ , and σ , and then using Bayes's theorem. This leads to the conclusion that solutions of the formal maximum likelihood equations should be used, with $\hat{\theta}$ satisfying

$$\sum_{j=1}^n (X_j - \hat{\theta})^{-1} + [\hat{\sigma}(\hat{\theta})] \left\{ \sum_{j=1}^n (X_j - \hat{\theta})^{-1} Z'_j \right\} = 0, \quad (14.34)$$

where $Z'_j = [\log(X_j - \hat{\theta}) - \hat{\zeta}(\hat{\theta})]/\hat{\sigma}(\hat{\theta})$ and $\hat{\zeta}(\hat{\theta}), \hat{\sigma}(\hat{\theta})$ satisfy (14.33), with θ replaced by $\hat{\theta}$.

Formal calculation of limiting variances gives

$$n \text{Var}(\hat{\theta}) \doteq \sigma^2 e^{2\zeta} \omega^{-1} [\omega(1 + \sigma^2) - 2\sigma^2 - 1]^{-1}, \quad (14.35a)$$

$$n \text{Var}(\hat{\zeta}) \doteq \sigma^2 [\omega(1 + \sigma^2) - 2\sigma^2] [\omega(1 + \sigma^2) - 2\sigma^2 - 1]^{-1}, \quad (14.35b)$$

$$n \text{Var}(\hat{\sigma}) \doteq \sigma^2 [\omega(1 + \sigma^2) - 1] [\omega(1 + \sigma^2) - 2\sigma^2 - 1]^{-1}. \quad (14.35c)$$

Formulas equivalent to these have been given by Cohen (1951) and Hill (1963), but (14.35c) is unlikely to be valid [see Hill (1963) and below].

We may note that Harter and Moore (1966) carried out a sampling experiment, with $\zeta = 4$, $\sigma = 2$, and $\theta = 10$. Their results can be represented approximately, for sample size n in the range 50 to 200 by

$$n \text{Var}(\hat{\zeta}) \doteq 4.2,$$

$$n \text{Var}(\hat{\sigma}) \doteq 3.2,$$

$$n^2 \text{Var}(\hat{\theta}) \doteq 1800$$

(note the factor n^2 in the last formula). If θ is known, their results give $n \text{Var}(\hat{\zeta}) = 4.1$ —not much less than if θ is not known—but $n \text{Var}(\hat{\sigma})$ is now only about 2.1.

Tiku (1968) has suggested an approximate linearization of the maximum likelihood equations based on the approximate formula

$$Z(x)[1 - \Phi(x)]^{-1} = \alpha + \beta x \quad (14.36)$$

*It is clear that we must take $\theta \leq \min(X_1, X_2, \dots, X_n)$.

for Mills's ratio. Appropriate values of α and β depend on the range of values of \mathbf{x} . (See discussion of a similar technique in Chapter 13, Section 8.4.)

Over the last 20 years there has been further consideration of maximum likelihood estimation for the three-parameter lognormal and its difficulties. We are inclined to agree with the opinion expressed by Griffiths (1980), that "the method of maximum likelihood has been wrongly discredited because of supposed computational difficulties and theoretical uncertainties."

Calitz (1973) suggests using Cohen's (1951) method to solve the maximum likelihood equations. He solves (14.34) numerically using the Newton-Raphson method, which will converge provided the initial value of δ is chosen so that $\partial \log L(\theta) / \partial \theta < 0$. Using the value $\delta = \max(0.6 X_{(1)}, X_{(1)} - 0.1)$, where $X_{(1)}$ is the least of the observed values of X , provided satisfactory results. Lambert's (1964) failure to solve this problem—which triggered many denunciations of the maximum likelihood method—was due to his choice of method of iteration. He tried to iterate on all three maximum likelihood equations simultaneously.

Wingo (1976) proposed using penalty functions, maximizing the function

$$-n\{\hat{\zeta}(\theta) + \log \hat{\sigma}(\theta)\},$$

with $\hat{\zeta}(\theta)$, $\hat{\sigma}(\theta)$ given by (14.33), subject to constraints of form

$$\begin{cases} \theta + c > 0, \\ \theta < \min(X_1, \dots, X_n). \end{cases} \quad (14.37)$$

The constant c is chosen to be a large positive number (although its value can be problem dependent). Hawkins (1991) points out that a necessary condition for the maximum likelihood equations to "degenerate" so that they cannot be solved is that

$$2S_1 + \log(S_2 - S_1^2),$$

where $S_i = \sum_{j=1}^n [(\log(X_j + \alpha))^i / n]$ ($i = 1, 2$) be a decreasing function of α .

Noting that all data are in fact subject to grouping (and so are, in reality, discrete), Giesbrecht and Kempthorne (1976) have shown that the problem of an unbounded likelihood function can be removed by taking a suitable discretized model. Griffiths (1980) utilizes the discretization procedure to obtain a confidence interval for the threshold parameter δ . Provided that the group width is sufficiently small, the likelihood will be practically of the same form for both the (approximate) continuous and (correct) discrete models, except in the neighborhood of the singularity in the continuous model. Griffiths (1980) also discusses construction of approximate confidence intervals for δ .

Dahiya and Guttman (1982) construct a "shortest prediction interval" of level $1 - \alpha$ for a two-parameter lognormal variable. [This is not an estimated

interval, it is simply the interval (a, b) such that $b - a$ is minimized subject to $\Pr[a < X < b] = 1 - \alpha$.] Clearly we must have $a = \exp(\zeta + A\sigma)$ and $b = \exp(\zeta + B\sigma)$, with

$$\Phi(B) - \Phi(A) = 1 - \alpha \quad (14.38)$$

(to provide level $1 - \alpha$). Subject to (14.38) we have to minimize $b - a$, or equivalently

$$e^{B\sigma} - e^{A\sigma}. \quad (14.39)$$

From (14.38), $\phi(B)(\partial B/\partial A) - \phi(A) = 0$, whence

$$\frac{\partial B}{\partial A} = \frac{\phi(A)}{\phi(B)}. \quad (14.40a)$$

To minimize (14.39), we equate

$$\frac{\partial}{\partial A} (e^{B\sigma} - e^{A\sigma}) = \sigma \left(e^{B\sigma} \frac{\partial B}{\partial A} - e^{A\sigma} \right) \quad (14.40b)$$

to zero.

Inserting the value of $\partial B/\partial A$ from (14.40a), we obtain

$$e^{B\sigma} \cdot \phi(A) = e^{A\sigma} \phi(B),$$

whence $B\sigma - A^2/2 = A\sigma - B^2/2$; that is,

$$A + B = -2\sigma. \quad (14.41)$$

The values of A and B are easily determined from (14.38) and (14.41), but Dahiya and Guttman (1982) provide tables to facilitate the process. These authors also consider construction of shortest *confidence* intervals for the median (e^{ζ}). [Of course, if it is known that $\theta = 0$, confidence intervals for ζ ($= E[\log X]$) are easily constructed using normal theory results (see Chapter 13).]

Since

$$\overline{\log X} = n^{-1} \sum_{i=1}^n \log X_i$$

and

$$S^2 = (n - 1)^{-1} \sum_{i=1}^n (\log X_i - \overline{\log X})^2$$

are sufficient for the parameters of $\Lambda(\zeta, \sigma^2)$, a minimum variance unbiased estimator of

$$\mu'_1 = \log E[X] = \zeta + \frac{1}{2}\sigma^2$$

is

$$\tilde{\mu}'_1 = \overline{\log X} + \frac{1}{2}S^2; \quad (14.42a)$$

a minimum variance unbiased estimator of the variance of $\tilde{\mu}'_1$,

$$\text{Var}(\tilde{\mu}'_1) = \text{Var}(\overline{\log X}) + \frac{1}{4} \text{Var}(S^2),$$

(since $\overline{\log X}$ and S^2 are independent) is [Land (1972)]

$$\tilde{\gamma}^2 = \widetilde{\text{Var}}(\tilde{\mu}'_1) = n^{-1}S^2 + \frac{1}{2}(n+1)^{-1}S^4. \quad (14.42b)$$

Among other proposed modifications of **maximum** likelihood estimation we note the suggestions of Cohen and **Whitten** (1980) based on introduction of order statistics: They propose replacing the **maximum** likelihood equation $\log L/\partial\theta = 0$ by

$$\log(X'_r - \theta) = \zeta + \sigma E[U'_r] \quad (14.43)$$

where X'_r is the r th order statistic among X_1, \dots, X_n and U'_r is the r th order statistic among n mutually independent unit normal variables, or by

$$\log(X'_r - \theta) = \zeta + \sigma \Phi^{-1}\left(\frac{r}{n+1}\right). \quad (14.44)$$

Other modifications include: the equation is replaced by

$$E[X] = \bar{X}$$

or by

$$\text{Var}(X) = S^2 \quad \text{with} \quad S^2 = \frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}$$

The actual estimating equations for θ are

$$\theta = \bar{X} - e^{\zeta} \sqrt{\omega}$$

and

$$S^2 = e^{2\zeta} \omega (\omega - 1).$$

Nevertheless, uncertainties and difficulties in the use of (14.33) and (14.34) lead us to consider methods other than maximum likelihood.

If the first three sample moments are equated to the corresponding population values, we obtain the formulas

$$\bar{X} = \tilde{\theta} + \exp\left(\tilde{\zeta} + \frac{1}{2}\tilde{\sigma}^2\right), \quad (14.45a)$$

$$m_2 = n^{-1} \sum_{j=1}^n (X_j - \bar{X})^2 = e^{2\tilde{\zeta} + \tilde{\sigma}^2} (e^{\tilde{\sigma}^2} - 1), \quad (14.45b)$$

$$m_3 = n^{-1} \sum_{j=1}^n (X_j - \bar{X})^3 = e^{3\tilde{\zeta} + 3\tilde{\sigma}^2/2} (e^{\tilde{\sigma}^2} - 1)^2 (e^{\tilde{\sigma}^2} + 2), \quad (14.45c)$$

whence

$$\begin{aligned} b_1 &= m_3^2 m_2^{-3} = (e^{\tilde{\sigma}^2} - 1)(e^{\tilde{\sigma}^2} + 2)^2 \\ &= (\tilde{\omega} - 1)(\tilde{\omega} + 2)^2. \end{aligned} \quad (14.46)$$

From (14.46), G and then $\tilde{\sigma}$ can be determined. From (14.45b),

$$\tilde{\zeta} = \frac{1}{2} \log [m_2 \tilde{\omega}^{-1} (\tilde{\omega} - 1)^{-1}],$$

and finally $\tilde{\theta}$ can be determined from (14.45a).

Yuan (1933) provided a table of values of the right-hand side of (14.46) to aid in the solution of that equation. Aitchison and Brown (1957) give a table for $\tilde{\sigma}^2$ directly to four decimal places for $\sqrt{b_1} = 0.0(0.2)10.0(1)24$. Without using such tables, an iterative method using equation (14.46) in the form

$$\tilde{\omega} = 1 + (\tilde{\omega} + 2)^{-2} b_1 \quad (14.46)'$$

is quite easy to apply, or the explicit solution

$$\begin{aligned} \tilde{\omega} &= \left[1 + \frac{1}{2}b_1 + \sqrt{\left(1 + \frac{1}{2}b_1\right)^2 - 1} \right]^{1/3} \\ &\quad + \left[1 + \frac{1}{2}b_1 - \sqrt{\left(1 + \frac{1}{2}b_1\right)^2 - 1} \right]^{1/3} - 1 \end{aligned}$$

can be used.

This method is easy to apply but liable to be inaccurate because of sampling variation in b_1 . [However, Sinha (1981) found it to be quite reliable.] Even when θ is known, estimation of population variance by sample variance is relatively inaccurate (see Figure 14.3). Approximate formulas for

the variances of the estimators were obtained by Nydell (1919). They are

$$n \text{Var}(\tilde{\xi}) \doteq \frac{1}{6}[4u^{-1} + 54 + 306u + 895u^2 + 1598u^3 + 1753.5u^4 + 1242.7u^5],$$

$$n \text{Var}(\tilde{\sigma}) \doteq \frac{1}{2}u\sigma^{-2}\{8 + 106u + 332u^2 + 479u^3 + 404u^4 + 216u^5\},$$

where $u = \omega - 1 = e^{\sigma^2} - 1$ (square of coefficient of variation).

A modification of the method of moments is to estimate θ by this method and then use Finney's estimators M, V [see (14.28a) and (14.28b)] of expected value and variance, applied to the variables $\{X_i - \theta\}$.

Alternatively, if one is prepared to accept some loss in efficiency, it might be possible to use a relatively simple method of calculating estimates. Certain special forms of the method of percentile points give very simple formulas for the estimators. Using the relationship [see (14.1) and (14.11a)]

$$u_{\alpha_j} = \gamma + \delta \log(x_{\alpha_j} - \theta), \quad j = 1, 2, 3, \quad (14.47)$$

the following formula can be obtained:

$$\frac{u_{\alpha_1} - u_{\alpha_2}}{u_{\alpha_2} - u_{\alpha_3}} = \frac{\log[(x_{\alpha_1} - \theta)/(x_{\alpha_2} - \theta)]}{\log[(x_{\alpha_2} - \theta)/(x_{\alpha_3} - \theta)]}. \quad (14.48)$$

If estimated values \hat{X}_{α_j} of the x_{α_j} 's are inserted in (14.48), the solution of the resulting equation for θ must be effected by trial and error. However, if we choose $\alpha_2 = \frac{1}{2}$ (corresponding to the median) and $\alpha_1 = 1 - a$, then (noting that $u_{1/2} = 0$, and $u_{1-\alpha_1} = -u_{\alpha_1}$) the equations are (asterisk denoting "estimated value"):

$$\hat{X}_{\alpha_1} = \theta^* + e^{-\gamma^*/\delta^*} \exp\left[\frac{u_{\alpha_1}}{\delta^*}\right], \quad (14.49a)$$

$$\hat{X}_{1/2} = \theta^* + e^{-\gamma^*/\delta^*}, \quad (14.49b)$$

$$\hat{X}_{1-\alpha_1} = \theta^* + e^{-\gamma^*/\delta^*} \exp\left[-\frac{u_{\alpha_1}}{\delta^*}\right], \quad (14.49c)$$

whence

$$\frac{\hat{X}_{\alpha_1} - \hat{X}_{1/2}}{\hat{X}_{1/2} - \hat{X}_{\alpha_3}} = \exp\left[\frac{u_{\alpha_1}}{\delta^*}\right]$$

and

$$\delta^* = u_{\alpha_1} \left[\log \left\{ \frac{\hat{X}_{\alpha_1} - \hat{X}_{1/2}}{\hat{X}_{1/2} - \hat{X}_{1-\alpha_1}} \right\} \right]^{-1} \quad (14.50)$$

so that no solution by trial and error is needed. Aitchison and Brown (1957) suggest taking $\alpha_1 = 0.95$, but it is likely that any value between 0.90 and 0.95 will give about the same accuracy. Lambert (1970) suggested using values of the parameters obtained by this method as a starting point for an iterative formal solution of the maximum likelihood equations. He used the value $\alpha_1 = 61/64 = 0.953$.

It is possible for (14.50) to give a negative value of δ^* , but this happens only if

$$\hat{X}_{\alpha_1} - \hat{X}_{1/2} < \hat{X}_{1/2} - \hat{X}_{1-\alpha_1},$$

which is very unlikely to be the case if the distribution has substantial positive skewness.

If the sample median $\hat{X}_{1/2}$ is replaced by the sample arithmetic mean \bar{X} and equation (14.49b) by

$$\bar{X} = \theta^* + e^{-\gamma^*/\delta^*} \exp\left(\frac{1}{2}\delta^{*-2}\right), \quad (14.49d)$$

then from (14.49a), (14.49c), and (14.49d),

$$\frac{\bar{X} - \hat{X}_{1-\alpha_1}}{\hat{X}_{\alpha_1} - \bar{X}} = \frac{\exp\left(\frac{1}{2}\delta^{*-2}\right) - \exp\left(-u_{\alpha_1}\delta^{*-1}\right)}{\exp\left(u_{\alpha_1}\delta^{*-1}\right) - \exp\left(\frac{1}{2}\delta^{*-2}\right)}. \quad (14.51)$$

From this equation S^* can be found numerically. Aitchison and Brown (1957) give graphs of the function on the right-hand side of (14.51), for $\alpha_1 = 0.95, 0.90$, and 0.80 , which helps to give an initial value for the solution. This method of estimation is called Kemsley's method (1952). It can also give a negative value for δ^* , though this is unlikely to occur.

A method suggested by Boswell, Ord, and Patil (1979) is easy to apply: Consider the 100α th lower, 50th and 100α th upper percentiles of the normal variable $Z = \log(X - \theta)$. These are $\zeta - z\sigma$, ζ , and $\zeta + z\sigma$, respectively, where $\alpha = \Phi(-z) = 1 - \Phi(z)$. The corresponding (unknown) percentiles of X will be $x_{(1)} = \exp(\zeta - z\sigma) + 8$, $x_{(2)} = \exp(\zeta) + 8$, and $x_{(3)} = \exp(\zeta + z\sigma) + 8$. Solving for 8, from these three equations we obtain

$$\theta = \frac{x_{(1)}x_{(3)} - x_{(2)}^2}{x_{(1)} - 2x_{(2)} + x_{(3)}}. \quad (14.52)$$

Estimating $x_{(1)}$, $x_{(2)}$, and $x_{(3)}$ from the corresponding percentiles of lognormal data we obtain an estimator of 8.

Boswell, Ord, and Patil (1979) recommended choosing z in the range of 1.5 to 2. Aitchison and Brown (1957) made an experimental comparison of results of using the method of moments (14.461, the method of quantiles

(14.50), and Kemsley's method (14.51) to estimate θ . They came to the conclusion that (14.50) with $\alpha = 0.95$ is slightly better than (14.51) and that both are considerably better than the method of moments.

Other methods of estimating θ have been suggested. *Cohen's* method (1951) is based on the idea that in a large sample at least one observed value of X should be not much greater than the threshold value θ . The least sample value \hat{X}_{\min} is equated to the formula for the $100(n+1)^{-1}\%$ point of the distribution, giving the relationship

$$\hat{X}_{\min} = \theta^* + e^{-\gamma^*/\delta^*} \exp\left[\frac{u_{1/(n+1)}}{\delta^*}\right]$$

or

$$\hat{X}_{\min} = \theta^* + e^{\zeta^*} \exp[u_{1/(n+1)}\sigma^*]. \quad (14.53)$$

This is then combined with the first two maximum likelihood equations (14.33).

There are natural modifications of this method, to allow for cases when there are several equal (or indistinguishable, as in grouped data) minimum values. Using a variant of this method, an initial value of θ (for use in some iterative process) may be chosen as \hat{X}_{\min} minus some arbitrary (usually rather small) value.

Cohen, Whitten, and Ding's (1985) *modified* moment estimation method uses the equations (in an obvious notation)

$$E[X] = \bar{X}, \quad (14.54a)$$

$$\text{Var}(X) = S^2, \quad (14.54b)$$

$$\theta + \exp\{\zeta + \sigma E[U_{1,n}]\} = \hat{X}_{\min}. \quad (14.54c)$$

Equation (14.54c) is obtained from (14.53) by replacing $u_{1/(n+1)} - \Phi^{-1}((n+1)^{-1})$ by $E[U_{1,n}]$. Table 14.4 gives values of $-u_{1/(n+1)}$ and $-E[U_{1,n}]$. [More detailed tables of $E[U_{1,n}]$ are available in Harter (1961); see also Tippett (1925) and Chapter 13, Section 4.]

Table 14.4 Values of $-u_{1/(n+1)}$ and $-E(U_{1,n})$

n	5	10	20	30	40	50	60	70
$-u_{1/(n+1)}$	0.967	1.340	1.671	1.848	1.970	2.062	2.135	2.195
$-E(U_{1,n})$	1.163	1.539	1.867	2.043	2.161	2.249	2.319	2.377
n	80	90	100	150	200	300	400	1000
$-u_{1/(n+1)}$	2.246	2.291	2.330	2.477	2.578	2.714	2.808	3.093
$-E(U_{1,n})$	2.427	2.470	2.508	2.649	2.746	2.878	2.968	3.241

The explicit form of the estimating equations is

$$\theta^* + e^{\zeta^*} \omega^{*1/2} = \bar{X}, \quad (14.54a)'$$

$$e^{2\zeta^*} \omega^* (\omega^* - 1) = S^2, \quad (14.54b)'$$

$$\theta^* + e^{\zeta^*} \exp\{\sqrt{\log \omega^*} E[U_{1,n}]\} = \hat{X}_{\min}. \quad (14.54c)'$$

The above three equations give

$$f(\omega^*) = \frac{\omega^* (\omega^* - 1)}{[\sqrt{\omega^*} - \exp\{\sqrt{\log \omega^*} E[U_{1,n}]\}]^2} = \frac{S^2}{(\bar{X} - \hat{X}_{\min})^2}. \quad (14.55)$$

From (14.55), ω^* (and so $\alpha^* = \sqrt{\log \omega^*}$) can be determined numerically. Cohen, Whitten, and Ding (1985) and Cohen and Whitten (1988) provide graphs of $f(\omega^*)$ as a function of σ^* for $n = 10, 15, 20, 30, 50, 100$, and 400.

A pioneering paper by Cheng and Amin (1982) introduced a new method of estimation—maximum product-of-spacings (MPS). This overcomes difficulties involved in maximum likelihood estimation for the three-parameter lognormal distribution. The authors claim that Giesbrecht and Kempthorne's (1976) grouping and discretization method does not appear to identify the essential difficulty. "Whether it is possible in practice or not, it is still legitimate to hypothesize a situation where the observations are truly continuously distributed, when discretization is merely an approximation to the actual situation." The authors contend that in maximum likelihood estimation for a continuous density $p_X(x|\phi)$, one maximizes, approximately

$$\prod_{i=1}^n \Pr\{X_i \leq x_i \leq X_i + (\delta X_i) | \phi\} = \prod_{i=1}^n \int_{X_i}^{X_i + (\delta X_i)} p_X(x|\phi) dx, \quad (14.56)$$

replacing the probabilities on the right-hand side by the first-order approximations

$$\int_{X_i}^{X_i + (\delta X_i)} p_X(x|\phi) dx = p_X(X_i|\phi)(\delta X_i)$$

The quantities

$$D_i = Y_i - Y_{i-1} = \int_{X'_{i-1}}^{X'_i} p_X(x|\phi) dx, \quad i = 1, 2, \dots, n+1, \quad (14.57)$$

where $X'_0 = -\infty < X'_1 < X'_2 < \dots < X'_n < X'_{n+1} = \infty$ constitute an ordered random sample of size n , are called spacings of $\{Y\}$. The MPS method

chooses ϕ that maximizes

$$G_n(\phi, \mathbf{X}) = \left\{ \prod_{i=1}^{n+1} D_i \right\}^{1/(n+1)} \quad (14.58)$$

Under certain assumptions on $p_X(x|\phi)$ the MPS estimators are consistent. For the three-parameter lognormal distribution, if the true parameter $\phi = (\zeta, \sigma, \theta)$ lies in any set in $\{\phi: -\infty < \theta, \zeta < \infty, 0 < \sigma < \infty\}$, then the estimators are consistent as $n \rightarrow \infty$, which is a stronger result than is available for maximum likelihood estimators.

For the lognormal model we have to maximize

$$h(\zeta, \sigma, \theta | X_1, \dots, X_n) = \sum \log\{\Phi(Z_i) - \Phi(Z_{i-1})\}, \quad (14.59)$$

where $Z_i = \sigma^{-1}\{\log(X_i - \theta) - \zeta\}$, $Z_0 = -\infty$, $Z_{n+1} = +\infty$. Instead of direct maximization Cheng and Arin (1982) obtained the restricted maximum of $h(\cdot)$ with respect to ζ and σ for a sequence of values of 8, and then maximized with respect to 8. They used $\zeta_{a+1} = \bar{Z}_a = n^{-1}\sum_{i=1}^n Z_{ai}$ and $\sigma_{a+1} = \{n^{-1}\sum(Z_{ai} - \bar{Z}_a)^2\}^{1/2}$, with $Z_{ai} = \sigma_a^{-1}\{\log(X_i - \theta) - \zeta_a\}$, in an iterative procedure, and reported fast convergence, usually in three or four iterations, using the stopping rule

$$|h(\zeta_{a+1}, \sigma_{a+1}, \theta) - h(\zeta_a, \sigma_a, \theta)| < 10^{-6}.$$

Evans and Shaban (1974) discuss estimation of parameters of the form

$$\gamma = \exp(a\zeta + b\sigma^2),$$

where a and b are arbitrary constants. Other papers on this subject by Neyman and Scott (1960), Mehran (1973), Bradu and Mundlak (1970), Likeš (1980), Shimizu and Iwase (1981), and Shimizu (1983) are summarized in Crow and Shimizu (1988).

Zellner (1971), Sinha (1979), and Rukhin (1986) studied Bayesian estimation of parameters of the two-parameter lognormal distribution. The first two authors utilized improper priors $p(\zeta, \sigma) \propto 1/u^c$, $c > 0$. Rukhin utilizes generalized prior density which is also "uniform" in ζ . Wang, Ma, and Shi (1992) discuss, among other things, Bayesian estimation of the mean $\theta = \exp(\zeta + \sigma^2/2)$ of lognormal distribution $\Lambda(\zeta, \sigma^2)$. Using $g(\zeta, a) \propto \sigma^{-1}$ as a joint noninformative prior on (ζ, a) , they derive the marginal posterior for 8

in the form

$$g(\theta|x) \propto \theta^{(n-2)/2} \int_0^{+\infty} \sigma^{n-1} \\ \times \exp \left\{ - \left[\frac{(n-1)s_Z^2 + n(\log \theta - \bar{Z})^2}{2\sigma^2} + \frac{n\sigma^2}{8} \right] \right\} d\sigma, \\ 0 < \theta + \infty,$$

where $\bar{Z} = (1/n)\Sigma \log X_i$ and $s_Z^2 = \Sigma(\log X_i - \bar{Z})^2/(n-1)$ [which is Zellner's (1971) result].

For censored samples $X'_1 \mathbf{I} \dots \leq X'_r$ ($r < n$) with σ known and using prior normal distribution $N(\lambda_0, \psi_0^2)$ on 5, they obtain

$$h(\zeta|X'_r) = \left[\Phi \left(\frac{\zeta - \log X'_r}{\sigma} \right) \right]^{n-r} \\ \times \exp \left[- \frac{r^2 + \sigma^2/\psi_0^2}{2\sigma^2} \left(X'_r - \frac{X'_r + \lambda_0\sigma^2/\psi_0^2}{r + \sigma^2/\psi_0^2} \right)^2 \right] - I^{-1},$$

where

$$I = \int_{-\infty}^{+\infty} \left[\Phi \left(\frac{\zeta - \log X'_r}{\sigma} \right) \right]^{n-r} \\ \times \exp \left[- \frac{r^2 + \sigma^2/\psi_0^2}{2\sigma^2} \left(\zeta - \frac{X'_r + \lambda_0\sigma^2/\psi_0^2}{r + \sigma^2/\psi_0^2} \right)^2 \right] d\zeta.$$

The integral I has no closed form solution and must be numerically evaluated. These authors use two-parameter lognormal distributions $\Lambda(\zeta_i, \sigma_i^2)$ for independent variables X_i ($i = 1, 2$) with independent "noninformative prior" distributions for ζ_i 's and σ_i 's in analysis of environmental data.

The reliability function for two parameter lognormal distributions is given by

$$R(t; \zeta, \sigma) = 1 - \Phi \left[\frac{\log t - \zeta}{\sigma} \right], \quad t > 0.$$

The Bayesian estimator based on a sample of observations X_1, X_2, \dots, X_n is given by [cf. Padgett and Wei (1977)]:

$$\widetilde{R}_B(t) = 1 - \Pr \left[t_{2\alpha'} < \frac{(\log t - m')}{\sigma' \sqrt{1 + 1/(\tau^{-1} + n)}} \right],$$

where $t_{2\alpha'}$ is a random variable with t-distribution with $2\alpha'$ degrees of freedom, provided that (ζ, σ^2) has the "normal-gamma prior" [i.e., prior $(\zeta|\sigma)$ is $N(m, \tau\sigma^2)$ and prior (σ^{-2}) is $G(\alpha, \beta)$, with density $g(\nu) =$

$\{\beta^\alpha / \Gamma(\alpha)\nu^{\alpha-1}e^{-\beta\nu}, \nu \geq 0\}$. The joint prior is

$$p(\zeta, \sigma) \propto \sigma^{1-\alpha} \exp\left[-\beta\sigma^2 - \frac{(\zeta - m)^2}{2\tau\sigma^2}\right].$$

Here

$$m' = \frac{\tau^{-1}m + n\bar{Y}}{\tau^{-1} + n},$$

$$\beta' = \beta + \frac{1}{2} \sum_{i=1}^n (Y_i - \bar{Y})^2 + \frac{\tau^{-1}n(\bar{Y} - m)^2}{2(\tau^{-1} + n)},$$

where $Y_i = \log X_i \sim N(\zeta, \sigma^2)$ and $a' = a + n/2$. As $a \rightarrow 0, \beta \rightarrow 0,$ and $\tau^{-1} \rightarrow 0,$ corresponding to Jeffreys's "vague" prior, we have

$$\Pr\left[t_{2a'} < \sqrt{\frac{\alpha'}{\beta'}} \cdot \frac{\log t - m'}{\sqrt{1 + 1/(\tau^{-1} + n)}}\right]$$

$$\rightarrow \Pr\left[t_n < \frac{\log t - \bar{y}}{\sqrt{1 + 1/n}} \sqrt{\frac{n}{\sum_{i=1}^n (x_i - \bar{x})^2}}\right]. \tag{14.60}$$

Sinha (1989) obtains a very similar result directly assuming the joint prior: $p(\zeta, \sigma) \propto 1/\sigma$.

Comparison with the maximum likelihood estimator

$$\widehat{R}_{ML}(t) = 1 - \Phi\left[\frac{\log t - \hat{\zeta}}{\sigma}\right]$$

and with the minimum variance unbiased estimator

$$\widehat{R}_{MVU}(t) = \begin{cases} 1, & w \leq 0, \\ 0, & w \geq 1, \\ 1 - I_w\left(\frac{n-2}{2}, \frac{n-2}{2}\right), & 0 < w < 1, \end{cases}$$

where $I_z(a, b)$ is the incomplete beta function ratio and $w = \frac{1}{2} + \sqrt{n}[(\log t - \bar{X}) / (2S\sqrt{n-1})], t > 0,$ with $\bar{X} = \sum_{i=1}^n X_i / n$ and $S^2 = \sum_{i=1}^n (X_i - \bar{X})^2 / (n-1),$ shows, as might be expected, that the Bayes's estimator has the smallest variance when the assumed priors are actually the true priors. The estimator is, however, slightly biased.

4.3 Graphical Estimation

Wise (1952) has put forward the following interesting suggestion for a graphical method of estimating the parameters. It is particularly useful when the "rate of increase" of probability (i.e., probability density) is observed rather than actual frequencies, though it can also be used in the latter case, with sufficiently extensive data. He starts by observing that the tangents at the two points of inflexion of the probability density function remain close to the curve for a considerable length, and so should be estimable graphically with fair accuracy. The modulus of the ratio of the slopes (**lower/upper**) is

$$\exp\left[2 \sinh^{-1} \frac{1}{2} \sigma + a\right] 1 + \frac{1}{4} \sigma^2 . \quad (14.61)$$

Wise (1966a) provides tables of the logarithm of this quantity to four decimal places for $a = 0(0.01)0.80$, to aid in estimating a from the observed slopes of the inflection tangents. The initial point θ is estimated from the values x_1, x_2 of x at the points where these tangents cut the horizontal axis (see Figure 14.4). If $x_1 < x_2$, then θ is estimated from the formula

$$\frac{1}{2}(x_1 + x_2) - \frac{1}{2}(x_2 - x_1)L^{-1}, \quad (14.62)$$

where

$$L = \left[1 + \phi \tanh\left(\sigma\sqrt{1 + \frac{1}{4}\sigma^2}\right)\right] \left[\tanh\left(\sigma\sqrt{1 + \frac{1}{4}\sigma^2}\right) + \phi\right]^{-1}$$

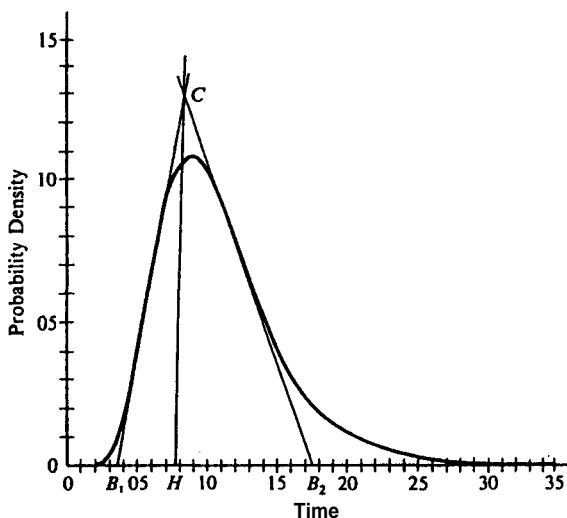


Figure 14.4 Geometrical Method of Estimating Lognormal Parameters

with

$$\phi = \left(1 + \frac{1}{2}\sigma^2\right) \left[\sigma\sqrt{1 + \frac{1}{4}\sigma^2}\right]^{-1}.$$

Wise (1966a) also provides values of L to four decimal places for $a = 0.(0.01)0.80$.

Finally ζ is estimated from the formula

$$\zeta = \frac{2}{3}\sigma^2 + \frac{1}{2}\log[(x_1 - \theta)(x_2 - \theta)]. \tag{14.63}$$

Sequential estimation and testing have been discussed by Zacks (1966) and Tomlinson (1957).

Issues of testing normality versus lognormality has received attention in the literature for the last 20 years. See Kotz (1973), Klimko, Rademaker, and Antle (1975), and more recently Al-Khalidi and Hwang (1991).

5 TABLES AND GRAPHS

Aitchison and Brown (1957) give values of the coefficient of variation, a , ($a, - 3$), the ratios [from (14.12b)] of mean to median ($e^{\sigma^2/2}$) and mean to mode ($e^{3\sigma^2/2}$), and the probability that X does not exceed $E[X]$ for

$$\sigma = 0.00(0.005)1.00(0.1)3.0.$$

(When $\sigma = 0$, values appropriate to the unit normal distribution are shown.) All values [except for coefficient of variation and ($a, - 3$) when $\sigma = 0.051$ are given to four significant figures.

Tables of percentile points of (two-parameter) lognormal distributions have been published by Moshman (1953): Upper and lower 10%, 5%, 2.5%, 1%, and 0.5% values to 4 decimal places, for $a, = 0(0.05)3.00$; and by Broadbent (1956): ratios of upper and lower 5% and 1% values to the expected value, to 4 decimal places, for coefficient of variation $[(e^{\sigma^2} - 1)^{1/2}]$ equal to $0(0.001)0.150$. (Note that this corresponds to $0 \leq \sigma \leq 0.15$ approximately.)

Tables of random lognormal deviates have been published by Hyrenius and Gustafsson (1962). These were derived from tables of random normal deviates (see Chapter 13) and are given to 2 decimal places for distributions with skewness $\alpha_3^2 = 0.2, 0.5, 1.0,$ and 2.0 (corresponding approximately to $a = 0.006, 0.16, 0.31,$ and 0.55).

Graph paper with the horizontal (abscissa) scale logarithmic and the vertical (ordinate) scale normal [marked with proportion P at a distance from the origin equal to x where $P = \Phi(x)$] is called *lognormal* probability paper. If X has a two-parameter lognormal distribution, plotting $P = \Pr\{X \leq x\}$ as ordinate against x as abscissa will give a straight-line plot. The

slope of the line is $6 (= \sigma^{-1})$; it meets the horizontal axis at $-\gamma/\delta (= \zeta)$. From sample plots these parameters may be estimated by observing the slope of a fitted line and its intersection with the horizontal axis. If a third parameter (θ) is needed, the plotted points tend to curve up, away from a straight line, as x decreases. It is possible, with some patience, to obtain a graphical estimate of θ by trial and error [as suggested by Gibrat (1930)], changing the value of θ until a plot using $(x - \theta)$ in place of x can be most closely fitted by a straight line. For a subjective method of this kind, it is not possible to obtain even an approximate formula for the standard deviation of the estimator of θ . However, the method seems to give quite useful results and can certainly be used to obtain initial values for use in iterative processes.

Graph paper of the kind described above is useful in **probit** analysis of **quantal** response data. Moments, product moments, and percentage points of various order statistics for standard lognormal distribution $\Lambda(0, 1)$ have been computed and tabulated for all samples of size 20 or less by Gupta, McDonald, and Galarneau (1974).

6 APPLICATIONS

Section 2 of this chapter indicates several fields in which lognormal distributions have been found applicable, and the references in the present section contain further examples. Application of the distribution is not only based on empirical observation but can, in some cases, be supported by theoretical argument—for example, in the distribution of particle sizes in natural aggregates (see Section 2), and in the closely related distribution of dust concentration in industrial atmospheres [Kolmogorov (1941); Tomlinson (1957); Oldham (1965)]. Geological applications have been described by Ahrens (1954–57), Chayes (1954), Miller and Goldberg (1955), and Prohorov (1963). Thébault (1961) gives a number of examples of such applications and includes some further references.

The three-parameter lognormal distribution was introduced to geology by Krige (1960) for modeling gold and uranium grades, and it is now widely regarded as the "natural" parametric model for low-concentration deposits. The lognormal model for minerals present in low concentrations has been experimentally verified for many minerals [Krige (1971); Harbaugh and Ducastaing (1981)]. Its use for gold deposits was pioneered by Sichel (1947). Further applications, mentioned by Oldham (1965), include duration of sickness absence and physicians' consultation time. Wise (1966) has described application to dye-dilution curves representing concentration of indicator as a function of time. Hermanson and Johnson (1967) found that it gives a good representation of flood flows, although extreme value distributions (see Chapter 22) are more generally associated with this field. Medical applications are summarized by Royston (1992), who mentions, in particular, model-

ing the weights of children [Rona and Altman (1977)] and construction of age-specific reference ranges for clinical variables [Royston (1991)]. Royston (1992) fits lognormal distributions to observations of antibody concentration in $\mu\text{g/ml}$ of type III group B streptococcus (BGS).

Leipnik (1991) mentions applications of sums of independent lognormal variables in telecommunication and studies of effects of the atmosphere on radar signals. Molecular particles are modeled in radar noise theory as having normal velocity distribution, while dust particles of a given type are assigned lognormal distributions.

The lognormal distribution has also been found to be a serious competitor to the Weibull distribution (Chapter 21) in representing lifetime distributions (for manufactured products). Among our references, Adams (1962), Epstein (1947, 1948), Feinlieb (1960), Goldthwaite (1961), Gupta (1962), and Nowick and Berry (1961) refer to this topic. Other applications in quality control are described by Ferrell (1958), Morrison (1958), and Rohn (1959). Aitchison and Brown (1957) cite various applications such as the number of persons in a census occupation class and the distribution of incomes in econometrics, the distribution of stars in the universe, and the distribution of the radical component of Chinese characters.

The 1974 distribution of wealth in the United Kingdom was studied by Chester (1979) who fitted a two-parameter lognormal distribution to data reported in the *Inland Revenue Statistics* (1977). Theoretical grounds for this application of lognormal distributions are developed by Sargan (1957) and Pestieau and Possen (1979) [see also Gibrat (1930, 1931)].

The two-parameter distribution is, in at least one important respect, a more realistic representation of distributions of characters like weight, height, and density than is the normal distribution. These quantities cannot take negative values, but a normal distribution ascribes positive probability to such events, while the two-parameter lognormal distribution does not. Furthermore, by taking σ small enough, it is possible to construct a lognormal distribution closely resembling any normal distribution. Hence, even if a normal distribution is felt to be really appropriate, it might be replaced by a suitable lognormal distribution. Such a replacement is convenient when obtaining confidence limits for the coefficient of variation. Koopmans, Owen, and Rosenblatt (1964) pointed out that if the normal distribution is replaced by a lognormal distribution, then confidence limits for the coefficient of variation are easily constructed (as described in Section 4 of this chapter). Wise (1966) has pointed out marked similarities in shape between appropriately chosen lognormal distributions and inverse Gaussian (Chapter 15) and gamma (Chapter 17) distributions.

The lognormal distribution is also applied, in effect, when certain approximations to the distribution of Fisher's $z = \frac{1}{2} \log F$ are used (see Chapter 27). It is well known that the distribution of z is much closer to normality than is that of F [e.g., Aroian (1939)]. Logarithmic transformations are also often used in attempts to "equalize variances" [Curtiss (1943); Pearce (1945)]. If

the standard deviation of a character is expected to vary (**e.g.**, from locality to locality) in such a **way** that the coefficient of variation remains roughly constant (**i.e.**, with standard deviation roughly proportional to expected value), then application of the method of statistical differentials (as described in Chapter 1) indicates that by use of logarithms of observed values, the dependence of standard deviation on expected value should be substantially reduced. Very often the transformed variables also have a distribution more nearly normal than that of the original variables.

Ratnaparkhi and Park (1986)—starting from Yang's (1978) deterministic model for the rate of change in the residual strength with respect to the number of fatigue cycles

$$\frac{dX(n)}{dn} = -\frac{f(n)}{c(X(n))^{c-1}}, \quad c \neq 0, \quad (14.64)$$

where $X(n)$ is the residual strength at cycle n , $f(n)$ is a nonnegative function of n , and c is a physical parameter—proposed using a lognormal distribution for $X(0)$, the initial (or "ultimate") strength. They deduced from this that the random variable N (the fatigue failure cycle) has a three-parameter lognormal distribution.

The relationship between leaving a company and employees tenure has been described by two-parameter lognormal distributions with great success [Young (1971); McClean (1976)]. It was found that the lognormal model accurately defines the leaving behavior for any "entry cohort" (defined as a group of people of about the same quality, performing roughly the same work and joining the company at about the same time). Agrafiotis (1985) estimated the early leavers for each entry cohort of a company based on the lognormal hypothesis by fitting an appropriate unweighted least-squares regression.

O'Neill and Wells (1972) point out that recent work in analyzing automobile insurance losses has shown that the lognormal distribution can be effectively used to fit the distribution for individual insurance claim payments. Many applications in biochemistry, including mechanisms generating the lognormal distribution can be found in Masuyama (1984) and its references.

Recently, for the U.S. population of men and women aged 17–84 years, Brainard and Burmaster (1992) showed that the lognormal distribution fits the marginal histograms of weight (in cells representing 10-lb intervals) for both genders.

7 CENSORING, TRUNCATED LOGNORMAL AND RELATED DISTRIBUTIONS

As pointed out in Section 4, estimation for the two-parameter lognormal distribution, and the three-parameter distribution with known value for θ ,

presents no special difficulties beyond those already encountered with normal distributions in Chapter 13. The same is true for censored samples from truncated forms of these distributions [see, e.g., Gajjar and Khatri (1969)].

If $\log X$ has a normal distribution with expected value ζ and standard deviation σ , truncated from below at $\log X_0$, then the r th moment of X about zero is

$$(\text{rth moment if not truncated}) \left(\frac{1 - \Phi(U_0 - ru)}{1 - \Phi(U_0)} \right), \quad (14.65)$$

with $U_0 = (\log X_0 - \zeta)/\sigma$ [Quensel (1945)]. For the three-parameter distribution, with θ not known, when censoring or truncation has been applied, estimation presents considerable difficulty.

Tiku (1968) has used his approximate linearization formula (described in Section 4) to simplify the maximum likelihood equations for the truncated lognormal; Tallis and Young (1962) have considered estimation from grouped data.

Thompson (1951) gives details of fitting a "truncated lognormal distribution" that is a mixed distribution defined by

$$\begin{aligned} \Pr[\log X = a] &= \Phi\left(\frac{a - \zeta}{\sigma}\right) \\ \Pr[a < \log X \leq z] &= \Phi\left(\frac{z - \zeta}{\sigma}\right) - \Phi\left(\frac{a - \zeta}{\sigma}\right) \quad \text{for } z > a. \end{aligned} \quad (14.66)$$

Tables are provided to assist estimation by moments.

Harter and Moore (1966) gave the results of some sampling experiments in which values of parameters were estimated for lognormal distributions censored by omission of proportions q_1 at the lower and q_2 at the upper limits of the range of variation, with $q_1 = 0$ or 0.01 and $q_2 = 0$ or 0.5. (The case $q_1 = q_2 = 0$ corresponds to a complete, untruncated lognormal distribution. These results have already been noted in Section 4.)

Taking $\zeta = 4$, $u = 2$, and $\theta = 10$, Table 14.5 shows the values that were obtained for the variances of estimators determined by solving the maximum likelihood equations. Although the results are applicable to a censored sample from lognormal distribution they should give a useful indication of the accuracy to be expected with truncated lognormal distributions. The substantial increase in $\text{Var}(\hat{\theta})$ with even a small amount of censoring ($q_1 = 0.01$) at the lower limits is notable. It would seem reasonable to suppose that variances and covariances are approximately inversely proportional to sample size, if estimates are needed for sample sizes larger than 100. The arithmetic means of the estimators were also calculated. They indicated a positive bias

Table 14.5 Variances and Covariances of Maximum Likelihood Estimators for Censored Three-Parameter Lognormal Distribution

q_1	q_2	$\text{Var}(\hat{\zeta})$	$\text{Var}(\hat{\sigma})$	$\text{Var}(\hat{\theta})$	$\text{Cov}(\hat{\sigma}, \hat{\theta})$	$\text{Cov}(\hat{\zeta}, \hat{\theta})$	$\text{Cov}(\hat{\zeta}, \hat{\sigma})$
0.00	0.5	0.0600	0.0961	0.2109	0.0628	0.0146	0.0296
0.01	0.0	0.0428	0.0351	0.2861	0.0064	0.0126	-0.0047
0.01	0.5	0.0628	0.1244	0.3011	0.0199	0.0239	0.0375
0.00 ^a	0.0 ^a	0.0416	0.0312	0.1733	0.0232	-0.0015	-0.0032

Note: In the sampling experiment with sample size of 100, $\zeta = 4$, $\sigma = 2$, and $\theta = 10$ (the value of θ was not used in the analysis).

^aNo censoring.

in $\hat{\theta}$ of about 0.8–0.9 when $q_1 = 0.01$ (whether or not $q_2 = 0$) and a positive bias of about 0.3 when $q_2 = 0.5$ with $q_1 = 0$. There was also a positive bias of about 0.5 in $\hat{\sigma}$ when $q_1 = 0.01$ and $q_2 = 0.5$.

It is of interest to compare the figures in Table 14.5 with corresponding values in Table 14.6, where the value 10 of θ was supposed known and used in the analysis. The variance of $\hat{\sigma}$ is considerably reduced (by comparison with Table 14.5), but that of $\hat{\zeta}$ is not greatly changed. The effect of varying q_1 is much smaller.

Progressively censored sampling of three-parameter lognormal distributions has been studied by Gajjar and Khatri (1969) and Cohen (1976). Let N designate the total sample size of items subject to a life or fatigue testing and n the number that fail (resulting in completely determined life spans). Suppose that censoring (i.e., removal) occurs in k stages at times $T_j > T_{j-1}$, $j = 1, 2, \dots, k$, and that r_j surviving items are removed (censored) from further observation at the j th stage. Thus $N = n + \sum_{i=1}^k r_i$.

Cohen (1976) discusses Type I censoring, with T_i 's fixed, and the number of survivors at these times are represented by random variables. For k -stage Type I progressively censored sampling the likelihood function, in an obvious notation, is

$$C \prod_{i=1}^n p_X(X_i) \prod_{j=1}^k (1 - F_X(T_j))^{r_j}.$$

Table 14.6 Maximum Likelihood Estimators for Censored Three-Parameter Lognormal Distribution Where Value of θ Is Supposed Known

q_1	q_2	$\text{Var}(\hat{\zeta} \theta)$	$\text{Var}(\hat{\sigma} \theta)$	$\text{Cov}(\hat{\zeta}, \hat{\sigma} \theta)$
0.00	0.5	0.0576	0.0460	0.0198
0.01	0.0	0.0406	0.0224	0.0000
0.01	0.5	0.0574	0.0473	0.0197
0.00 ^a	0.0 ^a	0.0416	0.0218	0.0002

^aNo censoring.

For the lognormal distribution (14.2) the local maximum likelihood estimating equations are

$$\begin{cases} \sum_1^n [\log(X_i - \theta) - \zeta] + \sigma \sum_1^k r_i Z_i = 0, \\ \sum_1^n [\log(X_i - \theta) - \zeta]^2 + \sigma^2 \left[\sum_1^k r_i \left(\frac{T_i - \zeta}{\sigma} \right) Z_i - n \right] = 0, \\ \sum_1^n \left[\frac{\log(X_i - \theta) - \zeta}{X_i - \theta} \right] + \sigma^2 \sum_1^n \left(\frac{1}{X_i - \theta} \right) + \sigma \sum_1^k \left(\frac{r_i Z_i}{T_i - \theta} \right) = 0, \end{cases} \quad (14.67)$$

where $Z_i = Z(T_i^*) = \phi(T_i^*)/[1 - \Phi(T_i^*)]$, with

$$T_i^* = \{\log(T_i - \theta) - \zeta\sigma/\theta\}/\sigma.$$

Cohen suggests selecting trial values θ_i for 6, solving the first two equations with $\theta = \theta_i$ for ζ_i and σ_i , using standard Newton-Raphson procedure, and then substituting these values into the third equation. If the third equation is not satisfied for any value of θ in the permissible interval $\theta \leq \hat{x}_{\min}$, he recommends application of a modified maximum likelihood method (which has proved satisfactory in many applications) in which the third equation is replaced by

$$\theta = X'_r - \exp \left[\zeta + \sigma \Phi^{-1} \left\{ \frac{r}{(N+1)} \right\} \right],$$

where $\Phi(\xi_r) = r/(N+1)$, and X'_r is the r th order statistic among the X 's for some $r > 1$.

The discretized form of the (truncated) lognormal distribution has been found to offer a competitive alternative to logarithmic series distributions in some practical situations (see Chapter 7). Quensel (1945) has described the logarithmic Gram-Charlier distribution in which $\log X$ has a Gram-Charlier distribution.

Kumazawa and Numakunai (1981) introduced a hybrid *lognormal* distribution $H(\alpha, \beta, \gamma)$ defined by the cdf,

$$H_X(x|\alpha, \beta, \gamma) = \int_0^x \frac{1}{\sqrt{2\pi}} \left(\frac{\alpha}{x} + \beta \right) \exp \left[- \frac{(\alpha \log x + \beta x + \gamma)^2}{2} \right] dx, \\ 0 < x < \infty, \alpha \geq 0, \beta \geq 0, \alpha + \beta > 0. \quad (14.68)$$

For $\alpha = 0$, the equation (14.68) represents a normal distribution with parameters $-\gamma\beta^{-1}$, β^{-2} , and for $\beta = 0$ it gives the lognormal distribution

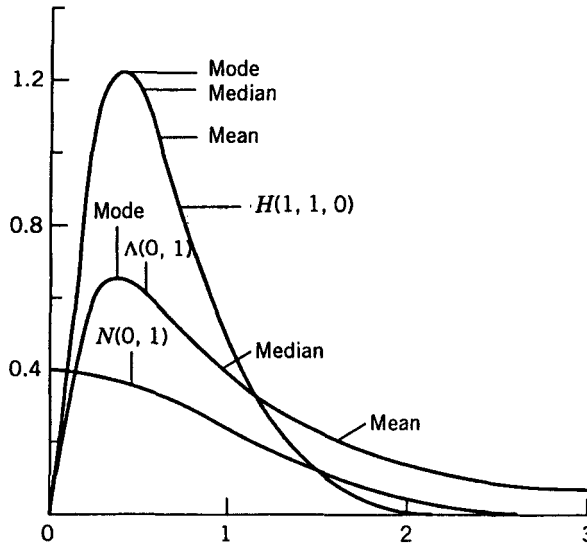


Figure 14.5 Frequency Curves of the Normal, Lognormal, and Hybrid Lognormal Distribution, $N(0, 1)$, $\Lambda(0, 1)$, and $H(1, 1, 0)$, Respectively

$\Lambda(-\gamma\alpha^{-1}, \alpha^{-2})$ [or $N(\log x | -\gamma\alpha^{-1}, \alpha^{-2})$]. Thus (14.68) can be viewed as the cdf of a hybrid normal-lognormal distribution. Figure 14.5 provides comparison of the three curves for standard values of these parameters.

For small $x \ll 1$ the curve of $H(1, 1, 0)$ approaches that of $\Lambda(0, 1)$, and for $x > 1.5$ it decreases faster than both $\Lambda(0, 1)$ and $N(0, 1)$. Data of occupational radiation exposures, as reported in the late 1970s by the U.S. Nuclear Regulatory Commission, are shown to be far better fitted by the hybrid lognormal distribution than by lognormal or normal.

Based on the relation

$$H(x|\alpha, \beta, \gamma) = N(\log \rho x + \rho x | \mu, \sigma^2), \quad (14.69)$$

where $\mu = \log(\beta/\alpha) - (\gamma/\alpha)$, $\sigma^2 = 1/a^2$, and $\rho = \beta/\alpha$, Kumazawa and Numakunai (1981) designed hybrid lognormal probability paper that provides a quick method of judging whether given data can be fitted by a hybrid lognormal distribution.

The S_U and S_B systems of distributions [Johnson (1949)], discussed in Chapter 12, are related to the lognormal distribution in that the lognormal distribution is a limiting form of either system and in that the "lognormal line" is the border between the regions in the (β_1, β_2) plane corresponding to the two systems.

The distribution corresponding to the S_B transformation, defined by

$$U = \gamma + \delta \log \left(\frac{X - \xi}{\xi + \lambda - X} \right) \quad (14.70)$$

which has four parameters γ , δ , ξ , and λ , was considered by van Uven as early as 1917. It has been termed the *four-parameter lognormal* distribution by Aitchison and Brown (1957). This name is not so well recognized as the two-parameter or three-parameter lognormal nomenclature. In view of the existence of other four-parameter transformations (e.g., (14.5)), the usefulness of this name is doubtful.

Lambert (1970) uses the form of pdf,

$$p_X(x) = \frac{(\theta - \tau)}{(x - \tau)(\theta - x)\sqrt{2\pi\beta}} \exp \left[-\frac{1}{2\beta} \left\{ \log \frac{x - \tau}{\theta - x} - \mu \right\}^2 \right],$$

$\tau < x < \theta$,

which is a reparametrization of Johnson's S_B distribution (Chapter 12, Section 4.3). The random variable $\log[(X - \tau)/(\theta - X)]$ has the $N(\mu, \beta)$ distribution. Johnson (1949) carried out estimation of μ and τ using quantiles and a method based on quantiles and points of the range. (See also Chapter 12.)

Estimation becomes a difficult problem when all four parameters must be estimated from observations. Lambert (1970) tackles maximum likelihood estimation of the parameters. The difficulties associated with the behavior of the likelihood function at $\tau = \min X_i$ or $\theta = \max X_i$ are overcome by assuming that observations are multiples of some unit δ (i.e., a recorded observation may differ from its true value by up to $\delta/2$). The likelihood equation is

$$L_1(X_1, X_2, \dots, X_n | \mu, \beta, \tau, \theta) = \begin{cases} \frac{(\theta - \tau)^n}{\prod (X_i - \tau) \prod (\theta - X_i) (2\pi\beta)^{n/2}} \\ \times \exp \left[-\frac{1}{2\beta} \sum \left\{ \log \frac{X_i - \tau}{\theta - X_i} - \mu \right\}^2 \right] & \text{if } \tau < X_1 \text{ and } X_n < \theta, \\ 0 & \text{if either } X_1 \leq \tau \text{ or } X_n \geq \theta. \end{cases} \quad (14.71)$$

(The parameter space is defined by $-\infty < \mu < \infty$; $0 < \beta < \infty$; $-\infty < \tau < X_1$;

$X_n < \theta < \infty$.) At any maximum of L_1 the following equations are satisfied:

$$\left\{ \begin{aligned} 0 &= \frac{\partial \log L_1}{\partial \mu} = \frac{1}{p} \mathbf{C} \{ \log(X_i - \tau) - \log(\theta - X_i) - p \}, \\ 0 &= \frac{\partial \log L_1}{\partial \beta} = -\frac{n}{2\beta} + \frac{1}{2\beta^2} \sum \{ \log(X_i - \tau) - \log(\theta - X_i) - \mu \}^2, \\ 0 &= \frac{\partial \log L_1}{\partial \tau} = -\frac{n}{\theta - \tau} + \sum \frac{1}{X_i - \tau} + \frac{1}{\beta} \sum \frac{\log(X_i - \tau) - \log(\theta - X_i) - \mu}{X_i - \tau}, \\ 0 &= \frac{\partial \log L_1}{\partial \theta} = \frac{n}{\theta - \tau} - \sum \frac{1}{\theta - X_i} + \frac{1}{\beta} \sum \frac{\log(X_i - \tau) - \log(\theta - X_i) - \mu}{\theta - X_i}. \end{aligned} \right. \quad (14.72)$$

Solving the first two equations for μ and β yields

$$\hat{\mu}(\tau, \theta) = \frac{\sum \{ \log(X_i - \tau) - \log(\theta - X_i) \}}{n},$$

$$\hat{\beta}(\tau, \theta) = \frac{\sum \{ \log(X_i - \tau) - \log(\theta - X_i) - \mu(\tau, \theta) \}^2}{n}$$

Then

$$\begin{aligned} L_1^{**}(\tau, \theta) &\equiv \sup_{\mu, \beta} L(\mu, \beta, \tau, \theta) \\ &= \frac{(\theta - \tau)^n}{\prod (X_i - \tau) \prod (\theta - X_i) \{ \hat{\beta}(\tau, \theta) \}^{n/2}} \times \frac{1}{(2\pi e)^{n/2}}. \end{aligned}$$

If the values $\hat{\tau}$ and $\hat{\theta}$ that maximize $L_1^{**}(\tau, \theta)$ are found, then the set $(\hat{\mu}, \hat{\beta}, \hat{\tau}, \hat{\theta})$ will be the solution of equations (14.72), and as long as $\hat{\tau} < X_1 - 6/2$ and $\hat{\theta} > X_n + \delta/2$, these may be taken as the maximum likelihood estimates.

To locate the greatest value of the likelihood, Lambert (1970) recommends that "the function $\log L_1^{**}(\tau, \theta)$ be plotted over a range of values of τ and θ . Examination of such a plot enables one either to locate a region in which the greatest value of $\log L_1^{**}(\tau, \theta)$ lies or to observe in which direction to shift to find this value; in this case the function was recalculated over a suitable new region. Once a region containing the greatest value is found, changing the intervals in τ and θ at which $\log L_1^{**}$ is calculated enables one to locate the greatest value with any desired accuracy and so to obtain $\hat{\tau}$ and $\hat{\theta}$." Lambert concludes that "although techniques have been developed for estimating, from the likelihood, the parameters of the four-parameter lognormal distri-

bution, and these appear to provide satisfactory estimates with artificial samples, the method has not so far yielded useful estimates."

We are unaware of any further development along these lines in estimating the Johnson four-parameter lognormal distribution using maximum likelihood method. Wasilewski (1988) studied mixtures of several two parameter lognormal distributions $\Lambda(\zeta_i, \sigma^2)$ ($i = 1, \dots, k$), with pdf

$$\begin{aligned}
 p_X(x|\sigma, \zeta_1, \dots, \zeta_k, p_1, \dots, p_k) &= p_X(x|\sigma, \zeta, p) \\
 &= \frac{1}{\sqrt{2\pi\sigma x}} \sum_{i=1}^k p_i \exp\left(-\frac{(\log x - \zeta_i)^2}{2\sigma^2}\right), \quad x > 0, \quad (14.73)
 \end{aligned}$$

where $p_i > 0$, $\sum_{i=1}^k p_i = 1$, and $0 < \zeta_1 < \dots < \zeta_k$.

The r th moment about zero of (14.73) is

$$E[X^r] = \sum_{i=1}^k p_i \exp(r\zeta_i + \frac{1}{2}r^2\sigma^2) = e^{r^2\sigma^2/2} \sum_{i=1}^k p_i e^{r\zeta_i}. \quad (14.74)$$

Wasilewski (1988) discusses estimation of the parameters (σ, ζ, p) by the method of moments, equating for $r = -k, -k + 1, \dots, k - 1, k$ the values of $E[X^r]$ to the observed values

$$m_r = n^{-1} \sum_{i=1}^n X_i^r$$

8 CONVOLUTION OF NORMAL AND LOGNORMAL DISTRIBUTIONS

Hawkins (1991) investigated, in detail, convolutions of normal and lognormal distributions. His work was motivated by application of lognormal distributions—namely, in measuring lognormally distributed quantities with instruments that give quick and inexpensive readings but have substantial random measurement errors. If $\log(Z + a)$ is distributed as $N(\zeta, \sigma^2)$ and X is a measurement of Z with an unbiased normally distributed error Y [$Y \sim N(0, \tau^2)$] independent of Z so that $X = Z + Y$ and $X|Z \sim N(Z, \tau^2)$, then

$$\begin{aligned}
 p_X(x|\alpha, \tau, \zeta, \sigma) &= \frac{1}{2\pi\sigma\tau} \int_0^\infty z^{-1} \exp\left[-\frac{1}{2}\left\{\left(\frac{\log z - \zeta}{\sigma}\right)^2 + \left(\frac{x - z + \alpha}{\tau}\right)^2\right\}\right] dz \\
 &= \frac{1}{2\pi\sigma\tau} \int_{-\infty}^\infty \exp\left[-\frac{1}{2}\left\{\left(\frac{t - \zeta}{\sigma}\right)^2 + \left(\frac{x - e^t + \alpha}{\tau}\right)^2\right\}\right] dt \quad (14.74)'
 \end{aligned}$$

(using the transformation $t = \log z$). The parameters α and τ are the location and scale parameters of the convolution.

The canonical form ($\alpha = 0, \tau = 1$) is

$$p_X(x|0, 1, \zeta, \sigma) = \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma} \exp\left\{-\frac{1}{2}\left[\frac{(t-\zeta)^2}{\sigma^2} + (x-e^t)^2\right]\right\} dt. \quad (14.75)$$

The moments of (14.74) are easily calculated from the relation

$$E(X^k) = \sum_{j=0}^k \binom{k}{j} E(Z^j) E(U^{k-j}),$$

where U denotes a unit normal variable. In particular,

$$E[X] = -\alpha + \exp(\zeta + \frac{1}{2}\sigma^2), \quad (14.76)$$

$$\text{Var}(X) = \tau^2 + \exp(2\zeta + \sigma^2)\{e^{\sigma^2} - 1\}. \quad (14.77)$$

Compare these equations with (14.8a) and (14.8b). The sequence of moments of X increases even more rapidly than that of Z , and (similarly to the lognormal distribution) the distribution of X is also not determined by its moments. Any normal distribution $N(\zeta, \delta^2)$, say, can be obtained as a degenerate limiting case of the convolution, letting $\alpha \rightarrow \infty, \sigma \rightarrow 0$, and keeping the mean and the variance equal to ζ and δ^2 , respectively.

Unlike the three-parameter lognormal distribution, the likelihood of the lognormal-normal convolution has no singularities, and the distribution is infinitely differentiable with respect to all its parameters. However, it is still possible that data may conform better to a normal than to a lognormal-normal distribution. Hawkins (1991) finds that his nondegeneracy test (see Section 4) is equally applicable in the lognormal-normal case with Z_i replaced by X_i .

Moment estimation is straightforward. Let $\bar{X} = \sum X_i/n$ and $S^2 = \sum (X_i - \bar{X})^2/n$, and let $M_3 = \sum (X_i - \bar{X})^3/n$ and $B_1 = M_3/S^3$, then utilizing equation (14.46) or its explicit solution when estimating moments of the three-parameter lognormal, we have

$$\begin{aligned} \hat{\sigma} &= \log \bar{\omega}, \\ \hat{\zeta} &= \frac{1}{2} \log \left[\frac{S^2}{\bar{\omega}(\bar{\omega} - 1)} \right], \end{aligned} \quad (14.78)$$

$$\hat{\alpha} = \exp(\hat{\zeta} + \frac{1}{2}\hat{\sigma}^2) - \bar{X}.$$

However, **Hawkins** (1991) finds that this modified method of moments in the case of lognormal-normal distribution is by far less effective than the conventional one. Moment estimators turn out to be highly biased, but still they may provide a useful starting point for maximum likelihood estimation. This approach is a very time-consuming routine operation for the **lognormal-normal** distribution, since it involves numerous evaluations of the density and its derivatives for each value in the sample. Especially undesirable are situations where the initial α is large and the initial σ close to zero (cases close to degeneracy). **Hawkins** recommends a hybrid algorithm behaving like steepest descent method in the initial steps and like Newton's method close to the optimum.

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CHAPTER 15

Inverse Gaussian (Wald) Distributions

1 INTRODUCTION

The name "inverse Gaussian" was first applied to a certain class of distributions by Tweedie (1947), who noted the inverse relationship between the cumulant generating functions of these distributions and those of Gaussian distributions. The same class of distributions was derived by Wald (1947) as an asymptotic form of distribution of average sample number in sequential analysis. The name "Wald distribution" is also used for members of this class. Wasan (1968b) calls these distributions *first passage time distributions of Brownian motion with positive drift* and uses the abbreviation T.B.M.P. distribution.

Inverse Gaussian distributions have attracted considerable attention during the last 20 years. A major influence was the Ph.D. dissertation of R. S. Chhikara, under J. L. Folks at Oklahoma State University, in 1972. This work was followed by several joint publications by Chhikara and Folks culminating in a review paper [Folks and Chhikara (1978)]. This paper attracted many discussants—including probabilists and both theoretical and applied statisticians—and continuing interest in the topic, resulting eventually in a book devoted to inverse Gaussian distributions [Chhikara and Folks (1989)]. In the early 1980s B. Jørgensen's M.Sc. thesis, under the direction of O. Barndorff-Nielsen, appeared as Jørgensen (1982). Tables of percentile points of inverse Gaussian distributions became available in a CRC *Handbook* (1988). Books by A. C. Cohen and B. J. Whitten (1989) and N. Balakrishnan and A. C. Cohen (1991) contain a chapter devoted to estimation of parameters in a three-parameter inverse Gaussian distributions.

In view of this partial consolidation of recent research on inverse Gaussian distributions, and to keep the length of this chapter with reasonable limits, we include here mostly results that are not emphasized in the above references and concentrate on post-1988 results as much as possible. Readers are advised to consult Chhikara and Folks (1989) and Jørgensen (1982) for

additional details. The bibliography of this chapter is, however, more comprehensive and contains some references that are not explicitly mentioned in the text but might be viewed as important contributions in regard to particular aspects of the distributions.

2 GENESIS

Suppose that a particle moving along a line tends to move with a uniform velocity v . Suppose also that the particle is subject to linear Brownian motion, which causes it to take a variable amount of time to cover a fixed distance d . It can be shown that the time X required to cover the distance is a random variable with probability density function

$$p_X(x) = \frac{1}{\sqrt{2\pi\beta x^3}} de^{-(d-vx)^2/(2\beta x)}, \quad 0 < x, \quad (15.1)$$

where β is a diffusion constant [Schrodinger (1915)]. Several heuristic and some more or less rigorous derivations of this result have been published [Huff (1974); Whitmore and Seshadri (1987, and references therein)].

Alternatively, when the time x is fixed, the distance D over which the particle travels is a random variable with the normal distribution

$$p_D(d) = \frac{1}{\sqrt{2\pi\beta x}} e^{-(d-vx)^2/(2\beta x)}. \quad (15.2)$$

While examining the cumulant generating functions of (15.1) and (15.2), Tweedie (1956) noticed the inverse relationship between these functions and suggested the name "inverse Gaussian" for the distribution (15.1).

Distributions of this kind were derived by Wald (1947) as a limiting form of distribution of sample size in certain sequential probability ratio tests. In a more general form, the distribution can be obtained as a solution to the following problem: Given that Z_1, Z_2, \dots are independent random variables, each having the same distribution with finite expected value $E[Z] > 0$ and nonzero variance $V(Z)$, what is the limiting distribution of the random variable N , defined by

$$\left[\bigcap_{j=1}^{N-1} \left(\sum_{i=1}^j Z_i < K \right) \right] \cap \left(\sum_{i=1}^N Z_i \geq K \right), \quad \text{with } K > 0?$$

Note that $\sum_{i=1}^N Z_i$ is the first of the sums $Z_1, Z_1 + Z_2, Z_1 + Z_2 + Z_3, \dots$, to be not less than K , with $K > 0$.

It can be shown that $E[N] = K/E[Z]$ and that

$$\lim_{E(N) \rightarrow \infty} \Pr[N \leq xE(N)]$$

is given by the integral up to x of

$$p_X(x) = \sqrt{\frac{\phi}{2\pi}} e^{\phi x^{-3/2}} \exp\left[-\frac{1}{2}\phi(x + x^{-1})\right], \quad x > 0, \quad (15.3)$$

with

$$\phi = \frac{KE[Z]}{V(Z)} > 0.$$

This is the *standard form* of probability density function of the *Wald distribution*. It is a special inverse Gaussian distribution.

3 DEFINITION

On substituting $v = d/\mu$ and $\beta = d^2/\lambda$ into (15.1), we obtain the standard ("canonical") form of the *two-parameter* inverse Gaussian distribution:

$$\begin{aligned} p_X(x|\mu, \lambda) &= \left[\frac{\lambda}{2\pi x^3}\right]^{1/2} \exp\left\{-\frac{\lambda}{2\mu^2 x}(x - \mu)^2\right\} \\ &= \left[\frac{\lambda}{2\pi x^3}\right]^{1/2} \exp\left\{-\frac{\lambda}{2\mu}\left(\frac{x}{\mu} - 2 + \frac{\mu}{x}\right)\right\}, \quad x > 0. \end{aligned} \quad (15.4a)$$

We will denote this distribution by $IG(\mu, \lambda)$. As we will see below, μ is the expected value and μ^3/λ is the variance of $IG(\mu, \lambda)$; μ/λ is the square of the coefficient of variation.

Alternatively, the distribution can be written in any of the three following equivalent forms [Tweedie (1957a)]:

$$p_X(x|\mu, \phi) = \left[\frac{\mu\phi}{2\pi x^3}\right]^{1/2} e^{\phi} \exp\left\{-\frac{1}{2}\phi\left(\frac{x}{\mu} + \frac{\mu}{x}\right)\right\}, \quad IG(\mu, \phi\mu), \quad (15.4b)$$

$$p_X(x|\phi, \lambda) = \left[\frac{\lambda}{2\pi x^3}\right]^{1/2} e^{\phi} \exp\left\{-\frac{1}{2}\left(\frac{\phi^2 x}{\lambda} + \frac{\lambda}{x}\right)\right\}, \quad IG\left(\frac{\lambda}{\phi}, \lambda\right), \quad (15.4c)$$

$$p_X(x|\alpha, \lambda) = \left[\frac{\lambda}{2\pi x^3}\right]^{1/2} \exp\left[-\frac{\lambda}{2}\left\{\alpha x - (2\alpha)^{1/2} + \frac{1}{2x}\right\}\right], \quad IG\left(\frac{\alpha^2}{2}, \lambda\right). \quad (15.4d)$$

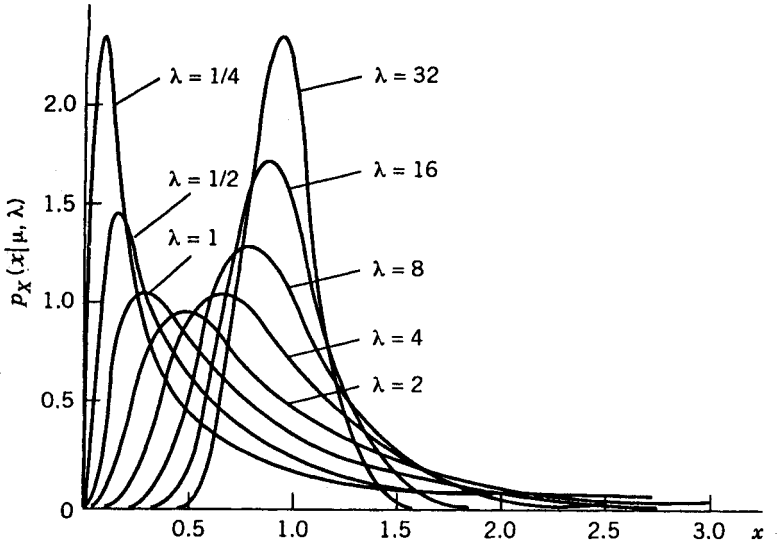


Figure 15.1 Inverse Gaussian Density Functions, $E[X] = \mu = 1$

In these equations $\phi = \lambda/\mu$, $a = \sqrt{2\mu}$; λ , μ , ϕ , and a are all positive. The Wald distribution (15.3) is obtained by taking $\mu = 1$ (and $\lambda = \phi$); in our notation it is $\text{IG}(1, \phi)$. Our distinction between standard Wald (**one-parameter**) and standard inverse Gaussian (two parameters) is arbitrary, but we find it to be convenient.

Note that if X is distributed as $\text{IG}(\mu, \lambda)$, then aX ($a > 0$) is distributed as $\text{IG}(a\mu, a\lambda)$. Some graphs of $p_X(x|\mu, \lambda)$ are shown in Figure 15.1. The cdf corresponding to (15.4a) is

$$F_X(x|\mu, \lambda) = \Phi\left\{\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} - 1\right)\right\} + e^{2\lambda/\mu}\Phi\left\{-\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} + 1\right)\right\} \quad (15.4e)$$

where $\Phi(\cdot)$ is the standard normal distribution function [Shuster (1968); Chhikara and Folks (1977)].

4 MOMENTS

From (15.4a) we obtain the cumulant generating function

$$\Psi_X(t; \mu, \lambda) = \frac{\lambda}{\mu} \left\{ 1 - \left(1 - \frac{2\mu^2 t}{\lambda} \right)^{1/2} \right\}. \quad (15.5a)$$

The corresponding characteristic function is

$$\exp\left[\frac{\lambda}{\mu}\left\{1 - \left(1 - \frac{2i\mu^2 t}{\lambda}\right)^{1/2}\right\}\right]$$

The cumulant generating functions corresponding to (15.4b), (15.4c), and (15.4e) are

$$\Psi_X(t; \mu, \phi) = \phi\left\{1 - \left(1 - \frac{2\mu t}{\phi}\right)^{1/2}\right\} \quad (15.5b)$$

$$\Psi_X(t; \phi, \lambda) = \phi\left\{1 - \left(1 - \frac{2\lambda t}{\phi^2}\right)^{1/2}\right\} \quad (15.5c)$$

$$\Psi_X(t; \alpha, \lambda) = 2^{1/2}\lambda\left\{\alpha^{1/2} - \left(\alpha - \frac{t}{\lambda}\right)^{1/2}\right\} \quad (15.5d)$$

respectively.

The first four cumulants corresponding to (15.5a) are

$$\begin{cases} \kappa_1 = \mu & (= E[X]), \\ \kappa_2 = \frac{\mu^3}{\lambda} & (= \text{Var}(X)), \\ \kappa_3 = \frac{3\mu^5}{\lambda^2}, \\ \kappa_4 = \frac{15\mu^7}{\lambda^3}. \end{cases} \quad (15.6)$$

Generally, for integer $r \geq 2$,

$$\kappa_r = 1 \times 3 \times 5 \dots \times (2r - 3) \frac{\mu^{2r-1}}{\lambda^{r-1}} \quad (15.7)$$

[Tweedie (1957a)]. The first two moment-ratios are

$$\sqrt{\beta_1} = \alpha_3 = 3\sqrt{\frac{\mu}{\lambda}} \quad (= 3\phi^{-1/2}), \quad (15.8a)$$

$$\beta_2 = \alpha_4 = 3 + \frac{15\mu}{\lambda} \quad (= 3 + 15\phi^{-1}). \quad (15.8b)$$

In the Pearson (β_1, β_2) plane the inverse Gaussian points fall on the straight line $\beta_2 = 3 + 5\beta_1/3$ which lies between the gamma (Type III) and lognormal lines.

The first three negative moments about zero of $IG(\mu, \lambda)$ are

$$\mu'_{-1} = \mu^{-1} + \lambda^{-1}, \quad (15.9a)$$

$$\mu'_{-2} = \mu^{-2} + 3\mu^{-1}\lambda^{-1} + 3\lambda^{-2}, \quad (15.9b)$$

$$\mu'_{-3} = \mu^{-3} + 6\mu^{-2}\lambda^{-1} + 15\mu^{-1}\lambda^{-2} + 15\lambda^{-3}. \quad (15.9c)$$

Note that for the Wald distribution, $\kappa_1 = 1$ whatever the value of ϕ , and that

$$\kappa_r = 1 \times 3 \times 5 \dots \times (2r - 3)\phi^{-(r-1)}.$$

From (15.4b) the density function of $Y = X^{-1}$ is

$$p_Y(y|\mu, \phi) = \left[\frac{\mu\phi}{2\pi y^3} \right]^{-1/2} y \exp\left\{ -\frac{\mu\phi y}{2} + \phi - \frac{\phi}{2\mu y} \right\}.$$

It follows that

$$E[X^{-r}|\mu, \phi] = E[Y^r|\mu, \phi] = \mu E[X^{r+1}|\mu^{-1}, \phi].$$

In particular for the standard Wald distribution ($\mu = 1$), we have the remarkable relation between negative and positive moments

$$\mu'_{-r} = \mu'_{r+1}. \quad (15.10)$$

For the standard Wald distribution, the mean deviation is

$$4e^{2\phi}\Phi(-2\sqrt{\phi}). \quad (15.11)$$

For ϕ large (whatever be the value of μ)

$$\begin{aligned} \frac{\text{Mean deviation}}{\text{Standard deviation}} &= 4\sqrt{\phi} e^{2\phi}\Phi(-2\sqrt{\phi}) \\ &= 4\sqrt{\phi} e^{2\phi} \left[(\sqrt{2\pi})^{-1} e^{-2\phi} (2\sqrt{\phi})^{-1} \left\{ 1 - (2\sqrt{\phi})^{-2} \right\} \right] \\ &\doteq \sqrt{\frac{2}{\pi}} \left(1 - \frac{1}{4}\phi^{-1} \right). \end{aligned} \quad (15.12)$$

Since taking $\mu = 0$ (to make $E[X] = 0$) also makes $\text{Var}(X) = 0$, a standardized form of the distribution has to be obtained circuitously. By taking the

variable

$$Y = X + \xi, \quad \xi < 0,$$

so that $E[Y] = \mu + 5$; $\text{Var}(Y) = \mu^3/\lambda$; $\sqrt{\beta_1(Y)} = 3\sqrt{(\lambda/\mu)}$ and then taking $\mu = -\xi$, $\lambda = -\xi^3$, we have

$$\begin{aligned} E[Y] &= 0, \\ \text{Var}(Y) &= 1, \\ \sqrt{\beta_1(Y)} &= 3|\xi|. \end{aligned}$$

The cdf of Y is

$$\begin{aligned} F_Y(y|\sqrt{\beta_1}) &= \Phi\left(y + \frac{1}{3}\sqrt{\beta_1}\right)^{-1/2} \\ &+ \exp\left(\frac{18}{\beta_1}\right)\Phi\left(-\left(y + 6/\sqrt{\beta_1}\right)\left(1 + \frac{1}{3}\sqrt{\beta_1}\right)^{-1}\right). \end{aligned} \quad (15.13)$$

The distribution of Y is a *three-parameter* inverse Gaussian $\text{IG}(\mu, \lambda, \xi)$. Its pdf is given in (15.45).

A one-parameter inverse Gaussian [different from Wald (15.3)], obtained by taking $\lambda = \mu^2$ in (15.4a), has been discussed by Vodá (1973). [See also Iliescu and Vodá (1977, 1981).] Its pdf is

$$p_X(x|\mu) = \mu(2\pi x^3)^{-1/2} \exp\left\{-\frac{1}{2}x^{-1}(x - \mu)^2\right\}, \quad x > 0, \mu > 0. \quad (15.14)$$

In our notation it is an $\text{IG}(\mu, \mu^2)$ distribution.

Yet another one-parameter inverse Gaussian distribution is obtained as a limiting form of $\text{IG}(\mu, \lambda)$ as $\mu \rightarrow \infty$. The pdf is

$$p_X(x|\lambda) = \left(\frac{\lambda}{2\pi x^3}\right)^{1/2} \exp\left(-\frac{\lambda}{2x}\right), \quad x > 0, \lambda > 0. \quad (15.15)$$

The expected value and variance (and indeed $E[X^a]$ for $a \geq \frac{1}{2}$) are infinite.

This is the distribution of first passage time of drift-free Brownian motion, which is the one-sided stable law (see Chapter 12) with exponent $\frac{1}{2}$. Letac and Seshadri (1989) point out that this distribution is also a member of a natural exponential family.

In the discussion following Folks and Chhikara (1978), Whitmore (1978) [see also Whitmore (1979)] introduced a class of modified inverse Gaussian distributions, which he termed *defective inverse Gaussian* distributions. They

have densities of form

$$p_X(x) = a^2(2\pi x^3\nu)^{-1/2} \exp\left\{-\frac{(a-\delta x)^2}{2\nu x}\right\} \quad \text{for } 0 < x < \infty, \delta < 0, \quad (15.16)$$

together with a nonzero probability

$$\Pr[X = \infty] = 1 - \exp\left(\frac{-2a\delta}{\nu}\right).$$

Note the reparametrization $\mu = a/161$, $A = a^2/\nu$.

The genesis of distribution (15.16) is as follows: Consider a Wiener process $\{W(t); t \geq 0\}$ with $W(0) = 0$, having drift and volatility parameters δ (< 0) and ν , respectively—namely for any interval of time (t_1, t_2) , $W(t_2) - W(t_1)$ is normally distributed with expected value $\delta(t_2 - t_1)$ and variance $\nu(t_2 - t_1)$. There is an absorbing barrier at a (> 0). The probability of eventual absorption is $\exp(2a\delta/\nu)$, and the distribution of first passage time, conditional on absorption occurring in finite time is $\text{IG}(a/|\delta|, a^2/\nu)$.

Over part of the parameter space (for $a^2|\delta|/\nu \geq 10$, $S < 0$) the inverse Gaussian distribution is approximately lognormal (see Chapter 14). However, when $a^2|\delta|/\nu$ is small, the two distributions differ.

5 PROPERTIES

As ϕ tends to infinity (with μ fixed) the standardized distribution tends to a unit normal distribution (see Figure 15.1). More precisely, there is the following relation between corresponding quantiles of the standard Wald distribution $X_p(\phi)$ and the normal distribution U_p , obtained by Sigangirov (1962):

$$1 + \frac{U_{p-\varepsilon}}{\sqrt{\phi}} + \frac{U_{p-\varepsilon}^2}{2\phi} + \frac{U_{p-\varepsilon}^3}{8\phi\sqrt{\phi}} - \frac{U_{p-\varepsilon}^5}{128\phi^2\sqrt{\phi}} < X_p(\phi) < 1 + \frac{U_p}{\sqrt{\phi}} + \frac{U_p^2}{2\phi} + \frac{U_p^3}{8\phi\sqrt{\phi}}, \quad (15.17)$$

where

$$\varepsilon = \Phi(-2\sqrt{\phi})e^{2\phi} < \frac{1}{2\sqrt{2\pi\phi}}.$$

For small ϕ ($\phi < U_p^2/16$),

$$\frac{\phi}{U_{p/2}^2 e^{2\phi}} < X_p(\phi) < \frac{\phi}{U_{p/2}^2}. \tag{15.17}'$$

As μ tends to infinity (λ remaining fixed), the distribution of $Y = X^{-1}$ tends to the gamma distribution:

$$p_Y(y) = \lambda(2\pi)^{-1/2} y^{-1/2} \exp(-\frac{1}{2}\lambda y), \quad y > 0 \tag{15.18}$$

[Wasan and Roy (1967)11.

Krapivin (1965) notes the following equations, satisfied by the Wald probability density function $p_X(x)$ [as given in (15.3)]:

$$\begin{aligned} W_\phi(x) = F_X(x) &= \int_0^x p_X(t) dt = \int_{1/x}^\infty t p_X(t) dt \\ &= 1 - \int_0^{1/x} t p_X(t) dt. \end{aligned} \tag{15.19}$$

This enables one to calculate the expected value of a Wald distribution from tables of $W_\phi(x)$. From (15.4e) with $\mu = 1$ and $\lambda = \phi$, we have the cdf

$$F_X(x) = \Phi\left((x-1)\sqrt{\frac{\phi}{x}}\right) + e^{2\phi}\Phi\left(-(x+1)\sqrt{\frac{\phi}{x}}\right). \tag{15.20a}$$

For x large

$$F_X(x) \doteq 1 - e^{-\phi x/2} e^{\phi} (\log x). \tag{15.20b}$$

If X_1, \dots, X_n are independent $IG(\mu_i, \lambda_i)$ variables ($i = 1, \dots, n$), then the distribution of

$$\sum_{i=1}^n (\mu_i^{-2} \lambda_i X_i)$$

is $IG(\mu, \lambda)$ with

$$\mu = \sum_{i=1}^n \left(\frac{\lambda_i}{\mu_i}\right), \quad \lambda = \mu^2.$$

It is thus a one-parameter inverse Gaussian distribution of the type described by **Vodá** (1973) with pdf given in (15.14).

If $\mu_i = \mu$ and $\lambda_i = A$ for all $i = 1, \dots, n$, we have

$$\frac{\lambda}{\mu^2} \sum_{i=1}^n X_i = \frac{\lambda}{\mu^2} n\bar{X}$$

distributed as $\text{IG}(n\lambda/\mu, n^2\lambda^2/\mu^2)$, whence

$$\bar{X} \text{ is distributed as } \text{IG}(\mu, n\lambda) \quad (15.21)$$

[since aX has an $\text{IG}(a\mu, a\lambda)$ distribution if X has an $\text{IG}(\mu, \lambda)$ distribution; see Section 3, following (15.4d)]. Property (15.21) is termed a *reproducibility* property.

The inverse Gaussian distribution may be characterized by the fact that if X_1, X_2, \dots, X_n are mutually independent $\text{IG}(\mu, A)$ variables, then $\bar{X} = (\sum_{i=1}^n X_i)/n$ and $V = n^{-1} \sum_{i=1}^n (X_i^{-1} - \bar{X}^{-1})$ are statistically independent [Tweedie (1957a)]. The converse is also true; that is, if the expected values of X , X^2 , $1/X$, and $(1/\sum_{i=1}^n X_i)$ exist and are different from zero, and if \bar{X} and $n^{-1} \sum_{i=1}^n (X_i^{-1} - \bar{X}^{-1})$ are independently distributed, then the distribution of each variate X_i is inverse Gaussian [Khatri (1962)].

Letac and Seshadri (1985) have provided a short proof of this characterization, replacing the hypothesis on moments by the assumption that X is positive. Seshadri (1983) extended Khatri's result by imposing constancy of expected values of suitable statistics, conditional on \bar{X} . One of his results is as follows: If X_1, X_2, \dots, X_n are independent and identically distributed, and $E[X_i]$, $E[X_i^2]$, $E[X_i^{-1}]$ for all $i = 1, \dots, n$, $E[(\sum_{i=1}^n X_i)^{-1}]$ all exist and are nonzero, and if $E[\sum_{i=1}^n a_i X_i^{-1} - n(\sum_{i=1}^n a_i)(\sum_{i=1}^n X_i)^{-1} | \sum_{i=1}^n X_i]$ ($\sum_{i=1}^n a_i > 0$) does not depend on $\sum_{i=1}^n X_i$, then the common distribution of the X_i 's is inverse Gaussian. Taking $a_i = 1$ ($i = 1, \dots, n$), we obtain Khatri's result.

Letac, Seshadri, and Whitmore (1985) have shown that if X_1, X_2, \dots, X_n are mutually independent $\text{IG}(\mu, A)$ variables, then

$$Q_1 = \frac{n\lambda(\bar{X} - \mu)^2}{\mu^2 \bar{X}}$$

and

$$Q - Q_1 = \lambda \left\{ \sum_{i=1}^n X_i^{-1} - n\bar{X}^{-1} \right\}$$

are mutually independent and $Q - Q_1$ is distributed as χ^2 with $n - 1$ degrees of freedom.

The distribution is unimodal and its shape depends only on the value of $\phi = \lambda/\mu$ [see Figure 15.11. The location of the mode is

$$\text{Mode}(X) = \mu \left\{ \left(1 + \frac{9}{4\phi^2} \right)^{1/2} - \frac{3}{2\phi} \right\}.$$

Shuster (1968) has pointed out that if X has distribution (15.4a), then $A(X - \mu)^2(\mu^2 X)^{-1}$ has a χ^2 distribution with one degree of freedom (Chapter 18). Some further details are given by Wasan (1968a, b).

Folks and Chhikara (1978) suggest the algebraic formulas

$$\frac{1}{2} \theta \mu^{-2} \sum_{i=1}^n X_i^{-1} (X_i - \mu)^2 = \frac{1}{2} \theta \sum_{i=1}^n (X_i^{-1} - \bar{X}^{-1}) + \frac{1}{2} n \theta \mu^{-2} \bar{X}^{-1} (\bar{X} - \mu)^2, \tag{15.22a}$$

$$\sum_{i=1}^k \sum_{j=1}^{n_i} (X_{ij}^{-1} - \bar{X}^{-1}) = \sum_{i=1}^k n_i (\bar{X}_i^{-1} - \bar{X}^{-1}) + \sum_{i=1}^k \sum_{j=1}^{n_i} (X_{ij}^{-1} - \bar{X}_i^{-1}), \tag{15.22b}$$

where $\bar{X}_i = n_i^{-1} \sum_{j=1}^{n_i} X_{ij}$ and $\bar{X} = (\sum_{i=1}^k n_i)^{-1} \sum_{i=1}^k n_i \bar{X}_i$. These are analogues, for IG parent populations, to the standard decompositions of sums of squares, used in analysis of variance for data in one-way classification by groups for normal parent populations.

They show that for the analogue of a standardized normal variable

$$U = (n\theta)^{1/2} (\bar{X} - \mu) (\mu \bar{X}^{1/2})^{-1}, \tag{15.23}$$

U^2 is distributed as χ^2 with one degree of freedom but U is not normally distributed.

More recently there has been some attention in the literature to the "length biased" pdf of $IG(\mu, A)$, which is generally defined as

$$p_Y(y) = \frac{y p_X(y)}{E[X]}. \tag{15.24}$$

For the length-biased inverse Gaussian — denoted $LBIG(\mu, A)$ —we have

$$p_Y(y) = \left(\frac{\lambda}{2\pi y \mu^2} \right)^{1/2} \exp \left\{ - \frac{\lambda(y - \mu)^2}{2\mu^2 y} \right\}. \tag{15.25}$$

We note that if X is distributed as $IG(\mu, A)$, then μ^2/X is distributed as $LBIG(\mu, A)$; conversely, if Y is distributed as $LBIG(\mu, A)$, then μ^2/Y is distributed as $IG(\mu, A)$.

If Y_1, Y_2, \dots, Y_n are mutually independent $LBIG(\mu, \lambda)$ variables, then their harmonic mean

$$\bar{Y} = n \left(\sum_{i=1}^n Y_i^{-1} \right)^{-1}$$

is distributed as

$$n\mu^2 \left(\sum_{i=1}^n X_i \right)^{-1} = \frac{\mu^2}{\bar{X}},$$

with X_1, \dots, X_n each distributed as $\text{IG}(\mu, A)$. Since \bar{X} is distributed as $\text{IG}(\mu, n\lambda)$, \bar{Y} is distributed as $\text{LBIG}(\mu, n\lambda)$.

Whitmore and Yalovsky (1978) approximate the $\text{IG}(\mu, A)$ distribution by ascribing a standard normal distribution to

$$\frac{1}{2} \sqrt{\frac{\mu}{\lambda}} + \sqrt{\frac{\lambda}{\mu}} \log\left(\frac{X}{\mu}\right). \quad (15.26)$$

This is an improvement over the simpler approximation

$$\sqrt{\frac{\lambda}{\mu}} (\mu^{-1}X - 1) = N(0, 1).$$

Sibuya (1992) has examined six rough approximations for the quantile function of the inverse Gaussian distribution. Among these approximations, four are based on fitting approximate normal, log-normal, gamma, and Birnbaum-Saunders distributions. The other two approximations make use of the specific features of the inverse Gaussian distribution. Through numerical comparisons, Sibuya has noted that no single approximation is uniformly better than the others and that approximating the upper tail of the distribution with a large coefficient of variation becomes particularly difficult. Consequently, these approximations may be used as starting value for the Newton method to numerically solving the equation equating the distribution function to a specified p-value.

6 ESTIMATION OF PARAMETERS

The statistic $(\sum_{i=1}^n X_i, \sum_{i=1}^n X_i^{-1})$ is minimal sufficient for the $\text{IG}(\mu, \lambda)$ distribution. Maximum likelihood estimators (MLEs) have been obtained [Tweedie (1957a)] for the following general case: let X_1, \dots, X_n be a series of observations on n distinct inverse Gaussian distributions $\text{IG}(\mu, A)$ ($i = 1, \dots, n$). Also let $A_i = w_i \lambda_0$, where λ_0 is unknown but w_i is a known positive value. The MLE's of μ and A_i satisfy the equations

$$\hat{\mu} = \bar{X} = \left[\sum_{i=1}^n w_i X_i \right] \left[\sum_{i=1}^n w_i \right]^{-1}, \quad (15.27a)$$

$$\frac{1}{\hat{\lambda}_0} = \frac{1}{n} \sum_{i=1}^n w_i (X_i^{-1} - \bar{X}^{-1}). \quad (15.27b)$$

When the w_i 's are all equal to unity, (15.27a) and (15.27b) become

$$\hat{\mu} = \bar{X} = \frac{\sum_{i=1}^n X_i}{n} \quad (15.28a)$$

$$\frac{1}{\hat{\lambda}_0} = V = n^{-1} \sum_{i=1}^n (X_i^{-1} - \bar{X}^{-1}). \quad (15.28b)$$

It is apparent that in this case \bar{X} is a sufficient statistic for μ . The distribution of \bar{X} is $IG(\mu, n\lambda_0)$. Tweedie (1957a) has shown that \bar{X} and $\hat{\lambda}_0$ are independent. An elementary proof of this basic property is given by Schwarz and Samanta (1991). It can be shown that

$$V(= \hat{\lambda}_0^{-1}) \text{ is distributed as } (\lambda_0 n)^{-1} \times (\chi^2 \text{ with } n - 1 \text{ degrees of freedom}). \quad (15.29)$$

Combining (15.27b) and (15.29), the following relation is obtained:

$$\sum_{i=1}^n w_i (X_i^{-1} - \bar{X}^{-1}) \text{ is distributed as } \lambda_0^{-1} \times (\chi^2 \text{ with } n - 1 \text{ degrees of freedom}). \quad (15.30)$$

Confidence intervals for λ_0 may be constructed using (15.30) [Tweedie (1957a)]. We also note that

$$(n - 1)^{-1} \sum_{i=1}^n w_i (X_i^{-1} - \bar{X}^{-1}) \quad (15.31)$$

is an unbiased estimator of $1/\lambda_0$. It is in fact the uniform minimum variance unbiased estimator [Roy and Wasan (1968)]. Note that the distribution of this estimator is the same form as that of the usual unbiased estimator of variance of a normal distribution [Tweedie (1957a)].

An approximately unbiased estimator of $1/\lambda_0$ is S^2/\bar{X}^3 , where

$$S^2 = \frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n - 1} \quad (15.32)$$

It is a consistent estimator and has asymptotic efficiency of $\phi/(\phi + 3)$. Some further notes on estimators of the cumulants will be found in Section 9.

If the value of μ is known, we may, by a suitable choice of scale, take it to be equal to 1. We are then in the situation of having to estimate the single parameter ϕ , of a standard Wald distribution.

If X_1, X_2, \dots, X_n are independent random variables, each having distribution (15.3), then the maximum likelihood estimator $\hat{\phi}$ of ϕ satisfies the

equation

$$\frac{n}{2}\hat{\phi}^{-1} + n - \frac{1}{2}\sum_{i=1}^n (X_i + X_i^{-1}) = 0,$$

whence

$$\hat{\phi} = \left[\frac{1}{n} \sum_{i=1}^n (X_i + X_i^{-1}) - 2 \right]^{-1}.$$

For n large

$$n \text{Var}(\hat{\phi}) \doteq 2\phi^2.$$

We note that if ϕ be estimated by equating observed and expected values of $m_2 = n^{-1}\sum_{i=1}^n (X_i - \bar{X})^2$, the resultant estimator is

$$\tilde{\phi} = m_2^{-1}. \quad (15.33)$$

For n large

$$n \text{Var}(\tilde{\phi}) \doteq 2\phi^2 + 15\phi. \quad (15.34)$$

The asymptotic efficiency of $\tilde{\phi}$, relative to $\hat{\phi}$, as an estimator of ϕ is

$$(1 + 7.5\phi^{-1})^{-1}.$$

From (15.10) it follows that

$$E(\hat{\phi}^{-1}) = E[X + X^{-1} - 2] = 1 + (1 + \phi^{-1}) - 2 = \phi^{-1},$$

that is, $\hat{\phi}^{-1}$ is an unbiased estimator of ϕ^{-1} and m_2 is also an unbiased estimator of ϕ^{-1} . Further

$$\text{Var}(\hat{\phi}^{-1}) = 2\phi^{-2}n^{-1}, \quad (15.35a)$$

$$\text{Var}(m_2) = (2\phi^{-2} + 15\phi^{-3})n^{-1}. \quad (15.35b)$$

It is of interest to compare these results with those when μ is unknown. The maximum likelihood estimators are then

$$\hat{\mu} = n^{-1} \sum_{i=1}^n X_i = \bar{X}, \quad (15.36a)$$

$$\hat{\phi} = \left[n^{-2} \left(\sum_{i=1}^n X_i \right) \left(\sum_{i=1}^n X_i^{-1} \right) - 1 \right]^{-1} \quad (15.36b)$$

Evidently

$$\text{Var}(\hat{\mu}) = \mu^2 \phi^{-1} n^{-1}. \quad (15.37a)$$

Also

$$n \text{Var}(\hat{\phi}) = 2\phi^2 + \phi, \quad (15.37b)$$

$$\text{Corr}(\hat{\mu}, \hat{\phi}) \doteq -(1 + 2\phi)^{-1/2}. \quad (15.37c)$$

The increase in variance of $\hat{\phi}$, arising from ignorance of the value of μ , should be noted.

Moment estimators are

$$\tilde{\mu} = \bar{X}, \quad (15.38a)$$

$$\tilde{\phi} = \frac{n\bar{X}^2}{\sum_{i=1}^n (X_i - \bar{X})} = (\text{sample coefficient of variation})^{-2}. \quad (15.38b)$$

Note that $\phi^{-1/2}$ is the coefficient of variation. The variance of $\tilde{\mu}$ is of course the same as that of $\hat{\mu}$ and

$$n \text{Var}(\tilde{\phi}) = 10\phi^2 + 19\phi \quad [\text{cf. (15.34)}]. \quad (15.39)$$

More recently moment and maximum likelihood estimation have been discussed by Padgett and Wei (1979) and maximum likelihood estimation by Cheng and Amin (1981), with special attention to consistency and asymptotic efficiency. The two methods of estimation have been compared by Jones and Cheng (1984) who find maximum likelihood to be clearly superior. Modified maximum likelihood and moment estimation, in which the equation obtained by equating expected and observed values of the first (least) order statistic replaces the maximum likelihood equation equating $\partial \log(\text{likelihood})/\partial \xi$ to zero, or the moment equation between sample and population values of the third moment about zero, are discussed by Chan, Cohen, and Whitten (1984). Cohen and Whitten [(1985), (1988)] and Balakrishnan and Cohen (1991) provide tables to assist in computation of the solution of the newly introduced equation for ξ in terms of μ and A (for the three-parameter case discussed in Section 4).

A uniform minimum variance unbiased estimator of the variance ($\sigma^2 = \mu^3/\lambda$) of $IG(\mu, A)$ was derived by Korwar (1989) as

$$\hat{\sigma}^2 = (n-1)^{-1} \bar{X}^3 V_2 F_1 \left(1, \frac{3}{2}; \frac{1}{2}(n+1); \bar{X}V \right), \quad (15.40)$$

where

$${}_2F_1(a, b; c; z) = \sum_{j=0}^{\infty} \frac{a^{[j]} b^{[j]} z^j}{c^{[j]} j!}$$

is the Gaussian hypergeometric function discussed in Chapter 1, and V is defined in (15.28b).

Hsieh and Korwar (1990) have shown that

$$\tilde{\sigma}^2 = \frac{(n-1)\hat{\sigma}^2}{n+1} \quad (15.41)$$

has mean square error never greater than that of $\hat{\sigma}^2$, as an estimator of σ^2 . The maximum likelihood estimator of σ^2 is $V\bar{X}^3/n$; the mean square error of $V\bar{X}^3/(n+1)$ is never greater than that of $V\bar{X}^3/n$.

In further work Hsieh, Korwar, and Rukhin (1990) have shown that the mean square error of \bar{X} , the maximum likelihood estimator of μ , is never less than that of an estimator of form

$$\bar{X} \left[1 - 2\varepsilon \exp\left\{-\frac{a n}{2\bar{X}V}\right\} \right] \quad (15.42)$$

for suitably chosen (positive) values of ε and a . In fact, for any given $a (> 0)$, this will be true for

$$0 < \varepsilon \leq \min\left(\inf_x g(x), 0.5\right),$$

where

$$g(x) = \frac{E\left[(\sqrt{1+aY^{-1}}+x-1)\exp\left\{-\frac{(\sqrt{1+aY^{-1}}-1)/\gamma}{\gamma}\right\}\right]}{E\left[(\sqrt{1+2aY^{-1}}+x)\exp\left\{-\frac{(\sqrt{1+2aY^{-1}}-1)/\gamma}{\gamma}\right\}\right]},$$

with Y distributed as $(n-1)^{-1} \times (\chi^2$ with $n-1$ degrees of freedom) and $\gamma = \mu/(n\lambda)$. To obtain an "optimal" choice for the values of ε and a , it is suggested to use $\varepsilon = \frac{1}{2}$, and the following table, with $\hat{\gamma} = \hat{\mu}/(n\hat{\lambda})$, for a :

$\hat{\gamma}$	0.1	0.5	1	5	10	20	50
a	0.46	1.75	3.19	13.84	26.64	51.80	126.25

A uniform minimum variance unbiased estimator of the squared coefficient of variation (μ/λ) is

$$T = n(n-1)^{-1}\bar{X}V. \quad (15.42)$$

Seshadri (1989) derives the distribution of T in terms of modified Bessel function of the third kind. Despite the complicated form of the distribution the variance of T is quite a simple expression. Since \bar{X} and V are mutually independent and \bar{X} has a $N(\mu, n^{-1}\mu^3/\lambda)$ distribution, while V has a

$n\lambda^{-1}\chi_{n-1}^2$ distribution,

$$\begin{aligned} E[T^2] &= n^2(n-1)^{-2}E[\bar{X}^{-2}]E[V^2] \\ &= n^2(n-1)^{-2}(\mu^2 + n^{-1}\mu^3\lambda^{-1})n^2\lambda^{-2}\{2(n-1) + (n-1)^2\} \end{aligned}$$

and

$$\begin{aligned} \text{Var}(T) &= E[T^2] - \{E[T]\}^2 = E[T^2] - \mu^2\lambda^{-2} \\ &= (n-1)^{-1}\left(\frac{\mu}{\lambda}\right)^2\left\{2 + \frac{n+1}{n}\left(\frac{\mu}{\lambda}\right)\right\}. \end{aligned} \quad (15.43)$$

For large n , $\sqrt{n-1}(T - \mu\lambda^{-1})$ has an approximately normal distribution with zero expected value and variance $[2 + (\mu/\lambda)](\mu/\lambda)^2$.

Seto and Iwase (1985) obtained a complicated formula for an UMVU estimator of the mode of an $\text{IG}(\mu, A)$ distribution. For $n = 3$ this estimator is

$$Y = \bar{X}\{{}_1F_2(-\frac{1}{2}; \frac{1}{2}, 1; -\frac{1}{4}W^2) - W\}, \quad (15.44)$$

where

$$\begin{aligned} W &= \frac{3}{2}\left\{\left(1 + \frac{1}{3}\bar{X}V\right)^{1/2} - 1\right\}, \\ {}_1F_2(a; b, c; z) &= \sum_{j=0}^{\infty} \frac{a^{[j]} z^j}{b^{[j]}c^{[j]} j!}. \end{aligned}$$

Estimation of the parameters of the three-parameter $\text{IG}(\mu, A, \xi)$ distribution with pdf

$$\begin{aligned} p_Y(y|\mu, \lambda, \xi) &= \left\{\frac{\lambda}{2\pi(y-\xi)^3}\right\}^{1/2} \exp\left\{-\frac{\lambda(y-\xi-\mu)^2}{2(y-\xi)\mu^2}\right\}, \\ & y > \xi; \mu, \lambda > 0, \end{aligned} \quad (15.45)$$

has been discussed by Padgett and Wei (1979), Cheng and Amin (1981), Jones and Cheng (1984), Chan, Cohen, and Whitten (1984), Cohen and Whitten (1985, 1988), and Balakrishnan and Cohen (1991). Putting $A = \mu^3/\sigma^2$, (15.45) can be written as

$$\begin{aligned} p_Y(y|\mu, \sigma, \xi) &= \frac{1}{\sigma\sqrt{2\pi}}\left(\frac{\mu}{y-\xi}\right)^{3/2} \exp\left\{-\frac{1}{2}\left(\frac{\mu}{y-\xi}\right)\left(\frac{y-\xi-\mu}{\sigma}\right)^2\right\}, \\ & y > \xi; \mu, \sigma > 0. \end{aligned} \quad (15.46)$$

Recent books by **Cohen** and **Whitten** (1988) and **Balakrishnan** and **Cohen** (1991) discuss estimation problems for distribution (15.45) in great detail. We do not present these in full here. It should, however, be noted that MLEs are not available if the sample third central moment is negative.

For the special case when the value of $a = E[X]/\text{Var}(X)$ is known—the corresponding distribution being $\text{IG}(\mu, \text{up}^2)$ —procedures for statistical inference on μ have been constructed by **Iwase** (1987) and **Joshi** and **Shah** (1991). **Iwase** (1987) showed that the uniform minimum variance unbiased estimator of μ , based on n independent $\text{IG}(\mu, c\mu^2)$ variables X_1, \dots, X_n is

$$\hat{\mu} = T \frac{\psi(\frac{1}{2}(n-1), \frac{3}{2}; \frac{1}{2}naT)}{\psi(\frac{1}{2}(n-1), \frac{1}{2}; \frac{1}{2}naT)}, \quad n \geq 2, \quad (15.47)$$

where $T = \{n^{-1}\sum_{i=1}^n X_i^{-1}\}^{-1}$ is the harmonic mean of the X 's, and

$$\psi(a, c; x) = x^{a-2} \sum_{j=0}^{\infty} (-1)^j \frac{a^{(j)}(a-c+1)^{(j)}}{j!} x^{-j} \quad (15.48)$$

is the confluent hypergeometric function. (See Chapter 1, Section A7.)

The maximum likelihood estimator of μ is

$$\hat{\mu} = \frac{1}{2}T \left[1 + \{1 + 4(cT)^{-1}\}^{1/2} \right], \quad n \geq 1. \quad (15.49)$$

Iwase (1987) showed that

$$\hat{\mu} = \hat{\mu} \{1 + o(n^{-1})\} \quad (15.50)$$

as $n \rightarrow \infty$. **Joshi** and **Shah** (1991) consider (from a Bayesian viewpoint) another special case, namely $\text{IG}(\mu, c^{-2}\mu)$, where $c = E[X]/\sqrt{\text{Var}(X)}$ is the coefficient of variation of X , and the value of c is known.

Bayesian analysis for the general $\text{IG}(\mu, A)$ distribution has been considered by **Betro** and **Rotondi** (1991) and by **Banerjee** and **Bhattacharyya** (1979). **Joshi** and **Shah** (1991) consider Bayesian estimation of the expected value μ of $\text{IG}(\mu, c^{-2}\mu)$, where the value of c (the coefficient of variation) is known.

7 TRUNCATED DISTRIBUTIONS—ESTIMATION OF PARAMETERS

It is frequently desirable to estimate the parameters of a truncated inverse Gaussian distribution. Estimators of the parameters and their asymptotic variances have been obtained [**Patel** (1965)] for both the singly and doubly truncated cases.

7.1 Doubly Truncated Distribution

The density function of the doubly truncated distribution may be written as

$$p_X(x|\mu, \lambda; x_1, x_2) = Kx^{-3/2} \exp\left\{-\frac{\lambda x}{2\mu^2} - \frac{\lambda}{2x}\right\}, \quad (15.51)$$

where

$$K = \left[\int_{x_1}^{x_2} x^{-3/2} \exp\left\{-\frac{\lambda x}{2\mu^2} - \frac{\lambda}{2x}\right\} dx \right]^{-1}, \quad x_1 \leq x \leq x_2.$$

The values of x_1 and x_2 denote the lower and upper points of truncation, respectively, of the distribution of X ($0 < x_1 < x_2$); the parameters μ and λ are positive.

A recurrence relation for the moments may be obtained by differentiating (15.51) partially with respect to x and multiplying both sides by x^r to give, after integration by parts:

$$a\mu'_r - \lambda\mu'_{r-2} - 2(x_1^r p_1 - x_2^r p_2) = (2r - 3)\mu'_{r-1}, \quad (15.52)$$

where

$$a = \lambda/\mu^2,$$

$$p_i = p_X(x_i|\mu, \lambda; x_1, x_2) \text{ for } i = 1, 2,$$

$$\mu'_r = \int_{x_1}^{x_2} x^r p_X(x|\mu, \lambda; x_1, x_2) dx \text{ for } r = 0, \pm 1, \pm 2, \dots$$

p_1 and p_2 are of course values of the density at the truncation points x_1 and x_2 .

If the population moments (μ'_r) are replaced by the sample moments (m'_r) in the recurrence relation (15.52), the following set of equations results:

$$\mathbf{M}\hat{\mathbf{h}} = \mathbf{c}, \quad (15.53)$$

where

$$\hat{\mathbf{h}} = \begin{pmatrix} \hat{a} \\ \hat{\lambda} \\ \hat{p}_1 \\ \hat{p}_2 \end{pmatrix}, \quad \mathbf{M} = \begin{pmatrix} 1 & -m'_{-2} & -2 & 2 \\ m'_1 & -m'_{-1} & -2x_1 & 2x_2 \\ m'_2 & -1 & -2x_1^2 & 2x_2^2 \\ m'_3 & -m'_1 & -2x_1^3 & 2x_2^3 \end{pmatrix}, \quad \mathbf{c} = \begin{pmatrix} -3m'_{-1} \\ -1 \\ m'_1 \\ 3m'_2 \end{pmatrix}.$$

($\hat{\mathbf{h}}$ is a vector of estimators of functions of the parameters.) Provided that \mathbf{M} is nonsingular, (15.53) may be solved as

$$\hat{\mathbf{h}} = \mathbf{M}^{-1}\mathbf{c} \quad (15.54)$$

from which $\hat{\mu}$ may be derived as $\sqrt{\hat{\lambda}/\hat{a}}$.

The asymptotic variances and covariances of the estimators ($\hat{\mathbf{h}}$) of the parameters may be obtained in matrix form by using a differential method [Patel (1965)]. The elements of this symmetric matrix are as follows:

$$n \text{Var}(\hat{a}) \doteq (14 + \lambda a)\mu'_{-2} + a\mu'_{-1} - P_{-1} - \lambda P_{-2}, \quad (15.55a)$$

$$n \text{Cov}(\hat{a}, \hat{\lambda}) \doteq 2\lambda\mu'_{-2} - \lambda P_{-1} + 3a, \quad (15.55b)$$

$$n \text{Cov}(\hat{a}, \hat{p}_1) \doteq \lambda\mu'_{-1} + 3a\mu'_1 - a\lambda - 3, \quad (15.55c)$$

$$n \text{Cov}(\hat{a}, \hat{p}_2) \doteq \lambda^2\mu'_{-1} - (9 + a\lambda)\mu'_1 + 3a\mu'_2, \quad (15.55d)$$

$$n \text{Var}(\hat{\lambda}) \doteq \lambda^2\mu'_{-2} + a^2\mu'_2 - 2a\lambda, \quad (15.55e)$$

$$n \text{Cov}(\hat{\lambda}, \hat{p}_1) \doteq a^2\mu'_3 - a\mu'_2 - a\lambda\mu'_1 + \lambda, \quad (15.55f)$$

$$n \text{Cov}(\hat{\lambda}, \hat{p}_2) \doteq 2a\mu'_3 - a\lambda\mu'_2 + 3\lambda\mu'_1 + aP_4 + \lambda^2, \quad (15.55g)$$

$$n \text{Var}(\hat{p}_1) \doteq 3a\mu'_3 + (1 + a\lambda)\mu'_2 + aP_4, \quad (15.55h)$$

$$n \text{Cov}(\hat{p}_1, \hat{p}_2) \doteq 18\mu'_3 + \mu'_2 + 3P_4 + aP_5, \quad (15.55i)$$

$$n \text{Var}(\hat{p}_2) \doteq \frac{30}{a}(5\mu'_3 + \lambda\mu'_2 + P_4) + 4\lambda\mu'_3 - \lambda P_4 + 3P_5 + aP_6, \quad (15.55j)$$

where $P_r = (2x_1^r p_1 - x_2^r p_2)$.

Two other useful general relations are

$$\text{Var}(\hat{\mu}) = \frac{1}{4\mu^2 a^4} [a^2 \text{Var}(\hat{\lambda}) + \lambda^2 \text{Var}(\hat{a}) - 2a\lambda \text{Cov}(\hat{a}, \hat{\lambda})], \quad (15.56)$$

$$\text{Cov}(\hat{\lambda}, \hat{\mu}) = \frac{a \text{Var}(\hat{\lambda}) - \lambda \text{Cov}(\hat{a}, \hat{\lambda})}{2\mu a^2}. \quad (15.57)$$

7.2 Truncation of the Lower Tail Only

If the truncation point is at x_0 where $x_0 > 0$, then the estimators $\hat{\mathbf{h}}_1$ of the parameters are

$$\hat{\mathbf{h}}_1 = \mathbf{M}_1^{-1} \mathbf{c}_1, \quad (15.58)$$

where \mathbf{M}_1 is a matrix of order 3 (obtained by deleting the last row and column of \mathbf{M} and putting $\mathbf{x}_1 = \mathbf{x}_0$). The vectors $\hat{\mathbf{h}}_1$ and \mathbf{c}_1 are obtained from $\hat{\mathbf{h}}$ and \mathbf{c} , respectively, by deleting the last element and putting $p_r = p_0$.

The asymptotic variance of $\hat{\lambda}$ can be obtained from (15.55e) and that of $\hat{\mu}$ and the covariance between $\hat{\lambda}$ and $\hat{\mu}$ from (15.56) and (15.57), respectively.

7.3 Truncation of the Upper Tail Only

This case may be dealt with in a similar manner. The general relations (15.53) of the first case are again applicable with $x_1 = 0$, $x_0 = x_2$, $p_0 = p_2$, and omitting the last row and column of M. The asymptotic variances and covariances of the estimators are obtained in the same way as in the second case.

8 CONDITIONAL EXPECTATIONS OF THE ESTIMATORS OF THE CUMULANTS

We now return to study the untruncated distribution. The section is of less general interest than Section 7, but contains some useful results. It may be shown that, given the arithmetic mean \bar{X} , the conditional expectation of any unbiased estimator \bar{k}_r of the r th cumulant must be

$$E[\bar{k}_r | \bar{X}] = 2\bar{X} \left(\frac{1}{2} \lambda n^2 \right)^{r-1} \exp\left(\frac{1}{2}G\right) \int_1^{\bar{X}} (u-1)^{2r-3} \times \exp\left(-\frac{1}{2}Gu^2\right) \frac{du}{(r-2)!}, \tag{15.59}$$

where $G = \lambda n / \bar{X}$. Since the distribution of \bar{X} has the same form as (15.4c) with ϕ replaced by ϕn , then the probability density function of G is

$$p_G(g) = \frac{\exp[-(\theta^2/2g) + \theta - (g/2)]}{\sqrt{2\pi g}}, \quad g > 0, \tag{15.60}$$

where $\theta = \phi n$. The moments of G may be obtained using the formulas developed for the inverse Gaussian variate X [see (15.7) and (15.10)].

The first few moments of G are

$$\begin{aligned} E[G] &= \theta + 1, \\ E[G^2] &= \theta^2 + 3\theta + 3, \\ E[G^3] &= \theta^3 + 6\theta^2 + 15\theta + 15, \\ E[G^4] &= \theta^4 + 10\theta^3 + 45\theta^2 + 105\theta + 105, \\ E[G^5] &= \theta^5 + 15\theta^4 + 105\theta^3 + 420\theta^2 + 945\theta + 945, \\ E[G^6] &= \theta^6 + 21\theta^5 + 210\theta^4 + 1260\theta^3 + 4725\theta^2 + 10395\theta + 10395. \end{aligned} \tag{15.61}$$

It can be shown [Tweedie (1957b)] that conditional expectations of unbiased estimators of the cumulants, calculated from (15.59) are

$$E[\bar{k}_2|\bar{X}; \lambda, n] = \lambda^2 n^3 G^{-2} J, \quad (15.62a)$$

$$E[\bar{k}_3|\bar{X}; \lambda, n] = \frac{1}{2} n^2 \bar{X}^3 \{(G+3)J - 1\}, \quad (15.62b)$$

$$E[\bar{k}_4|\bar{X}; \lambda, n] = \left(\frac{1}{8}\right) n^3 \bar{X}^4 \{(G^2 + 10G + 15)J - G - 7\}, \quad (15.62c)$$

where

$$J = 1 - G e^{G/2} \int_1^\infty e^{-Gu^2/2} du. \quad (15.63)$$

J has a maximum value of 1 and decreases monotonically to 0 as G increases to ∞ .

An asymptotic series expansion of (15.63) yields

$$\begin{aligned} J = & G^{-1} - 3G^{-2} + \dots + (-1)^{r+1} 3 \times 5 \dots \times (2r-1) G^{-r} \\ & + (-1)^r 3 \times 5 \dots \times (2r-1) \times (2r+1) G^{-r} e^{-G/2} \int_1^\infty u^{-2r-2} e^{-Gu^2/2} du \end{aligned} \quad (15.64a)$$

[Tweedie (1957b)]. A relatively large number of significant figures is required in J in order to yield accurate results when evaluating (15.62) numerically.

Tables of J and $e^{G/2} \int_1^\infty e^{-Gu^2/2} du$ ($= I$) were compiled [National Bureau of Standards (1942)]. Tweedie (1957b) gives tables of I and J for $G = 1(1)10$. Tweedie also gives "a useful expansion for moderately large values of G " in the form of the continued fraction

$$J = \frac{1}{G+3} \cfrac{1}{1+2} \cfrac{1}{G+5} \cfrac{1}{1+4} \cfrac{1}{G+\dots}, \quad (15.64b)$$

where the sequence of positive integers in the partial numerators is 1; 3, 2; 5, 4; 7, 6; 9, 8; and so on. For large values of G , asymptotic expansions of

finite polynomials may be used, giving

$$E[\bar{k}_r|\bar{X}; \lambda, n] \sim \frac{4\lambda}{\bar{X}} \left(\frac{\bar{X}^2}{2\lambda}\right)^r \sum_{i=0}^{\infty} \frac{(2i + 2r - 3)!}{i!(r - 2)!(-2G)^i}. \quad (15.65)$$

On using (15.65), or by applying the asymptotic series expansion (15.64a) to (15.62), the expected values of the estimators of the cumulants become

$$E[\bar{k}_2|\bar{X}; \lambda, n] \sim \lambda^{-1}\bar{X}^3(1 - 3G^{-1} + 15G^{-2} - 105G^{-3} + 945G^{-4} - \dots), \quad (15.66a)$$

$$E[\bar{k}_3|\bar{X}; \lambda, n] \sim 3\lambda^{-2}\bar{X}^5(1 - 10G^{-1} + 105G^{-2} - 1260G^{-3} + 17325G^{-4} - \dots), \quad (15.66b)$$

$$E[\bar{k}_4|\bar{X}; \lambda, n] \sim 15\lambda^{-3}\bar{X}^7(1 - 21G^{-1} + 378G^{-2} - 6930G^{-3} + 135135G^{-4} - \dots) \quad (15.66c)$$

[see (1957b)]. Experimental data involving the inverse Gaussian distribution exhibit a high correlation between changes in sample means and changes in sample variances in different sets of data. This fact can be accounted for theoretically by the relationship between the first and second cumulants $k_2 = k_1^2/\lambda$, as can be seen from (15.6). The regression function of the sample variance S^2 on the sample mean \bar{X} is

$$E[S^2|\bar{X}; \lambda, n] = \frac{GJ\bar{X}^3}{\lambda} = Jn\bar{X}^2 \quad (15.67)$$

[see (1957b)].

RELATED DISTRIBUTIONS

Reciprocal of an Inverse Gaussian Variate

Sometimes it may be convenient to use the reciprocal of a variate X having an inverse Gaussian distribution. [In terms of the moving particle (see Section 2) this corresponds to average velocity.] The probability density function of $Y (= 1/X)$ is (see also Section 3)

$$p_Y(y) = \exp\left\{-\frac{\lambda y}{2} + \frac{\lambda}{\mu} - \frac{\lambda}{2\mu^2 y}\right\} \left[\frac{\lambda}{2\pi y}\right]^{1/2}, \quad y > 0. \quad (15.68)$$

This distribution is called the *random walk distribution* [Wise (1966); Wasan (1968b)].

The positive moments about zero for Y are the same as the negative moments about zero for the inverse Gaussian variate X and are given by (15.9) and (15.10). The cumulant generating function of Y is

$$\psi_Y(t; \mu, \lambda) = \lambda \mu^{-1} \left\{ 1 - (1 + 2t\lambda^{-1})^{1/2} \right\} - \frac{1}{2} \log(1 + 2t\lambda^{-1}). \quad (15.69)$$

The first two cumulants are

$$\kappa_1(Y) = \frac{1}{\mu} + \frac{1}{\lambda}, \quad (15.70a)$$

$$\kappa_2(Y) = \frac{1}{\lambda\mu} + \frac{2}{\lambda^2}. \quad (15.70b)$$

The bias of Y as an estimator of μ^{-1} is λ^{-1} . The mean square error in using Y as an estimator of $1/\mu$ is

$$E \left[\left(Y - \frac{1}{\mu} \right)^2 \right] = (\lambda\mu)^{-1} + 3\lambda^{-2}. \quad (15.71)$$

The mode of the density function of Y is located at

$$\text{Mode}(Y) = \frac{1}{\mu} \left[\left(1 + \frac{\mu^2}{4\lambda^2} \right)^{1/2} - 1 \right]. \quad (15.72)$$

Wise (1966) has shown that the density function has two points of inflection, at values of y , satisfying the equation

$$u^4 + 2u^3 + u = \left(\frac{\lambda}{\mu} \right)^2 + \frac{1}{4},$$

where

$$u = \frac{1}{2} + \frac{1}{2} \left(\frac{\lambda}{\mu} \right) \left(\frac{y}{\mu} - \frac{\mu}{y} \right).$$

Figure 15.2 presents plots of the density function of Y for different values of λ [reproduced from Tweedie (1957a)].

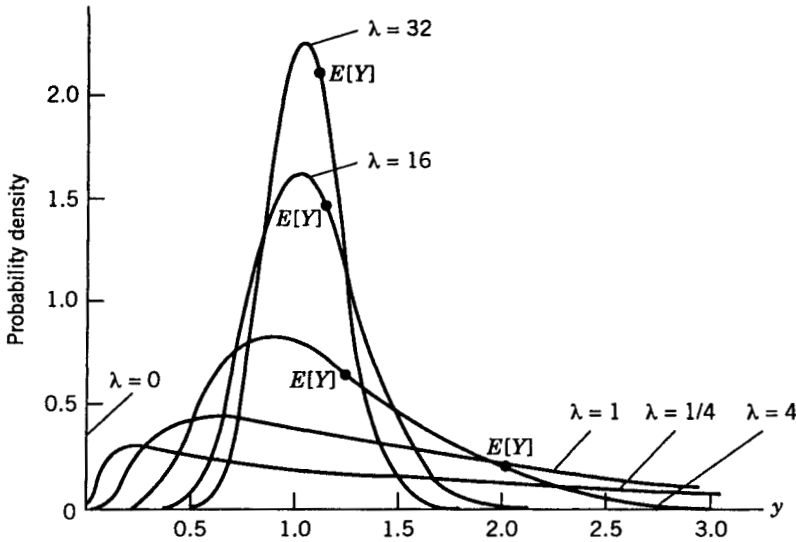


Figure 15.2 Density Functions of Reciprocals of Inverse Gaussian Variables ($\mu = 1$). Note that $\lim_{\lambda \rightarrow \infty} E[Y] = 1$.

9.2 Birnbaum-Saunders Distribution

Birnbaum and Saunders (1969a) have proposed the distribution with pdf,

$$\begin{aligned}
 p_X(x; \alpha, \beta) &= \frac{1}{2\alpha\beta} \left(\frac{x}{\beta}\right)^{-1/2} \left\{ 1 + \left(\frac{x}{\beta}\right)^{-1} \right\} \\
 &\times \frac{1}{\sqrt{(2\pi)}} \exp\left[-\frac{1}{2\alpha^2} \left(\frac{x}{\beta} - 2 + \frac{\beta}{x}\right) \right], \quad x > 0; \alpha, \beta > 0,
 \end{aligned}
 \tag{15.73}$$

to represent the distribution of lifetimes of components under specified condition of wear (a "fatigue life" distribution). Desmond (1986) has pointed out that formula (15.73) can be rewritten as

$$\begin{aligned}
 p_X(x; \alpha, \beta) &= \frac{1}{3} \left[\left(\frac{\alpha^{-2}\beta}{2\pi x^3}\right)^{1/2} \exp\left\{ -\frac{1}{2\alpha^2\beta} (x - 2\beta + \beta^2 x^{-1}) \right\} \right. \\
 &\left. + \left(\frac{\alpha^{-2}\beta^{-1}}{2\pi x}\right)^{1/2} \exp\left\{ -\frac{\beta}{2\alpha^2} (x^{-1} - 2\beta^{-1} + \beta^{-2}x) \right\} \right]. \tag{15.73}'
 \end{aligned}$$

Comparison with equations (15.4a) and (15.68) shows that the Birnbaum–Saunders distribution is a mixture, in equal proportions, of an $IG(\beta, \alpha^{-2}\beta)$ distribution and a reciprocal $IG(\beta, \alpha^{-2}\beta^{-1})$ distribution. Desmond (1985) provided a more general derivation of this distribution based on a biological model. In his derivation, Desmond has strengthened the physical justification for the use of this distribution by relaxing some of the assumptions made by Birnbaum and Saunders (1969a). Birnbaum and Saunders (1969b) derived the maximum likelihood estimators for the parameters α and β . They also presented a mean estimator for β . Ahmad (1988) discussed a jackknife estimator for β based on the mean estimator. Tests of hypotheses and interval estimation of parameters, based on the maximum likelihood estimates, have been developed by Engelhardt, Bain, and Wright (1981). Rieck and Nedelman (1991) discussed a log-linear model for this distribution, which is applicable in accelerated life-testing. Estimation of parameters based on symmetrically **Type-II** censored samples has been considered by Rieck (1994). Bhattacharyya and Fries (1982) have also studied reciprocal inverse Gaussian distributions. They emphasize the exponential family structure of the distributions. More details on the Birnbaum–Saunders distribution may be found in Chapter 33, Section 2.

9.3 Generalized Inverse Gaussian Distributions

An important generalization of inverse Gaussian distributions, introduced by Good (1953) and studied by Wise (1971, 1975), has attracted considerable attention, exemplified especially by an exhaustive and interesting monograph by Jørgensen (1982). He uses parameters ψ , χ , and θ , and defines the pdf of a generalized inverse Gaussian distribution [GIG(ψ, χ, θ)] as

$$p_X(x|\psi, \chi, \theta) = \frac{(\psi/\chi)^{\theta/2}}{2K_\theta(\sqrt{\psi\chi})} x^{\theta-1} \exp\left\{-\frac{1}{2}(\chi x^{-1} + \psi x)\right\},$$

$$x > 0; \psi, \chi > 0, \quad (15.74)$$

where $K_\theta(\cdot)$ is a modified Bessel function of the third kind. If $\theta = -\frac{1}{2}$ we have an $IG(\sqrt{\psi/\chi}, \chi)$ pdf. Other special cases are

- $\theta = \frac{1}{2}$ – reciprocal IG() distribution,
- $\chi = 0, \theta > 0$ – gamma distribution (Chapter 17),
- $\psi = 0, \theta < 0$ – reciprocal gamma distribution (Chapter 17)
- $\theta = 0$ – hyperbolic distribution of Barndorff-Nielsen, Blaesild, and Halgreen (1978) and Rukhin (1974) (Chapter 12).

Jørgensen (1982) also uses an alternative form for (15.74), more symmetrical

in appearance, obtained by putting $\omega = \sqrt{(\psi\chi)}$ and $\eta = \sqrt{(\chi/\psi)}$. This gives

$$p_X(x|\omega, \eta, \theta) = \{2\eta^\theta K_\theta(\omega)\}^{-1} x^{\theta-1} \exp\{-\frac{1}{2}\omega(\eta^{-1}x + \eta x^{-1})\},$$

$$x > 0, \omega, \eta > 0. \quad (15.74)'$$

If $\chi = 0$ or $\psi = 0$ so that $\omega = 0$, equation (15.4a) for $\text{IG}(\mu, \Lambda)$ corresponds to (15.74)', with $\theta = -\frac{1}{2}$, $\omega = \lambda/\mu$, and $\eta = \mu$ (and $K_{-1/2}(\omega) = \sqrt{\frac{1}{2}\pi}\omega^{-1/2}e^{-\omega}$). Jørgensen (1982) also reports an approximation based on supposing that

$$-\theta^{3/2}\chi^{-1}(2X + \theta^{-1}\chi) \quad (15.75)$$

has a standard normal [$N(0, 1)$] distribution and suggests that even better approximation might be secured by taking $\log X$ to have an approximate normal distribution (i.e., by approximating the GIG distribution by a lognormal distribution). He also shows that GIG distributions can be regarded as limiting cases of generalized hyperbolic distributions.

Barndorff-Nielsen, Blaesild, and Halgreen (1978) have shown that GIG distribution with $\theta < 0$ can arise as first passage times of a time-homogeneous diffusion process. The well-known analogy between analysis of data based on normal and IG parent distributions (see Section 6)—wherein the maximum likelihood estimators of μ and Λ for $\text{IG}(\mu, \Lambda)$ are

$$\hat{\mu} = \bar{X},$$

$$\hat{\lambda} = (\bar{X} - \bar{X}^{-1})^{-1} \quad (\text{see (15.27a), (15.27b)}),$$

with $\hat{\mu}$ having an $\text{IG}(\mu, n\lambda)$ distribution and $n\lambda/\hat{\lambda}$ having a χ_{n-1}^2 distribution—does not extend to GIG distributions. However, the set

$$\left(\sum_{i=1}^n X_i, \sum_{i=1}^n X_i^{-1}, \sum_{i=1}^n \log X_i \right) \quad (15.76)$$

is minimally sufficient for GIG distributions. Embrechts (1983) has shown that the GIG distribution belongs to a class of subexponential distributions.

9.4 Mixtures of $\text{IG}(\mu, \lambda)$ with Its Complementary Reciprocal

If X_1 is distributed as $\text{IG}(\mu, \sigma^{-2})$ and X_2^{-1} is distributed as $\text{IG}(\mu^{-1}, \sigma^{-2}\mu^2)$, we call X_2 the complementary reciprocal of X_1 . Jørgensen, Seshadri, and Whitmore (1991) introduced a mixture of the distributions of X_1 and X_2 in proportions $1 - p$ and p , respectively ($0 < p < 1$). They denote this distribu-

tion by $M\text{-IG}(\mu, \sigma^{-2}, p)$. The pdf of this distribution is

$$p_X(x|\mu, \sigma^{-2}, p) = (2\pi\sigma^2x^3)^{-1/2} \left(1 - p + \frac{px}{\mu}\right) \exp\left\{-\frac{(x - \mu)^2}{2\mu^2\sigma^2x}\right\},$$

$$x > 0; \mu, \sigma > 0; 0 < p < 1. \quad (15.77)$$

We have

$$E[X] = \mu + p\sigma^2\mu^2, \quad (15.78a)$$

$$\text{Var}(X) = \sigma^2\mu^3 + p(3 - p)\sigma^4\mu^4. \quad (15.78b)$$

Introducing $\gamma = \mu(1 - p)/p$, (15.77) can be written as

$$p_X(x|\mu, \sigma^{-2}, p) = (2\pi\sigma^2x^3)^{-1/2} \left(\frac{\gamma + x}{\gamma + \mu}\right) \exp\left\{-\frac{(x - \mu)^2}{2\mu^2\sigma^2x}\right\}. \quad (15.77)'$$

If γ is known, this is a two parameter exponential family. The cdf is

$$F_X(x|\mu, \sigma^{-2}, p) = \Phi\left(\frac{x - \mu}{\sigma\mu\sqrt{x}}\right) + \exp\left(\frac{2}{\sigma^2\mu}\right) \Phi\left(\frac{x + \mu}{\sigma\mu\sqrt{x}}\right). \quad (15.79)$$

For both $\text{IG}(\mu, \sigma^{-2})$ and $M\text{-IG}(\mu, \sigma^{-2}, p)$, the statistic $(X - \mu)^2/(\mu^2X)$ has a χ_1^2 distribution; (see page 269).

A $M\text{-IG}(\mu, \sigma^{-2}, p)$ random variable X can be represented as

$$X = X_1 + Y, \quad (15.80)$$

where X_1 and Y are mutually independent, X_1 has an $\text{IG}(\mu, \sigma^{-2})$ distribution, and $\text{Pr}[Y = 0] = 1 - p$, while Y is distributed as $\mu^2\sigma^2\chi_1^2$ if $Y \neq 0$. Thus $M\text{-IG}(\mu, \sigma^{-2}, p)$ is a convolution of an inverse Gaussian and a compound Bernoulli distribution.

Also if X is distributed as $M\text{-IG}(\mu, \sigma^{-2}, p)$, then

$$cX \text{ is distributed as } M\text{-IG}(\mu, c\sigma^{-2}, p)$$

and

$$X^{-1} \text{ is distributed as } M\text{-IG}(\mu^{-1}, \mu^2\sigma^{-2}, 1 - p).$$

Thus the M-IG family is "closed under reciprocation."

Figure 15.3 from Jørgensen, Seshadri, and Whitmore (1991) provides graphs of some $M\text{-IG}(1, 1, p)$ pdf's, and Figure 15.4 plots graphs of M-IG distribution with common expected value 1, $\gamma = 1$ [i.e., $\mu = p/(1 - p)$],

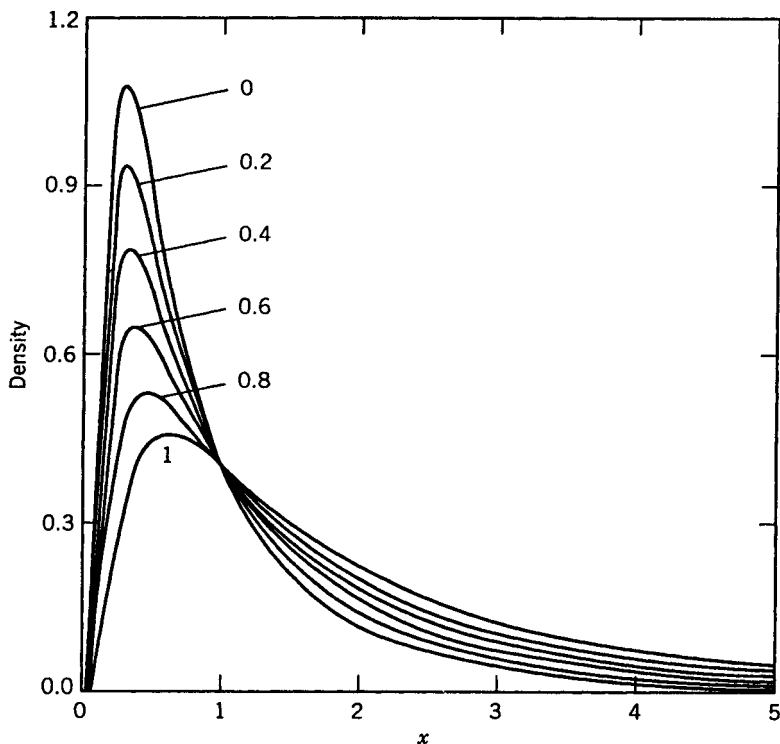


Figure 15.3 Density Functions of $M-IG(1, 1, p)$ for $p = 0, 0.2, 0.4, 0.6, 0.8,$ and 1 . From Jørgensen, Seshadri, and Whitmore (1991).

$\mu = 0.1(0.2)0.9, 0.95,$ and σ chosen so that the variance is 1 [i.e., $(1 - p)p^3\sigma^2 + (3 - p)p^5\sigma^4 = 1$]. The Birnbaum-Saunders distribution is a particular case of the $M-IG(\mu, \sigma^2, p)$.

Abd-El-Hakim and Ahmad (1992) have recently considered a mixture of two inverse Gaussian distributions and discussed its modal properties.

9.5 Other Related Distributions

Al-Hussaini and Abd-El-Hakim (1990) studied estimation of parameters of a inverse Gaussian-Weibull mixture of the form

$$f(x, \theta) = p \left(\frac{\lambda}{2\pi x^3} \right)^{1/2} \exp \left[-\frac{\lambda(x - \mu)^2}{2\mu^2 x} \right] + (1 - p) \left(\frac{c}{\alpha} \right) \left(\frac{x}{\alpha} \right)^{c-1} \exp \left[-\left(\frac{x}{\alpha} \right)^c \right]. \tag{15.81}$$

They derived equations for both maximum likelihood and weighted maximum likelihood estimators. In an earlier paper (1989) the same authors proposed this mixture as a failure model and investigated its failure rate function.

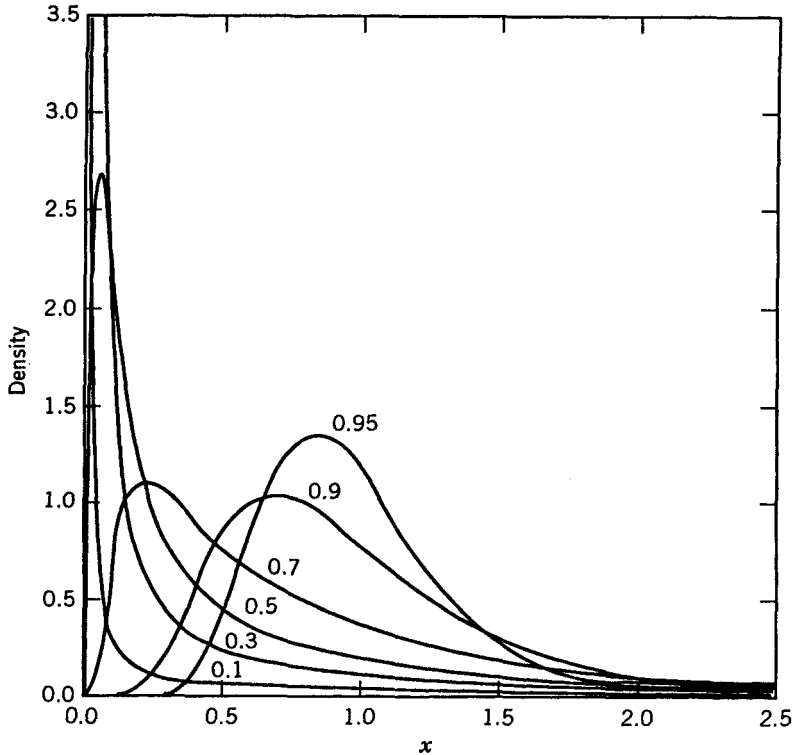


Figure 15.4 Density Functions of $M\text{-IG}(\mu, \sigma^2)$ Having Mean Value $m = 1$, $\gamma = 1$, and $\mu = 0.1$, 0.3, 0.5, 0.7, 0.9, and 0.95. From Jørgensen, Seshadri, and Whitmore (1991).

Holla (1966) has described a (discrete) compound Poisson distribution:

$$\text{Poisson}(\theta) \bigwedge_{\theta} \text{Inverse Gaussian (see Chapter 9)}$$

Robert (1991) proposes another form of *generalized inverse normal* as a generalization of the distribution of $1/X$, when X is distributed as $N(0, \sigma^2)$. The pdf of $Z = 1/X$ is

$$p_Z(z|\theta, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \frac{1}{z^2} \exp\left\{-\frac{1}{2\sigma^2}\left(\frac{1}{z} - \theta\right)^2\right\}.$$

Robert's family $TN(\alpha, \tau, \mu)$ is defined by

$$p_Z(z|\alpha, \mu, \tau) = \frac{K(\alpha, \mu, \tau)}{|z|^\alpha} \exp\left\{-\frac{(z^{-1} - \mu)^2}{2\tau^2}\right\}, \quad \alpha > 1, \tau > 0,$$

where K is a normalizing constant expressed in terms of a confluent hypergeometric function. The distribution is *bimodal* with modes at

$$z_1 = -\frac{\mu + \sqrt{\mu^2 + 4\alpha\tau^2}}{2\alpha\tau^2}$$

and

$$z_2 = \frac{\sqrt{\mu^2 + 4\alpha\tau^2} - \mu}{2\alpha\tau^2}.$$

For $\alpha = \mu = 2$ ($\tau = 1$) the distribution is indistinguishable from a distribution with positive support. The case $a = 2$ corresponds to the original inverse normal transformation. The k th moment is defined only if $a > k + 1$. This distribution generates a conjugate prior family for the parameters of $N(\theta, \sigma^2\theta^2)$ distribution.

10 TABLES

Tables of the cumulative distribution function corresponding to (15.4a) have been constructed by Wasan and Roy (1967). They give values of $\Pr[X \leq x]$ to four decimal places for $\mu = 5$ and

$$\lambda = 0.25(0.25)1.00(1)10, 16(8)32.$$

For $A < 0.25$ they suggest using a reciprocal gamma approximation, and for $A > 32$, a normal approximation (see section 5). If it is desired to evaluate $\Pr[X \leq x]$ for a value of μ different from 5, then one can evaluate

$$\Pr\left[Y = \frac{1}{5}\mu X \leq \frac{1}{5}\mu x\right],$$

since Y has distribution (15.4a) with μ equal to 5, and A equal to $5 \times$ (original λ)/ μ . The intervals of x in the tables vary between 0.005 and 0.5. They were chosen so that the differences between successive tabulated values of $\Pr[X \leq x]$ rarely exceed 0.005.

Tables of the standard Wald probability density function (15.3) and cumulative distribution function (15.16) have been published by Krapivin (1965). They contain values of each function to six significant figures for

$$\phi = 0.01(0.01)0.1(0.1)4.0(0.2)5.0(0.5)10$$

and for various values of x . The coverage of x decreases with the increase in

the values of ϕ . For example, when $\phi = 0.01$, one has

$$x = 0(0.0001)0.01(0.01)1(0.05)6(0.1)31(0.5)81(1)231(25)1181,$$

and when $\phi = 2.0$, $x = 0(0.01)2(0.05)7(0.2)12.0$. These tables also contain the modal values to six significant figures for

$$\phi = 0.0001(0.0001)0.0100(0.01)1.00(0.1)6.0(1)55, \\ 60(10)550, 800(100)5700, 60000(10000)550000.$$

Chan, Cohen, and Whitten (1983) give tables of $F_x(x)$ to 6 decimal places for $x = -3.0(0.1)5.9$ with $a_r = 0.0(0.1)1.2$ and $x = -1.5(0.1)7.4$ with $a_r = 1.3(0.1)2.5$. Extensive tables of percentage points of the $IG(\lambda, \lambda^2)$ distribution indexed by parameter A for

$$\lambda = 0.02(0.02)4(0.04)6(0.2)35(1)100(2)150(4)250(10)300(20) \\ 600(40)2000(80)4000$$

and for cumulative probability 0.001, 0.005, 0.01(0.01)0.99, 0.995, 0.999, are presented to eight significant figures in a CRC Handbook (1989) (J. A. Koziol, editor).

11 APPLICATIONS

Inverse Gaussian distributions have been used to explain the motion of particles influenced by Brownian motion [Wasan (1968b)]. In particular, they have been used to study the motion of particles in a colloidal suspension under an electric field [Tweedie (1947)].

It has been suggested [Tweedie (1957a)] that because of the statistical independence between \bar{X} and $1/\hat{\lambda}$, an analogue of the analysis of variance for nested classifications can be performed. This analogue uses the tables of χ^2 and F developed for the analysis of variance where the measure of dispersion is given by (15.22b).

The main, and the most familiar, applications of Wald distributions are in sequential analysis [e.g., Wald (1947); Bartlett (1956)]. Some authors have used this distribution in various physical applications connected with diffusion processes with boundary conditions. It appears in the calculation of the distribution of time of first hitting the boundary in a random walk.

In Russian literature on electronics and radiotechnique, the Wald distribution is often used, and several studies on this distribution have been published in these journals [e.g., Basharinov, Fleishman, and Samochina (1959); Sigangirov (1962)]. [The Krapivin (1965) extensive tables described above have also been published by the Soviet Institute of Radiotechnique and Electronics.]

Marcus (1975) has suggested that an inverse Gaussian distribution might be used in place of a lognormal distribution when a longtailed distribution is expected to be appropriate—for example, in distribution of particle size in aggregates [see Bardsley (1980) for a related application in meteorology and also Lawrence (1984) in business applications]. If distributions of sums of independent random variables (convolutions) are to be studied, it may be useful to remember that if the mutually independent random variables X_i ($i = 1, \dots, n$) are distributed as $\text{IG}(\mu_i, c\mu_i^2)$, respectively, then $(X_1 + X_2 + \dots + X_n)$ has an $\text{IG}(\sum_{i=1}^n \mu_i, c(\sum_{i=1}^n \mu_i)^2)$ distribution (see page 267).

In recent years the inverse Gaussian distribution has played versatile roles in models of stochastic processes including the theory of generalized linear models [McCullagh and Nelder (1983)], reliability and lifetime data analysis [Padgett and Tsai (1986)], accelerated life testing [Bhattacharyya and Fries (1982)], and repair time distributions, especially in cases of preponderance of early failures [Chhikara and Folks (1977)]. In industrial quality control Edgeman (1989a, b) has developed control charts and sampling plans based on inverse Gaussian process distributions.

More recently Dhulesia, Bernicet, and Deheuvels (1991) have provided theoretical justification, based on the properties of Brownian motion with drift, for preferring inverse Gaussian to lognormal or gamma distributions to describe distributions of slug lengths in pipelines, and verified this conclusion by fitting data. (The fit often breaks down for very short slug lengths, which are likely to be produced by special physical phenomena.)

Hougaard (1984) and Feaganes and Suchindran (1991) advocates the use of the inverse Gaussian distribution for distribution of "frailty" [a concept recently developed in survival analysis; e.g., see Hougaard (1984)]. Frailty occurs in models of heterogeneity. Ordinary life table analyses implicitly assume that population is homogeneous. If z is frailty, then the hazard rate (or death rate) at age t for a person with frailty z is assumed to be of the multiplicative form

$$\theta(t; z) = z\theta(t),$$

where $\theta(t)$ is independent of z and describes the age effect.

An advantage of using inverse Gaussian to represent the distribution of frailty is its closure property. If frailty in the population is distributed as an inverse Gaussian at the formation of the cohort (e.g., birth), then frailty will still have an inverse Gaussian distribution among survivors at any time after the formation of the cohort. In fact, if the frailty is distributed as $\text{IG}(\mu, A)$, then the distribution of z given $T \geq t$ is $\text{IG}(\mu_t, A)$, where $\mu_t = \mu \{1 - 2\lambda\mu^{-2} \int_0^t \theta(u) du\}^{-1/2}$.

Another advantage is that the coefficient of variation for this conditional distribution of heterogeneity decreases with age (unlike the case of the gamma distribution where it remains constant); that is to say, the survivors become more identical with the passage of time.

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CHAPTER 16

Cauchy Distribution

1 HISTORICAL REMARKS

The density function $\pi^{-1}(1+x^2)^{-1}$, that is commonly referred to as the Cauchy density, or rather curves proportional to $(x^2+a^2)^{-1}$ —have been studied in the mathematical world for over three centuries. An excellent historical account of the distribution has been prepared by **Stigler (1974)**. As he points out, the curve seems to have appeared first in the works of Pierre de Fermat in the midseventeenth century and was subsequently studied by many including Sir Isaac Newton, Gottfried Leibniz, Christian Huygens, Guido Grandi, and Maria Agnesi; interestingly the curve had acquired the name the "Witch of Agnesi" derived from the name of the last-mentioned Italian mathematician who lived from 1718 to 1799. She had discussed the properties of the Cauchy curve and referred to it as la *Versiera* (Italian for "witch"), following the term introduced by Grandi (1718). Grandi's construction and interpretation of the Cauchy density is very simply the locus of points C in Fig. 16.1 as K goes from $-\infty$ to ∞ with the angle at C remaining a right angle.

Siméon Denis Poisson (1824) was the first to notice that the distribution with density $\pi^{-1}(1+x^2)^{-1}$ has some peculiar properties and could provide counterexamples to some generally accepted results and concepts in statistics. For example, by presenting the characteristic function of the Cauchy distribution, Poisson showed that a proof given by **Laplace** for the **large-sample** justification for Legendre's principle of least squares through the central limit theorem breaks down as the second term in Laplace's expansion of the characteristic function would not be negligible for large n (the sample size). As Eisenhart (1971) indicated, it is this simple form of the characteristic function that may have led Poisson to consider this heavy-tailed density function. But this distribution, known as the "Cauchy **distribution**," became associated with **Augustin Louis Cauchy** (1853) when he, in response to an article by I. J. **Bienaymé** (1853) criticizing a method of interpolation suggested earlier by Cauchy, considered the density function and showed that Legendre's least-squares does not provide the "most probable results" in this case as it does in the case of normally distributed errors. More elaborate historical details in this regard are in **Stigler (1974)**.

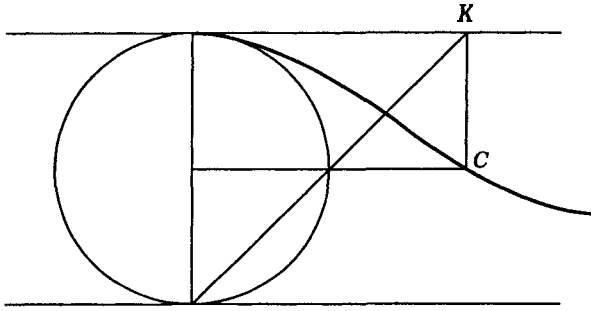


Figure 16.1 Grandi's 1718 Construction of the "Cauchy" Density.

2 DEFINITION AND PROPERTIES

The special form of the **Pearson** Type VII distribution, with **probability density function**

$$(\pi\lambda)^{-1} \left[1 + \left\{ \frac{x - \theta}{\lambda} \right\}^2 \right]^{-1}, \quad \lambda > 0, \quad (16.1)$$

is called the **Cauchy distribution** [Cauchy (1853) eq. (25), p. 2061. The cumulative distribution function is

$$\frac{1}{2} + \pi^{-1} \tan^{-1} \left[\frac{x - \theta}{\lambda} \right]. \quad (16.2)$$

The parameters θ and λ are location and scale parameters, respectively. The distribution is symmetrical about $x = \theta$. The median is θ ; the upper and lower quartiles are $\theta \pm \lambda$. The probability density function has points of inflexion at $\theta \pm \lambda/\sqrt{3}$. It may be noted that the values of the cumulative distribution at the points of inflexion are 0.273 and 0.727, as compared with the corresponding values 0.159 and 0.841 for the normal distribution.

If X has pdf (16.1), then the probability density function of $Y = A + BX$ is of the same form as that of X , with θ replaced by $A + B\theta$ and λ replaced by $|B|\lambda$. The distribution does not possess finite moments of order greater than or equal to 1, and so does not possess a finite expected value or standard deviation. (However, θ and λ are location and scale parameters, respectively, and may be regarded as being analogous to mean and standard deviation.) **Goria** (1978) derived expressions for the fractional absolute moments of a Cauchy variable. The most notable difference between the normal and Cauchy distributions is in the longer and flatter tails of the latter. These differences are illustrated in Tables 16.1 and 16.2.

It should be mentioned here that **Balanda** (1987) carried out a kurtosis comparison of the Cauchy and **Laplace** distributions. Although the coefficient

Table 16.1 Comparison of Cauchy and Normal Distributions

x	$\Pr\{X \leq x\}$		x	$\Pr\{X \leq x\}$	
	Cauchy	Normal		Cauchy	Normal
0.0	0.5000	0.5000	2.2	0.8642	0.9311
0.2	0.5628	0.5537	2.4	0.8743	0.9472
0.4	0.6211	0.6063	2.6	0.8831	0.9602
0.6	0.6720	0.6571	2.8	0.8908	0.9705
0.8	0.7148	0.7053	3.0	0.8976	0.9785
1.0	0.7500	0.7500	3.2	0.9036	0.9845
1.2	0.7789	0.7919	3.4	0.9089	0.9891
1.4	0.8026	0.8275	3.6	0.9138	0.9924
1.6	0.8222	0.8597	3.8	0.9181	0.9948
1.8	0.8386	0.8876	4.0	0.9220	0.9965
2.0	0.8524	0.9113			

Note: The Cauchy distribution is in standard form (16.3); the normal distribution has expected value zero and standard deviation $(0.67445)^{-1} = 1.4827$. The two distributions have the same median ($x = 0$) and upper and lower quartiles ($x = \pm 1$). Since both distributions are symmetrical about $x = 0$, there is no need to tabulate negative values of x .

of kurtosis β_2 is infinite for Cauchy and 6 for the double exponential, Balanda noted that this moment-based comparison is inadequate, since it fails to recognize the dominant features of the two distributions: the Cauchy's long tail and the double exponential's dramatic peak (see Chapter 24). For example, Horn (1983) classified the double exponential as being more peaked than the Cauchy distribution, while Rosenberger and Gasko (1983) classified the Cauchy as having heavier tails than the double exponential distribution. Since the moment-based orderings are not helpful because none of the Cauchy's moments are finite as mentioned earlier, Balanda made a kurtosis comparison using kurtosis orderings following the lines of van Zwet (1964) (see Chapter 33).

Table 16.2 Percentage Points of Standard Cauchy Distribution

$\Pr\{X \leq x\}$	x
0.5	0.0000
0.6	0.3249
0.7	0.7265
0.75	1.0000
0.8	1.3764
0.85	1.9626
0.9	3.0777
0.95	6.3138
0.975	12.7062

There is no standardized form of the Cauchy distribution, as it is not possible to standardize without using (finite) values of mean and standard deviation, which do not exist in this case. However, a standard form is obtained by putting $\theta = 0, A = 1$. The standard pdf is

$$\pi^{-1}(1 + x^2)^{-1} \tag{16.3}$$

and the standard cdf is

$$\frac{1}{2} + \pi^{-1} \tan^{-1}x. \tag{16.4}$$

(Note that this is the *t-distribution* with 1 degree of freedom; see Chapter 28.) Values of (16.4) are shown in Table 16.1. Percentage points [values X_α such that $\Pr[X \leq X_\alpha] = \alpha$] are shown in Table 16.2.

The characteristic function corresponding to (16.1) is

$$E[e^{itX}] = \exp[it\theta - |t|\lambda]. \tag{16.5}$$

If X_1, X_2, \dots, X_n are independent random variables with pdf's

$$p_{X_j}(x) = (\pi\lambda_j)^{-1} \left[1 + \left\{ \frac{x - \theta_j}{\lambda_j} \right\}^2 \right]^{-1}, \quad \lambda_j > 0; j = 1, 2, \dots, n, \tag{16.6}$$

then the characteristic function of $S_n = \sum_{j=1}^n X_j$ is

$$\exp \left[it \sum_{j=1}^n \theta_j - |t| \sum_{j=1}^n \lambda_j \right].$$

Hence S_n has a Cauchy probability density function, as in (16.1), with $A = \sum_{j=1}^n \lambda_j; \theta = \sum_{j=1}^n \theta_j$. More generally, $\sum_{j=1}^n a_j X_j$ has a Cauchy probability density function, as in (16.1) with $A = \sum_{j=1}^n |a_j| \lambda_j; \theta = \sum_{j=1}^n a_j \theta_j$. In particular, putting

$$\begin{aligned} \lambda_1 &\equiv \lambda_2 = \dots = \lambda_n = A, \\ \theta_1 &= \theta_2 = \dots = \theta_n = \theta, \\ a_1 &= a_2 = \dots = a_n = n^{-1} \end{aligned}$$

we see that the arithmetic mean $n^{-1} \sum_{j=1}^n X_j$ of n independent random variables each having probability density function (16.1) has the same Cauchy distribution as each of the X_j 's. It should be pointed out here that Dwass (1985), Nelsen (1985), and Blyth (1986) derived the distribution of a sum of

independent Cauchy random variables using the convolution formula (instead of the more advanced characteristic function approach described above).

Thus the Cauchy distribution is a "stable" distribution and is also "infinitely divisible." Puglisi (1966) has shown that a variable with a Cauchy distribution can be represented as the sum of two independent random variables, each having infinitely divisible, but *not* stable, distributions. **Dugué** (1941) presented a decomposition of Cauchy using Raikov theorem. Bondesson (1987) has shown that the half-Cauchy (or folded-Cauchy) distribution is infinitely divisible. Similarly Rohatgi, Steutel, and **Székely** (1990) have proved that the product and quotient of two *i.i.d.* standard Cauchy random variables, with density as in (16.3), are infinitely divisible too. Springer and Thompson (1966) have obtained explicit formulas for the probability density function of the product of n (≤ 10) independent and identically distributed Cauchy variables (each with $\theta = 0$, $A = 1$).

If X_1 and X_2 are independent, and each has a standard Cauchy distribution, then $(b_1X_1 + b_2X_2)$ has a Cauchy distribution and is in fact distributed as $(|b_1| + |b_2|)X_1$. **Pitman** and Williams (1967) have extended this result, obtaining [in a form suggested by Williams (1969)]:

"Suppose that the sets of numbers $\{w_j\}$ and $\{a_j\}$ are such that $w_j \geq 0$, $\sum_{j=1}^{\infty} w_j = 1$, and $\{a_j\}$ possesses no limit point. Then, if X has a standard Cauchy distribution, so does

$$\sum_{j=1}^{\infty} w_j(1 + a_jX)(a_j - X)^{-1}."$$

Similarly, when X has a standard Cauchy distribution, Kotlarski (1977) has shown that for $n = 2, 3, \dots$, the random variables

$$Z_2 = \frac{2X}{1 - X^2}, \quad Z_3 = \frac{3X - X^3}{1 - 3X^2}, \quad Z_4 = \frac{4X - X^3}{1 - 6X^2 + X^4},$$

$$\dots, \quad Z_n = \frac{\binom{n}{1}X - \binom{n}{3}X^3 + \binom{n}{5}X^5 - \dots}{1 - \binom{n}{2}X^2 + \binom{n}{4}X^4 - \binom{n}{6}X^6 + \dots}$$

all have the same standard Cauchy distribution.

Gupta and Govindarajulu (1975) derived the distribution of the quotient of two independent Hotelling's T^2 -variates in terms of a hypergeometric function of the second kind, which includes the distribution of the quotient of two independent Cauchy variates as a special case. Eicker (1985) proved that

sums of independent squared Cauchy variables grow quadratically, that is,

$$\Pr\left(n^2 o(1) < \sum_{i=1}^n X_i^2 < \frac{n^2}{o(1)}\right) \rightarrow 1 \text{ as } n \rightarrow \infty$$

for any positive $o(1)$ sequence; see Bose (1987) for some further remarks in this direction. Zhang (1990) has discussed the distribution of the squared sum of independent Cauchy variables. Salama (1983) has discussed additional problems associated with the Cauchy distribution.

3 ORDER STATISTICS

If X_1, X_2, \dots, X_n are independent random variables each with standard Cauchy density function (16.3), and $X'_1 \leq X'_2 \leq \dots \leq X'_n$ are the corresponding order statistics, then the density function of X'_r ($1 \leq r \leq n$) is

$$p_{X'_r}(x) = \frac{n!}{(r-1)!(n-r)!} \left(\frac{1}{2} + \frac{1}{\pi} \tan^{-1} x\right)^{r-1} \left(\frac{1}{2} - \frac{1}{\pi} \tan^{-1} x\right)^{n-r} \\ \times \frac{1}{\pi(1+x^2)}, \quad -\infty < x < \infty, \quad (16.7)$$

and the joint density function of X'_r and X'_s ($1 \leq r < s \leq n$) is

$$p_{X'_r, X'_s}(x, y) = \frac{n!}{(r-1)!(s-r-1)!(n-s)!} \left(\frac{1}{2} + \frac{1}{\pi} \tan^{-1} x\right)^{r-1} \\ \times \left(\frac{1}{\pi} \tan^{-1} y - \frac{1}{\pi} \tan^{-1} x\right)^{s-r-1} \left(\frac{1}{2} - \frac{1}{\pi} \tan^{-1} y\right)^{n-s} \\ \times \frac{1}{\pi^2(1+x^2)(1+y^2)}, \quad -\infty < x < y < \infty. \quad (16.8)$$

Since the standard Cauchy random variable does not possess finite moments of order ≥ 1 , an application of Sen's (1959) theorem immediately reveals that expected values of X'_1 and X'_n , and the variances of X'_1, X'_2, X'_{n-1} and X'_n are infinite; interested readers may also refer to Stoops and Barr (1971) for some insight into this existence-of-moments problem.

By employing numerical integration methods, Barnett (1966b) computed from (16.7) and (16.8) values of means, variances, and covariances of order statistics for sample size $n = 5(1)16(2)20$. Explicit expressions (involving infinite series) can be derived for the **single** and the product moments of order statistics as shown recently by Vaughan (1993). For example, one may

write from (16.7) that

$$\begin{aligned}
 E[X'_r] &= \int_{-\infty}^{\infty} y p_{X'_r}(y) dy \\
 &= \frac{n!}{(r-1)!(n-r)! \pi^n} \int_{-\pi/2}^{\pi/2} \left(\frac{\pi}{2} + y\right)^{r-1} \left(5 - y\right)^{n-r} \tan y dy \\
 &= \frac{n!}{(r-1)!(n-r)! \pi^n} (I_1 + I_2), \tag{16.9}
 \end{aligned}$$

where I_1 and I_2 are integrals over the ranges $[0, \pi/2]$ and $[-\pi/2, 0]$ with the same integrand. Using Gradshteyn and Ryzhik's (1965) integral formula that for $|y| < \pi$ and for any $a \geq 1$,

$$\int y^a \cot y dy = \sum_{i=0}^{\infty} (-1)^i \frac{2^{2i} B_{2i} y^{a+2i}}{(a+2i)(2i)!},$$

where B_{2i} is the Bernoulli number given by

$$B_0 = 1,$$

$$B_{2i} = (-1)^{i-1} (2i)! \zeta(2i) / (2^{2i-1} \pi^{2i}), \quad i \geq 1,$$

with $\zeta(2i) = \sum_{j=1}^{\infty} j^{-2i}$ [see Gradshteyn and Ryzhik (1965)], we get

$$I_1 = \sum_{j=0}^{r-1} (-1)^j \binom{r-1}{j} \pi^{r-1-j} \sum_{i=0}^{\infty} \frac{(-1)^i 2^{2i} B_{2i} (\pi/2)^{n-r+j+2i}}{(n-r+j+2i)(2i)!}. \tag{16.10}$$

Similarly we find

$$I_2 = - \sum_{j=0}^{n-r} (-1)^j \binom{n-r}{j} \pi^{n-r-j} \sum_{i=0}^{\infty} \frac{(-1)^i 2^{2i} B_{2i} (\pi/2)^{r-1+j+2i}}{(r-1+j+2i)(2i)!}. \tag{16.11}$$

Substitution of the expressions of I_1 and I_2 in (16.10) and (16.11), respectively, into (16.9) yields

$$\begin{aligned}
 E[X'_r] &= \frac{n!}{(r-1)!(n-r)! \pi} \\
 &\times \left\{ \sum_{j=0}^{r-1} (-1)^j \binom{r-1}{j} 2^{-(n-r+j)} \sum_{i=0}^{\infty} \frac{(-1)^i B_{2i} \pi^{2i}}{(n-r+j+2i)(2i)!} \right. \\
 &\left. - \sum_{j=0}^{n-r} (-1)^j \binom{n-r}{j} 2^{-(r-1+j)} \sum_{i=0}^{\infty} \frac{(-1)^i B_{2i} \pi^{2i}}{(r-1+j+2i)(2i)!} \right\}. \tag{16.12}
 \end{aligned}$$

Similar explicit expressions for the second moment and the product moment have been derived by Vaughan (1993).

For large n , of course, one may use David and Johnson's (1954) approximation to derive approximate expressions for the means, variances and covariances of order statistics as

$$E[X'_r] \doteq \tan\left\{\pi\left(\frac{r}{n} - \frac{1}{2}\right)\right\} = -\cot\left(\frac{\pi r}{n}\right), \quad (16.13)$$

$$\text{Var}(X'_r) \doteq \frac{1}{n}\pi^2\left(\frac{r}{n}\right)\left(1 - \frac{r}{n}\right)\text{cosec}^4\left(\frac{r\pi}{n}\right), \quad (16.14)$$

and

$$\text{Cov}(X'_r, X'_s) \doteq \frac{1}{n}\pi^2\left(\frac{r}{n}\right)\left(1 - \frac{s}{n}\right)\text{cosec}^2\left(\frac{r\pi}{n}\right)\text{cosec}^2\left(\frac{s\pi}{n}\right). \quad (16.15)$$

Writing, for example,

$$\begin{aligned} x(u) &= F_X^{-1}(u) = \cot\{\pi(1-u)\} = \sum_{i=0}^{\infty} (-1)^i 2^{2i} \pi^{2i-1} \frac{B_{2i}(1-u)^{2i-1}}{(2i)!} \\ &= \sum_{i=0}^{\infty} b_{2i}(1-u)^{2i-1}, \end{aligned} \quad (16.16)$$

Hall (1978) has derived an asymptotic formula for mean of X'_{n-r} (for $1 \leq r \leq n-2$) as

$$E[X'_{n-r}] = \frac{n!}{r!} \sum_{i=0}^N b_{2i} \frac{(r+2i-1)!}{(n+2i-1)!} + \varepsilon_N; \quad (16.17)$$

the error term ε_N is always negative and is bounded by

$$|\varepsilon_N| \leq b \frac{n!(r+2N+1)!}{r!(n+2N)!(n-r-1)!} \left\{ 1 - \frac{r+2N+2}{2(n+2N+1)} \right\}$$

where $b = \sup_{i \geq N+1} |b_{2i}|$. By using inequalities for B_{2i} [see Abramowitz and Stegun (1965, p. 208)], Hall has also shown that

$$\frac{2}{\pi} \ll -2b \leq \frac{2}{\pi(1-2^{1-2i})} \quad \text{for } i \geq 1,$$

so that $b_{2i} \rightarrow -2/\pi$ as $i \rightarrow \infty$, and the error $|b_{2i} + 2/\pi|$ is less than 4×10^{-7} if $i > 10$. Approximate expressions for the second single moment

and the product moment similar to that in (16.17) have also been derived by Hall (1978). Mention should also be made of Joshi (1969), who has modified the orthogonal inverse expansion method of Sugiura (1962) to derive bounds and approximations for moments of order statistics from the Cauchy distribution.

The asymptotic distribution of the largest order statistic X'_n can be obtained from the general formulas of Fréchet (1927), Fisher and Tippett (1928), and von Mises (1936) [see Galambos (1987)]. The Cauchy distribution belongs to the class for which

$$\lim_{x \rightarrow \infty} \{1 - F_X(x)\}x^2 = A > 0. \quad (16.18)$$

The asymptotic distribution of the **extremal** quotient ($= X'_n / |X'_1|$) has been discussed by Gumbel and Keeney (1950).

4 METHODS OF INFERENCE

It is not possible to use the method of moments to estimate θ and A by equating sample and population first and second moments. (It may be remembered, incidentally, that it was shown in Section 2 of this chapter that the arithmetic mean, $n^{-1}\sum_{j=1}^n X_j = \bar{X}$, has the same distribution as any one of the X 's. Thus \bar{X} is no more informative than any single one of the X_j 's, although one might feel it could be a useful estimator of θ .) It is possible to derive methods of estimation using moments of fractional order, but these are not used here.

4.1 Methods Based on Order Statistics

The simple form of cumulative distribution function (16.2) makes it possible to obtain simple estimators by equating population percentage points (quantiles) and sample estimators thereof. The $100p\%$ quantile X_p of the distribution satisfies the equation

$$\Pr[X \leq X_p] = p;$$

a convenient estimator from the sample is the r th-order statistic, X'_r , with $r = (n + 1)p$. We will denote this estimator by \hat{X}_p . The value of X_p depends on θ and A .

If p_1 and p_2 are distinct numbers between 0 and 1, then the equations

$$\hat{X}_{p_j} = X_{p_j}, \quad j = 1, 2,$$

lead to the estimators

$$\tilde{\lambda} = (\hat{X}_{p_1} - \hat{X}_{p_2})(\cot \pi p_2 - \cot \pi p_1)^{-1}, \quad (16.19)$$

$$\tilde{\theta} = (\hat{X}_{p_1} \cot \pi p_2 - \hat{X}_{p_2} \cot \pi p_1)(\cot \pi p_2 - \cot \pi p_1)^{-1}. \quad (16.20)$$

[Note that $\tan[\pi(p - \frac{1}{2})] = -\cot \pi p$ as in (16.13).]

In the symmetrical case with $p_1 = p > 1/2 > 1 - p = p_2$,

$$\tilde{\lambda} = \frac{1}{2}(\hat{X}_p - \hat{X}_{1-p})\tan[\pi(1 - p)], \quad (16.21)$$

$$\tilde{\theta} = \frac{1}{2}(\hat{X}_p + \hat{X}_{1-p}). \quad (16.22)$$

If the available observations can be represented by values of n independent random variables, X_1, X_2, \dots, X_n , each with probability density function of form (16.1), and \hat{X}_p, \hat{X}_{1-p} are appropriate order statistics [so that $E(\hat{X}_p) \doteq X_p, E(\hat{X}_{1-p}) \doteq X_{1-p}$], then

$$n \text{Var}(\tilde{\lambda}) \doteq \lambda^2 [2\pi^2(1 - p)(2p - 1)] \text{cosec}^2 2\pi p, \quad (16.23)$$

$$n \text{Var}(\tilde{\theta}) \doteq \lambda^2 [\frac{1}{2}\pi^2(1 - p)] \text{cosec}^4 \pi p. \quad (16.24)$$

The estimators $\tilde{\lambda}$ and $\tilde{\theta}$ are uncorrelated; $\tilde{\lambda}$ is an unbiased estimator of θ . The approximate variance [by (16.24)] of $\tilde{\theta}$ is minimized by taking $p = 55.65\%$; the corresponding value of the right-hand side of (16.24) is $2.33h^2$. The **Cramér-Rao** lower bound for the variance of an unbiased estimator of θ is $2h^2/n$, so the asymptotic efficiency of $\tilde{\theta}$ is 86%. (The quoted lower bound applies whether A is known or not.) Putting $r = n/2$ in (16.14), we see that the variance of the median is approximately $\frac{1}{4}\pi^2\lambda^2/n = 2.47h^2/n$. The median is an unbiased estimator of θ with asymptotic efficiency 81%.

Rothenberg, Fisher, and Tilanus (1964) obtained an approximation to the variance of the symmetrical censored arithmetic mean, θ' , say, where the censoring causes omission of the $\frac{1}{2}pn$ (approx.) lowest and $\frac{1}{2}pn$ (approx.) highest observed values in a random sample of size n . The formula they obtained is

$$n \text{Var}(\theta') \doteq \lambda^2 \left[p(1 - p)^{-2} \cot^2(\frac{1}{2}\pi p) + 2\pi^{-1}(1 - p)^{-2} \cot(\frac{1}{2}\pi p) - (1 - p)^{-1} \right]. \quad (16.25)$$

The statistic θ' is an unbiased estimator of θ . By taking $p \doteq 0.76$ the right-hand side of (16.25) attains its minimum value $2.28h^2$. The asymptotic efficiency of the estimator θ' is then 88%. [See also Bloch (1966).]

This "optimum" $\tilde{\theta}'$ uses the values of only the central 24% of the observations, while the "best" pair of order statistics to use in $\tilde{\theta}$ are separated by only the central 11% of observations. For the normal distribution (see Chapter 13, Section 8) considerably larger central groups of observations give "optimum" results. This reflects the greater variability in the "tails" of the Cauchy distribution.

Bloch (1966) discussed the asymptotic best linear unbiased estimation of θ based on k optimally selected quantiles, by following the method of Ogawa (1951). Let $X'_{n_1} \leq X'_{n_2} \leq \dots \leq X'_{n_k}$ be the k -order statistics of interest, and let $X_{\xi_1}, X_{\xi_2}, \dots, X_{\xi_k}$ be the corresponding population quantiles, that is, $F(X_{\xi_i}) = \xi_i$ for $i = 1, 2, \dots, k$. It is then known from Ogawa (1951) that the asymptotic relative efficiency of the BLUE of θ is

$$\varepsilon = \frac{K_1}{E[\{p'(X)/p(X)\}^2]} = 2K_1, \quad (16.26)$$

where

$$K_1 = \sum_{i=1}^{k+1} \frac{(p_i - p_{i-1})^2}{\xi_i - \xi_{i-1}}, \quad (16.27)$$

with $p_i = p_X(X_{\xi_i})$, $p_0 = p_{k+1} = 0$, $\xi_0 = 0$, $\xi_{k+1} = 1$. The optimal value of $\xi = (\xi_1, \dots, \xi_k)$ may be obtained by minimizing K_1 in (16.27) with respect to ξ_1, \dots, ξ_k . The corresponding ABLUE is then given by

$$\theta^{**} = \sum_{i=1}^k a_i X'_{n_i}, \quad (16.28)$$

$$a_i = \frac{p_i}{K_1} \left\{ \left(\frac{p_i - p_{i-1}}{\xi_i - \xi_{i-1}} \right) - \left(\frac{p_{i+1} - p_i}{\xi_{i+1} - \xi_i} \right) \right\}, \quad i = 1, 2, \dots, k. \quad (16.29)$$

We note here that Kariya, Sinha, and Subramanyam (1981) derived nearly efficient estimators for θ based on 3 or 5 optimally determined order statistics. Chan (1970) discussed the asymptotic best linear unbiased estimation of the parameters θ and A based on k optimally selected order statistics, when one or both parameters are unknown. For example, by assuming the spacing to be symmetric, he determined the optimal spacings for the estimation of θ when A is known. Chan also showed that the asymptotic best linear unbiased estimates of θ and A , when both are unknown, determined by the spacings $\xi_i = i/(k+1)$, $i = 1, 2, \dots, k$, have joint asymptotic relative efficiency of at least 65% for all $k > 2$.

Balmer, Boulton, and Sack (1974) showed however that in the case of the estimation of θ , when A is known, optimal k -spacings (corresponding to the maximum asymptotic relative efficiency) are asymmetric when $k = 4m - 1$,

which is in contrast to Chan's assumption of symmetric spacing. By combining a dynamic programming procedure and Newton-Raphson iteration methods, they determined accurately the optimal spacings for $k = 3, 7,$ and 11 . They also proved that the spacings $\xi_i = i/(k + 1)$, $i = 1, 2, \dots, k$, is in fact the optimal spacing for the joint estimation of θ and A ; see also Chan, Chan and Mead (1973) and Cane (1974). Furthermore the joint asymptotic relative efficiency of the ABLUES θ^{**} and A^{**} , based on the aforementioned k optimal spacings, is given by

$$\text{JARE} = \left\{ \frac{k+1}{\pi} \sin\left(\frac{\pi}{k+1}\right) \right\}^4, \quad (16.30)$$

and θ^{**} and A^{**} are given by

$$\theta^{**} = \sum_{i=1}^k a_i X'_{n_i} \quad \text{and} \quad A^{**} = \sum_{i=1}^k b_i X'_{n_i}, \quad (16.31)$$

where

$$a_i = -\frac{4}{k+1} \sin^2\left(\frac{\pi i}{k+1}\right) \cos\left(\frac{2\pi i}{k+1}\right),$$

$$b_i = -\frac{4}{k+1} \sin^2\left(\frac{\pi i}{k+1}\right) \sin\left(\frac{2\pi i}{k+1}\right).$$

[For details, see Sarhan and Greenberg (1962).] Tests of hypotheses concerning $\theta = \theta_0$ and $(\theta, A) = (\theta_0, \lambda_0)$ have been considered by Chan and Cheng (1971) and Saleh, Hassanein, and Brown (1985), respectively, based on these k -optimal ABLUES.

Among estimators of form $\sum_{j=1}^n \alpha_j X'_j$ (i.e., linear functions of order statistics) the following values of α_j give asymptotically optimum estimators:

For θ ,

$$\alpha_j = \frac{\sin 4\pi \left(j(n+1)^{-1} - \frac{1}{2} \right)}{\tan \pi \left(j(n+1)^{-1} - \frac{1}{2} \right)}.$$

For A ,

$$\alpha_j = \frac{8 \tan \pi \left(j(n+1)^{-1} - \frac{1}{2} \right)}{\sec^4 \pi \left(j(n+1)^{-1} - \frac{1}{2} \right)}.$$

[See Chernoff, Gastwirth and Johns (1967).] Barnett (1966b) determined the

BLUE of θ given by

$$\theta^* = \frac{\mathbf{1}^T \Sigma^{-1} \mathbf{X}'}{\mathbf{1}^T \Sigma^{-1} \mathbf{1}} = \sum_{i=3}^{n-2} c_i X'_i, \quad (16.32)$$

and its variance given by

$$\frac{\text{Var}(\theta^*)}{\lambda^2} = \frac{1}{\mathbf{1}^T \Sigma^{-1} \mathbf{1}}, \quad (16.33)$$

where $\mathbf{1}^T = (1, 1, \dots, 1)$ and Σ is the variance-covariance matrix of $n - 4$ central order statistics. He has tabulated the coefficients c_i in (16.32) and $\text{Var}(\theta^*)$ in (16.33) for sample sizes up to 20. Weiss and Howlader (1988) extended Barnett's work by tabulating the BLUEs of θ and A for sample sizes up to 20 (since θ^* and A^* are uncorrelated due to the symmetry of the Cauchy distribution, they had to present tables only for A^*). Weiss and Howlader (1988) also presented a simple linear estimator for A to be

$$\tilde{\lambda} = \sum_{i \in I_\lambda} c_i X'_i = -\frac{1}{r} \sum_{i \in I_\lambda} \tan(\pi \tilde{q}_i) X'_i, \quad (16.34)$$

where $r = n - 4$ for even n ($I_\lambda = \{3, 4, \dots, n - 2\}$) and $r = n - 5$ for odd n ($I_\lambda = \{3, 4, \dots, (n - 1)/2, (n + 3)/2, \dots, n - 2\}$) and $\tilde{q}_i = (i - 2 + \frac{1}{2}) / (n - 1)$ for $i < n/2$ with $\tilde{q}_{n-i+1} = 1 - \tilde{q}_i$. They show that the estimator $\tilde{\lambda}$ in (16.34) has almost minimum mean squared error even for small samples. Some simplified linear estimators for θ and A based on quasi-midranges and quasi-ranges, respectively, were proposed earlier by Raghunandan and Srinivasan (1972) for the complete sample case as well as in the case of symmetrically Type-II censored samples [also see Haq (1971)].

4.2 Maximum Likelihood Inference

Based on n observations x_1, x_2, \dots, x_n from the Cauchy density in (16.1), we have the likelihood equations for θ and A to be

$$\frac{\partial \log L}{\partial \theta} = \sum_{i=1}^n \frac{2(x_i - \theta)}{\lambda^2 + (x_i - \theta)^2} = 0 \quad (16.35)$$

and

$$\frac{\partial \log L}{\partial \lambda} = \frac{n}{\lambda} - \sum_{i=1}^n \frac{2\lambda}{\lambda^2 + (x_i - \theta)^2} = 0. \quad (16.36)$$

For the problem of estimating θ when A is known, the likelihood function is occasionally multimodal. In fact, for a sufficiently small A , it will have n

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local maxima—one close to each of the n observations [see Edwards (1972)]. In general, the MLE of θ when A is fixed is a root of a polynomial of degree $2n - 1$ [refer also to Reeds (1985)]. Barnett (1966a) discussed a numerical method of finding a global maximum of θ . For this global optimization problem, given an easily derived upper bound on the second derivative of the negative of the log-likelihood function, Wingo (1983) prescribed the usage of Brent's (1973) univariate numerical global optimization method to locate the absolute maximum among several relative maxima, instead of performing an exhaustive search over the entire real line. In this case, even though the likelihood equation for θ has multiple roots, Bai and Fu (1987) proved that the maximum likelihood estimator $\hat{\theta}$ (the global maximum) converges to θ exponentially and is an asymptotically efficient estimator in the Bahadur sense. Haas, Bain, and Antle (1970) developed numerical methods for solving the likelihood equations in (16.35) and (16.36). Hinkley (1978) conducted large-scale simulations (based on 40,000 samples of size 20 and 20,000 samples of size 40) and very rarely observed the Newton-Raphson procedure to fail to converge. Copas (1975) and Gabrielsen (1982) showed that the joint likelihood function for θ and A is unimodal. Hence the two-parameter situation is easier to handle than just the location-parameter case in that even simple schemes, such as the steepest ascent, will enable to determine the MLEs of θ and A .

For a sample of size 2, Haas, Bain, and Antle (1970) showed that the MLE of (θ, A) is not unique and that all MLEs $(\hat{\theta}, \hat{\lambda})$ for observations x_1 and x_2 with $x_1 < x_2$ are given by

$$x_1 \leq \hat{\theta} \leq x_2 \quad \text{and} \quad \hat{\lambda}^2 = (\hat{\theta} - x_1)(x_2 - \hat{\theta}). \quad (16.37)$$

For an arbitrary sample size, Copas (1975) showed that the only time the MLE of (θ, λ) is not unique is when half the observations are at a point x_1 and the other half at a point x_2 , when the MLE $(\hat{\theta}, \hat{\lambda})$ is again given by (16.37). When otherwise half or more of the observations are at a point x_1 , the maximum of the likelihood function occurs at $\hat{\theta} = x_1$ and $\hat{\lambda} = 0$, a singular point for the likelihood equations in (16.35) and (16.36). However, in all other cases, the MLE of (θ, A) is the unique root of the likelihood equations in (16.35) and (16.36). Curiously enough, Ferguson (1978) showed that closed-form expressions exist for the MLE $(\hat{\theta}, \hat{\lambda})$ for samples of size 3 and 4.

Based on a sample of size 3 denoted by x_1, x_2 and x_3 with $x_1 < x_2 < x_3$, Ferguson (1978) presented the MLEs of θ and A as

$$\hat{\theta} = \frac{x_1(x_3 - x_2)^2 + x_2(x_3 - x_1)^2 + x_3(x_2 - x_1)^2}{(x_3 - x_2)^2 + (x_3 - x_1)^2 + (x_2 - x_1)^2}, \quad (16.38)$$

$$\hat{\lambda} = \frac{\sqrt{3}(x_3 - x_2)(x_3 - x_1)(x_2 - x_1)}{(x_3 - x_2)^2 + (x_3 - x_1)^2 + (x_2 - x_1)^2}. \quad (16.39)$$

Observe that $\hat{\theta}$ in (16.38) is a weighted average of the three observations with weights proportional to the squares of **the differences** of the other two. A direct substitution of the expressions of $\hat{\theta}$ and \hat{A} in (16.38) and (16.39) into formulas (16.35) and (16.36) will readily reveal that these estimates are in fact the MLEs (due to the uniqueness of the MLE established by Copas).

Based on a sample of size 4 denoted by x_1, x_2, x_3 , and x_4 with $x_1 < x_2 < x_3 < x_4$, Ferguson (1978) similarly presented the MLEs of θ and A as

$$\hat{\theta} = \frac{x_2x_4 - x_1x_3}{x_4 - x_3 + x_2 - x_1}, \quad (16.40)$$

$$\hat{\lambda}^2 = \frac{(x_4 - x_3)(x_3 - x_2)(x_2 - x_1)(x_4 - x_1)}{(x_4 - x_3 + x_2 - x_1)^2}. \quad (16.41)$$

Observe that $\hat{\theta}$ in (16.40) is a weighted average of the two middle-order statistics with weights proportional to the distance of the opposite outlier from its neighbor, if we write $\hat{\theta} = \alpha x_2 + (1 - \alpha)x_3$, where $\alpha = (x_4 - x_3) / \{(x_4 - x_3) + (x_2 - x_1)\}$. Once again, a direct substitution of the expressions of $\hat{\theta}$ and \hat{A} in (16.40) and (16.41) into formulas (16.35) and (16.36) will readily reveal that $(\hat{\theta}, \hat{\lambda})$ is in fact the MLE.

The fact that $\hat{\theta}$ is a weighted average of the sample values can be established easily for any sample size n . To do this, let us first rewrite the likelihood equations in (16.35) and (16.36) as

$$\sum_{i=1}^n \frac{1}{1 + \{(x_i - \hat{\theta})/\hat{\lambda}\}^2} = \frac{n}{2}, \quad (16.42)$$

$$\sum_{i=1}^n \frac{x_i}{1 + \{(x_i - \hat{\theta})/\hat{\lambda}\}^2} = \frac{n}{2} \hat{\theta}. \quad (16.43)$$

Upon dividing (16.43) by (16.42), we see immediately that $\hat{\theta}$ is a weighted average of the sample observations x_i (a result we have seen already explicitly for $n = 3$ and 4).

An interesting property of θ in (16.38) and (16.40) is that outlying observations have a negative effect. To be precise, changes in the values of observations in the lower and upper extreme values have the effect of pushing the estimate in the opposite direction. As Ferguson pointed out, this occurs even for equally spaced observations in a sample of size 3. To see this effect, let $x_1 = -1, x_2 = 0$ and $x_3 > 0$ in (16.38) so that

$$\hat{\theta}(x_3) = \frac{x_3(1 - x_3)}{2(x_3^2 + x_3 + 1)}.$$

At $x_3 = 1$, we have $\hat{\theta}(x_3) = 0$ as it should be, due to the symmetry, but for $x_3 > 1$ we see that $\hat{\theta}(x_3) < 0$. In fact $(d/dx_3)\hat{\theta}(x_3) < 0$ for all $x_3 > (\sqrt{3} - 1)/2 = 0.366\dots$. This interesting property had been noticed earlier by

Barnett (1966b), Bloch (1966), Chan (1970) and Balmer, Boulton, and Sack (1974) in the best linear unbiased estimator of θ .

Quite recently McCullagh (1992a, b, c; 1993) established some remarkable results on properties of the MLEs. First of all, he considers n i.i.d. variables from a Cauchy population with density function

$$p_X(x; \eta) = \frac{|\lambda|}{\pi|x - \eta|^2} \quad (16.44)$$

in which x is a real number and $\eta = \theta + i\lambda$ is the Cauchy parameter represented as a complex number. The parameter space here should be taken as the complex plane in which complex conjugate pairs of points are identified; this set is isomorphic to the upper half-plane. He then proved that for any function $h(\cdot)$ analytic on the upper half-plane, $h(\hat{\eta})$ is unbiased for $h(\eta)$ provided that the expectation exists. For example, it immediately implies that $E(\hat{\eta}) = \eta$ for $n \geq 3$, $E(\hat{\eta}^k) = \eta^k$ for integer $k \leq n - 2$, $E(\log \hat{\eta}) = \log \eta$ for $n \geq 3$, and so on. Furthermore the Cauchy family has the property (as mentioned earlier in Section 2) that if $X \rightarrow \text{Cauchy}(\eta)$, then

$$\frac{aX + b}{cX + d} \rightarrow \text{Cauchy}\left(\frac{a\eta + b}{c\eta + d}\right) \quad (16.45)$$

for all real numbers a , b , c , and d with $ad - bc \neq 0$. That is, the Cauchy family of distributions is closed under the action of the real Mobius group G , and the parameter is equivariant. Let $T = T_1 + iT_2$ be the MLE of $\eta = \theta + i\lambda$ based on sample observations x_i , $i = 1, \dots, n$. It then immediately follows from (16.45) that

$$T\left(\frac{ax + b}{cx + d}\right) = \frac{aT(x) + b}{cT(x) + d}. \quad (16.46)$$

That is, if the components of x are transformed by $h \in G$, the MLE derived from hx will be the same as the transformation h applied to the MLE based on x . In other words, T is equivariant under G . Upon exploiting this equivariance feature, McCullagh proved that the joint density of T has the form

$$p(t_1, t_2; \eta) = \frac{1}{4\pi t_2^2} p_n(\chi), \quad (16.47)$$

where $\chi = |t - \eta|^2 / (4t_2\lambda)$. He derived explicit expressions for $p_3(\chi)$ and $p_4(\chi)$ and also the asymptotic large-sample limit. Note that in this derivation of the distribution of T , explicit closed-form expression of T is not required although the closed form expressions of the MLEs given earlier for $n = 3$ and 4 offer no help in obtaining the joint density function. It is the form of the density in (16.47) that is used by McCullagh to establish the remarkable property that $E[h(T)] = h(\eta)$ if $h(\cdot)$ is harmonic and the expectation is finite. As an immediate consequence, of course, we have the result that both components of the MLE are unbiased for $n \geq 3$.

Further, by using the explicit expressions of

$$p_3(\chi) = \frac{3\sqrt{3}}{\pi\{1 + 3\chi(1 + \chi)\}},$$

$$p_4(\chi) = \frac{12 \log(1 + 2\chi)}{\pi^2 \chi(\chi + 1)(2\chi + 1)},$$

McCullagh derived fairly simple forms for the marginal densities of $T_1 = \hat{\theta}$ and $T_2 = \hat{\lambda}$ for sample sizes 3 and 4. For example, when $n = 3$,

$$p_{T_1}(t_1) = \frac{3}{\pi(1 + t_1^2)\sqrt{4 + 3t_1^2}},$$

$$p_{T_2}(t_2) = \frac{2\sqrt{3}}{\pi(1 + t_2^2)^{3/2}} \times \frac{\sqrt{2}}{\sqrt{1 + \varepsilon} \{1 + \sqrt{1 + \varepsilon}\}^{1/2}}, \quad t_2 > 0,$$

where $\varepsilon = 4t_2^2 / \{3(1 + t_2^2)^2\}$. Interestingly the density of T_2 given above is approximately the positive half of a Student's t -distribution on two degrees of freedom (see Chapter 28), since the second factor is bounded between 0.83 and 1.0 as ε is between 0 and $\frac{1}{3}$.

4.3 Conditional Inference

Suppose that X_1, X_2, \dots, X_n , are i.i.d. random variables from Cauchy population with density as in (16.1). Fisher (1934) observed that the configuration statistic A with components $a_i = (X_i - \hat{\theta})/\hat{\lambda}$ is ancillary in the sense that the distribution of A does not depend on the parameter (θ, λ) as is evident from the invariance of A under location and scale transformations. Here $\hat{\theta}$ and $\hat{\lambda}$ need not be the maximum likelihood estimators. In fact, any pair of equivariant estimators for (θ, λ) will suffice. The basic philosophy behind this method of inference [Fisher (1934)] is that the precision with which the parameters θ and λ are estimated depends on the configuration observed, some configurations being more informative than others; as a result the appropriate distribution that should be used for inferential purposes is the conditional distribution of $(\hat{\theta}, \hat{\lambda})$ given the observed value of the configuration ancillary.

Lawless (1972) discussed conditional confidence interval estimation procedures for θ and λ . He discussed three cases separately: (1) θ unknown, λ known; (2) θ known, λ unknown; and (3) both θ and λ unknown. After discussing the computational aspects of using this conditional inference approach, he made some numerical comparisons of the conditional confidence interval procedures and the unconditional confidence interval procedures. We will describe this method of inference by considering case (3). First, we have the conditional joint density function of $\hat{\theta}$ and $\hat{\lambda}$, given $A = a$,

as

$$p(\hat{\theta}, \hat{\lambda} | a_1, \dots, a_{n-2}) = C \frac{\hat{\lambda}^{n-2}}{\lambda^n} \prod_{i=1}^n \left[\frac{1}{\pi \left\{ 1 + \left[(\hat{\theta} - \theta + a_i \hat{\lambda}) / \lambda \right]^2 \right\}} \right], \quad (16.48)$$

where $C = C(a_1, \dots, a_{n-2})$ is the normalizing constant. It is clear that $z_1 = (\hat{\theta} - \theta) / \lambda$ and $z_2 = \hat{\lambda} / \lambda$ are pivotal quantities, with joint conditional density

$$p(z_1, z_2 | a_1, \dots, a_{n-2}) = C z_2^{n-2} \prod_{i=1}^n \left[\frac{1}{\pi \{ 1 + (z_1 + a_i z_2)^2 \}} \right]. \quad (16.49)$$

From (16.49) it is of interest to consider the joint conditional density of $z_3 = z_1 / z_2$ and z_2 , which is given by

$$p(z_3, z_2 | a_1, \dots, a_{n-2}) = C z_2^{n-1} \prod_{i=1}^n \left[\frac{1}{\pi \{ 1 + z_2^2 (a_i + z_3)^2 \}} \right]. \quad (16.50)$$

To make inferences about θ when A is unknown, z_2 should be integrated out of (16.50) to obtain the marginal distribution of $z_3 = (\hat{\theta} - \theta) / \hat{\lambda}$, conditional on the observed a_1, \dots, a_{n-2} . Similarly, to make inferences about A when θ is unknown, z_3 should be integrated out of (16.50) to obtain the marginal distribution of $z_2 = \hat{\lambda} / \lambda$, conditional on the observed a_1, \dots, a_{n-2} . Computing probabilities for the marginal distributions of z_3 and z_2 is too complicated and quite time-consuming. So Lawless (1972) suggested either looking at a plot of contours of (16.50) or at plots of the conditional densities $p(z_3 | z_2)$ and $p(z_2 | z_3)$ for a few selected values of the conditioning variable. Recently McCullagh (1992a, b) gave a nice discussion on the choice of ancillary in reference to the Cauchy case. He specifically showed that the configuration ancillary is not unique and that the choice of ancillary has some effect on conditional probability calculations. For moderate deviations he showed that the choice of ancillary has very little effect on probability calculations with the asymptotic effect being at most of order $O_p(n^{-1})$. In case of large deviations, the relative or logarithmic difference between the two conditional densities is $O_p(n^{1/2})$ and unbounded in probability as $n \rightarrow \infty$. McCullagh (1992b) showed that there exist moderate deviation approximations with absolute error $O(n^{-1})$ that are independent of the choice of ancillary, given that $(\hat{\eta}, A)$ is sufficient.

4.4 Bayesian Inference

Starting with the "vague prior"

$$g(\theta, \lambda) \propto \frac{1}{\lambda} \quad (16.51)$$

and combining it with the likelihood function based on the sample x_1, \dots, x_n ,

we obtain the joint posterior density of θ and λ as

$$\Pi(\theta, \lambda | \mathbf{x}) \propto \lambda^{n-1} \prod_{i=1}^n \frac{1}{\lambda^2 + (x_i - \theta)^2}. \quad (16.52)$$

Then, the Bayesian estimators of θ and λ , under the squared-error loss function, are the posterior means given by

$$\begin{aligned} \hat{\theta}_B &= E(\theta | \mathbf{x}) = \int \int \theta \Pi(\theta, \lambda | \mathbf{x}) d(\theta, \lambda) \\ &= \frac{\iint \theta \lambda^{n-1} \prod_{i=1}^n \{\lambda^2 + (x_i - \theta)^2\}^{-1} d(\theta, \lambda)}{\iint \lambda^{n-1} \prod_{i=1}^n \{\lambda^2 + (x_i - \theta)^2\}^{-1} d(\theta, \lambda)}, \end{aligned} \quad (16.53)$$

$$\hat{\lambda}_B = \frac{\iint \lambda^n \prod_{i=1}^n \{\lambda^2 + (x_i - \theta)^2\}^{-1} d(\theta, \lambda)}{\iint \lambda^{n-1} \prod_{i=1}^n \{\lambda^2 + (x_i - \theta)^2\}^{-1} d(\theta, \lambda)}. \quad (16.54)$$

Note that these estimators, unlike in the case of a location parameter θ alone, do not minimize the squared-error loss among equivariant estimates. One needs to start with the prior density $d\theta d\lambda/\lambda^3$ in order to derive such estimates.

In deriving a best invariant test for the normal distribution against a Cauchy alternative, Franck (1981) evaluated integrals similar to those in (16.53) and (16.54). Spiegelhalter (1985) obtained closed-form expressions for the Bayesian estimators of θ and λ which, for odd values of n larger than 3, are

$$\hat{\theta}_B = \frac{1}{2} \frac{\sum \sum_{i < j} w_{ij} (x_i + x_j) \log d_{ij}}{\sum \sum_{i < j} w_{ij} \log d_{ij}}, \quad (16.55)$$

$$\hat{\lambda}_B = \frac{\pi}{4} \frac{\sum \sum_{i < j} w_{ij} d_{ij}}{\sum \sum_{i < j} w_{ij} \log d_{ij}}, \quad (16.56)$$

where

$$\begin{aligned} d_{ij} &= |x_i - x_j|, \\ w_{ij} &= \frac{(-1)^{i+j} d_{ij}^{n-1}}{\prod_{k=1}^n d_{ik} d_{jk}}. \end{aligned}$$

Refer to Spiegelhalter (1985) for similar expressions for the Bayesian estimators of θ and λ for even values of n .

Howlader and Weiss (1988a) pointed out that the exact formulas given above are difficult to compute and require great computational precision as these estimates are very unstable and often blow up in values. Through an empirical Monte Carlo study that they carried out, they also observed that the exact method often grossly overestimated λ , especially for small values of n . It is for this reason that Howlader and Weiss (1988a) derived some approximate Bayesian estimators by using a method of approximating ratios

of integrals [e.g., (16.53) and (16.54) due to Lindley (1980). They then showed that these approximate Bayesian estimators perform very well in comparison to the MLEs. It should be mentioned here that **Lindley's** (1980) expansion, a method similar to the one employed by Hinkley (1978) in correcting for the bias of the MLE and the method of Efron (1975) on second-order efficiency, has been compared by Howlader and Weiss (1987) to another method of approximating ratios of integrals due to **Tierney** and Kadane (1986). In comparing the performance of the two methods under the Cauchy model, Howlader and Weiss (1987) observed that the former (even though is computationally more tedious) remains quite stable even for small sample sizes (unlike the latter). It is of interest to add here that the Bayesian estimation of the reliability function $R_X(t)$ of the Cauchy density in (16.1) has been discussed by Howlader and Weiss (1988b).

4.5 Other Developments in Inference

Efron and Hinkley (1978), when making an excellent assessment of the normal approximations to the distribution of the maximum likelihood estimator in one-parameter families (with the variance approximation by either the expected total Fisher information or the observed information), used Cauchy distribution as an example. **Barnard** (1974), in response to an article by Bailey (1973), pointed out that in the problem of data reduction one's interest is typically to reduce a number of independent observations whose distribution involves an unknown parameter θ to an equivalent single observation (ESO), whose distribution also involves θ , in such a way that the information about θ in the set of observations is exactly (or at least nearly) equivalent to that in the ESO. When θ is the location parameter, it so happens that the form of the distribution of the ESO is the same (apart from a scaling factor) as that of the original observations in the case of normal and uniform distributions. However, **Barnard** (1974) mentioned that this property is rather exceptional and cited the Cauchy distribution in which case for $n = 2$ the distribution differs from Cauchy in being bimodal.

Higgins and **Tichenor** (1977) proposed "window estimates" for θ and A , and also established the consistency and asymptotic normality of these estimates. They further showed that the asymptotic distribution of these window estimates is the same as that of the MLEs. Through an empirical comparative study, Higgins and **Tichenor** (1978) showed that the window estimate of θ is nearly optimal for $n \geq 40$ and is as efficient as many other estimates for $n \geq 20$; further they displayed that the window estimate of A is nearly optimal even for samples of size 10.

Kadiyala and Murthy (1977) considered the problem of estimation of a linear regression with Cauchy disturbances. They compared the performance of the ML method and the minimum sum of absolute errors method for this specific estimation problem.

Koutrouvelis (1982) discussed a method of estimation of θ and A using the empirical characteristic function. Interestingly enough, the determination of

optimum values at which the empirical characteristic function needs to be evaluated for this method of estimation reduces to the determination of the asymptotically optimum quantiles for the parameter estimation of an exponential distribution by linear functions of order statistics; the latter has a known solution by Ogawa (1960) (also see Chapter 19). These estimators are shown to be asymptotically independent and normally distributed, achieving high asymptotic efficiencies. Feuerverger and McDunnough (1981a, b) also considered this empirical characteristic function approach but restricted it to the determination of the optimum uniform spacing between the points.

Beckman and Johnson (1987) discussed the fitting of the Cauchy distribution (Student t-distribution, more generally) to grouped experimental data by means of a grouped MLE approach. A final mention has to be made to the asymptotically optimal tests proposed by Philippou (1988) based on the concept of contiguity.

5 GENESIS AND APPLICATIONS

The standard Cauchy distribution with $\theta = 0$, $A = 1$, as in (16.3), is the distribution of central t with one degree of freedom (Chapter 28). It is thus the distribution of the ratio U/V , where U and V are independent unit normal variables. An interesting application of this distributional result was illustrated by Stigler (1989); he used this result to derive an explicit expression for bivariate normal orthant probabilities, namely $\Pr\{Z_1 \leq 0, Z_2 \leq 0\}$, where $(Z_1, Z_2)^T$ has a standard bivariate normal distribution with correlation coefficient ρ , as follows. Define $V = (Z_2 - \rho Z_1)/\sqrt{1 - \rho^2}$; then V is standard normal and independent of Z_1 (since the covariance is 0). Noting now that $Z_2 \leq 0$ is equivalent to $V \leq -cZ_1$, where $c = \rho/\sqrt{1 - \rho^2}$, we have

$$\begin{aligned}\Pr\{Z_1 \leq 0, Z_2 \leq 0\} &= \Pr\{Z_1 \leq 0, V \leq -cZ_1\} \\ &= \Pr\{Z_1 \leq 0, V \leq c|Z_1|\}.\end{aligned}$$

Now by the symmetry of the distribution of Z_1 (and since $\Pr\{Z_1 = 0\} = 0$)

$$\begin{aligned}\Pr\{Z_1 \leq 0, V \leq c|Z_1|\} &= \Pr\{Z_1 > 0, V \leq c|Z_1|\} \\ &= \frac{1}{2} \Pr\{V \leq c|Z_1|\} \\ &= \frac{1}{2} \Pr\left\{\frac{V}{|Z_1|} \leq c\right\} \\ &= \frac{1}{2} \left\{\frac{1}{2} + \frac{1}{\pi} \tan^{-1} c\right\} \\ &= \frac{1}{2} \left\{\frac{1}{2} + \frac{1}{\pi} \sin^{-1} \rho\right\}\end{aligned}$$

from the fact that $V/|Z_1|$ has a standard Cauchy distribution.

However, it should be mentioned that the common distribution of U and V need not be normal. For example, the ratio U/V has a Cauchy distribution if

$$\begin{aligned}
 p_U(u) &= \sqrt{2} \pi^{-1} (1 + u^4)^{-1}, \\
 p_V(v) &= \sqrt{2} \pi^{-1} (1 + v^4)^{-1}
 \end{aligned}
 \tag{16.57}$$

[Laha (1959b)]. Other examples have been given by Laha (1959a), Mauldon (1956), Fox (1965), Steck (1958), Kotlarski (1960), and Roslonek (1970). Note that since U and V have identical distributions, V/U and U/V must have identical distributions. Hence, if X has the probability density function (16.3), so does X^{-1} .

Since, provided b_1 and b_2 are not both zero,

$$\left(b_1 \left(\frac{V}{U} \right) + b_2 \right)^{-1} = b_1 (b_1^2 + b_2^2)^{-1} \left[\frac{b_1 U - b_2 V}{b_2 U + b_1 V} \right] + b_2 (b_1^2 + b_2^2)^{-1},$$

it follows that if X has a Cauchy distribution, so does $(b_1 X + b_2)^{-1}$. This result was obtained in this way by Savage (1966), and by direct calculation by Menon (1966). [Note that if U and V are independent standard normal variables, so are $(b_1 U - b_2 V)(b_1^2 + b_2^2)^{-1/2}$ and $(b_2 U + b_1 V)(b_1^2 + b_2^2)^{-1/2}$ (see Chapter 13, Section 3).] When X and Y are independent normal variables with means μ_1 and μ_2 and variances σ_1^2 and σ_2^2 , respectively, then Kamerud (1978) derived the density function of the random variable X/Y which, for the special case when $\mu_1 = \mu_2 = 0$ and $\sigma_1 = \sigma_2 = 1$, reduces to the standard Cauchy density.

Arnold and Brockett (1992) proved by simple arguments that, when $U = (U_1, \dots, U_n)^T$ has a spherically symmetric distribution, then for $i \neq j$, U_i/U_j has a standard Cauchy distribution [see also DeSilva (1979)]. More generally, Arnold and Brockett (1992) also established that when $V = (V_1, \dots, V_n)^T$ has an elliptically symmetric distribution, then for $i \neq j$, V_i/V_j has a general Cauchy distribution.

The Cauchy distribution is obtained as the limiting distribution of $n^{-1} \sum_{j=1}^n X_j^{-1}$ as $n \rightarrow \infty$, where X_1, X_2, \dots are independent identically distributed random variables with common density function $p_X(x)$ satisfying the conditions [Pitman and Williams (1967)]

1. $p_X(0) > 0$,
2. $p_X(x)$ continuous at $x = 0$,
3. $p_X(x)$ possesses left-hand and right-hand derivatives at $x = 0$.

Since the reciprocal of a Cauchy variable also has a Cauchy distribution, it follows that the limiting distribution of the harmonic mean, under these conditions, is Cauchy. Shapiro (1978) discussed the rate of convergence of distribution functions of sums of reciprocals of random variables to the

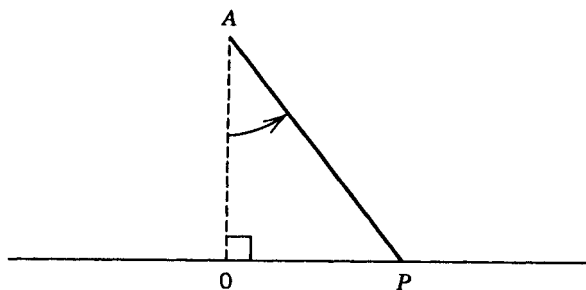


Figure 16.2 Geometric Description.

Cauchy distributions; the limit distributions in this case have also been discussed by Shapiro (1988).

The Cauchy distribution also arises in describing the distribution of the point of intersection P of a fixed straight line with another variable straight line, randomly oriented in two dimensions through a fixed point A . The distance OP of the point of intersection from the pivot (0) of the perpendicular from A to the fixed line has a Cauchy distribution with $\delta = 0$. The situation is represented diagrammatically in Figure 16.2. The angle $LOAP$ has a uniform (rectangular) distribution (Chapter 26) between $-\pi/2$ (corresponding to $OP = -\infty$) and $\pi/2$ (corresponding to $OP = +\infty$).

On the basis of this kind of model, the Cauchy distribution may be used to describe the distribution of points of impact of particles from a point-source A with a fixed straight line. It may be noted that if the space is of $s + 1$ dimensions instead of two dimensions, then the distance r , say, of the point of intersection with a fixed hyperplane from the foot of the perpendicular from A to the hyperplane is distributed as a multiple of central t with s degrees of freedom (Chapter 28).

Spitzer (1958) has shown that if $(R(t), \theta(t))$ are the polar coordinates of a random point under standard Brownian motion at time t (with $R(0) > 0$), then the distribution of $\{\Delta\theta(t)\}(\frac{1}{2} \log t)^{-1}$ tends to a Cauchy distribution as t tends to infinity, where $\{\Delta\theta(t)\}$ denotes the total algebraic angle turned through up to time t [so that $\{\Delta\theta(t)\} \equiv [\theta(t) - \theta(0)] \bmod 2\pi$]. Berman (1967) established that if τ is the first time that $R(\tau) = r_1$, then $\{\Delta\theta(\tau)\}|\log(r_1/R(0))|^{-1}$ has a Cauchy distribution with $\delta = 0$, $\lambda = |\log(r_1/R(0))|$.

Mukherjea, Nakassis, and Miyashita (1986) established an interesting property regarding the identification of Cauchy parameters by the distribution of the maximum random variable. Specifically, consider two sets of Cauchy distributions with cdf's given by

$$F_i(x) = \frac{1}{2} + \frac{1}{\pi} \tan^{-1}(a_i x), \quad i = 1, 2, \dots, n,$$

$$F_j^*(x) = \frac{1}{2} + \frac{1}{\pi} \tan^{-1}(b_j x), \quad j = 1, 2, \dots, m$$

for $-\infty < x < \infty$. Suppose that

$$F_1 F_2 \cdots F_n = F_1^* F_2^* \cdots F_m^*$$

They then proved in this case that the a 's are simply a rearrangement of the b 's.

6 CHARACTERIZATIONS

Menon (1962, 1966), gave several characterizations of the Cauchy distribution. Among them is the following (from (1966)):

If X_1, X_2, \dots, X_n are independent, identically distributed random variables, then the common distribution is a Cauchy distribution if and only if, for any set of real numbers $\{b_j \neq 0, a_j\} (j = 1, 2, \dots, n)$ there exist real numbers $B (\neq 0)$ and A such that $\sum_{j=1}^n (a_j + b_j X_j)^{-1}$ has the same distribution as $A(B + X_1)^{-1}$.

Obretenov (1961) has given the following characterization:

If X and Y are independent and have the same distribution, then a necessary and sufficient set of conditions for this to be a Cauchy distribution is (i) the characteristic function $\phi(t) = E(e^{itX}) = E(e^{itY})$ has a finite non-zero righthand derivative at $t = 0$, i.e., $\phi'_j(0) = A \neq 0$, and (ii) for any pair of positive real numbers a, b there is a positive real number c (depending on a and b) such that $aX + bY$ has the same distribution as cX (or cY).

Note that the normal distribution satisfies condition (ii), but not condition (i), when a and b are chosen so that $E(aX + bY) = 0$. A further remarkable characterization, due to Williams (1969), is: "If $(1 + aX)(a - X)^{-1}$ has the same distribution as X , and $\pi^{-1} \tan^{-1} a$ is not a rational number, then X has a standard Cauchy distribution." A related characterization, also due to Williams (1969), is "If $(\theta^2 + \lambda^2)(2\theta - X)^{-1}$ has the same distribution as X and $\pi^{-1} \tan^{-1}(\theta/\lambda)$ is not a rational number, then X has a Cauchy distribution with parameters θ, λ ."

As mentioned earlier in Section 5, it is known that if X and Y are independent standard normal variables, then X/Y has a standard Cauchy distribution. But the converse is not true [refer to Letac (1981) for some additional insight]. In an attempt to provide an additional condition that will guarantee the normality of X and Y , Ahsanullah and Hamedani (1988) prove the result that "if $\{\text{Min}(X, Y)\}^2$ and X/Y are distributed as chi-square with 1 degree of freedom and standard Cauchy, respectively, where X and Y are i.i.d. random variables from an absolutely continuous distribution, then X and Y are distributed as standard normal."

Knight (1976) proved the characterization result that a random variable X is of Cauchy type iff $(aX + b)/(cX + d)$ has a distribution with the same shape as X for every a, b, c, d , with $ad - bc \neq 0$. This result was extended by Knight and Meyer (1976) to the standard Cauchy distribution in the

Euclidean space R^n . Dunau and Senateur (1987) provided a simple proof for this characterization result.

Kotlarski (1979) showed that if X has a standard Cauchy distribution, then so does $2X/(1 - X^2)$. By making use of some characterization results for the uniform distribution and the fact that $X = \tan U$, where U is a uniform random variable on the interval $[0, \pi)$, has a standard Cauchy distribution, Arnold (1979) established some characterization results for the Cauchy distribution. Specifically, he proved that if X and Y are independent absolutely continuous random variables, then any one of

1. Y and $(X + Y)/(1 - XY)$ are independent,
2. X and $(X + Y)/(1 - XY)$ are identically distributed,
3. X and $2X/(1 - X^2)$ are identically distributed,

imply that X has a standard Cauchy distribution. Norton (1983) then proved the following characterization result: For X and Y i.i.d. symmetric random variables, X has a standard Cauchy distribution iff

4. X and $X^2/(1 + X^2)$ are distributed as $2X/(1 - X^2)$ and $1/(1 + X^2)$, respectively, or
5. X and $X^2/(1 + X^2)$ are distributed as $(X + Y)/(1 - XY)$ and $1/(1 + X^2)$, respectively.

It should be noted that Norton's characterization based on condition 4 or 5 requires one further condition than Arnold's characterization based on condition 3 or 2, respectively. But the latter is under the stronger assumption that the random variables X and Y are both absolutely continuous.

Kamps (1991) showed that a recurrence relation satisfied by the single moments of order statistics established by Barnett (1966b) given by

$$E[(X'_{r:n})^2] = \frac{n}{\pi} \{E[X'_{r:n-1}] - E[X'_{r-1:n-1}]\} - 1, \quad 3 \leq r \leq n - 2,$$

is in fact a characterization of the Cauchy distribution. He also proved that a generalization of Barnett's relation to the case of a doubly truncated Cauchy distribution with density function

$$p_{X_T}(x) = \frac{1}{(\tan^{-1} b - \tan^{-1} a)(1 + x^2)}, \quad a < x < b, \quad (16.58)$$

established by Khan, Yaqub, and Parvez (1983) characterizes this doubly truncated Cauchy distribution.

Bell and Sarma (1985) and Glänzel (1987) have given some additional characterizations, with the last author basing one on truncated moments. Further characterization results are presented by Kagan, Linnik, and Rao (1973).

7 GENERATION ALGORITHMS

A convenient method of sampling from a Cauchy distribution is based on the inversion of the distribution function $F(x)$; that is, if U is a uniform $(0, 1)$ variate, then $\tan(\pi(U - \frac{1}{2}))$ is distributed as standard Cauchy. This method of course uses the tan function and needs one uniform $(0, 1)$ deviate per observation from the Cauchy distribution. Even though this method can be programmed easily in high-level languages, it may be relatively slow. Some efficient generation algorithms have been proposed for the Cauchy case; three of these are discussed below.

7.1 Monahan's (1979) Algorithm

Let Y_1, Y_2, \dots be i.i.d. random variables from an arbitrary distribution function F (usually chosen to be standard uniform). Let $Z_1 \equiv 1$ and Z_2, Z_3, \dots be independent Bernoulli variates with $\Pr[Z_i = 1] = a_i/a_{i-1} = p_i$ for $i > 1$ and given constants $1 = a_1, a_2 \geq a_1, a_3 \geq a_2, \dots \geq 0$. Further let E_n be the event that $\max(Y_1, \dots, Y_n) = Y_1$ and $Z_1 = Z_2 = \dots = Z_n = 1$. Then the algorithm in its generality involves the following steps:

1. Generate X with distribution function P (chosen to be a simple distribution, for convenience, like uniform), and let $Y_0 = G(X)$. G is an appropriately chosen function, with the only condition on it being that it maps the support of P onto the support of F .
2. Continue to generate $Y_1, Y_2, \dots, Z_1, Z_2, \dots$ if $\max(Y_1, Y_2, \dots, Y_n) \leq Y_0$ and $Z_1 = Z_2 = \dots = Z_n = 1$.
3. If $Y_{n+1} > Y_0$ or $Z_{n+1} = 0$, stop.
4. If n is even, deliver X , else go to step 1.

Then

$$\Pr[X \leq x, Y_1 \leq G(x), E_n] = \int_{-\infty}^x \Pr[Y_1 \leq G(y), E_n] dP(y), \quad (16.59)$$

$$\begin{aligned} &\Pr[X \leq x, Y_1 \leq G(x), E_n, E_{n+1}^c] \\ &= \int_{-\infty}^x [a_n F(G(y))^n - a_{n+1} F(G(y))^{n+1}] dP(y). \quad (16.60) \end{aligned}$$

Let $h(w) = \sum_{n=0}^{\infty} a_n w^n$ with $1 = a_0, a_1 \geq a_0, a_2 \geq a_1, \dots \geq 0$. Convergence is implied for $w \in [-1, 1)$ by $a_n \rightarrow 0$. Summing (16.60) over even n beginning with 0, we get the distribution function of X as

$$\frac{\int_{-\infty}^x h(-F(G(y))) dP(y)}{\int_{-\infty}^{\infty} h(-F(G(y))) dP(y)}. \quad (16.61)$$

The denominator of (16.61) is the probability that X will be "delivered," p_D ,

say; the expected number of Y 's needed to produce a single X , EN_F , is

$$E[N_F] = \frac{\int_{-\infty}^x h(F(G(y))) dP(y)}{\int_{-\infty}^{\infty} h(-F(G(y))) dP(y)}; \quad (16.62)$$

the expected number of samples from the distribution P , EN , is the reciprocal of the probability that X will be delivered.

For the Cauchy case, we have

$$h(w) = (1 - w/2)^{-2} = 1 + w + \frac{3}{4}w^2 + \cdots + \frac{n+1}{2^n}w^n + \cdots,$$

$$F(u) = u, \quad u \in (0, 1),$$

$$P(x) = (1 + x)/2,$$

$$G(x) = 2[\sqrt{1 + x^2} - 1].$$

Algorithm

0. Generate u .
1. $X \leftarrow 2u - 1$; $n \leftarrow 0$; $y_0 \leftarrow G(X)$.
2. Generate $u_1, y_{n+1} \leftarrow u_1$.
3. If $y_{n+1} > p_{n+1}y_0$; go to 5.
4. $n \leftarrow n + 1$; go to 2.
5. $u \leftarrow (y_{n+1} - p_{n+1}y_0)/(1 - p_{n+1}y_0)$.
6. If n is odd, go to 1.
7. $u \leftarrow 2u$; if $u < 1$, deliver X .
8. Otherwise, $u \leftarrow u - 1$, and deliver $X \leftarrow 1/X$.

Monahan (1979) determined that $p_D = \pi/4$ and $EN_F \approx 1.88$. This method hence requires $\frac{1}{4}$ fewer uniform deviates than the synthetic tangent algorithm's [Kinderman, Monahan, and Ramage (1977)] $8/\pi \approx 2.56$.

7.2 Kronmal and Peterson's (1981) Acceptance-Complement Method

This method is a variant of the commonly used acceptance-rejection method for generating random variables [Knuth (1968)] that avoids rejection. In general, to generate random variables from the density $p(x)$ defined on $-\infty \leq a \leq x \leq b \leq \infty$, the method is as follows:

1. Choose a decomposition of the density $f(\cdot)$ into subdensities $g_1(\cdot)$ and $g_2(\cdot)$ such that $p(\cdot) = g_1(\cdot) + g_2(\cdot)$, with the mass of the subdensity $g_2(\cdot)$ being $q = \int_a^b g_2(x) dx$.
2. Choose a dominating density $h^*(\cdot) \geq g_1(\cdot)$.

Then:

3. a. Generate $X \sim h^*(\cdot)$.
- b. Generate $U \sim$ uniform $(0, 1)$, independent of X .
4. a. If $U \leq g_1(X)/h^*(X)$, then accept X .
- b. Otherwise, generate Y , independent of (X, U) from the density $g_2(\cdot)/q$, and return Y .

It may then be easily verified that

$$\Pr[X \leq t, \text{ acceptance in step 4a}] = \int_a^t g_1(x) dx,$$

$$\Pr[Y \leq t, \text{ nonacceptance in step 4a}] = \int_a^t g_2(y) dy$$

with the consequence that

$$\Pr[\text{random variable returned} \leq t] = \int_a^t p(x) dx,$$

as desired. Now, for generating standard Cauchy random variables, Kronmal and Peterson (1981) observe that if X is distributed as a truncated Cauchy with density

$$p(x) = \frac{2}{\pi(1+x^2)} I[|x| < 1], \quad (16.63)$$

then the random variable Z defined by

$$\begin{aligned} Z &\equiv X \quad \text{with probability } \frac{1}{2} \\ &\equiv \frac{1}{X} \quad \text{with probability } \frac{1}{2} \end{aligned} \quad (16.64)$$

will have a standard Cauchy distribution. Hence generation of X from (16.63) can be used in conjunction with the transformation in (16.64) to generate Cauchy random variables. Kronmal and Peterson use the decomposition

$$\begin{aligned} g_1(x) &= \left[\frac{2}{\pi(1+x^2)} - \left(\frac{2}{\pi} - \frac{1}{2} \right) \right] I[|x| < 1], \\ g_2(x) &= \left(\frac{2}{\pi} - \frac{1}{2} \right) I[|x| < 1], \end{aligned} \quad (16.65)$$

with the dominating density

$$h^*(x) = \frac{1}{2}I[|x| < 1]. \quad (16.66)$$

With this choice (as well as some other choices), they found this algorithm to be much more time efficient than the inverse distribution function method as well as the synthetic tangent method.

7.3 Ahrens and Dieter's (1988) Algorithm

This simple and efficient table-free method is based on the "exact approximation" method by Marsaglia (1984). The idea of an exact approximation is as follows: Let $x(t)$ be a monotonic differentiable function in $t \in [0, 1]$. Then the transformed random variable $X \leftarrow x(T)$ has the desired density $p(x)$ if the density of the T-variables is $g(t) = p(x(t))|x'(t)|$. As mentioned in the beginning of this section, the inversion method is based on the transformation $x(t) = F^{-1}(t)$ resulting in $g(t) = 1 \forall t \in [0, 1]$. Now, if $x(t)$ is only an easy-to-calculate approximation to $F^{-1}(t)$, $g(t)$ may still be close to 1, and then the approximation can be made exact in a statistical sense in the following way. Supposing that $\forall t \in [0, 1]$, $g(t)$ is such that $p < g(t) < r$, where $p < 1 < r$, and that the function $x(t)$ is chosen so that $h = r - p$ is small. Then generate a $U \rightarrow$ uniform $(0, 1)$ deviate, and if $U \leq p$ return $X \leftarrow x(U/p)$. Otherwise, use a new pair U, U' of uniform $(0, 1)$ deviates for an acceptance-rejection procedure: Return $X \leftarrow x(U)$ if $U' \leq (g(U) - p)/h$ or else try again with another (U, U') .

For the standard Cauchy distribution, Ahrens and Dieter (1988) suggested

$$\begin{aligned} x(t) &= t \left(\frac{a}{\frac{1}{4} - t^2} + b \right), \\ x'(t) &= a \frac{\frac{1}{4} + t^2}{\left(\frac{1}{4} - t^2\right)^2} + b, \end{aligned} \quad (16.67)$$

and found that the choice of $a = 0.638063$ and $b = 0.595949$ brought the function

$$g(t) = p(x)x'(t) = \frac{1}{\pi(1+x^2)} \left(a \frac{\frac{1}{4} + t^2}{\left(\frac{1}{4} - t^2\right)^2} + b \right) \quad (16.68)$$

even closer to 1 in $(-\frac{1}{2}, \frac{1}{2})$.

Then the exact approximate algorithm is as follows:

0. Constants:

$$\begin{aligned} a &= 0.6380631366077803 \\ b &= 0.5959486060529070 \\ c &= 0.9339962957603656 \\ W &= 0.2488702280083841 \\ A &= 0.6366197723675813 \\ B &= 0.5972997593539963 \\ H &= 0.0214949004570452 \\ P &= 4.9125013953033204 \end{aligned}$$

1. Generate U . Set $T \leftarrow U - \frac{1}{2}$ and $S \leftarrow W - T^2$. If $S \leq 0$, go to 3.
2. Return $X \leftarrow T(A/S + B)$.
3. Generate U . Set $T \leftarrow U - \frac{1}{2}$, $s \leftarrow \frac{1}{4} - T^2$, and $X \leftarrow T(a/s + b)$.
4. Generate U' . If $s^2((1 + X^2)(HU' + P) - q) + s > \frac{1}{2}$, go to 3.
5. Return X .

Ahrens and Dieter (1988) have shown that $p = 0.997738$ and $h = 0.004366$, and that the overall consumption of uniform variables is $N = p + 2h = 1.006429$ per pseudorandom observation from the standard Cauchy distribution.

8 RELATED DISTRIBUTIONS

We have already noted, in Section 2, that the Cauchy distribution is a central t distribution (Chapter 28) with one degree of freedom. It is related to other distributions in the same way as the t -distributions. Rider (1957) has studied the properties of a system that he has named the generalized Cauchy distributions. The probability density function of a random variable X with such a distribution is of the form:

$$p_X(x) = \frac{k\Gamma(h)}{2\lambda\Gamma(k^{-1})\Gamma(h - k^{-1})} \frac{1}{[1 + |(x - \theta)/\lambda|^k]^h}, \quad \lambda, k, h > 0,$$

$$hk > 1. \quad (16.69)$$

For $k = 2$ and $\theta = 0$, X is distributed as $\lambda(2h - 1)^{-1/2}$ times a central t variable with $(2h - 1)$ degrees of freedom, and for $k = 2$, $h = 1$, X is distributed according to (16.1).

Symmetrically truncated Cauchy distributions, with density function (in standard form)

$$[2(1 + x^2)\tan^{-1} \lambda]^{-1}, \quad -\lambda \leq x \leq \lambda, \quad (16.70)$$

have been discussed in Derman (1964). The distribution is symmetrical about

zero and has variance

$$\frac{A - \tan^{-1} A}{\tan^{-1} A},$$

so the variance of the arithmetic mean of n independent variables having this distribution is

$$\frac{n^{-1}(\lambda - \tan^{-1}\lambda)}{\tan^{-1}\lambda}, \quad (16.71)$$

while for large n the variance of the median is approximately

$$n^{-1}(\tan^{-1}\lambda)^2. \quad (16.72)$$

Formula (16.71) is larger than (16.72) for $A > 3.41$, so the median is asymptotically more efficient, as an estimator of the center of a symmetrically truncated Cauchy distribution, provided not more than $\frac{1}{2} - \pi^{-1}\tan^{-1}(3.41) = 0.0908$ of the distribution is truncated at either end.

The standard *half-Cauchy* distribution has density function

$$2\pi^{-1}(1+x^2)^{-1}, \quad 0 < x. \quad (16.73)$$

The analogy with the half-normal distribution (Chapter 13, Section 7.1) is clear. Mijnheer (1968) has carried out sampling experiments to investigate methods of estimating parameters of the general half-Cauchy distribution in which extreme observations are rejected.

The *folded-Cauchy* distribution [obtained by folding the distribution (16.1) about $x = 0$] has density function

$$\begin{aligned} & (\pi\lambda)^{-1} \left[\left\{ 1 + \left[\frac{x-\theta}{\lambda} \right]^2 \right\}^{-1} + \left\{ 1 + \left[\frac{x+\theta}{\lambda} \right]^2 \right\}^{-1} \right] \\ &= 2(\pi\lambda)^{-1} \left[\left\{ 1 + \left[\frac{x-\theta}{\lambda} \right]^2 \right\} \left\{ 1 + \left[\frac{x+\theta}{\lambda} \right]^2 \right\} \right]^{-1} \\ & \quad \times \left[1 + \frac{x^2 + \theta^2}{\lambda^2} \right], \quad x > 0. \end{aligned} \quad (16.74)$$

For $\theta \leq A/\sqrt{3}$, the mode is at $x = 0$; for $\theta > A/\sqrt{3}$ it is at

$$x = \theta \left[1 + \left(\frac{\lambda}{\theta} \right)^2 \right]^{1/2} \left[2 \left\{ 1 + \left(\frac{\lambda}{\theta} \right)^2 \right\}^{-1/2} - 1 \right]^{1/2}. \quad (16.75)$$

The *wrapped-up Cauchy distribution* is obtained by wrapping a Cauchy distribution around a circle and adding up the probability densities coinciding at each point. With mean angle δ and mean vector length ρ , the density

function of a wrapped-up Cauchy random variable T is given by

$$p(t) = \frac{1}{2\pi} \frac{1 - \rho^2}{1 + \rho^2 - 2\rho \cos(t - \theta)}, \quad 0 \leq t < 2\pi, \quad (16.76)$$

where θ represents a location parameter and ρ a scale parameter with $0 \leq \rho < 1$. Thus this is a location-scale family of distributions. When $\rho = 0$, (16.76) is simply the uniform distribution on the circle, and as $\rho \rightarrow 1$ (16.76) approaches a point mass distribution at θ . In general, the wrapped-up Cauchy distribution is unimodal and symmetric about θ . This distribution serves as an alternative to the Fisher-von Mises distribution for modeling symmetric data on the circle. For further discussion, one may refer to Mardia (1972) and Batschelet (1981). Kent and Tyler (1988) discussed the maximum likelihood estimation of the parameters θ and ρ . They showed that for $n \geq 3$, the MLEs exist and are unique and can be computed from the likelihood equations by means of a simple algorithm. Thus they noted that the two-parameter wrapped-up Cauchy distribution behaves just like the two-parameter Cauchy distribution as far as the maximum likelihood estimation of parameters is concerned. Reference should also be made to Best and Fisher (1979) who have used the wrapped-up Cauchy density as an envelope to present an acceptance-rejection method of simulation from the von Mises distribution.

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CHAPTER 17

Gamma Distributions

1 DEFINITION

A random variable X has a gamma distribution if its probability density function is of form

$$p_X(x) = \frac{(x - \gamma)^{\alpha-1} \exp[-(x - \gamma)/\beta]}{\beta^\alpha \Gamma(\alpha)}, \quad \alpha > 0; \beta > 0; x > \gamma. \quad (17.1)$$

This distribution—denoted gamma (α, β, γ)—is Type III of Pearson's system (Chapter 12, Section 4). It depends on three parameters α , β , and γ . If $\gamma = 0$, the distribution is termed a two-parameter gamma distribution, denoted gamma (α, β); see equation (17.23).

The standard form of distribution is obtained by setting $\beta = 1$ and $\gamma = 0$. This gives

$$p_X(x) = \frac{x^{\alpha-1} e^{-x}}{\Gamma(\alpha)}, \quad x \geq 0. \quad (17.2)$$

If $\alpha = 1$, we have an exponential distribution (see Chapter 19). If α is a positive integer, we have an Erlang distribution.

The distributions of $Y = -X$, namely

$$p_Y(y) = \frac{(-y - \gamma)^{\alpha-1} \exp[(y + \gamma)/\beta]}{\beta^\alpha \Gamma(\alpha)}, \quad y \leq -\gamma, \quad (17.1)'$$

and

$$p_Y(y) = \frac{(-y)^{\alpha-1} e^y}{\Gamma(\alpha)}, \quad y \leq 0, \quad (17.2)'$$

are also gamma distributions. But such distributions rarely need to be considered, and we will not discuss them further here.

The probability integral of distribution (17.2) is

$$\Pr[X \leq x] = [\Gamma(\alpha)]^{-1} \int_0^x t^{\alpha-1} e^{-t} dt. \quad (17.3)$$

This is an incomplete gamma function ratio. The quantity

$$\Gamma_x(\alpha) = \int_0^x t^{\alpha-1} e^{-t} dt \quad (17.4)$$

is sometimes called an incomplete gamma *function*, but this name is also quite commonly applied to the ratio (17.3) (Chapter 1, Section 3).

This ratio depends on x and α , and it would be natural to use a notation representing it as a function of these variables. However, **Pearson** (1922) found it more convenient to use $u = x\alpha^{-1/2}$ in place of x for tabulation purposes, and he defined the incomplete gamma function as

$$I(u, \alpha - 1) = \frac{1}{\Gamma(\alpha)} \int_0^{u\sqrt{\alpha}} t^{\alpha-1} e^{-t} dt. \quad (17.5)$$

The main importance of the (standard) gamma distribution in statistical theory is the fact that if U_1, U_2, \dots, U_ν are independent unit normal variables, the distribution of $\sum_{j=1}^\nu U_j^2$ is of form (17.1) with $\alpha = \nu/2$, $\beta = 2$, and $\gamma = 0$. This particular form of gamma distribution is called a chi-square distribution with ν degrees of freedom. The corresponding random variable is often denoted by χ_ν^2 , and we will follow this practice. It is clear that $\frac{1}{2}\sum_{j=1}^\nu U_j^2$ has a standard gamma distribution with $\alpha = \nu/2$. Expressed symbolically:

$$p_{\chi_\nu^2}(x^2) = \{2^{\nu/2} \Gamma(\frac{1}{2}\nu)\}^{-1} (x^2)^{(\nu/2)-1} \exp(-\frac{1}{2}x^2), \quad x^2 \geq 0. \quad (17.6)$$

Although in the definition above ν must be an integer, the distribution (17.6) is also called a " χ^2 distribution with ν degrees of freedom" if ν is any positive number. This distribution is discussed in detail in Chapter 18.

2 MOMENTS AND OTHER PROPERTIES

The moment generating function of the standard gamma distribution (17.2) is

$$E[e^{tX}] = \{\Gamma(\alpha)\}^{-1} \int_0^m x^{\alpha-1} \exp[-(1-t)x] dx = (1-t)^{-\alpha}, \quad t < 1. \quad (17.7)$$

The characteristic function is $(1-it)^{-\alpha}$.

Since distributions of form (17.1) can be obtained from those of form (17.2) by the linear transformation $X = (X' - \gamma)/\beta$, there is no difficulty in deriving formulas for moments, generating functions, and so on, for (17.1) from those for (17.2).

The formula for the r th moment about zero of distribution (17.2) is

$$\mu'_r = \{\Gamma(\alpha)\}^{-1} \int_0^\infty x^{\alpha+r-1} e^{-x} dx = \frac{\Gamma(\alpha+r)}{\Gamma(\alpha)}. \quad (17.8)$$

From (17.8) cumulants can be obtained. These are very simple:

$$\kappa_r = (r-1)! \alpha. \quad (17.9)$$

Hence for distribution (17.2)

$$\begin{aligned} E[X] &= \text{Var}(X) = \alpha, \\ \mu_3 &= 2\alpha, \\ \mu_4 &= 3\alpha^2 + 6\alpha, \end{aligned} \quad (17.10)$$

so

$$\begin{aligned} \alpha_3 &= \sqrt{\beta_1} = 2\alpha^{-1/2}, \\ \alpha_4 &= \beta_2 = 3 + 6\alpha^{-1}. \end{aligned} \quad (17.11)$$

The mean deviation of distribution (17.2) is

$$\frac{2\alpha^\alpha e^{-\alpha}}{\Gamma(\alpha)}. \quad (17.12)$$

The standard distribution (17.2) has a single mode at $x = a - 1$ if $a \geq 1$. [Distribution (17.1) has a mode at $x = y + \beta(\alpha - 1)$.] If $a < 1$, $p_X(x)$ tends to infinity as x tends to zero; if $a = 1$ (the standard exponential distribution), $\lim_{x \rightarrow 0} p_X(x) = 1$.

There are points of inflexion, equidistant from the mode, at

$$x = \alpha - 1 \pm \sqrt{\alpha - 1} \quad (17.13)$$

(provided that the values are real and positive). The standardized variable

$$W = \frac{X - \alpha}{\sqrt{\alpha}} \quad (17.14)$$

is referred to as the frequency factor by hydrologists in flood frequency analysis [see, e.g., Phien (1991) or Chow (1969)].

Vodă (1974) studies a reparametrized version of the gamma distribution (17.1), with $y = 0$, whose pdf is

$$p_X(x; \alpha, \theta) = \left(\frac{\alpha}{\theta}\right)^\alpha \times \frac{1}{\Gamma(\alpha)} x^{\alpha-1} \exp\left(\frac{-\alpha x}{\theta}\right), \quad x > 0; \alpha, \theta > 0. \quad (17.15)$$

Some typical probability density functions are shown in Figures 17.1 and 17.2. Figure 17.2 shows three different gamma distributions (17.1), each having the same expected value (zero) and standard deviation (unity).

$$\begin{aligned} a = 1; \quad p(x) &= \exp[-(x + 1)] & (x > -1) \quad \text{Mode at } -1 \\ \alpha = 4; \quad p(x) &= \frac{8}{3}(x + 2)^3 \exp[-2(x + 2)] & (x > -2) \quad \text{Mode at } -\frac{1}{2} \\ \alpha = 9; \quad p(x) &= \frac{2187}{4480}(x + 3)^8 \exp[-3(x + 3)] & (x > -3) \quad \text{Mode at } -\frac{1}{3} \end{aligned}$$

It can be seen from Figure 17.1 that, as a increases, the shape of the curve becomes similar to the normal probability density curve. In fact the standardized gamma distribution tends to the unit normal distribution as the value of the parameter a tends to infinity:

$$\lim_{\alpha \rightarrow \infty} \Pr[(X - \alpha)\alpha^{-1/2} \leq u] = \Phi(u) \quad (17.16)$$

for all real values of u , where $\Phi(u) = (2\pi)^{-1/2} \int_{-\infty}^u \exp(-\frac{1}{2}t^2) dt$.

A similar result holds for the general distribution (17.1), namely

$$\lim_{\alpha \rightarrow \infty} \Pr\left[\left\{\frac{X - \gamma}{\beta} - \alpha\right\}\alpha^{-1/2} \leq u\right] = \Phi(u). \quad (17.17)$$

For χ_ν^2 ,

$$\lim_{\nu \rightarrow \infty} \Pr[(\chi_\nu^2 - \nu)(2\nu)^{-1/2} \leq u] = \Phi(u). \quad (17.18)$$

It can be checked from (17.10) and (17.11) that $a, \rightarrow 0$, $a, \rightarrow 3$ (the values for the normal distribution) as a, ν , respectively, tend to infinity.

One of the most important properties of the distribution is the reproductive property: If X_1, X_2 are independent random variables each having a distribution of form (17.1), with possibly different values a', a'' of a , but with common values of β and y , then $(X_1 + X_2)$ also has a distribution of this form, with the same value of β , double the value of y , and with $a = a' + a''$.

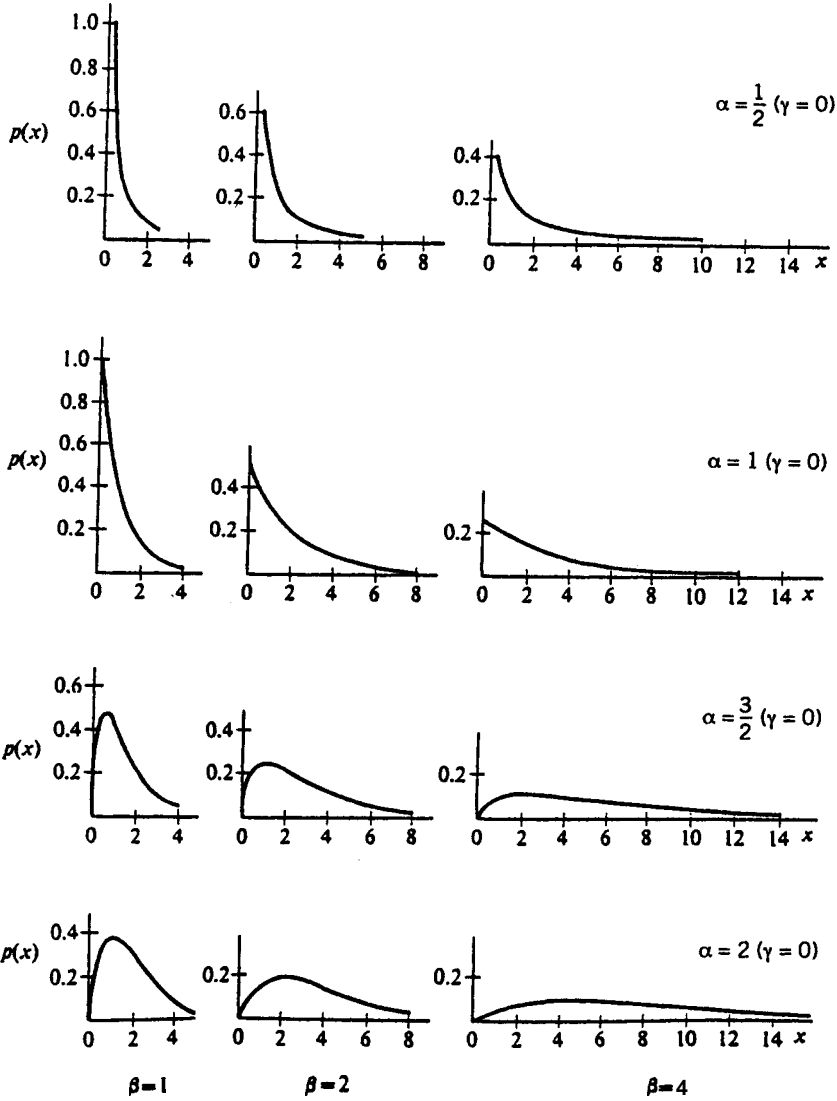


Figure 17.1 Gamma Density Functions

For distribution (17.2) Gini's concentration ratio is

$$G = \frac{\Gamma(\alpha + \frac{1}{2})}{\sqrt{\pi} \Gamma(\alpha + 1)}. \tag{17.19a}$$

The Lorenz concentration ratio is

$$L = 2B_{0.5}(\alpha, \alpha + 1), \tag{17.19b}$$

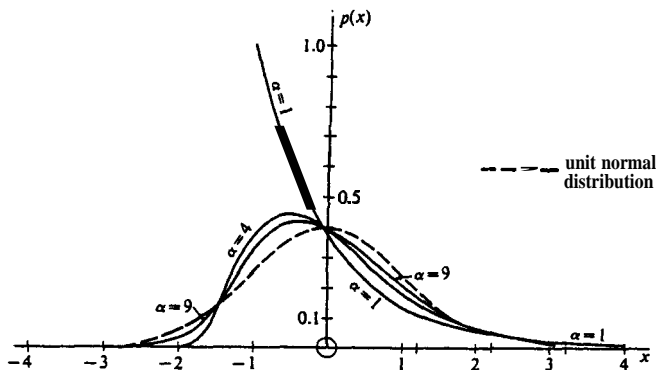


Figure 17.2 Standardized Type III Density Functions

$\alpha = 1;$	$p(x) = \exp[-(x + 1)]$	$(x > -1)$	Mode at -1
$\alpha = 4;$	$p(x) = (8/3)(x + 2)^3 \exp[-2(x + 2)]$	$(x > -2)$	Mode at $-1/2$
$\alpha = 9;$	$p(x) = (2187/4480)(x + 3)^8 \exp[-3(x + 3)]$	$(x > -3)$	Mode at $-1/3$

where $B_p(a, b) = \int_0^p y^{a-1}(1-y)^{b-1} dy$ is the incomplete beta function. The Pietra ratio is

$$\rho = \left\{ \frac{\alpha^\alpha e^{-\alpha}}{\Gamma(\alpha + 2)} \right\} {}_1F_1(2, \alpha + 2; \alpha). \quad (17.20)$$

The Theil entropy measure of inequality is

$$T = \frac{1}{\alpha} + \Psi(\alpha) - \log \alpha \quad (17.21)$$

$[\Psi(\alpha) = d \log \Gamma(\alpha) / d\alpha]$ [Salem and Mount (1974); McDonald and Jensen (1979)]. Saunders and Moran (1978) show that the ε -quantile of the gamma distribution (17.1), denoted by $y_{\varepsilon|\alpha}$, where

$$\int_0^{y_{\varepsilon|\alpha}} e^{-y} y^{\alpha-1} dy / \Gamma(\alpha) = \varepsilon \quad (17.22)$$

has the property that when $1 > \varepsilon_2 > \varepsilon_1 > 0$, the ratio $\gamma_\alpha = y_{\varepsilon_2|\alpha} / y_{\varepsilon_1|\alpha}$ is a decreasing function of α and thus the equation

$$\gamma_\alpha = b$$

has a unique solution, $\phi(b)$ for any $b \in (1, \infty)$. Moreover $\gamma_\alpha \rightarrow 1$ as $\alpha \rightarrow \infty$.

The reproductive property is utilized, among other things, for determination of gamma priors in Bayesian reliability analysis [see Waller and Waterman (1978)]. Also $y_{\varepsilon_2|\alpha} - y_{\varepsilon_1|\alpha}$ increases with α , implying that the gamma distributions are "ordered in dispersion" (see Chapter 33).

3 GENESIS AND APPLICATIONS

Lancaster (1966) quotes from **Laplace** (1836) in which the latter obtains a gamma distribution as the posterior distribution of the "precision constant" ($h = \frac{1}{2}\sigma^{-2}$), (Chapter 13, Section 1) given the values of n independent normal variables with zero mean and standard deviation σ (assuming a "uniform" prior distribution for h). Lancaster (1966) also states that **Bienaymé** (1838) obtained the (continuous) χ^2 distribution as the limiting distribution of the (discrete) random variable $\sum_{i=1}^k (N_i - np_i)^2 (np_i)^{-1}$, where (N_1, \dots, N_k) have a joint multinomial distribution with parameters n, p_1, p_2, \dots, p_k .

The gamma distribution appears naturally in the theory associated with normally distributed random variables, as the distribution of the sum of squares of independent unit normal variables. (See Chapter 18.) The use of the gamma distribution to approximate the distribution of quadratic forms (particularly positive definite quadratic forms) in multinormally distributed variables is well established and widespread. One of the earliest examples was its use, in 1938, to approximate the distribution of the denominator in a test criterion for difference between expected values of two normal populations with possibly different variances [Welch (1938)]. It has been used in this way many times since. The use of gamma distributions to represent distributions of range and quasi-ranges in random samples for a normal population has been discussed in Chapter 13. In most applications the two-parameter form ($\gamma = 0$),

$$p_X(x) = \frac{x^{\alpha-1} e^{-x/\beta}}{\beta^\alpha \Gamma(\alpha)}, \quad x > 0; \alpha > 0, \beta > 0, \quad (17.23)$$

is used (this is equivalent to approximating by the distribution of $\frac{1}{2}\beta\chi_{2\alpha}^2$). However, the three-parameter form has also been used with good effect [e.g., see **Pearson** (1963)].

The gamma distribution may be used in place of the normal distribution as "parent" distribution in expansions of Gram-Charlier type (Chapter 12, Section 4.2). Series with Laguerre polynomial multipliers rather than Hermite polynomial multipliers are obtained in this situation. Formulas for use with such expansions and their properties have been described by **Khamis** (1960). These *Laguerre series* have been used by **Barton** (1953) and **Tiku** (1964a, b) to approximate the distributions of "smooth test" (for goodness-of-fit) statistics and noncentral F (Chapter 30).

In applied work, gamma distributions give useful representations of many physical situations. They have been used to make realistic adjustments to exponential distributions in representing lifetimes. The "reproductive" property (mentioned in Section 1) leads to the appearance of gamma distributions in the theory of random counters and other topics associated with random

processes in time, in particular in meteorological precipitation processes [Kotz and Neumann (1963); Das (1955)]. Some other applications from diverse fields are described in papers cited in references. Among the latter papers Salem and Mount (1974) provide a comparison of the gamma and lognormal distributions and demonstrate that the gamma distributions provides a better fit for personal income data in the United States for the years 1960 to 1969.

Dennis and Patil (1984) discuss applications of gamma distribution in statistical ecology (standard model for sampling dispersion). Among more recent applications we note Costantino and Desharnais's (1981) empirical fit of the steady-state abundances of laboratory flour beetle (*Tribolium*) populations. Dennis and Patil (1984) generalize this result and show that a gamma distribution is an approximate stationary distribution for the abundance of a population fluctuating around a stable equilibrium. Starting from the stochastic model of population growth

$$\frac{dn}{dt} = n[g(u) + h(n)z(t)],$$

where n is population density at time t , $g(u)$ is the specific growth rate, $z(t)$ is a Gaussian process (noise) with variability α^2 , and $h(n)$ is a function specifying the density dependence on the effects of the noise, Dennis and Patil (1984) approximate Wright's formula for the equilibrium pdf by a gamma distribution emphasizing its right-skewness in the distribution of single-species abundances at equilibrium and its positive range. Then, modifying their deterministic model from $du/dt = ng(u)$ to $du/dt = n[g(u) - p(u)]$, where $p(u)$ is a specific rate describing the effects of predation, harvesting and other forces, Dennis and Patil (1984) arrive at a weighted gamma distribution for the equilibrium pdf.

Gamma distributions share with lognormal distributions (Chapter 14) the ability to mimic closely a normal distribution (by choosing α large enough) while representing an essentially positive random variable (by choosing $\gamma \geq 0$).

4 TABLES AND COMPUTATIONAL ALGORITHMS

In 1922 there appeared a comprehensive Tables of the Incomplete Γ -Function, edited by Pearson (1922). This contains values of $I(u, p)$ [see (17.5) with $\alpha = p + 1$] to seven decimal places for $p = -1(0.05)0(0.1)5(0.2)50$ and u at intervals of 0.1. These are supplemented by a table of values of

$$\log I(u, p) - (p + 1)\log u$$

for $p = -1(0.05)0(0.1)10$ and $u = 0.1(0.1)1.5$. This function was chosen to make interpolation easier, particularly for low values of p (Section 5).

Harter (1964) published tables of $I(u, p)$ to nine decimal places for $p = -0.5(0.5)74(1)164$ and u at intervals of 0.1. In this work he covers a greater range of values of p and has two extra decimal places, although Pearson (1922) has p at finer intervals. Harter (1969) published further tables of Type III distributions, giving the 0.01, 0.05, 0.1, 0.5, 1, 2, 2.5, 4, 5, 10(10)90, 95, 96, 97.5, 98, 99, 99.5, 99.9, 99.95, and 99.99 percentage points to 5 decimal places for $\sqrt{\beta_1} = 0.0(0.1)4.8(0.2)9.0$. Harter (1971) extends his 1969 tables and provides percentage points of the one-parameter gamma distribution (Pearson Type III) corresponding to cumulative probabilities 0.002 and 0.998 as well as 0.429624 and 0.570376. The first pair is used for determination of the magnitude of an event (flood) corresponding to 500-year return period, while the second corresponds to a return period of 32,762 years (the so-called mean annual flood according to the guidelines of the U.S. Department of Housing and Urban Development). These are the most important direct tables of $I(u, p)$.

Pearson (1922) gave the more general formula for distribution (17.1):

$$\Pr\{X \leq x\} = e^{-y} \sum_{j=0}^{\infty} \left\{ \frac{y^{\alpha+j}}{\Gamma(\alpha+j+1)} \right\} \text{ for } y = (x - \gamma)/\beta > 0. \quad (17.24)$$

Salvosa (1929, 1930) published tables of the probability integral, probability density function and its first six derivatives for distribution (17.1), with β and γ so chosen that X is standardized (i.e., $\beta = \alpha_3/2$; $\gamma = -2/\alpha_3$). Values are given to six decimal places for $a_3 = 2\alpha^{-1/2} = 0.1(0.1)1.1$ at intervals of 0.01 for x . Cohen, Helm, and Sugg (1969) have calculated tables of the probability integral to nine decimal places for $a_3 = 0.1(0.1)2.0(0.2)3.0(0.5)6.0$ at intervals of 0.01 for x . Bobée and Morin (1973) provide tables of percentage points of order statistics for gamma distributions.

Thom (1968) has given tables to four decimal places of the distribution function $\Gamma_x(\alpha)/\Gamma(\alpha)$:

1. for $a = 0.5(0.5)15.0(1)36$ and $x = 0.0001, 0.001, 0.004(0.002)0.020(0.02)0.80(0.1)2.0(0.2)3.0(0.5)$ —the tabulation is continued for increasing x until the value of the tabulated function exceeds 0.9900;
2. values of x satisfying the equation

$$\frac{\Gamma_x(\alpha)}{\Gamma(\alpha)} = \varepsilon$$

for $a = 0.5(0.5)15.0(1)36$ and $\varepsilon = 0.01, 0.05(0.05)0.95, 0.99$. Burgin (1975) provides some interesting numerical computations of the gamma and associated functions. He cites the following representation for the

incomplete gamma function ratio:

$$I(u, p) = \frac{e^{-u}}{\Gamma(p+1)} u^p \sum_{n=0}^{\infty} \left(\frac{u^{n+1}}{\prod_{i=1}^n (p+i+1)} \right). \quad (17.25)$$

Lau (1980) uses a series expansion similar to Wilk, Gnanadesikan, and Huyett (1962a) to calculate the incomplete gamma function ratio. Moore (1982) finds this series expansion not always satisfactory. **Bhattacharjee** (1970) provides an alternative algorithm. **Phien** (1991) presents an algorithm for computing the quantile $y_{\varepsilon|\alpha}$. Newton's method seems to be appropriate to solving the equation

$$I(y_{\varepsilon|\alpha}, \alpha + 1) = \varepsilon.$$

Efficient computation requires a powerful algorithm for computing the incomplete gamma function ratio and a good initial value y_0 . **Phien** used Moore's algorithm (1982) for calculation of the incomplete gamma function ratio and the approximate value provided by Hoshi and Burges (1981) is used for the initial value y_0 .

Moore's algorithm is highly accurate. In the experiment conducted by **Phien** (1991) Moore algorithm's value agreed with those values tabulated by E. S. **Pearson** (1963) up to the sixth decimal place.

5 APPROXIMATION AND GENERATION OF GAMMA RANDOM VARIABLES

The best-known approximations for probability integrals of gamma distributions have been developed in connection with the χ^2 distribution. Modifications to apply to general gamma distributions are direct, using the linear transformation $y = 2(x - \gamma)/\beta$. The reader should consult Section 5 of Chapter 18.

From (17.25) it may be observed that for u small, $u^{-(p+1)}I(u, p)$ is very approximately, a linear function of u . It is for this reason that the values

$$\log I(u, p) - (p+1)\log u$$

tabulated by **Pearson** (1922) lead to relatively easy interpolation. Gray,

Thompson, and McWilliams (1969) have obtained the relatively simple approximation:

$$\frac{1}{x^{\alpha-1}e^{-x}} \int_x^\infty t^{\alpha-1}e^{-t} dt \doteq \frac{x}{x-\alpha+1} \left[1 - \frac{\alpha-1}{(x-\alpha+1)^2+2x} \right], \quad (17.26)$$

which gives good results when x is sufficiently large.

If Y has the standard uniform distribution (Chapter 26, Section 1)

$$p_Y(y) = 1, \quad 0 < y < 1, \quad (17.27)$$

then $(-2 \log Y)$ is distributed as χ^2 with 2 degrees of freedom. If Y_1, Y_2, \dots, Y_s each have distribution (17.27) and are independent then $\sum_{j=1}^s (-2 \log Y_j)$ is distributed as χ_{2s}^2 ; that is, it has a gamma distribution with $a = s$, $\beta = 2$, and $\gamma = 0$. Using this relation, it is possible to generate gamma distributed variables from tables of random numbers. Extension to cases when a is not an integer can be effected by methods of the kind described by Bánkóvi (1964).

If X has distribution (17.2), then the moment generating function of $\log X$ is

$$E[e^{t \log X}] = E[X^t] = \frac{\Gamma(\alpha + t)}{\Gamma(\alpha)}. \quad (17.28)$$

Hence the r th cumulant of $\log X$ is

$$\kappa_r(\log X) = \psi^{(r-1)}(\alpha). \quad (17.29)$$

Note that for a large

$$\begin{aligned} \beta_1(\log X) &\doteq \alpha^{-1}, \\ \beta_2(\log X) &\doteq 3 + 2\alpha^{-1}, \end{aligned} \quad (17.30)$$

which may be compared with

$$\begin{aligned} \beta_1(X) &= 4\alpha^{-1}, \\ \beta_2(X) &= 3 + 6\alpha^{-1}. \end{aligned}$$

The distribution of $\log X$ is more nearly normal than the distribution of X . Although this approximation is not generally used directly, it is often very useful when approximating the distributions of functions of independent gamma variables.

For example, suppose that X_1, X_2, \dots, X_k are independent variables, each distributed as χ^2 with ν degrees of freedom. Then the distribution of

$$R_k = \frac{\max(X_1, X_2, \dots, X_k)}{\min(X_1, X_2, \dots, X_k)} \quad (17.31)$$

may be approximated by noting that

$$\log R_k = \max(\log X_1, \dots, \log X_k) - \min(\log X_1, \dots, \log X_k)$$

is approximately distributed as the range of k independent normal variables each having the same expected value, and standard deviation

$$\sqrt{\psi^{(1)}\left(\frac{\nu}{2}\right)} \doteq \sqrt{\frac{2}{\nu-1}}. \quad (17.32)$$

[See also (17.107).]

Gray and Schucany (1968) and Gray and Lewis (1971) apply the method of **H- and B_n -transforms** (see Chapter 12, Section 4) to approximate the tail probabilities of chi-squared (and hence of gamma) distributions. **Alfers** and **Dinges** (1984) sought an approximate normalizing transformation. They obtained a polynomial expression.

A recent survey of approximations for gamma distribution quantiles is contained in a paper by **Phien** (1991). He notes that for a variable X with pdf given by (17.2), the standardized variable is $W = (X - \alpha)/\sqrt{\alpha}$ (for which $E[W] = 0$, $\text{Var}(W) = 1$, and $\sqrt{\beta_1(W)} = 2/\sqrt{\alpha}$). The Wilson-Hilferty chi-squared approximation (see Chapter 18, Section 5) gives

$$W_\varepsilon \doteq \sqrt{\alpha} \left[\left\{ 1 - \frac{1}{9}\alpha^{-1} + \frac{1}{3}\alpha^{-1/2}z_\varepsilon \right\}^3 - 1 \right], \quad (17.33)$$

where $\Phi(z_\varepsilon) = \varepsilon$. When α is small (skewness is large), the values of W_ε given by (17.33) are too low.

Kirby (1972) modifies (17.33) and obtains the following approximation:

$$W_\varepsilon \doteq A(U - B), \quad (17.34)$$

where $A = \max(\sqrt{\alpha}, 0.40)$, $B = 1 + 0.0144 [\max(0, 2\alpha^{-1/2} - 2.25)]^2$, and

$$U = \max \left[B - \sqrt{\alpha}/A, \left\{ 1 - \left(\frac{1}{6}D\right)^2 + \left(\frac{1}{6}D\right)z_\varepsilon \right\}^3 \right]$$

with

$$D = 2\alpha^{-1/2} - 0.063\{\max(0, 2\alpha^{-1/2} - 1)\}^{1.85}.$$

Kirby (1972) provides tables to assist in the calculation of A , B , and D . Kirby's approximation was in turn modified by **Hoshi and Burges** (1981) who express A , B , $B - A/\alpha$, and D as polynomials of degree 5 in $\alpha^{-1/2}$. **Phien** (1991) reproduces the values given by **Hoshi and Burges** (1981). **Harter** (1969) provided tables of exact values of W_ε , to which **Bobée** (1979) fitted polynomials in $\alpha^{-1/2}$ of degree four. For $\sqrt{\beta_1} = 2/\sqrt{\alpha} < 4$ (i.e., $\alpha > \frac{1}{4}$) **Bobée's**

approximation is superior to those of Hoshi and Burges (1981) and Kirby (1979), but it is not satisfactory for smaller values of a .

Tadikamalla and **Ramberg (1975)**, Wheeler (1975), and Tadikamalla (1977) approximate the gamma distribution (17.2) by a four-parameter Burr distribution (see Chapter 12, Section 4.5) by equating the first four moments—expected value, variance, skewness, and kurtosis.

For the Burr distribution with cdf,

$$F_X(x) = 1 - \left\{ 1 + \left(\frac{x-a}{b} \right)^c \right\}^{-k},$$

the $100p\%$ points of the largest and smallest order statistics from a random sample of size n are

$$a + b\{(1-p)^{-1/(nk)} - 1\}^{1/c}, \quad (17.35a)$$

$$a + b\{(1-p^{1/n})^{-1/k} - 1\}^{1/c}, \quad (17.35b)$$

respectively. These equations give good approximations to the corresponding value for the appropriate gamma distributions. Tables are available from Tadikamalla (1977) to facilitate calculation of appropriate values for a , b , k , and c .

Values of c and k for given values of a are given in Tadikamalla and **Ramberg (1975)** and Wheeler (1975). These two papers were published in the same issue of the same journal, and yet they do not cross-reference each other. (Fortunately the values of c and k given in the two papers agree.)

Many papers on generation of gamma random variables have been written in the years 1964 to 1990. It is impossible to survey them in detail. We draw attention to **Ahrens** and Dieter (1974, "GO algorithm"), **Fishman (1976)**, **Johnk (1964)**, **Odell** and Newman (1972), **Wallace (1974)**, and **Whittaker (1974)**—all are based on the general von Neumann rejection method. Cheng and Feast (1979, 1980) use the ratio of uniform random variables on the lines suggested by **Kinderman** and **Monahan (1977)**.

Bowman and **Beauchamp (1975)** warn of pitfalls with some gamma distribution simulation routines. They note that an algorithm given by **Phillips** and **Beightler (1972)** does not actually generate random variables with gamma distributions, but rather with Weibull distributions (see Chapter 21).

6 CHARACTERIZATIONS

If X_1 and X_2 are independent standard gamma random variables [i.e., having distributions of form (17.2), possibly with different values of a ; $\alpha_1, a,$

say], then the random variables

$$X_1 + X_2 \quad \text{and} \quad \frac{X_1}{X_1 + X_2}$$

are mutually independent. [Their distributions are, respectively, a standard gamma with $\alpha = \alpha_1 + \alpha_2$ and a standard beta (Chapter 25) with parameters α_1, α_2 .]

Lukacs (1965) showed that this property characterizes the gamma distribution in that, if X_1 and X_2 are independent positive random variables, and $X_1 + X_2$ and $X_1/(X_1 + X_2)$ are mutually independent, then X_1 and X_2 must each have gamma distributions of form (17.1) with $\gamma = 0$, common β , but possibly different values of α . If it be assumed that X_1 and X_2 have finite second moments and identical distributions, it is sufficient to require that the regression function

$$E \left[\frac{a_{11}X_1^2 + 2a_{12}X_1X_2 + a_{22}X_2^2}{(X_1 + X_2)^2} \middle| X_1 + X_2 \right], \quad a_{11} + a_{22} \neq 2a_{12},$$

be independent of $X_1 + X_2$ to ensure that the common distribution is a gamma distribution [Laha (1964)].

Marsaglia (1974) extended Lukacs's result by removing the condition that X_1 and X_2 should be positive. He shows that "If X_1 and X_2 are independent nondegenerate random variables, then $X_1 + X_2$ is independent of X_1/X_2 if and only if there is a constant c such that cX_1 and cX_2 have standard gamma distributions." Marsaglia (1989) provides a simpler proof of this result. He uses a method of deriving Lukacs's (1965) result, which was developed by Findeisen (1978), without use of characteristic functions (although a disclaimer, suggested by the referees of the Findeisen paper, claims that characteristic functions are implicit in the argument). Marsaglia (1989) also remarks that the " $X_1 + X_2, X_1/X_2$ " characterization has been used in developing computer methods for generating random points on surfaces by projections of points with independent (not necessarily positive) components.

Earlier Marsaglia (1974) had obtained the following result "Let X_1, X_2, \dots, X_n ($n \geq 2$) be independent random variables. Then the vector

$$\left(\frac{X_1}{S_n}, \frac{X_2}{S_n}, \dots, \frac{X_n}{S_n} \right),$$

where $S_n = \sum_{j=1}^n X_j$, is independent of S_n if and only if there is constant c such that cX_1, cX_2, \dots, cX_n are gamma." Wang and Chang (1977) used this result to develop several sensitive nonparametric tests of **exponentiality**. Many multivariate generalizations of these results are surveyed in Wang (1981).

On the one hand, the distribution of X_1/X_2 is not sufficient to establish that each $|X_j|$ has a gamma distribution. If X_j is distributed as standard gamma (a, \cdot) , $(j = 1, 2)$ and X_1 and X_2 are mutually independent then the probability density function of $G = X_1/X_2$ is

$$p_G(g) = [B(\alpha_1, \alpha_2)]^{-1} g^{\alpha_1-1} (1 + g)^{-(\alpha_1+\alpha_2)}, \quad g > 0, \quad (17.36)$$

which is a **Pearson** Type VI distribution (see Chapter 12 and also Chapter 25). However, it is possible for X_1 and X_2 to be independent, identically distributed positive random variables, and for $G = X_1/X_2$ to have distribution (17.36), without each X_j having a gamma distribution [**Laha** (1954); **Mauldon** (1956); **Kotlarski** (1962, 1965)]. However, **Kotlarski** (1967) showed that the joint distribution of ratios $X_1/X_3, X_2/X_3$ (in a similar situation) does characterize the distribution (up to a constant multiplier).

It follows that any result depending only on the distribution (17.36) of the ratio X_1/X_2 cannot characterize the distribution of each X_j . In particular, it can be shown that if X_1 and X_2 are independent and identically distributed as in (17.2), then

$$\sqrt{\frac{a}{2}} \left(\sqrt{\frac{X_1}{X_2}} - \sqrt{\frac{X_2}{X_1}} \right)$$

has a t_{2a} distribution (as defined in Chapter 28), although this property is not sufficient to establish the form of the common distribution of X_1 and X_2 (given they are positive, independent, and identically distributed).

However, if X_3 is a third random variable (with the same properties relative to X_1 and X_2), then the joint distribution of

$$\sqrt{\frac{a}{2}} \left(\sqrt{\frac{X_1}{X_2}} - \sqrt{\frac{X_2}{X_1}} \right) \quad \text{and} \quad \sqrt{\frac{a}{2}} \left(\sqrt{\frac{X_1}{X_3}} - \sqrt{\frac{X_3}{X_1}} \right)$$

is sufficient to establish that common distribution is a gamma distribution with $y = 0$. [**Kotlarski** (1967).]

Khatri and **Rao** (1968) have obtained the following characterizations of the gamma distribution, based on constancy of various regression functions:

1. If X_1, X_2, \dots, X_n ($n \geq 3$) are independent positive random variables and

$$Y_1 = \sum_{i=1}^n b_{1i} X_i, \quad b_{1i} \neq 0, \quad i = 1, 2, \dots, n,$$

$$Y_j = \prod_{i=1}^n X_i^{b_{ji}}, \quad j = 2, \dots, n,$$

with the $(n-1) \times n$ matrix (b_{ji}) ($j = 2, \dots, n$, $i = 1, 2, \dots, n$) nonsingular, then the constancy of

$$E\{Y_1|Y_2, \dots, Y_n\}$$

ensures that the X 's must have a common gamma distribution (unless they have zero variances).

Setting $b_{11} = b_{12} = \dots = b_{1n} = 1$ and $b_{j,j-1} = -1$, $b_{j,j} = 1$, with all other b 's zero, the condition becomes the constancy of

$$E\left[\sum_{j=1}^n X_j \left| \frac{X_2}{X_1}, \frac{X_3}{X_1}, \dots, \frac{X_n}{X_1} \right.\right].$$

2. In the conditions of 1, if $E[X_j^{-1}] \neq 0$ ($j = 1, 2, \dots, n$) and

$$Z_1 = \sum_{i=1}^n b_{1i} X_i^{-1},$$

$$Z_j = \sum_{i=1}^n b_{ji} X_i, \quad j = 2, \dots, n,$$

with the b 's satisfying the same conditions as in 1, then the constancy of

$$E\{Z_1|Z_2, Z_3, \dots, Z_n\}$$

ensures that each X_j has a gamma distribution (not necessarily the same for all j), unless they have zero variances. Choosing special values of b 's as in 1, we obtain the condition that $E[\sum_{j=1}^n X_j^{-1} | X_2 - X_1, \dots, X_n - X_1]$ should be constant.

3. Under the same conditions as in 1, if $E[X_1 \log X_1]$ is finite, then the constancy of

$$E\left[\sum_{j=1}^n a_j X_j \left| \prod_{i=1}^n X_i^{b_i} \right.\right],$$

with $\sum_{j=1}^n a_j b_j = 0$, $|b_n| > \max(|b_1|, |b_2|, \dots, |b_{n-1}|)$, and $a_j b_j / a_n b_n < 0$ for all $j = 1, 2, \dots, n-1$ ensures that X_1 has a gamma distribution (unless it has zero variance).

As a special case, setting $a_1 = a_2 = \dots = a_n = 1$, $b_n = n-1$, $b_1 = b_2 = \dots = b_{n-1} = -1$, we obtain the condition as the constancy of

$$E\left[\sum_{j=1}^n X_j \left| X_n^{n-1} \left\{ \prod_{j=1}^{n-1} X_j \right\}^{-1} \right.\right].$$

4. If X_1, \dots, X_n are independent, positive, and identically distributed random variables, and if $E[X_i^{-1}] \neq 0$ ($i = 1, 2, \dots, n$) and

$$E \left[\sum_{j=1}^n a_j X_j^{-1} \middle| \sum_{j=1}^n b_j X_j \right]$$

is constant with the same conditions on the a's and b's as in 3, the common distribution of the X's is a gamma distribution (unless it has a zero variance).

Giving the a's and b's the same special values as in 3, we obtain the condition of constancy of

$$E \left[\sum_{j=1}^n X_j^{-1} \middle| X_n - \bar{X} \right],$$

where $\bar{X} = n^{-1} \sum_{j=1}^n X_j$.

Khatri and Rao (1968) have also obtained a number of further conditions characterizing gamma distributions. Hall and Simons (1969) have shown that if X and Y are mutually independent and nondegenerate, and if

$$E[X^2(X+Y)^{-2}|X+Y] \quad \text{and} \quad E[Y^2(X+Y)^{-2}|X+Y]$$

do not depend on $X+Y$, then either X and Y or $-X$ and $-Y$ have two-parameter gamma distributions with a common value of the scale parameter β .

The following characterization based on conditional expectation was suggested by Wang (1972): "If $\beta = (b_{jk})$ be a $n \times n$ real matrix satisfying

$$\sum_{j=1}^n b_{jj} = 1 \quad \text{and} \quad \sum_{j,k} b_{jk} = c \neq 0,$$

$X = (X_1, X_2, \dots, X_n)$ is a $n \times 1$ random vector, $Q^* = X' \beta X$, and $L = C'X$, where $C = (c_1, c_2, \dots, c_n)'$ is an $n \times 1$ real vector such that $\sum_{j=1}^n c_j = 1$ and $c_j = c_k \neq 0$ for some j, k, then provided the distribution F of X_i ($i = 1, 2, \dots, n$) is nondegenerate, the conditional expectation $E[Q^*|L]$ is zero almost everywhere if and only if each X_i has a gamma distribution." If N is a random variable defined by

$$N = 0 \quad \text{if } X_1 > x$$

and

$$N = n \quad \text{if } X_1 + \dots + X_n \leq x < X_1 + \dots + X_{n+1},$$

where X_1, X_2, \dots, X_n are independent random variables each having distribution (17.1) with a an integer and with $\gamma = 0$ (Erlang distribution), then N has the generalized Poisson distribution (Chapter 9, Section 3)

$$\Pr[N \leq n] = e^{-x/\beta} \sum_{j=0}^{(n+1)a-1} \left\{ \frac{(x/\beta)^j}{j!} \right\}.$$

Nabeya (1950) showed that for $a = 1$, the converse is true. That is to say, it is a characterization of the common distribution of X_1, \dots, X_n (exponential in this case) given that they are positive, independent, identically distributed, and continuous. Goodman (1952) extended the result to apply to any positive integer value of $a \geq 2$, thus providing a characterization of a gamma distribution.

Under conditions (4), Linnik, Rukhin, and Stzelic (1970) characterize the gamma distribution by the property

$$E \left\{ P_k \left(\frac{X_1}{S_n}, \dots, \frac{X_n}{S_n} \right) \middle| S_n \right\} \text{ does not depend on } S_n = \sum_{j=1}^n X_j,$$

where P_k is a polynomial of degree k , $n \geq 2$, and $n > k$. Some conditions on the behavior of the cdf of the positive i.i.d. X_i and its derivative in an interval $[0, \varepsilon]$ were required to prove the validity of this result.

If X_1, X_2, \dots, X_n are independent gamma variables with the same scale parameter β_j , and $S(X_1, X_2, \dots, X_n)$ is a statistic invariant under the scale transformation $X \rightarrow cX$ (for all $c \neq 0$), then $U = \sum_{j=1}^n X_j$ and $S = S(X_1, X_2, \dots, X_n)$ are independent [Wang (1981)]. However, whether the gamma distribution can be characterized by the independence of U and S seems still to be an open problem.

The following characterization has been proved by Wang (1981): Let X_1, \dots, X_n ($n > 2$) be nondegenerate i.i.d. positive random variables and I_1 and I_2 be arbitrary nonempty subsets of $(1, 2, \dots, n)$ of size $k \leq n/2$. Define $T_1 = \prod_{j \in I_1} X_j$ and $T_2 = \prod_{j \in I_2} X_j$. If

$$E[T_1^2 | U] = \theta E(T_1 + T_2)^2,$$

then the X_i 's have a (two-parameter) gamma distribution (17.23).

Characterization of gamma distributions by the negative binomial has been provided by Engel and Zijlstra (1980):

Let events A occur independently and at random so that the number of events occurring in a given interval is a Poisson random variable with rate θ . The waiting time between events has a negative exponential distribution with mean θ^{-1} , and the total time T between $r + 1$ events has a gamma (r, θ^{-1}) distribution.

Consider now a second process independent of the first in which events B occur at an average rate β . If we start from a specified instant and count the number N_B of B events occurring before the r th A event, the distribution of N , is negative binomial with parameters r and $p = \alpha/(\alpha + \beta)$.

Engel and Zijlstra (1980) have shown that T has a gamma (r, a) distribution if and only if N_B has a negative binomial distribution.

Letac (1985) characterizes the gamma distributions as follows: Given two positive independent random variables X and Y , if the distribution of Y is defined by its moments

$$E[Y^s] = \left(1 + \frac{s}{a}\right)^{a+s} \quad \text{for } s > 0$$

and a fixed given positive a , then $X \exp\{-X/\alpha\}Y$ and X have the same distribution if and only if the distribution of X is gamma with shape parameter a [as in (17.2)]. Motivation for this characterization is that $(UV)^{uv}$ and U^u have the same distribution provided U and V are independent uniform $[0, 1]$ variables.

She (1988) has proved several theorems dealing with characterizations of the gamma distribution based on regression properties; see also Wesolowski (1990) for a characterization result based on constant regression, and Yeo and Milne (1991) for a characterization based on a mixture-type distribution.

7 ESTIMATION

Estimation of parameters of gamma distribution has also received extensive attention in the literature in the last two decades. The contributions of Bowman and Shenton and of A. C. Cohen and his coworkers should be particularly mentioned. Bowman and Shenton's (1988) monograph provides detailed analysis of maximum likelihood estimators for two-parameter gamma distributions with emphasis on the shape parameter and presents valuable information on distributions and moments of these estimators, including their joint distributions. Careful discussion of estimation problems associated with the three-parameter gamma density is also presented. The major emphasis of the monograph is on the distribution of sample standard deviation, skewness and kurtosis in random samples from a Gaussian density. The authors also deal with the moments of the moment estimators. The list of references in the monograph covers the development of the authors' work on this area from 1968 onwards.

A. C. Cohen's contributions to estimation of parameters of the gamma distribution are covered in the monographs by Cohen and Whitten (1988) and Balakrishnan and Cohen (1991) with an emphasis on modified moment estimators and censored samples. As in Chapters 14 and 15 we will concen-

trate on results not available in monographic literature and especially those discussed in less easily available sources.

7.1 Three Parameters Unknown

We will first consider estimation for the three parameter distribution (17.1), although in **many** cases it is possible to assume γ is zero, and estimate only α and β in (17.1). Given values of n independent random variables X_1, X_2, \dots, X_n , each distributed as in (17.1), the equations satisfied by the maximum likelihood estimators $\hat{\alpha}$, $\hat{\beta}$, and $\hat{\gamma}$ of α , β , and γ , respectively, are

$$\sum_{j=1}^n \log(X_j - \hat{\gamma}) - n \log \hat{\beta} - n\psi(\hat{\alpha}) = 0, \quad (17.37a)$$

$$\sum_{j=1}^n (X_j - \hat{\gamma}) - n\hat{\alpha}\hat{\beta} = 0, \quad (17.37b)$$

$$- \sum_{j=1}^n (X_j - \hat{\gamma})^{-1} + n\{\hat{\beta}(\hat{\alpha} - 1)\}^{-1} = 0. \quad (17.37c)$$

From (17.37c) it can be seen that if $\hat{\alpha}$ is less than 1, then some X_j 's must be less than $\hat{\gamma}$. This is anomalous, since for $x < \gamma$ the probability density function (17.1) is zero. It is also clear that equations (17.37) will give rather unstable results if $\hat{\alpha}$ is near to 1, even though it exceeds 1. It is best, therefore, not to use these equations unless it is expected that $\hat{\alpha}$ is at least 2.5, say.

It is possible to solve equations (17.37) by iterative methods. A convenient (but not the only) method is to use (17.37a) to determine a new value for $\hat{\beta}$, given $\hat{\alpha}$ and $\hat{\gamma}$. Then (17.37b) for a new $\hat{\gamma}$, given $\hat{\alpha}$ and $\hat{\beta}$, and (17.37c) for a new $\hat{\alpha}$, given $\hat{\beta}$ and $\hat{\gamma}$.

The asymptotic variance-covariance matrix of $\hat{\alpha}$, $\hat{\beta}$, and $\hat{\gamma}$ is the inverse of the matrix

$$\begin{pmatrix} \psi'(\alpha) & \beta^{-1} & \beta^{-1}(\alpha - 1)^{-1} \\ \beta^{-1} & \alpha\beta^{-2} & \beta^{-2} \\ \beta^{-1}(\alpha - 1)^{-1} & \beta^{-2} & \beta^{-2}(\alpha - 2)^{-1} \end{pmatrix}.$$

The determinant of this matrix is

$$\beta^4 \left[\frac{2\psi'(\alpha)}{\alpha - 2} - \frac{2\alpha - 3}{(\alpha - 1)^2(\alpha - 2)} \right].$$

Hence

$$\text{Var}(\hat{\alpha}) \doteq 2n^{-1} [2\psi'(\alpha) - (2\alpha - 3)(\alpha - 1)^{-2}]^{-1}, \quad (17.38a)$$

$$\text{Var}(\hat{\beta}) \doteq n^{-1}\beta^2 [(\alpha - 1)^2\psi'(\alpha) - \alpha + 2] [2(\alpha - 1)^2\psi'(\alpha) - 2\alpha + 3]^{-1}, \quad (17.38b)$$

$$\text{Var}(\hat{\gamma}) \doteq n^{-1}\beta^2(\alpha - 2) \{ \alpha\psi'(\alpha) - 1 \} [2\psi'(\alpha) - (2\alpha - 3)(\alpha - 1)^{-2}]^{-1}. \quad (17.38c)$$

Using the approximation

$$\psi'(\alpha) \doteq \alpha^{-1} + \frac{1}{2}\alpha^{-2} + \frac{1}{6}\alpha^{-3}, \quad (17.39)$$

we obtain the simple formulas,

$$\text{Var}(\hat{\alpha}) \doteq 6n^{-1}\alpha^3, \quad (17.38a)'$$

$$\text{Var}(\hat{\beta}) \doteq 3n^{-1}\beta^2\alpha, \quad (17.38b)'$$

$$\text{Var}(\hat{\gamma}) \doteq \frac{3}{2}n^{-1}\beta^2\alpha^3, \quad (17.38c)'$$

giving the orders of magnitude of the variances when n is large. Fisher (1922) obtained the more precise approximation:

$$\text{Var}(\hat{\alpha}) = 6n^{-1} [(\alpha - 1)^3 + \frac{1}{5}(\alpha - 1)] \quad (17.40)$$

by using more terms in the expansion (17.39).

If the method of moments is used to estimate α , β , and γ , the following simple formulas are obtained:

$$\tilde{\gamma} + \tilde{\alpha}\tilde{\beta} = \bar{X}, \quad (17.41a)$$

$$\tilde{\alpha}\tilde{\beta}^2 = m_2, \quad (17.41b)$$

$$2\tilde{\alpha}\tilde{\beta}^3 = m_3, \quad (17.41c)$$

where

$$\bar{X} = n^{-1} \sum_{j=1}^n X_j,$$

$$m_2 = n^{-1} \sum_{j=1}^n (X_j - \bar{X})^2,$$

$$m_3 = n^{-1} \sum_{j=1}^n (X_j - \bar{X})^3$$

are the sample mean, second, and third central moments. (Since this method would be used only when n is rather large, there is no need to attempt to make the estimators unbiased; it is also not clear whether this would improve the accuracy of estimation.) Note that (17.41a) and (17.37b) γ are identical. From equations (17.41) the following formulas for the *moment estimators* $\tilde{\alpha}$, $\tilde{\beta}$, and $\tilde{\gamma}$ are obtained:

$$\tilde{\alpha} = \frac{4m_2^3}{m_3^2} = \frac{4}{b_1} \quad \left(\text{where } \sqrt{b_1} = \frac{m_3}{m_2^{3/2}} \right) \quad (17.42a)$$

$$\tilde{\beta} = \frac{\frac{1}{2}m_3}{m_2}, \quad (17.42b)$$

$$\tilde{\gamma} = \bar{X} - \frac{2m_2^2}{m_3}. \quad (17.42c)$$

Although these are simple formulas, the estimators are often, **unfortunately**, considerably less accurate than the maximum likelihood estimators $\hat{\alpha}$, $\hat{\beta}$, and $\hat{\gamma}$.

It can be shown that if n and a are large

$$\text{Var}(\tilde{\alpha}) \doteq 6\alpha(\alpha + 1)(\alpha + 5)n^{-1} \quad (17.43)$$

[Fisher (1922)]. Comparing (17.40) and (17.43), it can be seen that the ratio of approximate values $\text{Var}(\hat{\alpha})/\text{Var}(\tilde{\alpha})$ is substantially less than 1 unless a is rather large. The ratio

$$\frac{(\alpha - 1)^3 + \frac{1}{5}(\alpha - 1)}{\alpha(\alpha + 1)(\alpha + 5)}$$

increases with a and reaches the value 0.8 at $a = 39.1$.

On the other hand, we have already noted that when a is less than 2.5, the maximum likelihood estimators are of doubtful utility. It then becomes necessary to consider yet other methods of estimation. When a is less than 1, the distribution is shaped like a reversed **J**, with the probability density function tending to infinity as x tends to γ (see Figure 17.1). If n is large (as it usually is if a three-parameter distribution is being fitted), it is reasonable to estimate γ as the smallest observed value among X_1, X_2, \dots, X_n , or a value slightly smaller than this. Estimation of a and β then proceeds as for the two-parameter case, to be described later. Using the value of a so estimated, a new value for γ can be estimated, and so on.

As in the case of the lognormal and inverse Gaussian distributions (Chapters 14 and 15), Cohen and Whitten (1988) advocate the use of

modified moment estimators

$$E[X] = \bar{X} = \tilde{\gamma} + \tilde{\alpha}\tilde{\beta}, \tag{17.44a}$$

$$\text{Var}(X) = s^2 = \tilde{\alpha}\tilde{\beta}^2, \tag{17.44b}$$

$$E[F(X'_{1:n})] = \frac{1}{n+1} = F\left(\frac{X'_{1:n} - \bar{X}}{s}; 0, 1, \tilde{\alpha}\right). \tag{17.44c}$$

Tables and graphs to facilitate solution of (17.44c) are given by Cohen and Whitten (1986, 1988), Bai, Jakeman, and Taylor (1990). Note that (17.37b) and (17.37c) can be written as

$$\hat{\alpha} = \sum_{i=1}^n \left(\frac{X_i - \hat{\gamma}}{n\hat{\beta}} \right), \tag{17.45a}$$

$$\hat{\beta} = \sum_{i=1}^n \left(\frac{X_i - \hat{\gamma}}{n} \right) - \frac{n}{\sum_{i=1}^n (X_i - \hat{\gamma})^{-1}}, \tag{17.45b}$$

respectively. Assuming a value for $\hat{\gamma}$, $\hat{\alpha}(\hat{\gamma})$, and $\hat{\beta}(\hat{\gamma})$ can be computed, the corresponding likelihood $L(\hat{\gamma})$ calculated. The value of $\hat{\gamma}$ maximizing $L(\hat{\gamma})$ is then found numerically. [See Bai, Jakeman, and Taylor (1990).]

Cheng and Arnin (1983) applied their maximum product of spacings (MPS) estimator method (see Chapters 12, 14, and 15) to provide consistent estimators of α , β , and γ . This method yields the following first-order equations:

$$\frac{\partial \log G}{\partial \gamma} \equiv \frac{\sum_{i=1}^{n+1} \frac{\int_{X'_{i-1}}^{X'_i} [-(\alpha - 1) + \beta^{-1}(x - \gamma)](x - \gamma)^{\alpha-2} e^{-(x-\gamma)/\beta} dx}{(n+1) \int_{X'_{i-1}}^{X'_i} (x - \gamma)^{\alpha-1} e^{-(x-\gamma)/\beta} dx}}{\quad}, \tag{17.46a}$$

$$\frac{\partial \log G}{\partial \beta} \equiv -\frac{\alpha}{\beta} + \frac{1}{n+1} \frac{\sum_{i=1}^{n+1} \frac{\int_{X'_{i-1}}^{X'_i} (x - \gamma)^\alpha \beta^{-2} e^{-(x-\gamma)/\beta} dx}{\int_{X'_{i-1}}^{X'_i} (x - \gamma)^{\alpha-1} e^{-(x-\gamma)/\beta} dx}}{\quad} = 0, \tag{17.46b}$$

$$\begin{aligned} \frac{\partial \log G}{\partial \alpha} &\equiv -\log \beta - \log \psi(\alpha) \\ &+ \sum_{i=1}^{n+1} \frac{\int_{X'_{i-1}}^{X'_i} (x - \gamma)^{\alpha-1} e^{-(x-\gamma)/\beta} \log(x - \gamma) dx}{(n+1) \int_{X'_{i-1}}^{X'_i} (x - \gamma)^{\alpha-1} e^{-(x-\gamma)/\beta} dx} = 0, \end{aligned} \tag{17.46c}$$

where $X'_1 \leq X'_2 \leq \dots \leq X'_n$ are the order statistics corresponding to X_1, \dots, X_n .

7.2 Some Parameters Unknown

We now consider estimation when the value of one of the three parameters α , β , and γ is known. The commonest situation is when the value of γ is known (usually it is zero). Occasionally α is known (at least approximately) but not β or γ . Inadmissibility of standard estimators of gamma parameters in the case when $\gamma = 0$ has received attention in the literature.

Let X_1, X_2, \dots, X_k be independent random variables with two-parameter gamma distributions with parameters α_i, β_i ($i = 1, \dots, k$) where the values of the α_i 's are known but the β_i 's (> 0) are unknown. Berger (1980) considered weighted quadratic losses $\sum_{i=1}^k \beta_i^{-m} (\delta_i \beta_i^{-1} - 1)^2$ for $m = 0, 2, 1, -1$, and showed that the standard estimator of $(\beta_1, \beta_2, \dots, \beta_k)$, namely $(X_1/(\alpha_1 + 1), \dots, X_k/(\alpha_k + 1))$ is inadmissible for $k \geq 2$ except when $m = 0$, in which case it is inadmissible for $k \geq 3$. Ghosh and Parsian (1980) also discussed this problem for the same weighted quadratic losses. Gupta (1984) has shown that inadmissibility also holds for the loss function

$$L(\underline{\beta}', \underline{\delta}) = \sum_{i=1}^k \delta_i \beta_i - \sum_{i=1}^k \log \delta_i \beta_i - k.$$

The vector of natural estimators $(X_1/\alpha_1, \dots, X_k/\alpha_k)$ is an inadmissible estimator of $(\beta_1, \dots, \beta_k)$ for $k \geq 3$. It would seem, however, that the critical dimension for inadmissibility is typically 2; three dimensions are required only in special cases. The problem whether the natural estimator is admissible for $k = 2$ is an open question. Zubrzycki (1966) has considered the case when β is known to exceed some positive number β_0 . He has shown that with a loss function $(\beta^* - \beta)^2/\beta^2$, where β^* denotes an estimator of β , and given a single observed value of X , estimators

$$\beta^* = (\alpha + 1)^{-1} X + b, \quad (17.47)$$

with

$$\beta_0(\alpha + 1)^{-1} \leq b \leq 2\beta_0(\alpha + 1)^{-1},$$

have minimax risk [equal to $(\alpha + 1)^{-1}$] and are admissible in the class of estimators linear in X .

If γ is known, the maximum likelihood estimators of α and β might be denoted $\hat{\alpha}(\gamma), \hat{\beta}(\gamma)$ to indicate their dependence on y . We will, however, simply use $\hat{\alpha}$ and $\hat{\beta}$; no confusion between this use and that in Section 7.1 should arise.

If γ is known to be zero, the probability density function is of form (17.23). If X_1, X_2, \dots, X_n are independent random variables each having

distribution (17.23), then equations for the maximum likelihood estimators $\hat{\alpha}, \hat{\beta}$ are

$$n^{-1} \sum_{j=1}^n \log X_j = \log \hat{\beta} + \psi(\hat{\alpha}), \quad (17.48a)$$

$$\bar{X} = \hat{\alpha} \hat{\beta}. \quad (17.48b)$$

From (17.48b), $\hat{\beta} = \bar{X}/\hat{\alpha}$. Inserting this in (17.48a), we obtain the following equation for $\hat{\alpha}$:

$$n^{-1} \sum_{j=1}^n \log X_j - \log \bar{X} = \psi(\hat{\alpha}) - \log \hat{\alpha}; \quad (17.48c)$$

that is,

$$R_n = \log \left[\frac{\text{Arithmetic mean } (X_1, X_2, \dots, X_n)}{\text{Geometric mean } (X_1, X_2, \dots, X_n)} \right] = \log \hat{\alpha} - \psi(\hat{\alpha}).$$

(Note that $R_n \geq 0$.)

It is readily seen that the estimator $\hat{\alpha}$, of α the shape parameter, and the ratio $\hat{\beta}/\beta$ are distributed independently of β . In particular, the variance of $\hat{\beta}/\beta$ does not depend on the parent population value of β . The value of $\hat{\alpha}$ can be determined by inverse interpolation in a table of the function $[\log \alpha - \psi(\alpha)]$. Such a table has been published by Masuyama and Kuroiwa (1952). Chapman (1956) has published a table giving the results of such inverse interpolation (i.e., values of $\hat{\alpha}$) corresponding to a few values of the ratio of arithmetic to geometric mean. (He reported that a more complete table was available from the Laboratory of Statistical Research, University of Washington.)

Greenwood and Durand (1960) pointed out that the function $\alpha[\log \alpha - \psi(\alpha)]$ progresses much more smoothly than does $[\log \alpha - \psi(\alpha)]$ and so is more convenient for interpolation. They gave a table of values of $\alpha[\log \alpha - \psi(\alpha)]$ as a function of α to eight decimal places for argument values 0.00(0.01)1.40, and to seven decimal places for argument values 1.4(0.2)18.0. This method eliminates the necessity of inverse interpolation and assures high accuracy using linear interpolation. Bain and Engelhardt (1975) show that $2n\alpha \log R_n$ is approximately distributed as $c\chi_\nu^2$ for appropriate values of c and ν (depending on n and α). For $\alpha \geq 2$ we have $2n\alpha \log R_n$ approximately distributed as χ_{n-1}^2 . [See also (17.107).]

$$H = \frac{\text{Arithmetic mean}}{\text{Arithmetic mean} - \text{Geometric mean}}$$

except when $\hat{\alpha}$ is less than about 2. They give a table of solutions of equation (17.48c) to five decimal places for

$$H = 1.000(0.001)1.010(0.002)1.030(0.005)1.080(0.01)1.16(0.02)1.40(0.05) \\ 2.00(0.1)3.0(0.2)5.0(0.5)7.0(1)10(2)20(10)50.$$

For $H > 1.001$, linear interpolation gives four decimal place accuracy for 6.

If $\hat{\alpha}$ is large enough, the approximation $\psi(\alpha) = \log(\alpha - \frac{1}{2})$ may be used. Then from (17.48c) we have

$$\frac{\text{Arithmetic mean}}{\text{Geometric mean}} = \frac{\hat{\alpha}}{\hat{\alpha} - \frac{1}{2}};$$

that is,

$$\hat{\alpha} \doteq \frac{\text{Arithmetic mean}}{2(\text{Arithmetic mean} - \text{Geometric mean})} = \frac{1}{2}H. \quad (17.49)$$

For a better approximation $1/12$ ($= 0.083$) should be subtracted from the right-hand side.

Thom (1968) suggests the approximation

$$\hat{\alpha}_T \doteq \frac{1}{4}R_n^{-1} \left(1 + \sqrt{1 + \frac{4}{3}R_n} \right). \quad (17.50)$$

Thom further suggests adding the correction $[(\hat{\alpha}_T - 1)(24 - 96\hat{\alpha}_T)^{-1} + 0.00921]$ if $\hat{\alpha}_T > 0.9$, and gives a table of corrections for $\hat{\alpha}_T < 0.9$. It is stated that with these corrections the value of $\hat{\alpha}_T$ should be correct to three decimal places.

Asymptotic formulas (as $n \rightarrow \infty$) for the variances of $\sqrt{n}\hat{\alpha}$ and $\sqrt{n}\hat{\beta}$, and the correlation between these statistics, are

$$\begin{cases} \text{Var}(\sqrt{n}\hat{\alpha}) \doteq \alpha\{\alpha\psi'(\alpha) - 1\}^{-1}, \\ \text{Var}(\sqrt{n}\hat{\beta}) \doteq \beta^2\psi'(\alpha)\{\alpha\psi'(\alpha) - 1\}^{-1}, \\ \text{Corr}(\hat{\alpha}, \hat{\beta}) \doteq -\{\alpha\psi'(\alpha)\}^{-1/2}. \end{cases} \quad (17.51)$$

Masuyama and Kuroiwa (1952) give tables with values of $\alpha\{\alpha\psi'(\alpha) - 1\}^{-1}$ and $\psi'(\alpha)\{\alpha\psi'(\alpha) - 1\}^{-1}$. If the approximation $\psi'(\alpha) = (\alpha - \frac{1}{2})^{-1}$, useful for α large, is used, we have

$$\begin{cases} \text{Var}(\sqrt{n}\hat{\alpha}) \doteq 2\alpha(\alpha - \frac{1}{2}), \\ \text{Var}(\sqrt{n}\hat{\beta}) \doteq \beta^2\alpha, \\ \text{Corr}(\hat{\alpha}, \hat{\beta}) \doteq -\sqrt{1 - \frac{1}{2}\alpha^{-1}}. \end{cases} \quad (17.52)$$

Bowman and Shenton (1968) investigated the approximate solutions [due to Greenwood and Durand (1960)11

$$\hat{\alpha} \doteq R_n^{-1}(0.500876 + 0.1648852R_n - 0.0544274R_n^2), \quad 0 < R_n \leq 0.5772, \quad (17.53a)$$

$$\hat{\alpha} \doteq R_n^{-1}(17.79728 + 11.968477R_n + R_n^2)^{-1}(8.898919 + 9.059950R_n + 0.9775373R_n^2), \quad 0.5772 \leq R_n \leq 17. \quad (17.53b)$$

The error of (17.53a) does not exceed 0.0088% and that of (17.53b) does not exceed 0.0054%.

If α is known but not β or γ , maximum likelihood estimators $\hat{\beta} = \hat{\beta}(\alpha)$, $\hat{\gamma} = \hat{\gamma}(\alpha)$ satisfy equations (17.37b)' and (17.37c)' with $\hat{\alpha}$ replaced by α . From (17.37b)',

$$\hat{\gamma} = \bar{X} - \alpha\hat{\beta},$$

and hence (17.37b)' can be written as an equation for β ,

$$(\alpha - 1)\hat{\beta} = \left[n^{-1} \sum_{j=1}^n (X_j - \bar{X} + \alpha\hat{\beta})^{-1} \right]^{-1}. \quad (17.37c)''$$

Alternatively, using the first two sample moments, we have for moment estimators $\tilde{\beta} = \tilde{\beta}(\alpha)$ and $\tilde{\gamma} = \tilde{\gamma}(\alpha)$,

$$\tilde{\gamma} = \bar{X} - \alpha\tilde{\beta},$$

$$\alpha\tilde{\beta}^2 = m_2 \quad [\text{cf. (17.41a) and (17.41b)}],$$

whence

$$\tilde{\beta} = \sqrt{\frac{m_2}{\alpha}}, \quad (17.54)$$

$$\tilde{\gamma} = \bar{X} - \sqrt{\alpha m_2}.$$

In this case (α known) for n large,

$$\begin{cases} \text{Var}(\hat{\beta}) = \beta^2 n^{-1}, \\ \text{Var}(\hat{\gamma}) = \frac{1}{2} \beta^2 \alpha (\alpha - 2) n^{-1}, \\ \text{Corr}(\hat{\beta}, \hat{\gamma}) \doteq -\frac{(\alpha + 1)}{\alpha + 3} \end{cases} \quad (17.55)$$

while

$$\begin{cases} \text{Var}(\tilde{\beta}) \doteq \frac{1}{2} \beta^2 (1 + 3\alpha^{-1}) n^{-1}, \\ \text{Var}(\tilde{\gamma}) \doteq \frac{1}{2} \beta^2 \alpha (\alpha + 3) n^{-1}, \\ \text{Corr}(\tilde{\beta}, \tilde{\gamma}) \doteq -\frac{(\alpha + 1)}{\alpha + 3}. \end{cases} \quad (17.56)$$

The advantage of the maximum likelihood estimators is not so great in this case as when all three parameters have to be estimated.

Glaser (1976a) observes that the distribution of R_n is the same as that of $\prod_{i=1}^{n-1} V_i$, where the V_i 's are independently distributed beta random variables with parameters α and i/n ($i = 1, \dots, n-1$). Various methods for calculation of the distribution of R_n and its lower critical values are available in the literature.

Provost (1988) provides expression for the j th moment of R_n , and provides an expression for its probability density function by inverting the Mellin transform. In their seminal paper and book Bowman and Shenton (1983, 1988) provide an approximation to the distribution of R_n , along with a new approximation to the inverse function $\hat{\alpha} = \phi^{-1}(R_n)$, namely

$$\hat{\alpha} = \frac{1}{2R_n} + \frac{1}{6} - \frac{R_n}{18} - \frac{4R_n^2}{135} + \frac{47R_n^3}{810} \dots \quad (17.57a)$$

This can be used when R_n is not too small; if R_n is small, the formula

$$\hat{\alpha} \sim (R_n + \log R_n)^{-1} \quad (17.57b)$$

is suggested. They also suggest using Thom's formula (17.50) as a starting value for an iterative procedure, calculating the m th iterate, $\hat{\alpha}_m$ from the formula

$$\hat{\alpha}_m = \frac{\hat{\alpha}_{m-1} \{ \log \hat{\alpha}_{m-1} - \psi(\hat{\alpha}_{m-1}) \}}{R_n} \quad (17.58)$$

They observe that about ten iterations suffices for reasonable accuracy.

Bowman and Shenton (1983) also obtain the formula

$$\kappa_s(R_n) = (-1)^s \{n^{1-s} \psi^{(s-1)}(\alpha) - \psi^{(s-1)}(n\alpha)\} \quad (17.59)$$

for the s th cumulant of R_n . As $n \rightarrow \infty$,

$$\mu'_1(R_n) \sim \frac{n-1}{2n\alpha}, \quad (17.60a)$$

$$\mu_2(R_n) \sim \frac{n-1}{2n^2\alpha^2}, \quad (17.60b)$$

$$\mu_3(R_n) \sim -2\sqrt{\frac{2}{n-1}}, \quad (17.60c)$$

$$\mu_4(R_n) \sim 3 + \frac{12}{n-1}. \quad (17.60d)$$

These values suggest that for n large R_n is approximately distributed as $\chi_{n-1}^2/(2n\alpha)$. For n large

$$E[\hat{\alpha}] \sim \frac{n\alpha}{n-3} - \frac{2}{3(n-3)} + \frac{n-1}{9(n-3)n\alpha} + \frac{7(n^2-9)}{54(n^2-9)n^2\alpha^2} \\ + \frac{(n^2-1)(26n^3+33n^2-324n-707)}{810(n^2-9)(n+5)n^3\alpha^3} + \dots, \quad (17.61a)$$

$$\text{Var}(\hat{\alpha}) \sim \frac{2n^2\alpha^2}{(n-3)^2(n-5)} - \frac{2n(n+1)\alpha}{3(n-3)^2(n-5)} \\ + \frac{2(n^2-3n+\delta)}{9(n-3)^2(n-5)} + \dots \quad (17.61b)$$

$$\sqrt{\beta_1(\hat{\alpha})} \sim \frac{4\sqrt{(2n-10)}}{n-7} \left\{ 1 - \frac{(n-3)^2}{24n^2\alpha^2} + \dots \right\}, \quad (17.61c)$$

$$\beta_2(\hat{\alpha}) \sim \frac{3(n+9)(n-5)}{(n-7)(n-9)} \left\{ 1 - \frac{4(n-3)^2}{3(n+9)n^2\alpha^2} - \dots \right\} \\ [\text{Bowman and Shenton (1988)}]. \quad (17.61d)$$

Bowman and Shenton (1982) give tables of coefficients of series expansions for the expected value, variance and third and fourth central moments of $\hat{\alpha}$ and $\hat{\beta}$ (terms up to n^{-6}) for $\alpha = 0.2(0.1)3(0.2)5(0.5)15$ and $n = 6(1)50(5)100(10)150$.

Choi and Wette (1969) present results of sampling investigations. As an example, with $\alpha = 2$ and $\beta = 1$ they obtain the average values (arithmetic means of 100 repetitions) shown below:

n	$\hat{\alpha}$	$\hat{\beta}$
40	2.10	1.03
120	2.04	1.02
200	2.03	1.01

The positive bias in $\hat{\alpha}$ is to be expected from the expansion (17.61a). Note that the next term in the expansion is

$$+ \frac{(n^2 - 1)\pi(n)}{17010(n^2 - 9)(n + 5)(n + 7)n^4\alpha^4},$$

where

$$\pi(n) = 1004n^5 + 9363n^4 + 13358n^3 - 82019n^2 - 296760n - 288472.$$

The expansion is asymptotic in nature, so only limited accuracy can be expected from its use. It is more accurate than an expansion simply in descending powers of n .

Anderson and Ray (1975), noting that the bias in $\hat{\alpha}$ can be considerable when n is small, suggest using the following, less biased estimator based on (17.61a):

$$\hat{\alpha}^* = \frac{n-3}{n}\hat{\alpha} + \frac{2}{3n}. \quad (17.62)$$

For estimating $\theta = \beta^{-1}$, these authors suggest $\hat{\beta}^{-1}f(\hat{\alpha}^*)$, where

$$f(a) = \left\{ 1 + \frac{3na}{(n-3)(na-1)} \left(1 + \frac{1}{9a} - \frac{1}{na} + \frac{n-1}{27na^2} \right) \right\}. \quad (17.63)$$

Shenton and Bowman (1973) introduce the "almost unbiased" estimators

$$\tilde{\alpha} = \bar{X} \left\{ \frac{2nR_n}{n-1} - \frac{2nR_n^2}{2(n-1)} + \frac{4n(n+1)R_n^3}{9(n-1)(n+3)} - \frac{2n(7n^2 + 60n + 7)R_n^4}{135(n-1)(n+3)(n+5)} \right\}, \quad (17.64a)$$

$$\tilde{\beta} = \frac{n-3}{2nR_n} + \frac{n+1}{6n} - \frac{(n+1)R_n}{18n} - \frac{(4n^2 - 10n + 4)R_n^2}{135n(n+3)}. \quad (17.64b)$$

Dahiya and Gurland (1978) develop generalized minimum chi-squared estimators of α and β . Stacy (1973) proposed "quasimaximum likelihood" estimators for $1/\alpha$ and β ,

$$\left(\frac{1}{\alpha}\right)' = n(n-1)^{-1} \sum (Z_i - n^{-1}) \log Z_i, \quad (17.65a)$$

$$\beta' = \bar{X} \left(\frac{1}{\alpha}\right)', \quad (17.65b)$$

where $Z_i = X_i/n\bar{X}$ ($i = 1, \dots, n$).

These estimators arise from the maximum likelihood estimators for Stacy and Mihran's (1965) generalized gamma distribution (see Section 8). The estimators are unbiased and

$$\text{Var}\left(\left(\frac{1}{\alpha}\right)'\right) = \frac{1}{(n-1)\alpha^2} \left\{ 1 + \frac{n\alpha^2 + \psi'(\alpha+1)}{n\alpha+1} \right\}, \quad (17.66a)$$

$$\text{Var}(\tilde{\beta}) = \frac{\beta^2}{(n-1)\alpha} \{1 + \alpha + \alpha^2\psi'(\alpha+1)\}. \quad (17.66b)$$

The asymptotic efficiencies are for $(1/\alpha)'$

$$\frac{n-1}{n} \left[\{1 + \alpha^2\psi'(\alpha+1)\} \left\{ 1 + \frac{n\alpha^2\psi'(\alpha+1)}{n\alpha+1} \right\} \right]^{-1}, \quad (17.67a)$$

and for $\tilde{\beta}$

$$\frac{n-1}{n} \{1 + \alpha + \alpha^2\psi'(\alpha+1)\}^{-1}. \quad (17.67b)$$

Grouped data can be tested by standard methods. Rosaiah, Kantam, and Narasimham (1991) give a detailed analysis for fitting a two-parameter gamma distribution. They provide tables for optimum group length d , in the sense of (1) minimum asymptotic generalized variance or (2) minimum sum of asymptotic variances, for $\alpha = 2(1)5$ and number of groups, $k = 2(1)10$ for the cases when neither α nor β are known or when only α or only β is known. The group boundaries are $0, d\beta, 2d\beta, \dots, (k-1)d\beta, \infty$. Since it is necessary to know both α and β to use the tables, they can be regarded as only providing a basis for intelligent selection of group length. Tables are also provided for use when group lengths may vary.

7.3 Estimation of Shape Parameter (β and γ Known)

Bowman and Shenton (1970) carried out an extensive study of the distributional properties of two different estimators of the shape parameters, a , of the gamma distribution (17.2). These were as follows:

1. The maximum likelihood estimator (MLE) $\hat{\alpha}$.
2. Thom's (1968) estimator $\hat{\alpha}_T$ [see (17.50)].

We recall that $\hat{\alpha}$ is the solution of the equation

$$R_n = \log \hat{\alpha} - \psi(\hat{\alpha}), \quad (17.48c)'$$

while

$$\hat{\alpha}_T = \frac{1}{4}R_n^{-1} \left(1 + \sqrt{1 + \frac{4}{3}R_n} \right), \quad (17.50)$$

which is applicable when $\tilde{\alpha}_T$ is not too small.

3. The moment estimator

$$\tilde{\alpha} = \frac{m_1'^2}{m_2} = \frac{\bar{X}^2}{S^2}. \quad (17.68)$$

The estimator (17.68) is much easier to compute than either $\hat{\alpha}$ or $\hat{\alpha}_T$. All three estimators are unaffected by the value of the scale parameter (β). Dusenberry and Bowman (1977) compare these three estimators. In regard to $\tilde{\alpha}$, they apply the techniques of David and Johnson (1951) to calculate the cdf of $\tilde{\alpha}$ by noting that

$$\Pr[\tilde{\alpha} < a] = \Pr\left[\frac{\bar{X}^2}{S^2} < a\right] = \Pr[\bar{X}^2 - aS^2 < 0].$$

It is not difficult to determine the moments of $(\bar{X}^2 - aS^2)$. These are then used to approximate the required probability. Dusenberry and Bowman (1977) use the Cornish-Fisher expansion to evaluate percentage points of the distribution of $\tilde{\alpha}$. They plot values of $\Pr[\tilde{\alpha} < a]$ for

$$\alpha = 0.5(0.5)3.0(1)5(5)20,$$

$$n = 50, 75, 100, 150, 200, 300, 750, 1000.$$

Figure 17.3 is the plot for $a = 2.0$.

The estimator $\hat{\alpha}_T$ is quite close to $\hat{\alpha}$. Although $\hat{\alpha}_T$ has a slight systematic bias, this is offset by a somewhat lower variance and greater ease of calculation. The moment estimator $\tilde{\alpha}$ is much easier to compute than either

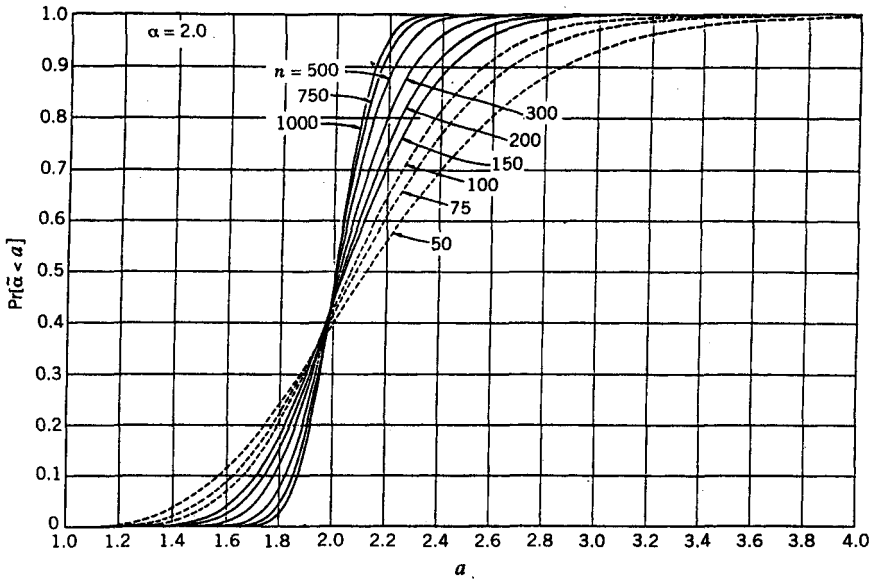


Figure 17.3 $\text{Pr}[\tilde{\alpha} < a]$ for $\alpha = 2.0$.

a or $\hat{\alpha}_T$ but has a greater bias and variance than either of these two estimators. As measured by $\sqrt{\beta_1}$ and β_2 , the distribution of $\tilde{\alpha}$ is closer to normality than that of either $\hat{\alpha}$ or $\hat{\alpha}_T$ for nearly all the values of a and n considered by Dusenberry and Bowman (1977).

Blischke (1971) constructed a BAN (best asymptotically normal) estimator of a , when β is known, as

$$\tilde{\alpha}' = \tilde{\alpha} + \frac{n^{-1} \sum_{i=1}^n \log(X_i/\beta) - \psi(\tilde{\alpha})}{\psi'(\tilde{\alpha})} \tag{17.69}$$

Since $\tilde{\alpha}$ is a consistent estimator of α and

$$E \left[\log \left(\frac{X}{\beta} \right) \right] = \psi(\alpha),$$

the estimator $\tilde{\alpha}'$ is asymptotically unbiased.

Results from 50 simulated samples of sizes $n = 11, 31,$ and 51 are set out in Table 17.1, comparing values of $\hat{\alpha}$ and $\tilde{\alpha}'$. Note that $\hat{\alpha}$ has a positive bias, except for the case where $a = 2.00$ and $n = 31$. Huque and Katti (1976) and Bar-Lev and Reiser (1983) discuss maximum *conditional* likelihood estimation of a . There is little to choose between the two estimators. Note the generally positive bias of the maximum likelihood estimator.

Table 17.1 Results of Simulation for $\tilde{\alpha}$ and $\hat{\alpha}$

α	n	BAN Estimator ($\hat{\alpha}'$)		ML Estimator ($\hat{\alpha}$)	
		Arithmetic Mean	Sample Variance	Arithmetic Mean	Sample Variance
0.25	11	0.234 ⁿ	0.00565 ⁿ	0.269	0.0067
	31	0.243	0.00214	0.258	0.0020
	51	0.238	0.00088	0.252	0.0010
0.50	11	0.530	0.0271	0.543	0.0219
	31	0.476	0.0059	0.498	0.0052
	51	0.494	0.0025	0.506	0.0045
0.75	11	0.760	0.0480	0.773	0.0339
	31	0.743	0.0101	0.765	0.0135
	51	0.745	0.0063	0.747	0.0069
1.25	11	1.228	0.0678	1.301	0.0879
	31	1.195	0.0204	1.257	0.0221
	51	1.253	0.0171	1.260	0.0172
1.50	11	1.533	0.0958	1.537	0.1010
	31	1.487	0.0362	1.508	0.0355
	51	1.529	0.0233	1.525	0.0199
2.00	11	2.063	0.121	2.036	0.1270
	31	1.965	0.067	1.996	0.0514
	51	1.979	0.031	2.004	0.0321

ⁿBased on 48 values; in two cases negative estimates were obtained.

7.4 Order Statistics and Estimators Based on Order Statistics

A considerable amount of work has been done in evaluating the lower moments of order statistics $X'_1 \leq X'_2 \leq \dots \leq X'_n$ corresponding to sets of independent random variables X_1, \dots, X_n having a common standard gamma distribution of form (17.2). Since γ and β are purely location and scale parameters, the results are easily extended to the general form (17.1). [Moments of order statistics of the exponential distribution ($\alpha = 1$) are discussed in some detail in Chapter 19, Section 6.] Tables of moments of order statistics from random samples of size n from the standard gamma distribution (17.2) are summarized in Table 17.2.

We next note that Kabe (1966) has obtained a convenient formula for the characteristic function of any linear function $\sum_{j=1}^n a_j X'_j$ of the order statistics. The characteristic function is

$$E \left[\exp \left\{ it \sum_{j=1}^n a_j X'_j \right\} \right] = n! [\Gamma(\alpha)]^{-n} \int_0^\infty \dots \int_0^{x_3} \int_0^{x_2} \left\{ \prod_{j=1}^n x_j \right\}^{\alpha-1} \\ \times \exp \left\{ - \sum_{j=1}^n (1 - ia_j t) x_j \right\} dx_1 dx_2 \dots dx_n. \quad (17.70)$$

Applying the transformation

$$x_r = \prod_{j=r}^n w_j$$

so that $0 < w_j < 1$ for $j = 1, 2, \dots, (n - 1)$, and $w_n > 0$, we obtain the formula

$$\begin{aligned} n! [\Gamma(\alpha)]^{-n} \int_0^1 \int_0^1 \dots \int_0^1 \int_1^\infty \left\{ \prod_{j=1}^n w_j^{j\alpha-1} \right\} \exp\{-w_n D(w)\} dw_n dw_{n-1} \dots dw_1 \\ = \frac{n! \Gamma(n\alpha)}{[\Gamma(\alpha)]^n} \int_0^1 \int_0^1 \dots \int_0^1 \left\{ \prod_{j=1}^{n-1} w_j^{j\alpha-1} \right\} [D(w)]^{-n\alpha} dw_{n-1} \dots dw_1, \end{aligned} \tag{17.71}$$

where

$$\begin{aligned} D(w) = (1 - ia_n t) + w_{n-1}(1 - ia_{n-1} t) + w_{n-2}w_{n-1}(1 - ia_{n-2} t) + \dots \\ + w_1 w_2 \dots w_{n-1}(1 - ia_1 t). \end{aligned}$$

Table 17.2 Details of Available Tables on Moments of Gamma Order Statistics

Reference	Values of n	Shape Parameter α	Order of Moments	Serial Number (j) of Order Statistics	Number Figures ^c
Gupta (1961) ^a	(1(1)10 11(1)15)	1(1)5 1(1)5	1(1)4 7(1)4	1(1) n 1	6 s.f.
Breiter and Krishnaiah (1968)	1(1)16	0.5(1)5.5 (0.5)10.5	1(1)4	1(1) n	5 s.f.
Harter (1970)	1(1)40	0.5(0.5)4.0	1	1(1) n	5 d.p.
Prescott (1974)	2(1)10	2(1)5	1	1(1) n	4 d.p.
Walter and Stitt (1988)	{ 1(1)25 1(1)5 10(5)25 }	{ 1(1)10(5)20 1, 5(5)20 1, 5(5)20 }	{ 1 1 1 }	{ 1, n 1(1) n 1, 5(5) n }	4 d.p.
Balasoorya and Hapuarachchi (1991) ^b	1(1)10 (5)40	5(1)8	1(1)5	1(1)2	5 d.p.

^aThe values of BS (1992) occasionally differ from those of Gupta (1961) by more than 0.00001.

^bThe last of these references also includes covariances for $n = 15(5)25$, $a = 2(1)5$, extending Prescott (1974) which includes covariances for $n = 2(1)10$ and the same values of a . More extensive tables of expected values of order statistics for $n = 15(1)40$, $\alpha = 5(1)8$, and covariances for $n = 2(1)25$ and $a = 2(1)8$ are available on request from Balasoorya and Hapuarachchi (Memorial University of Newfoundland, St. John's).

^cs.f. = significant figures; d.p. = decimal places.

The multiple integral can be expanded as a series of beta functions. Although we will not use it here directly, equation (17.71) is very convenient as a starting point for studying the distributions of linear functions of order statistics from gamma distributions.

The distribution of X'_r , the r th smallest among n independent random variables each having distribution (17.2), has the probability density function

$$p_{X'_r}(x) = \frac{n!}{(r-1)!(n-r)!} \left[\frac{\Gamma_x(\alpha)}{\Gamma(\alpha)} \right]^{r-1} \left[1 - \frac{\Gamma_x(\alpha)}{\Gamma(\alpha)} \right]^{n-r} \frac{x^{\alpha-1} e^{-x}}{\Gamma(\alpha)}, \quad x > 0. \quad (17.72)$$

In general, this expression does not lend itself to simple analytic treatment. However, if α is a positive integer,

$$\frac{\Gamma_y(\alpha)}{\Gamma(\alpha)} = \frac{1}{\Gamma(\alpha)} \int_0^y t^{\alpha-1} e^{-t} dt = 1 - e^{-y} \sum_{j=0}^{\alpha-1} \left\{ \frac{y^j}{j!} \right\} \quad [\text{cf. (17.24a)}]$$

and so (17.72) becomes

$$p_{X'_r}(x) = \frac{n!}{(r-1)!(n-r)!} \left[1 - e^{-x} \sum_{j=0}^{\alpha-1} \left\{ \frac{x^j}{j!} \right\} \right]^{r-1} \times \left[\sum_{j=0}^{\alpha-1} \left\{ \frac{x^j}{j!} \right\} \right]^{n-r} \frac{x^{\alpha-1} e^{-(n-r+1)x}}{(\alpha-1)!}, \quad x > 0. \quad (17.73)$$

In this case it is possible to express all moments (of integer order) of X'_r and all product moments (of integer orders) of order statistics as finite sums of terms involving factorials, although these expression will usually be cumbersome.

Johnson (1952) has obtained an approximation to the distribution of range $(X'_n - X'_1)$ for random samples from (17.2). Tiku and Malik (1972) provide β_1 and β_2 values of the r th-order statistic X'_r for the gamma distribution and compare them with approximate values obtained by equating the first three moments of χ^2_f with those of $(X'_r + a)/g$. Numerical comparisons are presented in Table 17.3. The agreement is excellent except for $a = 0.01$. It is, however, doubtful whether any method of approximation based on moments can provide accurate values for the extreme lower tail, as the classical paper of E. S. Pearson (1963) indicated.

Lingappaiah (1974) obtained the joint density of X'_r and X'_s ($s > r$), from the standard gamma distribution (17.1), and he derives from it that of the difference $U_{r,s} = X'_s - X'_r$. More recently Lingappaiah (1990) has obtained the distribution of $U_{r,s}$ in the presence of a single outlier—when $n-1$ observations are from a standard gamma α distribution but one observation is from a gamma $\alpha + \delta$ distribution. Typical values of $\Pr\{U_{r,s} > u\}$ under these conditions are shown in Table 17.4.

Table 17.3 Comparison of the Percentage Points of r th-Order Statistics from Standard Gamma Distribution with values from Tiku and Malik's (1972) Approximation (with $a = 2$, sample size $n = 6$)

		Upper Percentage Points				
		50	75	90	95	99
$r = 2$	Exact	1.135	1.536	1.963	2.250	2.854
	Approximate	1.135	1.535	1.962	2.249	2.854
$r = 4$	Exact	2.376	3.036	3.744	4.225	5.254
	Approximate	2.370	3.040	3.754	4.234	5.245
		Lower Percentage Points				
		25	10	05	01	
$r = 2$	Exact	0.807	0.570	0.453	0.280	
	Approximate	0.808	0.571	0.453	0.276	
$r = 4$	Exact	1.829	1.423	1.214	0.885	
	Approximate	1.821	1.423	1.224	0.924	

As is to be expected, in Table 17.4 $\Pr\{U_{r,s} > u\}$ increases with 6. Note that the values depend only on αu , so a single table (with $a = 1$) might suffice. Lingappaiah (1991) also provides tables (to 5 d.p.) with negative moments $E[X_r'^{-i}]$ of the standard gamma a distribution for $n = 2(1)5$ with $i = -(\alpha - 1), -(a - 2), \dots, -1$. As far as we know, the most general recurrence relationship in the literature for moments of order statistics from gamma a samples are those in Thomas and Moothathu (1991).

These formulas relate values of (descending) factorial moments

$$\mu_{n:n}^{(i)} = E[X_n^{(i)}] = E[X_n'(X_n' - 1) \cdots (X_n' - i + 1)]$$

of the greatest X in a random sample of size n from the standard gamma distribution (17.1). The recurrence formula is

$$\frac{\Gamma(k + \alpha n - n + 1)}{\{\Gamma(\alpha)\}^n} \times \frac{1}{n^{k+n(\alpha-1)}} = \sum_{j=1}^n A_{n-1,j} \mu_{n,n}^{(k-n+j)},$$

$$n \geq 2; k \geq \max[1 - \alpha, n(1 - a)], \quad (17.74)$$

Table 17.4 Values of $\Pr\{U_{r,s} > u\}$ for $n = 5, r = 1, s = 2$

u	$\alpha = 0.5$				$a = 1.0$			
	0.25	0.5	0.75	1.0	0.25	0.5	0.75	1.0
δ								
0	0.6065	0.3679	0.2231	0.1353	0.3679	0.1353	0.0498	0.0183
1	0.6672	0.4414	0.2901	0.1895	0.4414	0.1895	0.0796	0.0329
2	0.6831	0.4654	0.3161	0.2138	0.4654	0.2138	0.0968	0.0432

Note: Included are four observations from gamma a , one from gamma $\alpha + \delta$.

where

$$A_{r,r} = 1,$$

$$A_{r,1} = -r^{-1}\{k - r + 1 + (n - r)(\alpha - 1)\}A_{r-1,1},$$

$$A_{r,j} = r^{-1}(n - r)A_{r-1,j-1} - r^{-1}\{k - r + j + (n - r)(\alpha - 1)\}A_{r-1,j} \\ (j = 2, 3, \dots, r - 1)$$

$$A_{r,r} = r^{-1}(n - r)A_{r-1,r}.$$

If α is an integer, expected values and moments of the other order statistics can be evaluated using Joshi's (1979) formula:

$$\mu'_{k:n}{}^{(i)} = \mu'_{k-1:n-1}{}^{(i)} + in^{-1}\Gamma(\alpha) \sum_{j=0}^{\alpha-1} \left\{ \frac{\mu'_{k:n}{}^{(i+j-\alpha)}}{j!} \right\}, \quad (17.75)$$

with $\mu'_{k:n}{}^{(i)} = E[X'_{k:n}{}^i]$; $\mu'_{k:n}{}^{(0)} = 1$; $\mu'_{0:n}{}^{(i)} = 0$ for $i \geq 1$. Prescott (1974) shows that

$$E[X'_r X'_s] = \frac{C}{\{\Gamma(\alpha)\}^2} \sum_b \sum_c \sum_u \sum_v \sum_j (-1)^{b+c} \binom{r-1}{b} \binom{s-r-1}{c} \\ \times a_u(\alpha, t-1) a_v(\alpha, q-1) \frac{\Gamma(u+\alpha+1)\Gamma(u+\alpha+j+1)}{t^{u+\alpha-j+1}(t+q)^{v+\alpha+j+1} j!}, \quad (17.76)$$

where $t = n - s + c + 1$, $q = b + s - r - c$, and summation is over $0 \leq b \leq r - 1$, $0 \leq c \leq r - s - 1$, $0 \leq u \leq (\alpha - 1)(t - 1)$, $0 \leq v \leq (\alpha - 1)(q - 1)$, $0 \leq j \leq u + \alpha$, and

$$C = \frac{n!}{(r-1)!(s-r-1)!(n-s)!},$$

and where $a_g(h, i)$ is the coefficient of z^g in the expansion of $\{\sum_{j=1}^{h-1} (z^j/j!)\}$

Gupta (1962) obtained recurrence formulas for the crude moments $\mu'_{k:n}{}^{(i)} = E[X'_{k:n}{}^i]$ of the k th-order statistic $(X'_{k:n})$. These are

$$\mu'_{1:n}{}^{(i)} = \frac{n}{\Gamma(\alpha)} \sum_{j=0}^{(n-1)(\alpha-1)} a_j(\alpha, n-1) \frac{\Gamma(\alpha+i+j)}{n^{\alpha+i+j}}, \quad (17.77)$$

$$\mu'_{k:n}{}^{(i)} = \frac{n!}{(k-1)!(n-k)!} \sum_{j=0}^{k-1} (-1)^j \binom{k-1}{j} \frac{\mu'_{1:n-k+j+1}{}^{(i)}}{n-k+j+1}, \quad (17.77')$$

where $a_j(\alpha, p)$ is as defined in (17.76); see Balakrishnan and Cohen (199

Prescott (1974) provided a table of variances and covariances of all order statistics for $n = 2(1)10$ with $\alpha = 2(1)5$ to four decimal places. (He used log-gamma computer routine, accurate to about ten decimal places, to avoid errors occurring in tables prepared by Gupta (1962)—which have been ascribed to the way in which ratios of gamma functions were calculated.)

Using **Gupta's** tables (1962), it is possible to construct best linear unbiased estimators of the parameter β if α and γ are known. Coefficients of such estimators have been given by **Musson** (1965). Coefficients for best linear unbiased estimators, not using all of the sample values have been given by

1. Karns (1963) using only one-order statistic,
2. Bruce (1964) using the least M values out of n ,
3. Hill (1965) using only the least number of order statistics (from a complete or censored sample) to give a specified efficiency relative to the best linear unbiased estimator using all available order statistics,
4. Sarndal (1964) using the best k -order statistics. (Sarndal also considers estimation of β and y , α being known.)

Returning now to situations where it is necessary to estimate all three parameters α , β , and y , we consider maximum likelihood estimation when the least r_1 and greatest r_2 of the X 's have been censored. The maximum likelihood equations are [introducing $\hat{Z}_j = (X_j - \hat{\gamma})/\hat{\beta}$ for convenience]

$$\sum_{j=r_1+1}^{n-r_2} \log \hat{Z}_j - n\psi'(\hat{\alpha}) + \frac{\Gamma'(\hat{\alpha}) - \Gamma'_{\hat{Z}_{n-r_2}}(\hat{\alpha})}{\Gamma(\hat{\alpha}) - \Gamma_{\hat{Z}_{n-r_2}}(\hat{\alpha})} r_2 + \frac{\Gamma'_{\hat{Z}_{r_1+1}}(\hat{\alpha})}{\Gamma_{\hat{Z}_{r_1+1}}(\hat{\alpha})} r_1 = 0, \quad (17.78a)$$

$$-(n - r_1 - r_2)\hat{\alpha} + \sum_{j=r_1+1}^{n-r_2} \hat{Z}_j + \frac{\hat{Z}_{n-r_2}^{\hat{\alpha}} e^{-\hat{Z}_{n-r_2}}}{\Gamma(\hat{\alpha}) - \Gamma_{\hat{Z}_{n-r_2}}(\hat{\alpha})} r_2 - \frac{\hat{Z}_{r_1+1}^{\hat{\alpha}} e^{-\hat{Z}_{r_1+1}}}{\Gamma_{\hat{Z}_{r_1+1}}(\hat{\alpha})} r_1 = 0, \quad (17.78b)$$

$$-(\hat{\alpha} - 1) \sum_{j=r_1+1}^{n-r_2} \hat{Z}_j^{-1} + (n - r_1 - r_2) + \frac{\hat{Z}_{n-r_2}^{\hat{\alpha}-1} e^{-\hat{Z}_{n-r_2}}}{\Gamma(\hat{\alpha}) - \Gamma_{\hat{Z}_{n-r_2}}(\hat{\alpha})} r_2 - \frac{\hat{Z}_{r_1+1}^{\hat{\alpha}-1} e^{-\hat{Z}_{r_1+1}}}{\Gamma_{\hat{Z}_{r_1+1}}(\hat{\alpha})} r_1 = 0. \quad (17.78c)$$

The equations simplify if either $r_1 = 0$ or $r_2 = 0$. For the case $r_1 = 0$ (censoring from above) a method of solving the equations is given by Harter and Moore (1965); also see Balakrishnan and Cohen (1991).

Estimation is simplified if the value of γ is known. Without loss of generality it may be arranged (if γ is known) to make $\gamma = 0$ (by adding, if necessary, a suitable constant to each observed value). For this case, with data censored from above ($r_1 = 0$), Wilk, Gnanadesikan, and Huyett (1962a, b) have provided tables which considerably facilitate solution of the

maximum likelihood equations. They express these equations in terms of

$$P = \frac{(\prod_{j=1}^{n-r_2} X'_j)^{1/(n-r_2)}}{X'_{n-r_2}}, \quad (17.79)$$

$$S = \frac{(\sum_{j=1}^{n-r_2} X'_j)}{(n-r_2)X'_{n-r_2}}; \quad (17.80)$$

that is, the ratios of the geometric and arithmetic means of the available **observed** values to their maximum. The maximum likelihood equations for $\hat{\alpha}$ and $\hat{\beta}$ are

$$(n-r_2)\log P = n \left[\psi'(\hat{\alpha}) - \log \left(\frac{X'_{n-r_2}}{\hat{\rho}} \right) \right] - r_2 \frac{a \log J(\hat{\alpha})}{\hat{\alpha}}, \quad (17.81a)$$

$$\frac{SX'_{n-r_2}}{\hat{\beta}} = \hat{\alpha} - \left\{ \frac{r_2}{n-r_2} \right\} \frac{e^{-X'_{n-r_2}/\hat{\beta}}}{J(\hat{\alpha})}, \quad (17.81b)$$

where

$$J(\hat{\alpha}) = \int_1^{\infty} t^{\hat{\alpha}-1} e^{-X'_{n-r_2}t/\hat{\beta}} dt. \quad (17.82)$$

Note that r_2 and n enter the equations only in terms of the ratio r_2/n , and X'_{n-r_2} and $\hat{\beta}$ only as the ratio $X'_{n-r_2}/\hat{\beta}$. Wilk, Gnanadesikan, and Huyett (1962b) provide tables, giving $\hat{\alpha}$ and $\hat{\alpha}\hat{\beta}/X'_{n-r_2}$ to three decimal places for

$$\frac{n}{r_2} = 1.0, 1.1, 1.2(0.2)2.0, 2.3, 2.6, 3.0,$$

$$P = 0.04(0.04)1.00, \quad \text{and} \quad S = 0.08(0.04)1.00.$$

The values for $n/r_2 = 1$ of course correspond to uncensored samples. A special table, which we have already mentioned in Section 7.2, is provided for this case. Wilk, Gnanadesikan, and Lauh (1966) discuss generalizations and modifications of these techniques for estimation of an unknown common scale parameter based on order statistics from a sample of gamma random variables with known shape parameters not necessarily all equal.

If a is known, it is possible to use "gamma probability paper," as described by Wilk, Gnanadesikan, and Huyett (1962a) to estimate β and γ graphically. This entails plotting the observed order statistics against the corresponding expected values for the standard distribution (17.2) (which of course depends on a) or, if these are not available, the values ξ_j satisfying

the equations

$$\frac{j}{n+1} = [\Gamma(\alpha)]^{-1} \int_0^{\xi_j} x^{\alpha-1} e^{-x} dx. \quad (17.83)$$

In the case of progressively censored sampling, Cohen and Norgaard (1977) and Cohen and Whitten (1988) suggest the following procedure for solving the maximum likelihood equations (in the case when $\alpha > 1$): Let n denote the total sample size and D , the number of failing items, for which there are completely determined life spans. Suppose that censoring occurs in k stages at times $T_1 < T_2 < \dots < T_k$ and that C_j surviving items are selected randomly and withdrawn (censored) from further observation at time T_j . Then

$$n = D + \sum_{j=1}^k C_j. \quad (17.84)$$

The sample data consist of the ordered life span observations $\{X_i\}$ ($i = 1, 2, \dots, D$), the censoring times $\{T_j\}$ and the numbers of censored items $\{C_j\}$ ($j = 1, 2, \dots, k$). The likelihood function is

$$L = K \prod_{i=1}^D p_X(X_i) \prod_{j=1}^k \{1 - F_X(T_j)\}^{C_j}, \quad (17.85)$$

where K is a constant, and $p_X(\cdot)$ and $F_X(\cdot)$ are the pdf and cdf of the lifetime distribution, respectively.

For the three-parameter gamma lifetime distribution (17.1), we have

$$\begin{aligned} \log L = & -D \log \Gamma(\alpha) - n\alpha \log \beta - \beta^{-1} \sum_{i=1}^D (X_i - \gamma) \\ & + (\alpha - 1) \sum_{i=1}^D \log(X_i - \gamma) + \sum_{j=1}^k C_j \log(1 - F_j) + \log K, \end{aligned} \quad (17.86)$$

where

$$F_j = \{\beta^\alpha \Gamma(\alpha)\}^{-1} \int_0^{T_j - \gamma} y^{\alpha-1} \exp\left(\frac{-y}{\beta}\right) dy. \quad (17.87)$$

The corresponding maximum likelihood equations are

$$\frac{\partial \log L}{\partial \alpha} = -D\psi(\alpha) - D \log \beta + \sum_{i=1}^D \log(X_i - \gamma) - \sum_{j=1}^k \frac{C_j}{1 - F_j} \frac{\partial F_j}{\partial \alpha} = 0, \quad (17.88a)$$

$$\frac{\partial \log L}{\partial \beta} = -\frac{D\alpha}{\beta} + \frac{1}{\beta^2} \sum_{i=1}^D (X_i - \gamma) - \sum_{j=1}^k \frac{C_j}{1 - F_j} \frac{\partial F_j}{\partial \beta} = 0, \quad (17.88b)$$

$$\frac{\partial \log L}{\partial \gamma} = \frac{D}{\beta} - (a - 1) \sum_{i=1}^D (X_i - \gamma)^{-1} - \sum_{j=1}^k \frac{C_j}{1 - F_j} \frac{\partial F_j}{\partial \gamma} = 0 \quad (17.88c)$$

[cf. (17.37a)–(17.37c) for the case of uncensored samples].

Evaluation of the partial derivatives of F_j with respect to a , β , and γ and computational details are given in Cohen and Whitten (1988). They caution that convergence problems may arise in iterative solution of equations (17.88) unless $a \gg 1$ (in our opinion, $a \geq 2.5$). Cohen and Norgaard (1977) assert that for $a \geq 4$, the formulas can be used "without any hesitation."

When a is less than 1, the likelihood function tends to infinity as $\gamma \rightarrow X'_1$. Cohen and Norgaard (1977) suggest setting an initial value $\hat{\gamma} = X'_1 - \frac{1}{2}\eta$, where η is "the precision with which observations are made," and then proceeding iteratively. They also provide **computational details** for calculation of the asymptotic variance-covariance matrix of $\hat{\alpha}$, $\hat{\beta}$, and $\hat{\gamma}$.

The maximum likelihood estimator $\hat{\alpha}$ is the solution of

$$n^{-1} \sum_{i=1}^n \log\left(\frac{X_i}{\beta}\right) = \psi(\hat{\alpha}). \quad (17.90)$$

A median estimator a^* is the solution of

$$\log\left(\frac{\text{Median}(X)}{\beta}\right) = \psi(a^*). \quad (17.91)$$

Harner, Shyu, and Trutzer (1991) carried out simulation studies of robustness of these estimators with respect to contamination of a gamma ($a, 1$) distribution by a gamma ($a, 1$) distribution. They took sample sizes $n = 25, 75$, with $a = 1, 2, 5$ and $a_c = 0.1, 1, 5, 10$; the proportions of contaminant [gamma ($a_c, 1$)] were $p = 0, 0.01, 0.05$, and 0.1. They concluded the following:

1. The moment estimator ($\tilde{\alpha}$) "greatly overestimates" the value of a .
2. The maximum likelihood estimator ($\hat{\alpha}$) "is competitive except when $a_c = 0.1$."
3. The median estimator (a^*) is "fairly stable over all combinations of the simulation parameters," with positive bias for small a , decreasing to "negligible amounts" as a or n increase.

Harner, Shyu, and Trutzer (1991) also consider trimmed mean estimators $(\hat{\alpha}_{\theta_1, \theta_2})$ satisfying the equation

$$\frac{\sum_{i=k_1}^{k_2} \log(X'_i/\beta)}{n - [\theta_1 n + \frac{1}{2}] - [\theta_2 n] - 1} = \psi(\alpha), \quad (17.92)$$

where X'_i is the i th order statistic among X_1, \dots, X_n , $k_1 = [\theta_1 n + \frac{1}{2}] + 1$ and $k_2 = n - [\theta_2 n] - 1$. Simulations were carried out for the same values of the parameters as for $\tilde{\alpha}$, $\hat{\alpha}$, and \mathbf{a}^* , with

$$(\theta_1, \theta_2) = (0.025, 0.075) \quad \text{and} \quad (0.0, 0.1).$$

The trimmed means gave good results with $(\theta_1, \theta_2) = (0.025, 0.075)$, and it was suggested that a trimmed mean, omitting the first few order statistics, might be used in place of the maximum likelihood estimator if α is thought to be small (giving rise to observations near zero).

8 RELATED DISTRIBUTIONS

If Y has the standard uniform (rectangular) distribution

$$p_Y(y) = 1, \quad 0 \leq y \leq 1, \quad (17.93)$$

then $Z = -\log Y$ has the exponential distribution

$$p_Z(z) = e^{-z}, \quad 0 \leq z, \quad (17.94)$$

which is a special form of gamma distribution. If Y_1, Y_2, \dots, Y_k are independent random variables, each distributed as Y , and $Z_j = -\log Y_j$ ($j = 1, \dots, k$), then $Z_{(k)} = \sum_{j=1}^k Z_j$ has a gamma distribution with parameters $\alpha = k$, $\beta = 1$, $\gamma = 0$. [$2Z_{(k)}$ is distributed as χ_{2k}^2 ; see Chapter 18.1 Relationships between gamma and beta distributions are described in Chapter 25 (see also Section 6 of this chapter).

Apart from noting these interesting relationships, we will devote this section to an account of classes of distributions that are related to gamma distributions, in particular

1. truncated gamma distributions,
2. compound gamma distributions,
3. transformed gamma distributions especially the generalized gamma distributions (which are assigned a special section of their own),
4. distributions of mixtures, sums, and products of gamma variables.

8.1 Truncated Gamma Distributions

The most common form of truncation of gamma distributions, when used in life-testing situations, is truncation from above. This is omission of values exceeding a **fixed** number τ , which is usually (though not always) known. If τ is not known, and the distribution before truncation is of the general form (17.1), there are four parameters (a, β, γ, τ) to estimate, and technical problems become formidable. However, it is not difficult to construct fairly simple (but quite likely not very accurate) formulas for estimating these parameters.

Fortunately it is often possible to assume that γ is zero in these situations [see Parr and Webster (1965) for examples], and we will restrict ourselves to this case. We will suppose that we have observations that can be regarded as observed values of independent random variables X_1, X_2, \dots, X_n , each having the probability density function

$$\frac{x^{\alpha-1}e^{-x/\beta}}{\int_0^\tau t^{\alpha-1}e^{-t/\beta} dt}, \quad 0 \leq x \leq \tau. \quad (17.95)$$

This may be denoted as a gamma ($a, \beta | \tau$) distribution. Estimation of the parameters a and β has been discussed by Chapman (1956), Cohen (1950, 1951), Das (1955), Des Raj (1953), and Iyer and Singh (1963).

The moments of distribution (17.95) are conveniently expressed in terms of incomplete gamma functions:

$$\mu'_r(X) = \beta^r \Gamma_{\tau/\beta}(\alpha + r) / \Gamma_{\tau/\beta}(\alpha). \quad (17.96)$$

Gross (1971) notes that this is an increasing function of both a and β and, further, that μ'_{r+1}/μ'_r is an increasing function of a for $r > 0$.

The preceding results imply that

$$0 \leq \mu'_1 \leq \frac{\beta\tau}{\beta + 1} \quad \text{for all } a > 0, \quad (17.97)$$

$$\frac{\mu'_{r+s}}{\mu'_r} \leq (\beta + r) \frac{\tau^s}{\beta + r + s} \quad \text{for all } a > 0. \quad (17.98)$$

Nath (1975) obtained the minimum variance unbiased estimator of the reliability function ($R(t) = \Pr\{X > t\}$) for the gamma ($a, \beta | \tau$) distribution with integer a . In his analysis he showed that the sum of n independent

gamma($\alpha, \beta|\tau$) variables, $Y_n = X_1 + \dots + X_n$ has cdf

$$\begin{aligned}
 P_{Y_n}(y|\alpha, \beta; \tau) &= \frac{C^n\{\Gamma(\alpha)\}^n}{\beta^{n\alpha}\Gamma(n\alpha)} e^{-y/\beta} \\
 &\times \sum_{r=0}^{k_y} (-1)^r \binom{n}{r} (y - r\tau)^{n\alpha-1} \theta\left(n\alpha - 1, \frac{\tau}{y - r\tau}\right) \\
 &\text{for } k_y\tau < y < (k_y + 1)\tau; k = 0, 1, \dots, n - 1, \quad (17.99)
 \end{aligned}$$

with

$$\theta\left(n\alpha - 1, \frac{\tau}{y - r\tau}\right) = \sum_{\mathbf{r}}^* \frac{r!s(\mathbf{r})!}{\prod_{j=0}^{\alpha-1} (r_j)! \prod_{j=0}^{\alpha-1} (j!)^{r_j}} \binom{n\alpha - 1}{s(\mathbf{r})} \left(\frac{\tau}{y - r\tau}\right)^{s(\mathbf{r})}, \quad (17.100)$$

where $s(\mathbf{r}) = \sum_{j=0}^{\alpha-1} jr_j$; the multinomial summation C^* is over all nonnegative $\mathbf{r} = (r_1, \dots, r_{\alpha-1})$ satisfying $\sum_{j=0}^{\alpha-1} r_j = r$.

The formula for the MVU estimator of $R(t)$ appears to be extremely cumbersome, although Nath (1975) claims that "it is not so in practical application, particularly when the sample size is small."

As $\tau \rightarrow \infty$, the distribution of Y_n tends to gamma ($n\alpha, \beta$), as is to be expected. The MVU estimator of $R(t)$ tends to the incomplete beta function ratio $I_{t/Y_n}(\alpha, (n - 1)\alpha)$, corresponding to Basu's (1964) MVU estimator of $R(t)$, with corrected factorial term. [See also Wani and Kabe (1971), and for exponential distributions, Pugh (1963).]

8.2 Compound Gamma Distributions

Starting from (17.1), compound gamma distributions can be constructed by assigning joint distributions to a , β , and y . The great majority of such distributions used in applied work start from (17.2) (i.e., with $y = 0$) and assign a distribution to one of a and β (usually β).

If β^{-1} itself be supposed to have a gamma ($6, b^{-1}$) distribution with

$$p_{\beta^{-1}}(x) = \frac{b^\delta x^{\delta-1} e^{-xb}}{\Gamma(\delta)}, \quad 0 \leq x, \quad (17.101)$$

the resulting compound distribution has probability density function

$$p_X(x) = \frac{\Gamma(\alpha + \delta)}{\Gamma(\alpha)\Gamma(\delta)} x^{\alpha-1} (x + 1)^{-(\alpha+\delta)}, \quad 0 \leq x. \quad (17.102)$$

This belongs to Type VI of Pearson's system (Chapter 12, Section 4). It can be expressed formally as

$$\text{Gamma}(a, \beta, 0) \underset{\beta^{-1}}{\wedge} \text{Gamma}(\delta, b^{-1}, 0) \equiv \text{Type VI.}$$

See Dubey (1970) for further details and extensions.

The noncentral χ^2 distribution (Chapter 29) is a mixture of gamma distributions, each with β equal to 2 and a distributed as $\nu + 2j$, where j is a Poisson $\frac{1}{2}\lambda$ variable. Formally

$$\text{Gamma}(a, 2, 0) \underset{(\alpha-\nu)/2}{\wedge} \text{Poisson}(\tfrac{1}{2}\lambda) \equiv \chi_\nu^2(\lambda),$$

or equivalently

$$\chi_\alpha^2 \underset{(\alpha-\nu)/2}{\wedge} \text{Poisson}(\tfrac{1}{2}\lambda) \equiv \chi_\nu^2(\lambda).$$

Bhattacharya (1966) has considered the distribution

$$\text{Gamma}(\alpha, \beta, 0) \underset{\beta}{\wedge} \text{Gamma}(\alpha', \beta', 0).$$

This distribution is considerably more complicated than when β^{-1} has a gamma distribution. The probability density function is

$$2[\beta'\Gamma(\alpha)\Gamma(\alpha')]^{-1} \left(\frac{x}{\beta'}\right)^{\frac{1}{2}(\alpha+\alpha')-1} K_{\alpha'-\alpha}\left(2\sqrt{\frac{x}{\beta'}}\right), \quad 0 < x, \quad (17.103)$$

where $K_{\alpha'-\alpha}(2\sqrt{x/\beta'})$ is the modified Bessel function of the third kind, of order $\alpha' - \alpha$ [see Abramowitz and Stegun (1965)].

8.3 Transformed Gamma Distributions

Olshen (1937) published an account of a systematic investigation into the distribution of $\log X$ when X has a standard gamma distribution (17.2). The moment-generating function of $\log X$ is

$$E[e^{t \log X}] = E[X^t] = \frac{\Gamma(\alpha + t)}{\Gamma(\alpha)}, \quad (17.104)$$

and the cumulant generating function is

$$\log \Gamma(\alpha + t) - \log \Gamma(\alpha).$$

Hence

$$\kappa_r(\log X) = \psi^{(r-1)}(\alpha). \tag{17.105}$$

Introducing the approximation

$$\psi^{(s)}(\alpha) \doteq (-1)^{s-1}(s-1)! \left(\alpha - \frac{1}{2}\right)^{-s}, \quad s \geq 1,$$

we see that the shape factors of $\log X$ are approximately

$$\begin{aligned} \alpha_3(\log X) &\doteq -\left(\alpha - \frac{1}{2}\right)^{-1/2}, \\ \alpha_4(\log X) &\doteq 3 + 2\left(\alpha - \frac{1}{2}\right)^{-1}. \end{aligned} \tag{17.106}$$

By comparison with $\alpha_3(X)$ and $\alpha_4(X)$ [see (17.111), it can be seen that these are closer to the "normal values" 0 and 3 than are the moment ratios of the original distribution of X . The approximation "log X is normally distributed with expected value $\psi(\alpha)$ and variance $\psi'(\alpha)$ " is likely to be fairly accurate for a sufficiently large. The accuracy of this approximation has been studied by Bartlett and Kendall (1946).

If the approximation is accepted, it provides an approximation to the distribution of

$$R_n = \frac{\max(X_1, \dots, X_n)}{\min(X_1, \dots, X_n)}, \tag{17.107}$$

where the X_j 's are independent chi squared random variables with ν degrees of freedom. For

$$\begin{aligned} \log R_n &= \max(\log X_1, \dots, \log X_n) - \min(\log X_1, \dots, \log X_n) \\ &= \text{range}(\log X_1, \dots, \log X_n) \end{aligned}$$

is approximately distributed as

$$\sqrt{\psi'(\nu/2)} \times (\text{range of } n \text{ independent unit normal variables}).$$

The log-gamma distribution is defined as the distribution of a random variable Y when $-\log Y$ has a gamma (a, β) distribution. The pdf is

$$p_Y(y|\alpha, \beta) = \frac{1}{\beta^\alpha \Gamma(\alpha)} \times \frac{(-\log y)^{\alpha-1}}{y^{1+1/\beta}}, \quad 0 < y < 1. \tag{17.108}$$

[See Consul and Jain (1971).] The r th moment about zero is

$$\begin{aligned} E[Y^r] &= E[e^{rX}] \\ &= \{\beta^\alpha \Gamma(\alpha)\}^{-1} \int_0^\infty x^{\alpha-1} \exp\{-(\beta^{-1} + r)x\} dx = \left(\frac{\beta}{\beta + r}\right)^\alpha. \end{aligned} \quad (17.109a)$$

In particular,

$$E[Y] = \left(\frac{\beta}{\beta + 1}\right)^\alpha, \quad (17.109b)$$

$$\text{Var}(Y) = \left(\frac{\beta}{\beta + 2}\right)^\alpha - \left(\frac{\beta}{\beta + 1}\right)^{2\alpha}, \quad (17.109c)$$

$$\alpha_3(Y) = \left(\frac{\beta}{\beta + 3}\right)^\alpha - 3\left(\frac{\beta}{\beta + 2}\right)^\alpha \left(\frac{\beta}{\beta + 1}\right)^\alpha + 2\left(\frac{\beta}{\beta + 1}\right)^{3\alpha}. \quad (17.109d)$$

Generalized gamma distributions with Z^c distributed as gamma (a, β, γ) will be described in Section 8.7.

8.4 Convolutions of Gamma Distributions

The distribution of $Y = \sum_{i=1}^n X_i$ with $X_i \sim \text{gamma}(\alpha_i, \beta_i)$ has received special attention in recent literature. The most recent result is due to Sim (1992) who shows that Y has pdf

$$\begin{aligned} p_Y(y|\alpha, \beta) &= \frac{1}{\Gamma(\alpha)} \left(\prod_{i=1}^n \beta_i^{-\alpha_i}\right) y^{\alpha-1} \exp\left(-\frac{y}{\beta_n}\right) \\ &\quad \times \sum_{r=0}^{\infty} \frac{b_n(r)(\alpha_{n-1}^{(r)})}{(\alpha_n^{(r)})r!} \{(\beta_n^{-1} - \beta_{n-1}^{-1})y\}^r, \end{aligned} \quad (17.110)$$

where $a = \sum_{i=1}^n \alpha_i$,

$$b_i(r) = \begin{cases} 1, & i = 2, \\ \sum_{j=0}^r \frac{b_{i-1}(j)(\alpha_{i-2}^{(j)})(-r)^{(j)}}{\alpha_{i-1}^{(j)}r!} c_i^j, & i = 3, 4, \dots, j^n, \end{cases}$$

for $r = 0, 1, 2$ and

$$c_i = \frac{\beta_{i-2}^{-1} - \beta_{i-1}^{-1}}{\beta_i^{-1} - \beta_{i-1}^{-1}}.$$

Sim (1992) claims that this result is easily obtained by mathematical induction. Moschopoulos (1985) gives the alternative expression

$$p_Y(y|\alpha, \beta) = C \sum_{i=0}^{\infty} \left[\frac{\delta_i y^{\alpha+i-1} e^{-y/\beta_i}}{\beta_i^{\alpha+i} \Gamma(\alpha+i)} \right], \tag{17.110}'$$

where

$$\delta_{i+1} = (i+1)^{-1} \sum_{i=1}^{k+1} \left[\sum_{j=1}^n \alpha_j \left(1 - \frac{\beta_i}{\beta_j} \right)^i \right] \delta_{k+1-i}.$$

His derivation is based on inversion of the moment generating function $\prod_{i=1}^n (1 - \beta_i t)^{-\alpha_i}$. Further expressions have been given by Mathai (1982), for cases when (1) all α_i 's are equal and (2) all α_i 's are integers.

Ratios of independent gamma (α_i, β_i) variables ($i = 1, 2$) are distributed as **Pearson** Type VI [see also *F* distributions (Chapter 27)]. Distributions of products (and ratios) of gamma variables have been discussed in Malik (1967, 1968a), Lee, Holland, and Flueck (1979), and Springer (1979).

As an example, here is a derivation of the distribution of $Y = X_1 X_2$, where X_1 and X_2 are mutually independent random variables and X_j has a gamma $(\alpha_j, 1)$ distribution ($j = 1, 2$). The joint density of X_1 and X_2 is

$$p_{X_1, X_2}(x_1, x_2) = \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} x_1^{\alpha_1-1} x_2^{\alpha_2-1} e^{-x_1-x_2}, \quad x_1, x_2 > 0. \tag{17.110a}$$

Making the one-to-one transformation

$$y = x_1 x_2, z = x_1 \text{ or inversely } x_1 = z, x_2 = y/z$$

with Jacobian

$$\frac{\partial(x_1, x_2)}{\partial(y, z)} = \begin{vmatrix} 0 & 1 \\ 1/z & -y/z^2 \end{vmatrix} = -1/z,$$

the joint density of $Y = X_1 X_2$ and $Z = X_1$ is

$$\begin{aligned} p_{Y,Z}(y,z) &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} z^{\alpha_1-1} (y/z)^{\alpha_2-1} e^{-z-(y/z)} \cdot \frac{1}{z} \\ &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} y^{\alpha_2-1} z^{\alpha_1-\alpha_2-1} e^{-z-(y/z)}, \quad y, z > 0. \end{aligned}$$

Hence, the density function of $Y = X_1 X_2$ is

$$\begin{aligned} p_Y(y) &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} y^{\alpha_2-1} \int_0^\infty z^{\alpha_1-\alpha_2-1} e^{-z-(y/z)} dz \\ &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} y^{\frac{1}{2}(\alpha_1+\alpha_2)-1} \int_0^\infty t^{\alpha_1-\alpha_2-1} e^{-(t+t^{-1})\sqrt{y}} dt \quad (z = t\sqrt{y}) \\ &= \frac{2}{\Gamma(\alpha_1)\Gamma(\alpha_2)} y^{\frac{1}{2}(\alpha_1+\alpha_2)-1} K_{\alpha_1-\alpha_2}(2\sqrt{y}), \quad y > 0, \quad (17.110b) \end{aligned}$$

where $K_\nu(h)$ is the modified Bessel function of the third kind [see Abramowitz and Stegun (1965) 11.4.1].

Kotz and Srinivasan (1969) have obtained this result by the use of Mellin transforms.

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where

$$\begin{aligned} K &= \left\{ 2 \int_0^\infty \left(a + \frac{t}{b} \right) e^{-t/b} dt \right\}^{-1} \\ &= \frac{1}{2} [be^\alpha \{\Gamma(\alpha) - \Gamma_a(\alpha)\}]. \end{aligned}$$

An attractive feature of this class of distributions, as compared with that of Borghi, is that the density is not, in general, zero at the point of symmetry (γ).

If a, b , and \mathbf{a} are known, the maximum likelihood estimator $\hat{\gamma}$ satisfies the equation

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This was defined (with $\gamma = 0$) by Stacy (1962) as the family of generalized gamma distributions [see also Cohen (1969)]. It includes Weibull distributions ($a = 1$), half-normal distributions ($a = \frac{1}{2}$, $c = 2$, $\gamma = 0$), and of course ordinary gamma distributions ($c = 1$). In addition the lognormal distribution is a limiting special case when $a \rightarrow \infty$. If $\gamma = 0$, the cdf can be expressed as

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where $G(a, a)$ is the incomplete gamma function ratio $\Gamma_a(\alpha)/\Gamma(\alpha)$.

Since $\{(Z - \gamma)/\beta\}^c$ has a standard gamma distribution, it is clear that [from (17.8)]

$$\begin{aligned} E\left[\left\{\frac{Z - \gamma}{\beta}\right\}^r\right] &= E\left[\left\{\frac{Z - \gamma}{\beta}\right\}^{c(r/c)}\right] \\ &= \frac{\Gamma(\alpha + r/c)}{\Gamma(\alpha)} \end{aligned} \quad (17.118)$$

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If $\gamma = 0$, the incomplete r th moment (up to ζ) of Z is

$$\begin{aligned} & \frac{c}{\beta^{c\alpha}\Gamma(\alpha)} \int_0^\zeta z^{c\alpha+r-1} \exp\left\{-\left(\frac{z}{\beta}\right)^c\right\} dz \\ &= \frac{\beta^h \exp\{-(\zeta/\beta)^c\}}{(\alpha + r/c)\Gamma(\alpha)} \left(\frac{\zeta}{\beta}\right)^{c\alpha+r} {}_1F_1\left(\alpha + r + r/c \mid \left(\frac{\zeta}{\beta}\right)^c\right), \end{aligned} \tag{17.119}$$

where ${}_1F_1\left(\begin{smallmatrix} a \\ b \end{smallmatrix} \mid y\right)$ is the confluent hypergeometric function, which is a special case of the generalized hypergeometric function ${}_pF_q\left(\begin{smallmatrix} a_1, \dots, a_p \\ b_1, \dots, b_q \end{smallmatrix} \mid x\right)$ (see Chapter 1).

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If $\gamma = 0$, we have

$$\log Z = c^{-1}(\log X + \log \beta), \tag{17.120}$$

with X having a standard gamma (a) distribution. Hence the shape factors (a , and a .) of $\log Z$ are the same as those of $\log X$, and they depend only on a , not on c . The distribution is bell-shaped for $c\alpha > 1$ and reverse J-shaped otherwise. If the values of c and γ are known, problems of estimation can be reduced to similar problems for ordinary gamma distributions by using the transformed variable $(Z - \gamma)^c$.

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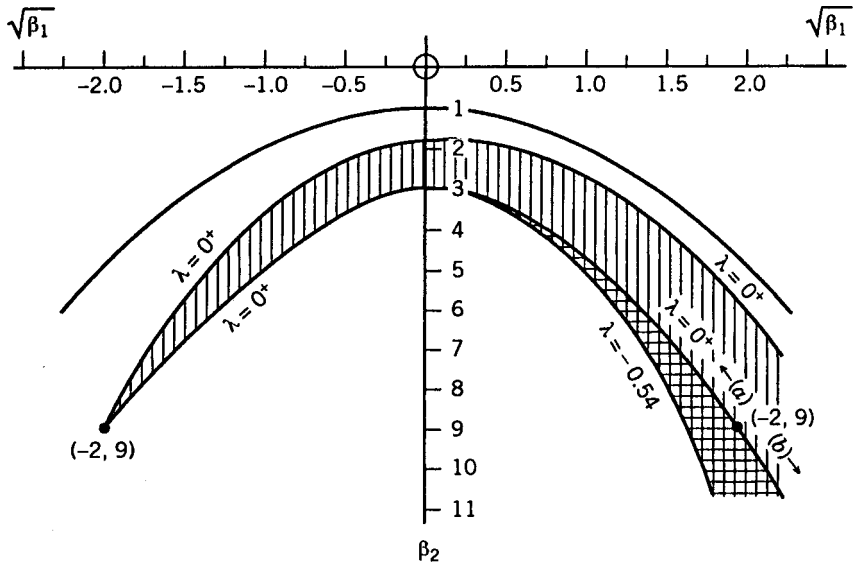


Figure 17.4 Region of Existence of $(\text{Gamma})^\lambda$ Distributions, Shaded; Region Where Two Distributions Exist, Cross-hatched.

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the joint density of $Y = X_1 X_2$ and $Z = X_1$ is

$$\begin{aligned} p_{Y,Z}(y,z) &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} z^{\alpha_1-1} (y/z)^{\alpha_2-1} e^{-z-(y/z)} \cdot \frac{1}{z} \\ &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} y^{\alpha_2-1} z^{\alpha_1-\alpha_2-1} e^{-z-(y/z)}, \quad y, z > 0. \end{aligned}$$

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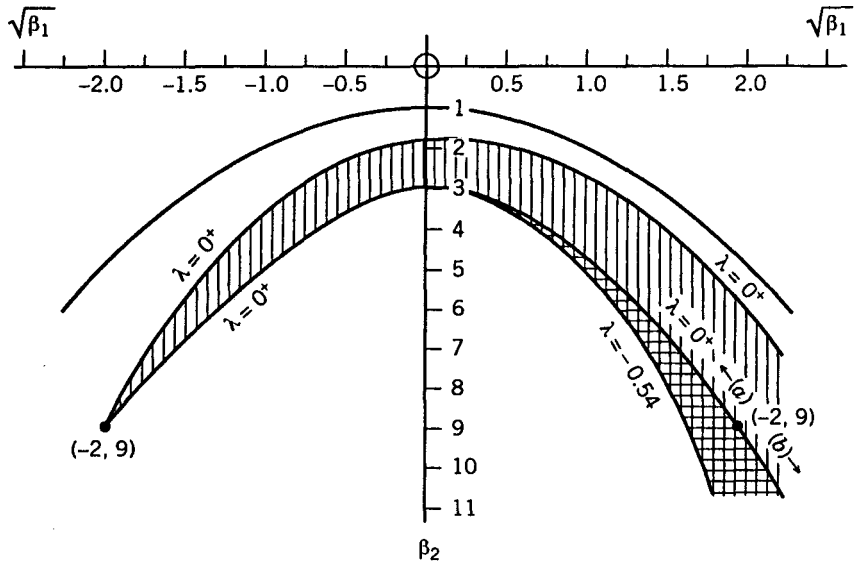


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with

$$h(w) + h(-w) = |c| \{ \beta^\alpha \Gamma(\alpha) \}^{-1} \quad \text{for all } w.$$

[Roberts and Geisser (1966) had previously obtained this result for $c = 2$.] Jakuszenkova (1973) further extended this result, obtaining a characterization in terms of the joint distribution of variables

$$\sqrt{Z_i Z_0^{-1}} - \sqrt{Z_i^{-1} Z_0}, \quad i = 1, \dots, n,$$

where Z_0, Z_1, \dots, Z_n are mutually independent positive random variables.

Lefante and Turner (1985) calculated an "average likelihood" for distribution (17.116) with $\gamma = 0$ by integrating the likelihood (based on sample values Z_1, Z_2, \dots, Z_n):

$$\frac{c^n (\prod_{i=1}^n Z_i^c)^{\alpha-1/c}}{\{\Gamma(\alpha)\}^n} (\beta^{-c})^{n\alpha} \exp \left\{ -(\beta^{-c}) \sum_{i=1}^n Z_i^c \right\}$$

with respect to β^{-c} (from zero to infinity), obtaining the value

$$\frac{|c|^n \Gamma(n\alpha + 1)}{\{\Gamma(\alpha)\}^n} \left(\prod_{i=1}^n Z_i^c \right)^{\alpha-1/c} \left(\sum_{i=1}^n Z_i^c \right)^{-(n\alpha+1)} \quad (17.123)$$

They describe the use of this statistic in a form of Bayesian estimation.

The essential difficulty in estimation for generalized gamma distributions with $\gamma = 0$ is estimation of c . In fact, if c is known, one can apply the transformation $X = Z^c$ and use the methods appropriate to gamma distributions.

Maximum likelihood estimation of c , a , and β (assuming γ to be known) was described by Parr and Webster (1965). Taking $\gamma = 0$, the maximum likelihood equations are [Hager and Bain (1970)]:

$$-n\hat{\alpha} + \sum_{i=1}^n \left(\frac{Z_i}{\hat{\beta}} \right)^{\hat{c}} = 0, \quad (17.124a)$$

$$\frac{n}{\hat{c}} + \hat{\alpha} \sum_{i=1}^n \log \left(\frac{Z_i}{\hat{\beta}} \right) - \sum_{i=1}^n \left(\frac{Z_i}{\hat{\beta}} \right)^{\hat{c}} \log \left(\frac{Z_i}{\hat{\beta}} \right) = 0, \quad (17.124b)$$

$$-n\psi(\hat{\alpha}) + \hat{c} \sum_{i=1}^n \log \left(\frac{Z_i}{\hat{\beta}} \right) = 0. \quad (17.124c)$$

Equation (17.124a) yields $\hat{\beta} = \hat{\beta}(\hat{\alpha}, \hat{c}) = \left\{ \sum_{i=1}^n Z_i^{\hat{c}} / (n\hat{\alpha}) \right\}^{1/\hat{c}}$. Substituting this expression for $\hat{\beta}$ into (17.124b) we have

$$\hat{\alpha} = \hat{\alpha}(\hat{c}) = \frac{1}{\hat{c} \left[(\sum_{i=1}^n \log Z_i / n) - \left(\sum_{i=1}^n Z_i^{\hat{c}} \log Z_i \right) / \left(\sum_{i=1}^n Z_i^{\hat{c}} \right) \right]}. \quad (17.125)$$

Substituting into (17.124c) yields an equation in the single unknown \hat{c} , and then the problem is to solve $H(\hat{c}) = 0$ for \hat{c} , where

$$H(\hat{c}) = -\psi(\hat{\alpha}) + \hat{c} \frac{\sum_{i=1}^n \log Z_i}{n} - \log \left(\sum_{i=1}^n Z_i^{\hat{c}} \right) + \log n\hat{\alpha}, \quad (17.126)$$

and $\hat{\alpha}$ is given by (17.125).

Extensive investigation of $H(\hat{c})$ conducted by Hager (1970) in his doctoral dissertation indicated that it is not always possible to determine if $H(\hat{c}) = 0$ has a root. The complication is that as $\hat{c} \rightarrow 0$, $\hat{\alpha}$ becomes quite large. There are conflicting reports in the literature as to the possibility of solving the equation $H(\hat{c}) = 0$. Hager and Bain (1970) and Lawless (1980) report persistent divergence of their iterative numerical methods. Their experience led them to conclude that MLE may not exist unless $n > 400$, say. Stacy (1973), on the other hand, reports on multiple distinct solutions to $H(\hat{c}) = 0$ for sample sizes as small as 20. It has been found that the Newton-Raphson method does not work well and that the existence of solutions to the log-likelihood equations is sometimes in doubt. When maximum likelihood estimates could be found, the asymptotic normal distribution of $\hat{a}^?$ was not in effect even for samples of size 400 when sampling with a values of 1 and 2.

Lawless's (1980) method maximizes the likelihood function over a subset of the parameters with the remaining parameters temporarily held fixed at some initial values. This is then followed by a heuristic interpolation scheme that refines further values of the fixed parameter. This approach guarantees only a local maximum of the likelihood function and is not very efficient computationally.

Wingo (1987b) recommends the root isolation method developed by Jones, Waller, and Feldman (1978) which assures globally optimal maximum likelihood estimators of generalized gamma distribution parameters. See also Wingo (1987a) for additional justification of the method.

Cohen and Whitten (1988) recommend the reparametrization $\theta = \beta^c$, which results in the three equations:

$$\hat{\theta} = \sum_{i=1}^n \frac{Z_i^{\hat{c}}}{n\hat{\alpha}}, \quad (17.127a)$$

$$\sum_{i=1}^n Z_i^{\hat{c}} - \frac{n\hat{\alpha} \sum_{i=1}^n Z_i^{\hat{c}} \log Z_i}{(n/\hat{c}) + \hat{\alpha} \sum_{i=1}^n \log Z_i} = 0, \quad (17.127b)$$

$$\hat{c} \sum_{i=1}^n \log Z_i - n \log \hat{\theta} - \psi(\hat{\alpha}) \equiv D(\hat{\theta}, \hat{\alpha}, \hat{c}) = 0. \quad (17.127c)$$

They suggest, for example, starting with a first approximation c_0 , for \hat{c} , substituting it into (17.127b) and solving this equation for $\hat{\alpha} - a_0$, substituting

and c_1 into (17.127a) and solving for $\hat{\theta} - \theta_1$, and then substituting the free approximation into (17.127c). The cycle is to be repeated until a pair α_i and c_i of successive approximations are sufficiently close to each other, and then interpolating for the final estimates. They do not address directly the convergence problem.

We note two possible parametrizations of the three-parameter generalized gamma distribution (with $\gamma = 0$): the form

$$p_Z(z; a, d, b) = \frac{b}{a^d \Gamma(d/b)} z^{d-1} e^{-(z/a)^b}, \quad a, d, b > 0; z \geq 0, \tag{17.128a}$$

originally suggested by Stacy (1962), and another obtained by introducing d/b allowing the power parameter to be negative

$$p_Z(z; a, k, b) = \frac{|b|}{\Gamma(k) a^{bk}} z^{bk-1} e^{-(z/a)^b}, \quad a, k > 0, b \neq 0; z \geq 0. \tag{17.128b}$$

The second form was suggested by Stacy and Mihram (1965) and is commonly in practice. Straightforward moment estimation of parameters based on moments of log Z was proposed by Stacy and Mihram (1965) (see pages 396).

Estimation in Four-parameter Generalized Gamma Distribution

Stacy (1966) studied maximum likelihood estimation of all four parameters $a, b, c,$ and k . He gives tables of asymptotic variances and covariances and includes an extract from these tables in Harter (1967), which also contains results of a number of applications of the method of maximum likelihood to complete samples of size 40, and also to such samples censored by retention of the greatest 10, 20, or 30 observed values [also see Harter 1967]. From the evidence of some sampling experiments, it appears that

maximum likelihood estimates have a definite bias in samples of this size,

estimators of a and c have high negative correlations.

The generalized gamma distribution is not recommended as a model for analysis of sample data, unless the sample size is large enough to group the data into a frequency table. Cohen and Whitten (1988) suggest a minimum sample size of 100 observations—even more if a four-parameter model is used.

Stacy and Whitten recommend a modified moment estimation procedure, equating sample and population values for the first three moments but equating the fourth sample moment to $(n + 1)^{-1}$, in place of equating fourth sample population moments (which can involve large sampling errors). First,

assuming a trial value c_1 for c , solve the fourth equation for the moment-ratio $\alpha_3 (= \sqrt{\beta_1})$ and proceed iteratively until a final value \bar{c} , say, is obtained producing close agreement with the sample value of α . Using this value for c , the estimators for a , β , and γ are calculated from the remaining equations.

Cohen and Whitten (1988) provide extensive tables of a , as a function of c and a for $c = 0.2, 0.5(0.5)3.5$, and also of the corresponding cdf for $c = 0.5(0.5)3.5$. Rao, Kantam, and Narasimham (1991) has derived Lloyd-type (1952) BLUE of the location γ and scale β parameters of the four-parameter generalized gamma distribution. They give coefficients of BLUEs based on order statistics $(Z'_{r_1+1}, \dots, Z'_{n-r_2})$ —that is, excluding the r_1 least and the r_2 greatest—for $c = 0.25, 0.5, 2, 4$, $a = 2(1)4$, and $n = 3(1)10$, together with their variances. This paper also includes analyses (for three-parameter generalized gamma) for (1) Gupta-type BLUEs, γ_G^* and β_G^* , of γ and β , respectively, in which the order statistics are treated as if they were uncorrelated and had a common variance (see Chapter 13), (2) "trimmed-type" estimators

$$\beta_T^* = \frac{\Sigma^*(Z'_i - Z'_{r_1+1})}{\Sigma^* E^*[Z'_i - Z'_{r_1+1} | \beta = 1]}, \quad (17.129)$$

(3) Winsorized-type estimators

$$\beta_W^* = \frac{r_1 Z'_{r_1+1} + \Sigma^* Z'_i + r_2 Z'_{n-r_2} - n Z'_{r_1+1}}{E^*[r_1 Z'_{r_1+1} + \Sigma^* Z'_i + r_2 Z'_{n-r_2} - n Z'_{r_1+1} | \beta = 1]}, \quad (17.130)$$

and (4) median-type estimators

$$\beta_M^* = \begin{cases} \frac{Z'_{(n+1)/2} - Z'_{r_1+1}}{E^*[Z'_{(n+1)/2} - Z'_{r_1+1} | \beta = 1]} & \text{if } n \text{ is odd,} \\ \frac{Z'_{(n+2)/2} + Z'_{n/2} - 2Z'_{r_1+1}}{E^*[Z'_{(n+2)/2} + Z'_{n/2} - 2Z'_{r_1+1} | \beta = 1]} & \text{if } n \text{ is even.} \end{cases} \quad (17.131)$$

In each of equations (17.129)–(17.131) the expected values (E^*) are calculated on the basis $\beta = 1$; in (17.29) and (17.130), C^* denotes summation from $i = r_1 + 1$ to $i = n - r_2$. Rao, Kantam, and Narasimham (1991) report that in all patterns of censoring Gupta-type BLUEs (γ_G^* and β_G^*) perform well, with minimum relative efficiencies of 84% for $c = 2$ and 87% for $c = 4$. In decreasing order of preference for the other estimators of β we have $\beta_W^*, \beta_T^*, \beta_M^*$, but for $0.25 \leq c \leq 1$, β_T^* is preferable to β_W^* .

Some investigations have been aimed at estimation of reliability—that is, the survival function $\Pr\{Z > z\} = 1 - F_Z(z)$. Since this is just a particular function of the parameters, one would expect difficulties to arise when there

are difficulties in estimation of a , β , and γ . So it is not surprising that Hager, Bain, and Antle (1971) and Hager and Bain (1970) found that no MLE of reliability may exist for small sample sizes or when c is small.

Log (Generalized) Gamma Distribution Estimation

Stacy and Mihram (1965) were first to propose a method estimation based on the moments of $\log Z$. [Of course if the known value of γ is not zero, $\log(Z - \gamma)$ would be used.] The moment-generating function of $T = \log(Z/\beta)$ is

$$E[e^{Tt}] = E\left[\left(\frac{Z}{\beta}\right)^t\right] = \frac{\Gamma\left(\alpha + \frac{t}{c}\right)}{\Gamma(\alpha)} \quad (\text{cf. Section 2}).$$

Hence the cumulant generating function of T is

$$\begin{aligned} &\log \Gamma\left(\alpha + \frac{t}{c}\right) - \log \Gamma(\alpha), \\ &\kappa_r(T) = c^{-r}\psi^{(r-1)}(\alpha), \end{aligned}$$

so that

$$\begin{cases} \kappa_1(\log Z) = c^{-1}\psi(\alpha) + \log \beta \\ \kappa_r(\log Z) = c^{-r}\psi^{(r-1)}(\alpha), \quad r \geq 2. \end{cases} \quad (17.132)$$

The equations

$$\begin{cases} \mu'_1(\log Z) = c^{-1}\psi(\alpha) + \log \beta \\ \mu_2(\log Z) = c^{-2}\psi'(\alpha) \\ \mu_3(\log Z) = c^{-3}\psi''(\alpha) \end{cases} \quad (17.133)$$

can be written in the form

$$\frac{\mu_3}{\mu_2^{3/2}} = \frac{\psi''(\alpha)}{[\psi'(\alpha)]^{3/2}} \quad (17.133a)$$

$$c = \frac{\mu_2\psi''(\alpha)}{\mu_3\psi'(\alpha)} \quad (17.133b)$$

$$\beta = \exp[\mu'_1 - c^{-1}\psi(\alpha)]. \quad (17.133c)$$

Replacing population moments in (17.133) by sample moments and solving successively for a , c , and β gives the required moment estimators.

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CHAPTER 18

Chi-Square Distributions, Including Chi and Rayleigh

1 HISTORICAL REMARKS

As we noted in Chapter 17, the standard chi-square distribution with ν degrees of freedom is in fact a gamma distribution with shape parameter $\nu/2$ and scale parameter 2. As a result many properties and results discussed for the gamma distribution in Chapter 17 will continue to hold (with suitable changes) for the chi-square distribution. In this chapter, however, we present specific developments that have taken place on the chi-square distribution and related issues. It is important to mention here the book by Lancaster (1969) which, even though it is more than 20 years old, gives a fine account of this distribution and will still serve as a good basic reference source.

Lancaster (1966) noted that **Bienaymé** (1838) obtained the chi-square distribution as the limiting distribution of the random variable $\sum_{i=1}^k (N_i - np_i)^2 / (np_i)$, where N_1, N_2, \dots, N_k have a joint **multinomial** distribution with parameters n, p_1, p_2, \dots, p_k (see Chapter 11 of the first edition). It is also well-known that if U_1, U_2, \dots, U_ν are independent standard normal variables, then $\sum_{i=1}^\nu U_i^2$ has a chi-square distribution with ν degrees of freedom (here ν has to be an integer by definition, but the distribution is defined for any real $\nu > 0$ as can be seen in the next section). Lancaster (1966) also pointed out that the result, that if V_1, V_2, \dots, V_k are independent chi-square random variables each with two degrees of freedom (*i.e.*, they are exponential random variables), then $\sum_{i=1}^k V_i$ is distributed as chi-square with $2k$ degrees of freedom, was demonstrated by Ellis (1844). The general reproductive property of chi-square distributions was proved by **Bienaymé** (1852) and also by Helmer (1875) using a different method. Helmer (1876a, b) also established the result that if X_1, X_2, \dots, X_n are independent normal $N(\mu, \sigma^2)$ variables then $\sum_{i=1}^n (X_i - \bar{X})^2 / \sigma^2$ (with \bar{X} being the sample mean) is distributed as a chi-square variable with $n - 1$ degrees of freedom and that this variable is statistically independent of \bar{X} . Because of this historical fact

Kruskal (1946) recommended calling the joint distribution of the two random variables *Helmert's* distribution; this recommendation was also supported by Lancaster (1966).

Kendall (1971), through his investigations, concluded that **Abbé (1863)** was the first to deduce the chi-square law; interested readers may also refer to Sheynin (1966, 1971, 1988), Matsunawa (1981), and Plackett (1983) for additional illuminating details on the history of the chi-square distribution. In 1860 Maxwell derived the chi-square distribution for the case $\nu = 3$; during the years 1878 to 1881, Boltzmann used the chi-square distribution first with $\nu = 2$ and then with $\nu = 3$ (in 1878) and published a general formula later in 1881. The formula provided by **Boltzmann (1878)** for the case $\nu = 3$, however, contained an error. Quite interestingly, Sheynin (1988) (following a clue from **Bol'shev**) discovered that **Gauss (1816)**, in one of his papers in geodetics (the branch of applied mathematics that determines the shape and area of large tracts of land, the exact position of geographical points, and the curvature, shape, and dimensions of the earth), presented a derivation of the asymptotic distribution of the chi-square (as $\nu \rightarrow \infty$) which (in modern day notation) is the well-known normal distribution with mean ν and standard deviation $\sqrt{2\nu}$. Sheynin (1971, 1988) also pointed out that Herschel came close to deriving chi-square for $\nu = 2$ in the year 1869 [as was discovered earlier by **Kruskal (1946)**].

The chi-square distribution also appeared in **Pearson (1900)** as the approximate distribution for the chi-square statistics used for various tests in contingency tables (of course the exact distribution of this statistic is discrete). The use of chi-square distribution to approximate the distribution of quadratic forms (particularly positive definite ones) in **multinormally** distributed variables is well established and widespread. One of the earliest ones in this direction is the work of Welch (1938) who used a chi-square approximation for the distribution of the denominator in a test criterion for difference in means of two normal populations with possibly different variances. Interested readers may refer to the commentaries of Lancaster (1982), Koch and Bhapkar (1982), and Koch and Stokes (1982) to see many other situations where the chi-square distribution plays a vital role.

2 DEFINITION

Let us denote a chi-square random variable with ν degrees of freedom by χ_ν^2 . Then the probability density function of χ_ν^2 is

$$p_{\chi_\nu^2}(x) = \frac{1}{2^{\nu/2}\Gamma(\nu/2)} e^{-x/2} x^{(\nu/2)-1}, \quad x \geq 0, \quad (18.1)$$

where $\Gamma(\cdot)$ is the complete gamma function. As mentioned in the last section, this is precisely the density function of $\sum_{i=1}^{\nu} U_i^2$ when U_i 's are

independent standard normal variables. Although in this derivation of the density, ν must be an integer, the distribution in (18.1) is referred to as a χ^2 distribution with ν degrees of freedom for any positive ν .

From (18.1) we find

$$\frac{d}{dx} p_{\chi^2_\nu}(x) = \frac{e^{-x/2}}{2^{\nu/2}\Gamma(\nu/2)} \left\{ -\frac{1}{2}x^{(\nu/2)-1} + \left(\frac{\nu}{2} - 1\right)x^{(\nu/2)-2} \right\} \quad (18.2)$$

which immediately reveals that for $\nu \geq 2$ the mode of the distribution is at 0 while for $\nu > 2$ the mode is at $\nu - 2$. For any $\nu > 0$, we can also find the cumulative distribution function from (1) to be

$$F_{\chi^2_\nu}(x) = \Pr[\chi^2_\nu \leq x] = \frac{\Gamma_{x/2}(\nu/2)}{\Gamma(\nu/2)}, \quad x > 0, \quad (18.3)$$

where $\Gamma_x(\alpha)$ denotes the *incomplete gamma function* defined by

$$\Gamma_x(\alpha) = \int_0^x e^{-t} t^{\alpha-1} dt, \quad x > 0. \quad (18.4)$$

Of course, for even values of ν , by repeated integration it can be shown from (18.3) that $1 - F_{\chi^2_\nu}(x)$ is equal to the probability that a Poisson random variable with mean $x/2$ does not exceed $(\nu/2) - 1$. For the purpose of illustration, plots of $p_{\chi^2_\nu}(x)$ are presented in Figure 18.1 for $\nu = 1(1)8$. Gulli (1989) recently made an analogy between the χ^2_ν density function in (18.1) and the impulse response of a fractional system.

The distribution of the positive square root of a variable having a chi-square distribution with ν degrees of freedom is called a *chi-distribution with ν degrees of freedom*, and the corresponding variable denoted by χ_ν . From (18.1) we then obtain the pdf of χ_ν as

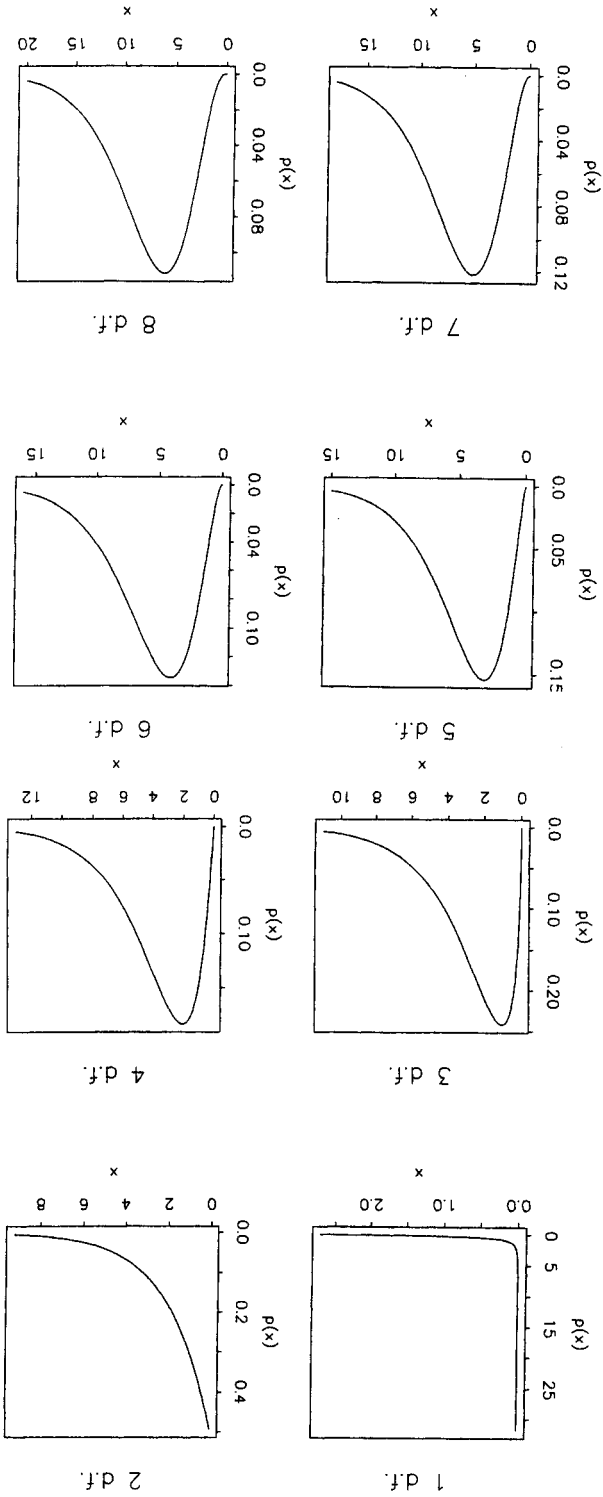
$$p_{\chi_\nu}(y) = \frac{1}{2^{(\nu/2)-1}\Gamma(\nu/2)} e^{-y^2/2} y^{\nu-1}, \quad y > 0, \nu > 0. \quad (18.5)$$

This includes as special cases the half-normal ($\nu = 1$), Rayleigh ($\nu = 2$), and Maxwell-Boltzmann ($\nu = 3$) density functions. From (18.5), we immediately find that for $\nu \geq 1$ the mode of the distribution is at 0, while for $\nu > 1$ the mode is at $\sqrt{\nu - 1}$. One can also find the cumulative distribution of χ_ν easily from (18.3) to be

$$F_{\chi_\nu}(y) = \Pr[\chi_\nu \leq y] = \frac{\Gamma_{y^2/2}(\nu/2)}{\Gamma(\nu/2)}, \quad y > 0, \nu > 0. \quad (18.6)$$

For the purpose of illustration, plots of $p_{\chi_\nu}(y)$ are presented in Figure 18.2 for $\nu = 1(1)8$.

Figure 18.1 Plots of Chi-square Density in (18.1)



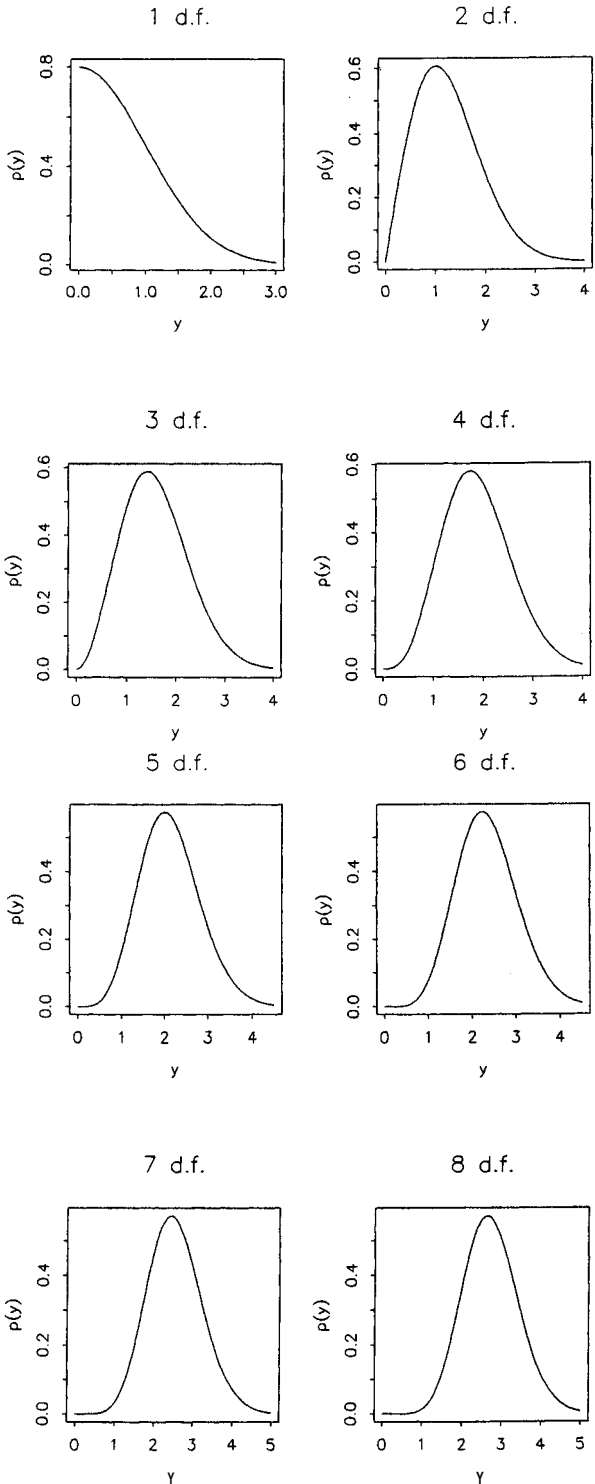


Figure 18.2 Plots of Chi Density in (18.5)

3 MOMENTS AND OTHER PROPERTIES

From (18.1) we find the moment-generating function of χ_ν^2 to be

$$\begin{aligned} E[e^{t\chi_\nu^2}] &= \frac{1}{2^{\nu/2}\Gamma(\nu/2)} \int_0^\infty e^{-x(1-2t)/2} x^{(\nu/2)-1} dx \\ &= (1-2t)^{-\nu/2}, \quad t < \frac{1}{2}, \end{aligned} \quad (18.7)$$

and, similarly, the characteristic function to be $(1-2it)^{-\nu/2}$. From (18.7), one may obtain the raw moments of χ_ν^2 . Instead, one can derive the r th raw moment of χ_ν^2 directly from (18.1) to be

$$\begin{aligned} E[\chi_\nu^2]^r &= \mu'_r(\chi_\nu^2) = \frac{1}{2^{\nu/2}\Gamma(\nu/2)} \int_0^\infty e^{-(x/2)} x^{(\nu/2)+r-1} dx \\ &= \frac{2^r \Gamma[(\nu/2) + r]}{\Gamma(\nu/2)} \\ &= \nu(\nu+2) \cdots \{\nu+2(r-1)\}. \end{aligned} \quad (18.8)$$

From (18.7) we also find the cumulant generating function of χ_ν^2 to be $-(\nu/2)\log(1-2t)$, from which we find the r th cumulant to be

$$\kappa_r(\chi_\nu^2) = \nu 2^{r-1} (r-1)!, \quad r = 1, 2, 3, \dots \quad (18.9)$$

Thus for the χ_ν^2 distribution we find that

$$\begin{aligned} E[\chi_\nu^2] &= \nu, & \text{Var}(\chi_\nu^2) &= 2\nu, \\ \sqrt{\beta_1(\chi_\nu^2)} &= \sqrt{\frac{8}{\nu}}, & \beta_2(\chi_\nu^2) &= 3 + \frac{12}{\nu} \end{aligned} \quad (18.10)$$

and the mean deviation to be

$$\frac{e^{-\nu/2} \nu^{\nu/2}}{2^{(\nu/2)-1} \Gamma(\nu/2)}. \quad (18.11)$$

It can be seen from the plots of the χ_ν^2 density function in Figure 18.1 that as ν increases, the shape of the curve becomes similar to that of the normal density curve. As a matter of fact, the χ_ν^2 distribution (after standardization)

tends to the unit normal distribution; that is,

$$\lim_{\nu \rightarrow \infty} \Pr \left[\frac{\chi_\nu^2 - \nu}{\sqrt{2\nu}} \leq x \right] = \Phi(x), \tag{18.12}$$

where $\Phi(\cdot)$ denotes the cumulative distribution function of a unit normal variable. It can also be checked from (18.10) that $\sqrt{\beta_1(\chi_\nu^2)} \rightarrow 0$ and $\beta_2(\chi_\nu^2) \rightarrow 3$ (the values for the unit normal distribution) as $\nu \rightarrow \infty$.

One of the important properties of the chi-square distribution is its reproductive property (described for the gamma distribution in Chapter 17): If X_1 and X_2 are independently distributed as $\chi_{\nu_1}^2$ and $\chi_{\nu_2}^2$, respectively, then $X_1 + X_2$ is distributed as $\chi_{\nu_1 + \nu_2}^2$.

Causey (1986) derived a formula for the expected absolute departure of χ_ν^2 variable from its median, that is, $\text{Disp}(\chi_\nu^2) = E[|\chi_\nu^2 - \text{Median}(\chi_\nu^2)|]$. Since for any continuous random variable X , the measure $E[|X - c|]$ (as a function of c) is minimum when $c = \text{Median}(X)$, this measure can be regarded as a measure of dispersion of the variable X . For the χ_ν^2 distribution, for example, Causey reported the values of the median and this measure of dispersion as

ν	1	2	3	4
Median(χ_ν^2)	0.4549	1.386	2.366	3.357
Disp(χ_ν^2)	0.8573	1.386	1.779	2.103

The moments of a χ_ν random variable can be derived easily from (18.8). For example, the r th raw moment is given by

$$\begin{aligned} E[\chi_\nu^r] &= \mu'_r(\chi_\nu) = \mu'_r([\chi_\nu^2]^{r/2}) \\ &= \frac{2^{r/2} \Gamma[(\nu + r)/2]}{\Gamma(\nu/2)}, \quad r = 1, 2, \dots \end{aligned} \tag{18.13}$$

Specifically, we have

$$E[\chi_\nu] = \sqrt{2} \frac{\Gamma[(\nu + 1)/2]}{\Gamma(\nu/2)} \quad \text{and} \quad \text{Var}(\chi_\nu) = \nu - 2 \left\{ \frac{\Gamma[(\nu + 1)/2]}{\Gamma(\nu/2)} \right\}^2. \tag{18.14}$$

Johnson and Welch (1939) gave formulas for computing the first six cumulants of χ_ν ; they also presented a series expansion for $E[\chi_\nu]$ in (18.14) as:

$$\begin{aligned} E[\chi_\nu] &= \sqrt{\nu} \left\{ 1 - \frac{1}{4\nu} + \frac{1}{32\nu^2} + \frac{5}{128\nu^3} - \frac{21}{2048\nu^4} \right. \\ &\quad \left. - \frac{399}{8192\nu^5} + \frac{869}{65536\nu^6} + \dots \right\}. \end{aligned} \tag{18.15}$$

They also presented the following recurrence relations for the cumulants $\kappa_r(\chi_\nu)$ (with $\kappa_1(\chi_\nu) = E[\chi_\nu]$):

$$\begin{aligned}\kappa_2(\chi_\nu) &= \nu - \{\kappa_1(\chi_\nu)\}^2, \\ \kappa_3(\chi_\nu) &= \kappa_1(\chi_\nu)\{1 - 2\kappa_2(\chi_\nu)\}, \\ \kappa_4(\chi_\nu) &= \frac{1}{2} - (2\nu - 1)\{1 - 2\kappa_2(\chi_\nu)\} - \frac{3}{2}\{1 - 2\kappa_2(\chi_\nu)\}^2, \\ \kappa_5(\chi_\nu) &= \kappa_1(\chi_\nu)\left[-2\kappa_4(\chi_\nu) + 3\{1 - 2\kappa_2(\chi_\nu)\}^2\right],\end{aligned}$$

and

$$\begin{aligned}\kappa_6(\chi_\nu) &= 2(2\nu - 1)\kappa_4(\chi_\nu) + 3\{1 - 2\kappa_2(\chi_\nu)\} \\ &\quad - 12(2\nu - 1)\{1 - 2\kappa_2(\chi_\nu)\}^2 - 15\{1 - 2\kappa_2(\chi_\nu)\}^3.\end{aligned}$$

Deutler (1984) pointed out correctly that the terms in the formula for $\kappa_r(\chi_\nu)$ are each of the same order and hence a dangerous numerical cancellation results for large ν , since the χ_ν -distribution tends to normal for large ν and as a result $\kappa_r(\chi_\nu/\sqrt{\nu}) \rightarrow 0$ for $r \geq 3$ as $\nu \rightarrow \infty$. Therefore by making use of Luke's (1969) series expression for the ratio of two gamma functions, Deutler (1984) derived series expansions for the cumulants $\kappa_r(\chi_\nu)$ similar to the one in (18.15) for $E[\chi_\nu]$. For example,

$$\begin{aligned}\nu^{-3/2}\kappa_3(\chi_\nu) &= \frac{1}{2^2\nu^2} + \frac{1}{2^4\nu^3} - \frac{13}{2^7\nu^4} - \frac{75}{2^9\nu^5} + \frac{1215}{2^{13}\nu^6} \\ &\quad + \frac{17403}{2^{15}\nu^7} - \frac{122101}{2^{18}\nu^8} + \dots, \\ \nu^{-2}\kappa_4(\chi_\nu) &= \frac{3}{2^4\nu^4} + \frac{3}{2^4\nu^5} - \frac{45}{2^7\nu^6} - \frac{57}{2^6\nu^7} + \frac{4875}{2^{12}\nu^8} + \dots.\end{aligned}$$

These series expressions demonstrate how quickly $\kappa_r(\chi_\nu/\sqrt{\nu}) \rightarrow 0$ for $r \geq 3$ as ν increases, giving a rough criterion for the convergence rate of $(\chi_\nu/\sqrt{\nu}) - 1$ to standard normality. Keiding, Jensen, and Ranek (1972), among others, studied properties of the χ_ν distribution and observed that it quickly approaches normal distribution as ν gets large.

4 TABLES AND NOMOGRAMS

One of the earliest tables of probability integrals of chi-square distributions was published in 1902. It contained values of $\Pr[\chi_\nu^2 > x]$ to six decimal places for $\nu = 2(1)29$ and $x = 1(1)30(10)70$, and was prepared by Elderton (1902). In 1922 Pearson edited a comprehensive *Tables of the Incomplete Γ -Function*.

These tables contained values of the function $I(u, p)$ defined by (also see Chapter 17)

$$I(u, p) = \frac{1}{\Gamma(p + 1)} \int_0^{u\sqrt{p+1}} e^{-t} t^p dt = \frac{\Gamma_{u\sqrt{p+1}}(p + 1)}{\Gamma(p + 1)} \quad (18.16)$$

to seven decimal places for $p = -1(0.05)0(0.1)5(0.2)50$ and u at intervals of 0.1. These values were also supplemented by a table of values of

$$\log I(u, p) - (p + 1)\log u \quad (18.17)$$

for $p = -1(0.05)0(0.1)10$ and $u = 0.1(0.1)1.5$. This function was chosen to make interpolation easier, particularly for low values of p . Harter (1964a, b) published tables of $I(u, p)$ to nine decimal places for $p = -0.5(0.5)74(1)164$ and u at intervals of 0.1 (thus covering a greater range of values of p than that considered by Pearson (1922), although not at such fine intervals, and also with a higher accuracy) and a table of percentage points of the χ^2_ν distribution. As mentioned earlier in Section 2, special values of the survival function (or the cumulative distribution function) of a chi-square distribution can be obtained from tables of the cumulative Poisson distribution using the formulas (for integral values of ν)

$$\Pr[\chi^2_{2\nu} \geq x] = e^{-x/2} \sum_{i=0}^{\nu-1} (x/2)^i / i! \quad (18.18)$$

and

$$\Pr[\chi^2_{2\nu-1} \geq x] = e^{-x/2} \sum_{i=0}^{\nu-2} \left\{ (x/2)^{i+\frac{1}{2}} / \Gamma(i + \frac{3}{2}) \right\} + 2\{1 - \Phi(\sqrt{x})\}. \quad (18.19)$$

Khamis and Rudert (1965) published extensive tables of $\Pr[\chi^2_{2\nu} \geq x]$ to ten decimal places for

$$\begin{aligned} \nu &= 0.05(0.05)10(0.1)20(0.25)70, \\ x &= 0.0001(0.0001)0.001(0.001)0.01(0.01)1.00(0.05)6.0(0.1) \\ &16.0(0.5)66(1)166(2)250. \end{aligned}$$

The varied intervals for x were chosen to make interpolation easier just as Pearson (1922) used equal intervals for $u = x/(2\sqrt{\nu})$ for the same reason. Thompson (1941) and Pearson and Hartley (1954) presented tables of lower ϵ percentage points of χ^2_ν , viz., $\chi^2_{\nu, \epsilon}$ such that

$$\Pr[\chi^2_\nu \leq \chi^2_{\nu, \epsilon}] = F_{\chi^2_\nu}(\chi^2_{\nu, \epsilon}) = \epsilon \quad (18.20)$$

to six significant figures for $\nu = 1(1)30(10)100$ and $\varepsilon = 0.005, 0.01, 0.025, 0.05, 0.10, 0.25, 0.50, 0.75, 0.90, 0.95, 0.975, 0.99, 0.995$. Pearson and Hartley (1954) also presented values for $\varepsilon = 0.999$. Vanderbeck and Cooke (1961) used the same values of ε , with the addition of the value 0.80, and tabulated $\chi_{\nu, \varepsilon}^2$ to four decimal places or significant digits, whichever turned out to be more accurate (except for $\nu = 1$), for $\nu = 1(1)300$; an approximation was used by them when $\nu > 30$. The less easily accessible tables prepared by these authors give values of $1 - F_{\chi_{\nu}^2}(x)$ for $x = 0.1(0.1)3.2$ with $\nu = 0.05(0.05)0.2(0.1)6.0$, and for $x = 3.2(0.2)7.0(0.5)10(1)35$ with $\nu = 0.1(0.1)0.4(0.2)6.0$. The noninteger choices of ν in these tables is a valuable feature. To facilitate interpolation for small values of x , tables of $F_{\chi_{\nu}^2}(x)/(x/2)^{\nu/2}$ were also presented for $x = 0.05(0.05)0.2(0.1)1.0$ with $\nu = 0.05(0.05)0.2(0.1)6.0$. For large values of x , another table presented values of $1 - F_{\chi_{\nu}^2}(x)$ for $\sqrt{2x} - \sqrt{2\nu} = -4.0(0.1)4.8$ with $\sqrt{2/\nu} = 0.02(0.02)0.22(0.01)0.25$.

Hald and Sinkbaek (1950) presented tables of $\chi_{\nu, \varepsilon}^2$ to three decimal places or significant digits, whichever turned out to be more accurate, for $\nu = 1(1)100$ and $\varepsilon = 0.0005, 0.001, 0.005, 0.01, 0.025, 0.05, 0.1(0.1)0.9, 0.95, 0.975, 0.99, 0.995, 0.999, 0.9995$. Harter (1964a) presented tables of $\chi_{\nu, \varepsilon}^2$ to six significant figures for $\nu = 1(1)150(2)330$ and the above choices of ε and also $\varepsilon = 0.0001$ and 0.9999 . Part of these tables corresponding to $\nu = 1(1)100$ was published by Harter (1964b). As pointed out by Bol'shev in his review of these tables, the correct values for $\chi_{60, 0.6}^2$, $\chi_{74, 0.8}^2$, and $\chi_{80, 0.4}^2$ are 62.1348, 83.9965, and 76.1879, respectively. Russell and Lal (1969) tabulated values of $1 - F_{\chi_{\nu}^2}(x)$ to five decimal places for $\nu = 1(1)50$ and $x = 0.001(0.001)0.01(0.01)0.1(0.1)10.0$. Slustskii (1950) compiled the first comprehensive tables of the χ_{ν}^2 distribution in the Soviet Union.

A nomogram produced by Boyd (1965) connects values of $P = \Pr[\chi_{\nu}^2 \geq \chi_0^2]$ with those of ν and χ_0^2 by means of a straight-edge. Boyd's nomogram is presented here in Figure 18.3. Stammberger (1967) produced another nomogram for the χ_{ν}^2 distribution. Krauth and Steinebach (1976) produced extended tables of percentage points of the chi-square distribution with at most ten degrees of freedom. Specifically they tabulated the percentage points corresponding to

$$\begin{aligned} \varepsilon = & 0.0000001, 0.0000005, 0.000001, 0.000005, 0.00001, 0.00005, \\ & 0.0001(0.0001)0.001(0.001)0.01(0.005)0.1(0.01)0.2, 0.8(0.1)0.9 \\ & (0.005)0.99(0.001)0.999(0.0001)0.9999, 0.99995, 0.99999, \\ & 0.999995, 0.999999, 0.9999995, 0.9999999. \end{aligned}$$

Gilbert (1977) provided a simple formula for interpolating tables of χ_{ν}^2 . He implemented an approximation of the form

$$\chi_{\nu, \varepsilon}^2 \approx a + a_1\nu + a_2\nu^2 + a, \log \nu, \quad (18.21)$$

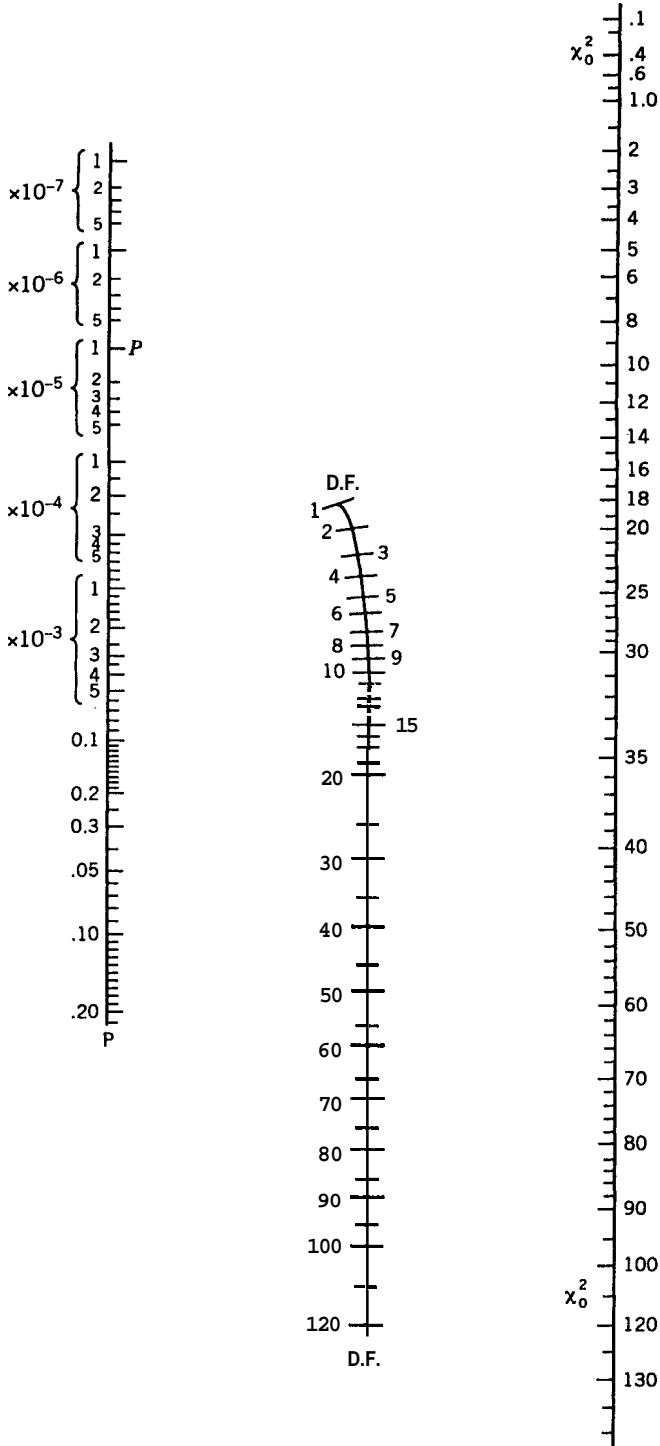


Figure 18.3 Boyd's χ^2 Nomogram

where the coefficients a_i depend only on ϵ (or the significance level $1 - \epsilon$). By employing Dwyer's (1951) method of pivotal condensation to solve the normal equations obtained from (18.21) for $\nu = 1(1)30$ and the tabled values of $\chi_{\nu, \epsilon}^2$ for $\epsilon = 0.95, 0.99$ and 0.999 , Gilbert determined the following values for the coefficients a_i :

	SIGNIFICANCE LEVEL, $1 - \epsilon$		
	0.05	0.01	0.001
a_0	2.518232	5.174627	9.205913
a_1	1.282189	1.402766	1.542498
a_2	-0.00211427	-0.00303260	-0.00411568
a_3	1.371169	1.858993	2.314035

Gilbert has discussed the maximum error incurred while using the interpolation formula in (18.21); he has shown that this interpolation method provides quite reasonable values (often correct to two decimal places or more) for ν small and even nonintegral for the values of ϵ considered.

5 APPROXIMATIONS AND COMPUTATIONAL ALGORITHMS

As mentioned earlier in Section 3, the standardized χ_{ν}^2 distribution tends to the unit normal distribution as $\nu \rightarrow \infty$ [see (18.12)]. The simple approximation obtained from (18.12) given by

$$F_{\chi_{\nu}^2}(x) \approx \Phi\left(\frac{x - \nu}{\sqrt{2\nu}}\right), \quad (18.22)$$

however, is not very accurate unless ν is rather large. Better approximations may be obtained by using the asymptotic normality of various functions of χ_{ν}^2 , even though only approximate standardization is effected. Among the best-known simple approximations are Fisher's (1922) approximation given by

$$F_{\chi_{\nu}^2}(x) \approx \Phi(\sqrt{2x} - \sqrt{2\nu - 1}) \quad (18.23)$$

and the Wilson-Hilferty (1931) approximation given by

$$F_{\chi_{\nu}^2}(x) \approx \Phi\left(\sqrt{\frac{9\nu}{2}} \left\{ \left(\frac{x}{\nu}\right)^{1/3} - 1 + \frac{2}{9\nu} \right\}\right). \quad (18.24)$$

Of these two approximations the second one is definitely more accurate, but both the approximations are better than the one in (18.22). From the approximations in (18.23) and (18.24), one may obtain approximations to the

percentage point $\chi_{\nu, \varepsilon}^2$, as

$$\chi_{\nu, \varepsilon}^2 \approx \frac{1}{2} (U_\varepsilon + \sqrt{2\nu - 1})^2, \tag{18.25}$$

$$\chi_{\nu, \varepsilon}^2 \approx \nu \left(\sqrt{\frac{2}{9\nu}} U_\varepsilon + 1 - \frac{2}{9\nu} \right)^3 \tag{18.26}$$

respectively; here U_ε denotes $\Phi^{-1}(\varepsilon)$, the lower ε percentage point of the standard normal distribution. It should be mentioned that the addition of $(U_\varepsilon^2 - 1)/6$ to (18.25) will make it very nearly equal to the usually better approximation in (18.26), unless ν is small or ε is close to 0 or 1. This point is illustrated by the values in Table 18.1.

Table 18.1 Comparison of Approximations to χ^2 Percentile Points

ε	ν	$\chi_{\nu, \varepsilon}^2$	Approximation		Difference (18.26)-(18.25)	$\frac{1}{6}(U_\varepsilon^2 - 1)$
			(18.25)	(18.26)		
0.01	5	0.5543	0.2269	0.5031	0.2762	0.7353
	10	2.5582	2.0656	2.5122	0.4466	
	25	11.5240	10.9215	11.4927	0.5712	
0.05	5	1.1455	0.9182	1.1282	0.3100	0.2843
	10	3.9403	3.6830	3.9315	0.2485	
	25	14.6114	14.3388	14.6086	0.2698	
0.10	5	1.6103	1.4765	1.6098	0.1333	0.1071
	10	4.8652	4.7350	4.8695	0.1345	
	25	16.4734	16.3503	16.4788	0.1285	
0.50	5	4.3515	4.5000	4.3625	-0.1375	-0.1667
	10	9.3418	9.5000	9.3480	-0.1520	
	25	24.3366	24.5000	24.3392	-0.1608	
0.90	5	9.2364	9.1658	9.2078	0.0420	0.1071
	10	15.9872	15.9073	15.9677	0.0604	
	25	34.3816	34.2920	34.3701	0.0781	
0.95	5	11.0705	10.7873	11.0439	0.2666	0.2843
	10	18.3070	18.0225	18.2918	0.2693	
	25	37.6525	37.3667	37.6452	0.2785	
0.99	5	15.0862	14.1850	14.4599	0.2749	0.7353
	10	23.2093	22.3463	23.2393	0.8930	
	25	44.3141	43.4904	44.3375	0.8471	

Vanderbeck and Cooke (1961) used the Cornish-Fisher expansion to give

$$\begin{aligned} \chi_{\nu, \varepsilon}^2 &\approx \nu + \sqrt{2\nu} U_\varepsilon + \frac{2}{3} (U_\varepsilon^2 - 1) + \frac{1}{9\sqrt{2\nu}} (U_\varepsilon^3 - 7U_\varepsilon) \\ &\quad - \frac{1}{405\nu} (106U_\varepsilon^4 - 486U_\varepsilon^2 + 168) \\ &\quad + \frac{1}{4860\nu\sqrt{2\nu}} (9U_\varepsilon^5 + 256U_\varepsilon^3 - 433U_\varepsilon) \end{aligned} \quad (18.27)$$

[also see Goldberg and Levine (1946); Peiser (1943)]. They also presented a table comparing exact values of $\chi_{\nu, \varepsilon}^2$ with those given by (18.27) for $\nu = 10(10)100$ and $\varepsilon = 0.005, 0.010, 0.025, 0.05, 0.10, 0.25, 0.50, 0.75, 0.90, 0.95, 0.975, 0.99, 0.995$. For $\nu \geq 60$ the difference was only occasionally greater than 0.0001. In fact, even when $\nu = 30$, the difference exceeded 0.0001 only for ε outside the range 0.1–0.9.

A power series expression for $F_{\chi_\nu^2}(x)$ can be derived in the following way:

$$\begin{aligned} F_{\chi_\nu^2}(x) &= \frac{1}{2^{\nu/2}\Gamma(\nu/2)} \int_0^x e^{-t/2} t^{(\nu/2)-1} dt \\ &= \frac{1}{2^{\nu/2}\Gamma(\nu/2)} \int_0^x \sum_{i=0}^{\infty} (-1)^i \{t^{(\nu/2)+i-1} / (2^i i!)\} dt \\ &= \frac{2(x/2)^{\nu/2}}{\Gamma(\nu/2)} \sum_{i=0}^{\infty} (-1)^i \frac{x^i}{(\nu+2i)2^i i!}. \end{aligned} \quad (18.28)$$

The above series converges to all $x > 0$, and the true value will lie between $\sum_{i=0}^m$ and $\sum_{i=0}^{m+1}$. The series expression in (18.28) may be used as a basis for evaluating $F_{\chi_\nu^2}(x)$ approximately when x is small (e.g., $x < \nu$). Pearson and Hartley (1954) suggested an iterative procedure for calculating $\chi_{\nu, \varepsilon}^2$, based on (18.28). Since $F_{\chi_\nu^2}(\chi_{\nu, \varepsilon}^2) = \varepsilon$, (18.28) can be written in the form

$$\chi_{\nu, \varepsilon}^2 = 2 \left\{ \varepsilon \Gamma\left(\frac{\nu}{2}\right) \right\}^{2/\nu} \left\{ \sum_{i=0}^{\infty} (-1)^i \frac{(\chi_{\nu, \varepsilon}^2)^i}{(\nu+2i)2^i i!} \right\}^{-2/\nu}. \quad (18.29)$$

By inserting a trial value of $\chi_{\nu, \varepsilon}^2$ on the right-hand side of (18.29), a new value can be obtained. The first term of the series could be used for the initial value, while one additional term could be included at each successive iteration. Harter (1964a, b) used this iterative method in the construction of his tables.

Gray, Thompson, and McWilliams (1969) used an approximation for the incomplete gamma integral, together with Stirling's approximation, to get

$$1 - F_{\chi^2_\nu}(x) \approx \frac{\nu\sqrt{\nu} e^{\nu/2}}{(\nu + \frac{1}{6})\sqrt{\pi}} \left(\frac{x}{\nu}\right)^{\nu/2} e^{-x/2} \left\{ 1 - \frac{2(\nu - 2)}{(x - \nu + 2)^2 + 4\nu} \right\}. \tag{18.30}$$

This approximation gives an accuracy of three decimal places when $1 - F_{\chi^2_\nu}(x)$ is of order 0.1, even for ν as small as 2.

Wallace (1959) derived definite bounds for the survival function of the χ^2_ν distribution and for the corresponding equivalent standard normal deviate. He showed that

$$d_\nu \{1 - \Phi(w(x))\} > 1 - F_{\chi^2_\nu}(x) > d_\nu e^{1/(9\nu)} \{1 - \Phi(w_2(x))\}, \tag{18.31}$$

where

$$d_\nu = \left(\frac{\nu}{2}\right)^{(\nu-1)/2} \frac{e^{-\nu/2} \sqrt{2\pi}}{\Gamma(\nu/2)},$$

$$w(x) = \left\{ x - \nu - \nu \log\left(\frac{x}{\nu}\right) \right\}^{1/2},$$

$$w_2(x) = w(x) + \frac{\sqrt{2}}{3\sqrt{\nu}}.$$

From Stirling's formula it is easily noted that d_ν is very nearly equal to 1. Defining the equivalent normal deviate by the equation

$$1 - F_{\chi^2_\nu}(x) = 1 - \Phi(u(x)), \tag{18.32}$$

Wallace also proved that

$$w(x) \leq u(x) \leq w_2(x) + \frac{1}{w_2(x)} \max\left(0, \frac{1}{d_\nu} e^{-1/(9\nu)} - 1\right) \tag{18.33}$$

with the lower limit being valid for $\nu > 0.37$ and the **max** can be replaced by $0.6\sqrt{\nu}$. While the bounds in (18.33) are less precise than the Wilson-Hilferty approximation in (18.24) for most of the distribution, the upper bound in (18.33) gives useful approximation in the extreme upper tail. Hill (1969)

presented an expansion of $u(x)$ in terms of $w(x)$ as

$$u(x) \approx w(x) + \frac{\sqrt{2}}{3\sqrt{\nu}} - \frac{1}{18\nu}(w(x))^2 - \frac{\sqrt{2}}{810\nu\sqrt{\nu}}\{(w(x))^2 - 13\} \\ + \frac{7}{9720\nu^2}\{6(w(x))^3 + 17w(x)\} + \dots, \quad (18.34)$$

which gives $\Phi(u(x))$ to five decimal places for $\nu > 20$ (in fact, to eight decimal places if terms up to order ν^{-4} are retained). Cornish (1969) reported high accuracy for Hill's expansion in (18.34). Hill also presented a Cornish-Fisher type expansion for the chi-square percentiles as

$$\chi_{\nu, \varepsilon}^2 \approx \left(\nu - \frac{2}{3}\right) \exp\left\{U_\varepsilon c_\nu - \frac{1}{6}U_\varepsilon^2 + \frac{1}{36c_\nu}(U_\varepsilon^3 - U_\varepsilon) \right. \\ \left. - \frac{1}{1620c_\nu^2}(6U_\varepsilon^4 - 31U_\varepsilon^2 - 32) \right. \\ \left. + \frac{1}{38880c_\nu^3}(9U_\varepsilon^5 - 308U_\varepsilon^3 - 481U_\varepsilon)\right\}, \quad (18.35)$$

where $c_\nu = \sqrt{(\nu/2) - (1/3)}$ and U_ε is the lower ε percentage point of the standard normal distribution (as before). The approximation in (18.35) is much more accurate than Vanderbeck and Cooke's (1961) Cornish-Fisher expansion in (18.27) for ε values close to 0 or 1.

In his algorithm for the computation of χ^2 -quantiles, Goldstein (1973) used the extended formula

$$\chi_{\nu, \varepsilon}^2 \approx \nu \left[1 - \frac{2}{9\nu} + \frac{1}{1215\nu^2}(4x^4 + 16x^2 - 28) \right. \\ \left. + \frac{1}{229635\nu^3}(8x^6 + 720x^4 + 3216x^2 + 2904) \right. \\ \left. + \sqrt{\frac{2}{\nu}} \left\{ \frac{x}{3} + \frac{1}{162\nu}(-x^3 + 3x) - \frac{1}{5832\nu^2}(3x^5 + 40x^3 + 45x) \right. \right. \\ \left. \left. + \frac{1}{7873200\nu^3}(301x^7 - 1519x^5 - 32769x^3 - 79349x) \right\} \right]^3, \quad (18.36)$$

to which the following polynomial was fitted:

$$\begin{aligned} \chi_{\nu, \varepsilon}^2 \approx \nu & \left\{ \left(1.0000886 - \frac{0.2237368}{\nu} - \frac{0.01513904}{\nu^2} \right) \right. \\ & + \frac{x}{\sqrt{\nu}} \left(0.4713941 + \frac{0.02607083}{\nu} - \frac{0.008986007}{\nu^2} \right) \\ & + \frac{x^2}{\nu} \left(0.0001348028 + \frac{0.01128186}{\nu} + \frac{0.02277679}{\nu^2} \right) \\ & + \frac{x^3}{\nu\sqrt{\nu}} \left(-0.008553069 - \frac{0.01153761}{\nu} - \frac{0.01323293}{\nu^2} \right) \\ & + \frac{x^4}{\nu^2} \left(0.00312558 + \frac{0.005169654}{\nu} - \frac{0.006950356}{\nu^2} \right) \\ & + \frac{x^5}{\nu^2\sqrt{\nu}} \left(-0.0008426812 + \frac{0.00253001}{\nu} + \frac{0.001060438}{\nu^2} \right) \\ & \left. + \frac{x^6}{\nu^3} \left(0.00009780499 - \frac{0.001450117}{\nu} + \frac{0.001565326}{\nu^2} \right) \right\}^3, \end{aligned} \quad (18.37)$$

where $x \equiv U_{\varepsilon}$ is the lower ε percentage point of the standard normal distribution. Goldstein's approximation in (18.36) seems to be quite good even for extreme significance limits. The polynomial fit in (18.37) is slightly better than (18.36), but is unwieldy and is useful primarily for computer implementation.

Severo and Zelen (1960) considered the approximation to the normal distribution function $\Phi(x+h)$ as given by the Taylor series expansion about x , and the following terms of the Gram-Charlier series

$$F_{\chi^2}(x) = \Phi(x) - \frac{\gamma_1}{6} \Phi^{(3)}(x) + \frac{\gamma_2}{24} \Phi^{(4)}(x),$$

where $\Phi^{(k)}(x)$ is the k th derivative of $\Phi(x)$ and γ_1 and γ_2 are the measures of skewness and kurtosis, respectively, given by

$$\gamma_1 = \frac{\sqrt{128}}{27\nu\sqrt{\nu}} \quad \text{and} \quad \gamma_2 = -\frac{4}{9\nu} - \frac{64}{81\nu^2},$$

to propose a modification to the Wilson-Hilferty formula in (18.26) as

$$\chi_{\nu, \varepsilon}^2 \approx \nu \left\{ 1 - \frac{2}{9\nu} + \sqrt{\frac{2}{9\nu}} (U_\varepsilon - h_\nu) \right\}^3, \quad (18.38)$$

where

$$h_\nu = -\frac{2}{27\nu} \left(\frac{2\sqrt{2}(U_\varepsilon^2 - 1)}{3\sqrt{\nu}} - \frac{(U_\varepsilon^3 - 3U_\varepsilon)}{4} \right). \quad (18.39)$$

In obtaining the correction factor h_ν in (18.39), Severo and Zelen (1960) used only the first term in the above expression of γ_2 . By using both terms of γ_2 and proceeding similarly, Zar (1978) proposed a modified Severo-Zelen approximation as

$$\chi_{\nu, \varepsilon}^2 \approx \nu \left\{ 1 - \frac{2}{9\nu} + \sqrt{\frac{2}{9\nu}} (U_\varepsilon - h'_\nu) \right\}^3, \quad (18.40)$$

where

$$h'_\nu = \frac{1}{486\nu^2} \{ (9\nu + 16)(U_\varepsilon^3 - 3U_\varepsilon) - 24\sqrt{2\nu}(U_\varepsilon^2 - 1) \}. \quad (18.41)$$

Another simple approximation to the percentage points of the χ_ν^2 distribution is the time-honored Haldane's (1937) approximation given by

$$\chi_{\nu, \varepsilon}^2 \approx \frac{1}{13} \left[12\nu \left\{ \frac{5U_\varepsilon}{6 \left(1 - \frac{1}{18\nu} \right) \sqrt{2\nu}} + 1 - \frac{5}{18\nu} \left(1 + \frac{7}{48\nu} \right) \right\}^{13/5} + \nu \right]. \quad (18.42)$$

Aroian (1943) used the coefficient of skewness ($= \sqrt{8/\nu}$) of the χ_ν^2 distribution to determine empirically a relationship

$$\chi_{\nu, \varepsilon}^2 \approx \nu + \sqrt{2\nu} \left\{ U_\varepsilon + b_1 \sqrt{\frac{8}{\nu}} + b_2 \left(\frac{8}{\nu} \right) \right\} \quad (18.43)$$

reporting values of b_1 and b_2 for various choices of ε .

Hoaglin (1977), upon examining the tables of percentage points for $\nu = 3$ to 30, gave an approximation for the right-tail of the χ_ν^2 distribution to be

$$\chi_{\nu, \varepsilon}^2 \approx \left\{ 1.00991\sqrt{\nu} + 1.95188\sqrt{-\log_{10}(1 - \varepsilon)} - 1.14485 \right\}^2, \quad (18.44)$$

which he called the "additive" fit. A better approximation, which he called the "extended" fit, is

$$\chi_{\nu, \varepsilon}^2 = \left\{ 1.06807\sqrt{\nu} + 2.13161\sqrt{-\log_{10}(1 - c)} - 0.04589\sqrt{\nu[-\log_{10}(1 - \varepsilon)]} - 1.37266 \right\}^2, \quad (18.45)$$

and a "simplified" fit was given as

$$\chi_{\nu, \varepsilon}^2 \approx \left\{ \sqrt{\nu} + 2\sqrt{-\log_{10}(1 - \varepsilon)} - \frac{7}{6} \right\}^2. \quad (18.46)$$

Similarly, for the left-tail, Hoaglin provided the "additive" fit to be

$$\chi_{\nu, \varepsilon}^2 \approx \left\{ 0.97657\sqrt{\nu} + 1.46049\sqrt{-\log_{10}(1 - \varepsilon)} + 0.59025 \right\}^2, \quad (18.47)$$

the "extended fit" to be

$$\chi_{\nu, \varepsilon}^2 \approx \left\{ 1.14309\sqrt{\nu} - 0.94591\sqrt{-\log_{10}(1 - \varepsilon)} - 0.13138\sqrt{\nu[-\log_{10}(1 - \varepsilon)]} - 0.06198 \right\}^2, \quad (18.48)$$

and a "simplified fit" to be

$$\chi_{\nu, \varepsilon}^2 \approx \left\{ \sqrt{\nu} - 1.5\sqrt{-\log_{10}(1 - \varepsilon)} - 0.6 \right\}^2. \quad (18.49)$$

A very interesting comparative study of all these approximation formulas was carried out by Zar (1978) at a number of different significance levels. He also included in this study an improved approximation derived from Severo and Zelen's approximation in (18.38) and its modification in (18.40) given by

$$\chi_{\nu, \varepsilon}^2 \approx \nu \left\{ 1 - \frac{2}{9\nu} + \sqrt{\frac{2}{9\nu} \left(U_\varepsilon - \frac{K}{\nu} \right)} \right\}^3, \quad (18.50)$$

where $K = H = ch$, $\approx \nu h$, or $K = H' = ch'_c \approx \nu h'_c$, whichever provides the better approximation, where h_ν and h'_ν are as given in (18.39) and (18.41), respectively. The values of c , and H or H' that were found empirically to yield the most accurate approximation using (18.50) have been tabulated by Zar (1978).

Zar (1978) assessed the accuracy of all the above described approximation formulas by determining the minimum value of ν necessary to achieve a specified absolute relative error for various values of ε . These are reported in Table 18.2. The relative error defined by (Approximate value - Actual

Table 18.2 Accuracy of Several Chi-squared Approximation Formulas

$1 - \varepsilon$	= 0.999	0.995	0.990	0.975	0.950	0.900	0.750	0.500	0.250	0.100	0.050	0.025	0.010	0.005	0.001
 RE = 1%															
F	—	123	97	65	42	21	7	17	10	4	18	33	54	69	107
WH	2 5	1 7	1 4	9	6	4	4	3	1	2	2	2	1	1	6
EWH	6	5	4	3	3	2	1	1	2	2	2	2	2	2	2
PWH	1	3	2	2	2	2	2	2	1	2	2	1	2	2	2
SZ	1	2	9	8	6	5	4	3	3	2	3	4	4	4	4
MSZ	12	8	7	6	5	5	4	3	3	4	4	3	1	1	5
ESZ	9	7	6	6	5	4	2	1	2	2	1	1	1	1	1
A	21	15	14	10	8	5	5	4	3	1	2	3	4	4	6
H	19	14	12	8	6	4	3	3	2	2	2	1	1	2	4
CF	8	7	7	6	5	4	2	2	2	1	1	2	2	2	3
ESZ & CF		6	4	4	3	3			2					1	
		(17)	(16)	(14)	(14)	(9)			(6)					(9)	
 RE = 0.5%															
F	—	—	—	119	75	35	17	34	19	10	42	74	118	—	—
WH	36	24	19	12	8	4	6	4	2	4	4	3	2	5	1
EWH	7	5	5	4	3	2	2	2	2	2	2	2	2	2	3
PWH	4	3	3	3	2	2	2	2	1	2	2	1	2	2	3
SZ	17	12	10	7	6	5	4	4	2	4	5	5	6	5	5
MSZ	1	5	1	0	8	7	6	5	5	4	3	5	5	3	7
ESZ	9	8	7	6	6	5	3	1	2	2	1	1	1	3	1
A	26	19	17	13	10	6	6	5	3	1	3	4	6	7	9
H	25	18	15	11	8	5	4	4	3	2	2	1	3	4	6
CF	9	9	8	7	6	4	2	3	2	3	2	2	3	3	3
ESZ & CF		7	4	4	3	3			2					2	

$ \mathbf{RE} = 0.1\%$															
F	—	—	—	—	—	136	89	—	93	82	—	—	—	—	—
WH	87	57	43	26	14	5	15	9	9	12	9	5	14	24	47
EWH	9	7	6	5	4	3	2	2	3	3	3	3	3	3	4
PWH	5	4	4	5	2	3	4	3	3	2	2	3	3	2	3
SZ	31	21	16	12	9	7	7	7	3	8	10	11	11	10	7
MSZ	28	18	14	11	9	9	9	7	6	9	10	10	7	4	15
ESZ	12	12	10	9	7	6	4	2	4	5	1	2	2	4	4
A	41	30	28	22	16	9	10	10	7	2	7	10	14	17	21
H	45	32	26	18	13	7	7	6	6	4	3	5	9	12	18
CF	13	13	12	10	8	7	4	5	4	3	3	3	5	5	6
ESZ & CF	—	11	9	8	6	5	—	—	2	—	—	—	—	4	—
$ \mathbf{RE} = 0.05\%$															
F	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
WH	131	83	62	37	18	18	25	12	25	20	15	7	26	43	80
EWH	10	9	7	6	6	4	4	4	3	3	4	4	4	3	5
PWH	8	6	6	5	6	3	5	3	3	2	3	3	3	2	3
SZ	42	26	20	15	15	12	16	9	4	11	14	15	15	14	9
MSZ	37	23	18	13	10	10	11	9	8	13	14	13	10	5	21
ESZ	12	15	13	12	10	7	4	3	4	6	2	3	3	7	6
A	48	35	49	27	22	11	13	12	9	3	11	13	19	24	29
H	61	43	35	25	16	8	10	9	8	6	3	8	14	19	28
CF	16	15	15	11	10	11	6	5	5	3	5	4	6	7	8
ESZ & CF	—	12	10	9	9	5	—	—	3	—	—	—	—	5	—

Note: Shown is the minimum ν necessary to achieve the indicated accuracy (\mathbf{RE} = relative error). F = Fisher(18.25); WH = Wilson-Hilferty(18.26); EWH = extended Wilson-Hilferty(18.36); PWH = polynomial extension of Wilson-Hilferty(18.37); SZ = Severo-Zelen(18.38); MSZ = modified Severo-Zelen(18.40); ESZ = empirically modified Severo-Zelen(18.50); A = Aroian(18.93); H = Haldane(18.42); CF = Cornish-Fisher(18.27); ESZ & CF = mean of ESZ and CF, use for ν up to that in parentheses, with CF alone used for higher ν . The — indicates that the indicated accuracy was not reached for ν up to 140.

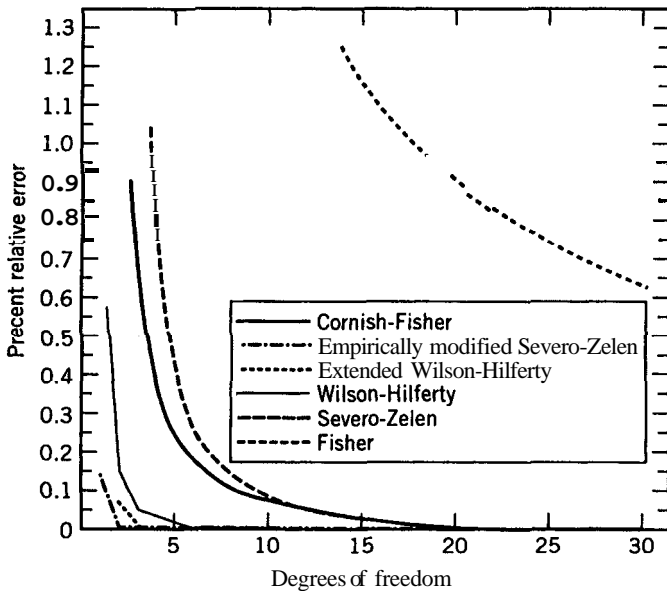


Figure 18.4 The Accuracy of Several Formulas for Approximating χ^2 at the 5% Significance Level ($\epsilon = 0.95$). Fisher (18.25), Wilson and Hilferty (18.26); extended Wilson-Hilferty (18.36), Severo and Zelen (18.38), Cornish-Fisher expansion (18.27), empirically modified Severo-Zelen formula (18.50). On this plot, Haldane's approximation (18.42) would appear very near the Cornish-Fisher approximation, the modified Severo-Zelen (18.40) would appear very near the Severo-Zelen, and the Aroian (18.43) would lie between the Wilson-Hilferty and the Cornish-Fisher. Relative error = (Approximation - Actual value)/(Actual value)

value)/(Actual value) is presented in Figure 18.4, for example, for the various approximation formulas at the 5% significance level (i.e., $\epsilon = 0.95$). It is clear from Table 18.2 and Figure 18.4 that Fisher's approximation in (18.25) is the poorest. The Wilson-Hilferty approximation in (18.26) is impressively good, especially for ϵ no more extreme than 0.05 or 0.995. The Severo-Zelen approximation in (18.38) and its modification in (18.40) do not differ much from the Wilson-Hilferty, except when ϵ is more extreme than 0.10 or 0.99, at which they become better. The extended Wilson-Hilferty formula in (18.36) is even better, and the polynomial fit in (18.37) improves a bit on that. Hence these two approximations are quite appropriate for computer implementation. The direct approximations of Gilbert in (18.21) and of Hoaglin in (18.44)–(18.49) do not provide asymptotically improving approximations to $\chi^2_{v,\epsilon}$ as v increases as do the other procedures. This is to be expected after all, since these approximations were developed based on tabulated values for v up to 30. Further these approximations as well as that of Aroian in (18.43) are not decided improvements over the Wilson-Hilferty approximation in (18.26) and hence are not as good as the Cornish-Fisher approximation in (18.27) or the modified Severo-Zelen approximation in

(18.50). The Haldane approximation in (18.42), as simple as it may be, provides good results and generally just a little inferior to the approximations secured by the Cornish-Fisher formula in (18.27) for ε in the range 0.025 to 0.999, but it does become poor at extreme levels of significance. In conclusion, the Wilson-Hilferty approximation in (18.26) will perform quite satisfactorily for many routine uses, except when ν is very small. Should more accuracy be required, the Cornish-Fisher approximation in (18.27) could be used. For computer implementation, the extended Wilson-Hilferty approximations in (18.36) or (18.37) could be used. One may instead use the algorithm of Best and Roberts (1975) that is described below in order to achieve greater accuracy. Interestingly Zar (1978) also noted that the average of the Cornish-Fisher approximation in (18.27) and the formula in (18.50) provided better approximations than either of them in many cases as one tended to overestimate and the other tended to underestimate.

Similar comparative studies have also been carried out by Sahai and Thompson (1974), Ling (1977, 1978), and on a very minor scale by Liddell (1983). In the former the authors concluded that for $\nu \geq 40$ the four-term Cornish-Fisher expansion considered by Peiser (1943) [see (18.27)] is accurate enough with an error less than 0.1%; however, for small ν and values of ε quite close to 1, one may need to use additionally seventh and eighth terms in the approximation in (18.27) which are given by

$$\frac{1}{25515\nu^2} (12U_\varepsilon^6 - 243U_\varepsilon^4 - 923U_\varepsilon^2 + 1472)$$

and

$$-\frac{1}{9185400\nu^2\sqrt{2\nu}} (3753U_\varepsilon^7 + 4353U_\varepsilon^5 - 289517U_\varepsilon^3 - 289717U_\varepsilon),$$

respectively.

Ling (1977, 1978), on the other hand, compared the asymptotic—the Fisher and Wilson-Hilferty approximations of $F_{x\nu}^2(x)$ in (18.22), (18.23), and (18.24), respectively—with the approximation due to Peizer and Pratt (1968) given by

$$\begin{aligned} F_{x\nu}^2(x) &\approx \Phi \left\{ -\frac{(1/3) + (0.08/\nu)}{\sqrt{2\nu} - 2} \right\} && \text{if } x = \nu - 1, \\ &\approx \Phi \left\{ \frac{x - \nu + (2/3) - (0.08/\nu)}{|x - (\nu - 1)|} \right. \\ &\quad \left. \times \left[(\nu - 1) \log \left(\frac{\nu - 1}{x} \right) + x - (\nu - 1) \right]^{1/2} \right\} && \text{if } x \neq \nu - 1. \end{aligned} \tag{18.51}$$

Table 18.3 Maximum Absolute Error in Approximations of $F_{\chi^2_\nu}(x)$ in (18.22), (18.23), (18.24), and (18.51)

ν	(18.22)	(18.23)	(18.51)	(18.24)
5	8.4(-2) ^a	2.0(-2)	3.3(-4)	2.6(-3)
6	7.7(-2)	1.9(-2)	2.1(-4)	2.2(-3)
7	7.1(-2)	1.7(-2)	1.4(-4)	1.8(-3)
8	6.7(-2)	1.6(-2)	1.0(-4)	1.6(-3)
9	6.3(-2)	1.5(-2)	7.5(-5)	1.4(-3)
10	6.0(-2)	1.5(-2)	5.8(-5)	1.3(-3)
11	5.7(-2)	1.4(-2)	4.6(-5)	1.1(-3)
12	5.4(-2)	1.3(-2)	3.7(-5)	1.0(-3)
13	5.2(-2)	1.3(-2)	3.1(-5)	9.6(-4)
14	5.0(-2)	1.2(-2)	2.6(-5)	8.9(-4)
15	4.9(-2)	1.2(-2)	2.2(-5)	8.2(-4)
20	4.2(-2)	1.0(-2)	1.2(-5)	6.1(-4)
25	3.8(-2)	9.3(-3)	7.3(-6)	4.8(-4)
30	3.4(-2)	8.5(-3)	5.0(-6)	3.9(-4)
40	3.0(-2)	7.4(-3)	2.9(-6)	2.9(-4)
50	2.7(-2)	6.6(-3)	1.9(-6)	2.3(-4)
60	2.4(-2)	6.1(-3)	1.4(-6)	1.9(-4)
100	1.9(-2)	4.7(-3)	5.5(-7)	1.1(-4)
120	1.7(-2)	4.3(-3)	4.1(-7)	9.2(-5)
150	1.5(-2)	3.8(-3)	2.8(-7)	7.3(-5)
200	1.3(-2)	3.3(-3)	1.8(-7)	5.4(-5)
240	1.2(-2)	3.0(-3)	1.3(-7)	4.5(-5)

$${}^a c(d) = c \times 10^d.$$

Ling determined the maximum absolute error in these approximations of $F_{\chi^2_\nu}(x)$ in the interval (0.0001, 0.9999) with x in increments of 0.001 for integral values of ν between 5 and 240. These values are presented in Table 18.3 from which it is quite evident that the Peizer-Pratt approximation in (18.51) is even better than the good Wilson-Hilferty approximation in (18.24) in the range studied and probably beyond.

El Lozy (1982), through a similar study, determined that Hill's modified Cornish-Fisher expansion in (18.35) performs better than the Peizer-Pratt approximation in (18.51), but that this greater accuracy is achieved at the cost of involving considerably more mathematical operations. One may also refer to Narula and Li (1977) to get an idea about the computational effort involved (in terms of number of arithmetic and special function operations) in the different methods of approximating the distribution function $F_{\chi^2_\nu}(x)$ and of approximating the percentage points $\chi^2_{\nu, \epsilon}$.

Best and Roberts (1975) provided an algorithm (along with a Function Subprogram in Fortran) for computing quite accurately the percentage points

of the χ_ν^2 distribution. This algorithm is both more general and more accurate than an algorithm given earlier by Goldstein (1973). In this method, for a given value of ϵ , $\chi_{\nu,\epsilon}^2$ is found from the Taylor series expansion [Hill and Davis (1968)] given by

$$\chi_{\nu,\epsilon}^2 = \chi_0^2 + \sum_r \frac{1}{r!} c_r(\chi_0^2) \left(\frac{E}{p_{\chi_0^2}(\chi_0^2)} \right)^r, \quad (18.52)$$

where χ_0^2 is a suitable starting approximation,

$$c_1(u) = 1,$$

$$c_{r+1}(u) = \left\{ r \left[\frac{1}{2} - \frac{1}{u} \left(\frac{\nu}{2} - 1 \right) \right] + \frac{d}{du} \right\} c_r(u),$$

$$E = \epsilon - F_{\chi_0^2}(\chi_0^2).$$

For many choices of ν and ϵ , the **Wilson-Hilferty** approximation in (18.26) is used for χ_0^2 (say, χ_{01}^2). However, better starting approximations than this one are used for the three limiting cases $\epsilon \rightarrow 0$, $\epsilon \rightarrow 1$, and $\nu \rightarrow 0$:

1. $\epsilon \rightarrow 0$ (small $\chi_{\nu,\epsilon}^2$): $\chi_{02}^2 = \{\epsilon \nu 2^{(\nu/2)-1} \Gamma(\nu/2)\}^{2/\nu}$.
2. $\epsilon \rightarrow 1$ (large $\chi_{\nu,\epsilon}^2$): $\chi_{03}^2 = -2\{\log(1 - \epsilon) - [(\nu/2) - 1]\log(\chi_{01}^2/2) + \log \Gamma(\nu/2)\}$.
3. $\nu \rightarrow 0$: For the special case $\nu \leq 0.32$, ϵ is expressed in terms of **Hastings's (1955)** approximation to the exponential integral, and in this case χ_{04}^2 is determined by Newton-Raphson iteration.

In this vein, it should be added here that **Shea (1988)** has presented an algorithm (along with a Function Subprogram in Fortran 77) for computing accurately the incomplete gamma integral and hence the cumulative distribution function of χ_ν^2 . This algorithm performs more effectively than the ones given earlier by **Hill and Pike (1967)**, **Bhattacharjee (1970)**, **El Lozy (1976)**, **Gautschi (1979a, b)**, and **Lau (1980)** [also see **Rice and Gaines Das (1985)**].

Further discussions have been made by **Acock and Stavig (1976)**, **Gander (1977)**, **Fettis (1979)**, **Watts (1979)**, **Bukač and Burstein (1980)**, **Cheng and Fu (1983)**, **Chernick and Murthy (1983)**, and **Haines (1988)** regarding some other approximations for the percentage points of χ_ν^2 distribution. Similarly **Dunlap and Duffy (1975)**, **Weintraub (1979)**, **Sletten (1980)**, **Craig (1984)**, **Knüsel (1986)**, and **Terrell (1987)** have all discussed the computation of the distribution function of χ_ν^2 distribution. Interestingly, for even integral values of ν , **Terrell (1987)** noted that the following continued fraction

approximation

$$F_{\chi^2_\nu}(x) = 2p_{\chi^2_\nu}(x) \left[\frac{x}{\nu} - \frac{\nu x}{\nu + 2} + \frac{2x}{\nu + 4} - \frac{(\nu + 2)x}{\nu + 6} + \frac{4x}{\nu + 8} - \dots \right] \quad (18.53)$$

converges significantly faster than the Poisson series expression in (18.18) for the left-tail of the distribution. Lin (1988) presented a very simple approximation to the cumulative distribution (for large ν) as

$$F_{\chi^2_\nu}(x) = \begin{cases} \frac{1}{2}e^{b_1z+a_1z^2} & \text{if } z \leq 0, \\ 1 - \frac{1}{2}e^{b_2z+a_2z^2} & \text{if } z > 0, \end{cases} \quad (18.54)$$

where $z = \sqrt{x} - \sqrt{\nu}$, $a_1 = -0.9911$, $b_1 = 0.8055$, $a_2 = -0.6763$, and $b_2 = -1.2451$. As Lin (1988) noted, a simple approximation for $\chi^2_{\nu, \epsilon}$ can also be secured from (18.54) by equating the right-hand side to ϵ , taking logs, and then solving for z from a quadratic equation.

Tables to facilitate the construction of shortest confidence intervals for a parameter θ based on a pivotal quantity Q having χ^2_ν distribution have been prepared by many authors including Tate and Klett (1959), Guenther (1969), and Akhlagi and Parsian (1986). These tables give the values of a and b such that $\Pr[a \leq Q \leq b] = 1 - \alpha$ which yields the shortest confidence interval for the parameter θ , for various choices of ν and α .

It must be remarked here that the Wilson-Hilferty approximation in (18.24) or (18.26) is essentially based on the fact that the cube root transformation of chi-square brings it close to normality. Hawkins and Wixley (1986) showed that the fourth root transformation transforms the chi-squared distribution to very near normality for all degrees of freedom. The fourth root transformation turns out to be also superior than the cube root transformation for small degrees of freedom like $\nu = 1$ and 2. The fourth root transformation also provides very close approximations to the tail percentage points. However, for large degrees of freedom, the cube root transformation turns out to be better, but both transformations are very accurate as measured by the moments and percentage points and even more so by the coverage probabilities. These points are well illustrated in Table 18.4 which shows, for each selected value of ν the coefficients of skewness and kurtosis, and the actual left- and right-tail areas at a nominal two-sided 90% of both the fourth root and the cube root transformations, fitted by the method of moments to the transformed variable.

Mention should also be made here to the work of Hernandez and Johnson (1980) and Taylor (1985) who used the Kullback-Leibler information to determine optimal values of A (power of the transform) for certain choices of

Table 18.4 Comparisons of the Cube Root and the Fourth Root Transformations

ν	Skewness		Kurtosis		True cdf at Nominal 5% Levels			
	3rd	4th	3rd	4th	3rd	4th	3rd	4th
	Root	Root	Root	Root	Root	Root	Root	Root
1	0.41	0.08	2.68	2.48	2.19	4.90	93.75	94.88
2	0.17	-0.08	2.73	2.75	4.52	5.52	94.52	95.40
3	0.09	-0.12	2.81	2.87	4.81	5.50	94.74	95.45
10	0.01	-0.10	2.98	2.99	4.98	5.31	94.96	95.32
50	0.00	-0.05	2.99	3.00	5.00	5.14	95.00	95.15
100	0.00	-0.04	3.00	3.00	5.00	5.10	95.00	95.10

v. For example,

ν	1	2	3	4	5
λ	0.2084	0.2654	0.2887	0.3006	0.3124

It is clear from these values, once again, that the fourth root transformation will be more accurate than the cube root transformation for small values of ν , while the latter becomes superior for large values of ν .

Nelson (1987) in fact suggested applying the cube root transformation of the chi-square values and then using the 2σ limits on an \bar{x} chart, instead of a control chart for chi-square values directly (since the latter will look peculiar, even when the process is in control, due to the fact that the χ^2 distribution is skewed to the right).

6 CHARACTERIZATIONS

First of all, it should be mentioned here that all the characterization results presented for the gamma distribution in Chapter 17 can simply be stated as characterization results for the chi-square distribution (with minor changes, of course). Hence we will not repeat those results once again; we present here some key characterization results for the chi-square that are based on quadratic forms of normal variables (as one would expect).

Let V_1, V_2, \dots, V_n be a random sample of size n from a normal $N(0, \sigma^2)$ population, and Q a quadratic form in these variables, with symmetric matrix A of rank r , $0 < r \leq n$. Then the variable Q/σ^2 is distributed as χ_r^2 if and only if $A^2 = A$. Further suppose that Q^* is another quadratic form in V_i 's with real symmetric matrix B . Then the variables Q and Q^* are stochastically independent if and only if $AB = O$.

Next, we note the celebrated Cochran's (1934) theorem which characterizes a χ^2 distribution based on its decomposition: "Let $\sum_{i=1}^n V_i^2 = \sum_{j=1}^k Q_j$, where Q_j is a quadratic form in V_1, V_2, \dots, V_n (a random sample from

$N(0, \sigma^2)$) with associated matrix A_j of rank r_j , $j = 1, 2, \dots, k$. Then, the random variables Q_j/σ^2 , $j = 1, 2, \dots, k$, are mutually independent with Q_j/u^2 distributed as $\chi_{r_j}^2$ if and only if $\sum_{j=1}^k r_j = n$."

Dykstra and Hewett (1972) presented two interesting examples of absolutely continuous bivariate distributions which shed further light in this regard. One example simply illustrates the fact that the sum of two random variables can be distributed as χ^2 with one of the variables also distributed as χ^2 and the other variable positive but not necessarily distributed as χ^2 . Their other example illustrates the fact that the sum of two variables can be distributed as χ^2 , with each variable also distributed as χ^2 and their degrees of freedom adding up properly, but still the two variables need not be independent.

Ruben (1974, 1975) characterized the normal distribution through the sample variance; the relevance of these results to this chapter comes from the chi-square distribution of the sample variance. Ruben's (1975) characterization is as follows: "Let X_1, X_2, \dots , be i.i.d. random variables. Define $Q = \sum_{i=1}^n (X_i - \bar{X}_n)^2$, where $\bar{X}_n = \sum_{i=1}^n X_i/n$. Let p and q be distinct integers ≥ 2 . Then constants A_p and A_q exist such that Q_p and Q_q are distributed as $\lambda_p \chi_{p-1}^2$ and $\lambda_q \chi_{q-1}^2$, respectively, if and only if X_1 is normally distributed." A simpler proof for this characterization result was provided by Bondesson (1977).

Khatri (1963, 1978), Shanbhag (1968), and Good (1969) all presented necessary and sufficient conditions for a quadratic form in **multinormal** random variables to be distributed as chi-square. Let $X \sim MVN(Q, \Sigma)$, where Σ is nonnegative definite and can be written as $\Sigma = BB^T$, B being an $n \times s$ matrix of rank $s = \text{rank}(\Sigma)$. Then the quadratic form $Q = X^TAX$ is distributed as chi-square if and only if (1) $\Sigma A \Sigma A \Sigma = \Sigma A \Sigma$ [Khatri (1963)], (2) $(A \Sigma)^3 = (A \Sigma)^2$ or $\text{trace}(A \Sigma) = \text{trace}((A \Sigma)^2) = \text{rank}(\Sigma A \Sigma)$ [Shanbhag (1968)], (3) the eigenvalues of AX are zeros and ones only or $\text{trace}(A \Sigma) = \text{trace}((A \Sigma)^2) = \dots = \text{trace}((A \Sigma)^n)$ [Good (1969)]. [Refer to Khatri (1978) for some comments on all these results.]

In trying to interpret what is so unique about the sum of squares in the definition of "a chi-square distribution with n degrees of freedom as the probability distribution of the sum of squares of n independent standard normal variates," Mitra (1974) presented an interesting uniqueness result concerning the sum of squares. Let V_1, V_2, \dots, V_n be i.i.d. normal variables with mean 0 and an unknown variance $\theta \in \Omega$, where the parameter space Ω is sufficiently rich so that $\sum_{i=1}^n V_i^2$ is a complete sufficient statistic for θ . Then, if $g(V)$ is a statistic such that $g(V)/\theta$ is distributed as χ_n^2 for every $\theta \in \Omega$, Mitra proved that $g(V) = \sum_{i=1}^n V_i^2$ a.e. It should be mentioned here that the degrees of freedom being n is very crucial in this result, for there is no dearth of examples of statistics distributed as χ^2 with **less** than n degrees of freedom that are not even second degree functions in V_i 's. Mitra (1974) also conjectured that the result may be true when the parameter space Ω is a set of finite cardinality.

Hussain (1986) has shown that a χ^2 random variable with even degrees of freedom can be decomposed and expressed as a sum of two identically distributed random variables each with a mixed chi-square distribution. More specifically, if $X \sim \chi_{2n}^2$, then there exists a representation $X = U + V$ with U and V being identically distributed, each as a mixture of χ^2 distributions with degrees of freedom $2j - 1$, $j = 1, 2, \dots, n$; further the random variables U and V are negatively correlated with the coefficient of correlation $\rho_{UV} = -(n - 1)/(n + 1)$. For the special case $n = 1$, we have $X \sim \chi_2^2$ and $\rho_{UV} = 0$ which is also evident from the fact that U and V are independent random variables each having χ_1^2 distribution in this case (due to Cochran's theorem stated in the beginning of this section).

7 SIMULATIONAL ALGORITHMS

First of all, it should be mentioned that a pseudorandom observation from a chi-square distribution with integer ν can be generated as the sum of squares of ν standard normal observations (generated by one of the efficient algorithms discussed in Chapter 13). This naturally can be quite time-consuming even for moderately large ν . One could also use an accurate approximation of $F_{\chi^2}^{-1}(\cdot)$ (discussed earlier in Section 5) along with an efficient standard uniform random generator to produce an observation from χ_ν^2 distribution via the usual inverse cumulative distribution function method.

On the other hand, one could use one of the many algorithms for generating gamma observations discussed earlier in Chapter 17 to produce a χ_ν^2 observation by appropriately scaling the simulated gamma deviate (with shape parameter $a = \nu/2$ and $\beta = 2$). Of course this requires the gamma algorithm to be able to cover an extended range ($a \geq 1/2$) instead of the usual lower bound of 1 (since $\nu \geq 1$). For example, the gamma simulational algorithms due to Best (1978) and Kinderman and Monahan (1980) are valid only for $a > 1$. But the algorithm given by Cheng and Feast (1980) meets the minimum requirement of $a \geq 1/2$ and hence may be utilized for the purpose of simulating pseudo-random observations from χ_ν^2 distribution.

If one requires to simulate random observations from χ_ν distribution, one could do this by first simulating random observations from χ_ν^2 distribution and then taking the positive square roots of these observations. One could also simulate random observations from χ_ν distribution directly by using the algorithm of Monahan (1987), which is essentially a ratio of uniforms algorithm [Kinderman and Monahan (1977)]. Of course Monahan's algorithm can be used to generate observations from χ_ν^2 distribution (by taking squares of the simulated χ_ν observations) or to generate random observations from the gamma distribution with shape parameter $a = \nu/2$ (by taking squares of the simulated χ_ν observations and then dividing by 2). Monahan (1987) also carried out a time-comparative study of his algorithm against that of Cheng and Feast (1980). The time-comparisons of these two algorithms, as reported

Table 18.5 A Time-Comparative Study of Two Algorithms

	$\nu = 1$	$\nu = 5$	$\nu = 9$	Varied #1 ^a	Varied #2 ^b
<i>Gamma Distribution</i>					
Monahan	49.2	53.4	53.4	325.4	324.6
Cheng-Feast	54.2	53.6	53.8	335.8	338.0
<i>Chi-square Distribution</i>					
Monahan	47.8	52.0	51.6	322.4	317.8
Cheng-Feast	55.0	54.6	55.0	342.2	348.2
<i>Chi Distribution</i>					
Monahan	46.8	51.6	51.4	320.2	316.2
Cheng-Feast	60.6	60.0	60.6	370.4	376.2

Note: Time is given in milliseconds for the average of five replications of 10,000 samples, except 50,000 for variable ν .

^aVaried #1 covered the range (1, 11).

^bVaried #2 covered (1, 101).

by Monahan (1987), are presented in Table 18.5. These comparisons reveal clearly that Monahan's algorithm is the faster of the two, although the time improvements are not dramatic.

8 DISTRIBUTIONS OF LINEAR COMBINATIONS

In this section, we present some important developments regarding the derivation (or computations) of distributions of linear combinations of independent χ^2 variables. More detailed treatment of this topic may be found in general sources on distributions of quadratic forms in normal variables. Let us consider specifically the distribution

$$Q_k = \sum_{i=1}^k c_i \chi_{\nu_i}^2, \quad (18.55)$$

where c_i 's are known constants. (Without loss of generality we can take $c_1 > c_2 > \dots > c_k$.) Two efficient methods of determining percentage points of Q_k are those given by Imhof (1961) and Johnson and Kotz (1968); the former inverts numerically the characteristic function of the distribution of Q_k to get $\Pr\{Q_k < t\}$ for specified t , while the latter gets the distribution based on Laguerre series. Exact significance points of Q_k , for selected nonnegative values of c_i and with all $\nu_i = 1$, were first published by Grad and Solomon (1955) and Solomon (1960) for $k = 2$ and 3, by Johnson and Kotz

(1968) for $k = 4$ and 5 , and by Solomon and Stephens (1977) for $k = 6, 8$, and 10 .

Davis (1977) showed that the distribution of Q_k in (18.55), with c_i nonnegative and any specified values of ν_i , is derivable from a k th-order linear differential equation. The computation of percentage points of Q_k by analytic continuation of the series solution at the origin becomes feasible by this method for a useful range of parameter values. This method thus avoids the slow convergence of the power series for large values of t (since the power series is about $t = 0$ and is effective only for small values of t).

For the case when all ν_i 's are equal to 1, Jensen and Solomon (1972) proposed a Wilson-Hilferty type approximation by taking $Z = (Q_k/E[Q_k])^h$ to be approximately a normal distribution with mean and variance depending on the first three cumulants of Q_k . Proceeding similarly, Solomon and Stephens (1977) proposed two more approximations, one by fitting a **Pearson** curve with the same first four moments as Q_k , and the other by fitting $Q_k = A(\chi_p^2)^r$ where A , p , and r are determined by the first three moments of Q_k . To evaluate the performance of these approximations, they carried out a study comparing the exact (E) values taken from Solomon's (1960) and Johnson and Kotz's (1968) tables, Imhof's (I) approximate value, the Jensen-Solomon (J) approximate value, the four-moment **Pearson (P)** approximate value, and the three-moment χ^2 (**S**) approximate value, of the a percentage points for different choices of c_i 's. These values are presented in Table 18.6.

From Table 18.6 it is clear that the Imhof method gives quite accurate values (to be expected since the method is essentially exact) at all levels of a . All three approximations P, J, and S give excellent accuracy in the upper tail, while S performs better than the other two in the lower tail. However, all (except Imhof's) approximations become relatively less accurate in the lower tails as the coefficients of skewness and kurtosis of Q_k increase.

For the positive definite case ($c_k > 0$), Oman and Zacks (1981) used Robbins and Pitman's (1949) method of mixtures to derive a very good approximation for the distribution function of Q_k for any specified values of c_i 's and ν_i 's. For example, for $a > 1$ using this mixture method, it is well-known that [Neuts and Zacks (1968)] the distribution of $a\chi_\nu^2$ can be represented as a negative binomial mixture of central chi-squared distributions:

$$a\chi_\nu^2 \sim \chi_{\nu+2J}^2, \quad (18.56)$$

where $J \sim NB(\psi, \mu)$ with its probability mass function

$$g(j|\psi, \mu) = \frac{\Gamma(\mu + j)}{\Gamma(\mu)\Gamma(j + 1)} \psi^j (1 - \psi)^\mu, \quad j = 0, 1, \dots, \quad (18.57)$$

Table 18.6 Comparison of Exact Percentage Points and Approximations for Q_k

k	c-Values	$[\sqrt{\beta_1}, \beta_2]$	Method	α							
				0.01	0.025	0.05	0.10	0.90	0.95	0.975	0.99
3	0.5, 0.4, 0.1	[1.974, 9.000]	E	—	—	0.098	0.164	2.188	2.820	—	—
			I	0.032	0.060	0.097	0.164	2.187	2.818	3.450	4.290
			P	0.061	0.079	0.109	0.166	2.191	2.818	3.447	4.284
			S	0.027	0.053	0.091	0.158	2.184	2.809	3.441	4.275
3	0.5, 0.3, 0.2	[1.932, 9.000]	E	—	—	0.110	0.183	2.122	2.708	—	—
			I	0.036	0.068	0.110	0.183	2.122	2.708	3.302	4.102
			P	0.056	0.082	0.119	0.187	2.127	2.712	3.302	4.093
			S	0.040	0.071	0.114	0.186	2.125	2.713	3.308	4.103
4	1.5, 1.5, 0.5, 0.5	[1.771, 7.920]	J	0.029	0.060	0.103	0.175	2.132	2.740	3.365	4.217
			E	0.261	0.425	0.627	0.947	8.120	10.203	12.283	15.033
			I	0.259	0.424	0.627	0.947	8.120	10.202	12.282	15.032
			P	0.387	0.510	0.673	0.953	8.141	10.205	12.261	14.984
4	1.5, 1.5, 0.5, 0.5	[1.771, 7.920]	S	0.252	0.415	0.614	0.933	8.115	10.177	12.247	14.990
			J	0.212	0.373	0.374	0.894	8.152	10.287	12.456	15.385

4	2.5, 0.5, 0.5, 0.5	[2.444, 12.612]	E	0.226	0.369	0.545	0.826	8.540	11.343	14.281	18.297
			I	0.225	0.368	0.545	0.826	8.540	11.342	14.279	18.294
			P	0.723	—	0.807	0.939	8.661	11.403	—	18.133
			S	0.202	0.331	0.495	0.765	8.564	11.232	14.051	17.980
			J	0.180	0.295	0.440	0.683	8.707	11.766	15.141	20.094
5	1.8, 1.8, 0.6, 0.4, 0.4	[1.773, 7.957]	E	0.448	0.677	0.943	1.347	9.921	12.419	14.914	18.214
			I	0.449	0.677	0.943	1.347	9.921	12.419	14.913	18.213
			P	0.667	0.813	1.011	1.351	9.951	12.419	14.879	18.143
			S	0.415	0.640	0.904	1.372	9.902	12.358	14.837	18.130
			J	0.370	0.589	0.850	1.253	9.983	12.567	15.208	18.801
5	3.0, 0.5, 0.5, 0.5, 0.5	[2.460, 12.750]	E	0.403	0.609	0.848	1.211	10.407	13.778	17.307	22.259
			I	0.404	0.609	0.848	1.211	10.407	13.778	17.308	22.127
			P	1.104	—	1.201	1.355	10.562	13.847	—	21.919
			S	0.344	0.528	0.750	1.103	10.428	13.591	16.958	21.735
			J	0.324	0.485	0.680	0.992	10.645	14.285	18.568	24.813

with $\psi = (a - 1)/a$ and $\mu = \nu/2$. As a result one can write

$$\Pr[a\chi_\nu^2 \leq x] = \sum_{j=0}^{\infty} g(j|\psi, \mu) F_{\chi_{\nu+2j}^2}(x), \quad 0 \leq x < \infty. \quad (18.58)$$

Using this method, Oman and Zacks (1981) obtained the mixture representation for the distribution function of Q_k as

$$\Pr[Q_k \leq x] = \sum_{j=0}^{\infty} F_{\chi_{\nu+2j}^2}(x) \Pr[J = j], \quad (18.59)$$

where $\nu = \nu_1 + \nu_2 + \dots + \nu_k$ and $J = J_1 + J_2 + \dots + J_k$, and the probability mass function of J can be obtained as a k -fold convolution of the corresponding mass functions of $NB(\psi_i, \mu_i)$, which incidentally is not negative binomial since the ψ_i 's are not equal. These authors have also suggested an approximation for the distribution of J in order to reduce the amount of computation required for (18.59). The formula in (18.59) provides quite an accurate approximation for the percentage points of Q_k both in lower and upper tails, as is illustrated in Table 18.7 for some selected choices of k , c_i 's, and ν_i 's.

It is of interest to add here that for the special case when all ν_i 's are 1, **Buckley and Eagleson** (1988) [based on earlier work of **Hall** (1983)] derived an approximation for the distribution function of Q_k , and they also derived an explicit upper bound for the error involved in this approximation. **Wood** (1989) proposed a three-parameter F approximation to the distribution of Q_k and showed that this approximation has clear superiority in the lower tail over both the **Buckley and Eagleson** approximation as well as the classical **Satterthwaite** (1946) approximation; but, the S approximation of **Solomon and Stephens** (mentioned earlier) seems to have an overall edge over **Wood's** F -approximation.

Generalizing the method of mixtures due to **Robbins and Pitman** (1949), **Ruben** (1962) considered a linear combination of noncentral chi-squares (with noncentrality parameters δ_i^2) as

$$Q_k^* = \sum_{i=1}^k c_i \chi_{\nu_i}^2(\delta_i^2), \quad (18.60)$$

and presented an infinite series expression for its distribution function as

$$\Pr[Q_k^* < x] = \sum_{j=0}^{\infty} a_j F_{\chi_{\nu+2j}^2}\left(\frac{x}{\beta}\right), \quad (18.61)$$

where $\nu = \nu_1 + \nu_2 + \dots + \nu_k$ and β is an arbitrary positive constant; **Ruben** has also shown that (18.61) converges uniformly on every finite interval of

Table 18.7 Percentage Points Using Imhof's Method (I), Solomon and Stephens's Method (S), and Mixture Approximation (M)

$c_1(\nu_1), \dots,$ $c_k(\nu_k)$	Method	N	α							
			0.01	0.025	0.05	0.10	0.90	0.95	0.975	0.99
0.5(1), 0.4(1), 0.1(1)	I		0.032	0.060	0.097	0.164	2.187	1.818	3.450	4.290
	S		0.027	0.053	0.091	0.158	2.184	2.809	3.441	4.275
	M	29	0.031	0.059	0.098	0.164	2.187	2.818	3.451	4.292
0.5(1), 0.3(1), 0.2(1)	I		0.036	0.068	0.110	0.183	2.122	2.708	3.302	4.102
	S		0.040	0.071	0.114	0.186	2.125	2.713	3.308	4.103
	M	12	0.036	0.067	0.110	0.183	2.121	2.708	3.303	4.105
1.5(2), 0.5(2)	I		0.259	0.424	0.627	0.947	8.120	10.202	12.282	15.032
	S		0.252	0.415	0.614	0.933	8.115	10.177	12.247	14.990
	M	18	0.259	0.425	0.627	0.947	8.120	10.203	12.283	15.040
2.5(1), 0.5(3)	I		0.225	0.368	0.545	0.826	8.540	11.342	14.279	18.294
	S		0.202	0.331	0.495	0.765	8.564	11.232	14.051	17.980
	M	26	0.224	0.368	0.545	0.826	8.540	11.343	14.280	18.296
1.8(2), 0.6(1), 0.4(2)	I		0.449	0.677	0.943	1.347	9.921	12.419	14.913	18.213
	S		0.415	0.640	0.904	1.372	9.902	12.358	14.837	18.130
	M	29	0.447	0.677	0.943	1.347	9.921	12.419	14.915	18.216
3.0(1), 0.5(4)	I		0.404	0.609	0.848	1.211	10.407	13.778	17.308	22.127
	S		0.344	0.528	0.750	1.103	10.428	13.591	16.958	21.735
	M	31	0.403	0.609	0.848	1.211	10.407	13.778	17.307	22.129
0.2(4), 0.1(2)	I		0.135	0.197	0.263	0.356	1.800	2.147	2.483	2.914
	S		0.139	0.198	0.263	0.355	1.801	2.148	2.484	2.912
	M	14	0.139	0.198	0.263	0.355	1.801	2.148	2.484	2.916
0.4(1), 0.2(1), 0.1(4)	I		0.122	0.178	0.238	0.324	1.879	2.332	2.799	3.429
	S		0.135	0.186	0.242	0.324	1.885	2.335	2.794	3.420
	M	20	0.125	0.178	0.237	0.323	1.879	2.333	2.798	3.434
0.3(1), 0.2(1), 0.1(2), 0.05(6)	I		0.208	0.268	0.331	0.416	1.741	2.101	2.463	2.950
	S		0.213	0.270	0.330	0.413	1.741	2.096	2.454	2.937
	M	33	0.209	0.268	0.330	0.414	1.746	2.105	2.464	2.940
0.4(1), 0.1(3), 0.05(6)	I		0.199	0.257	0.317	0.398	1.786	2.228	2.630	3.336
	S		0.204	0.256	0.312	0.389	1.794	2.214	2.655	3.274
	M	40	0.201	0.258	0.317	0.398	1.787	2.229	2.694	3.334

$x > 0$. If (18.61) is actually a mixture representation, that is, $a_j \geq 0$ and $\sum_{j=0}^{\infty} a_j = 1$, then the truncated series (up to $J - 1$) will necessarily lie between 0 and 1, and the truncation error will be bounded above by

$$\left| \sum_{j=J}^{\infty} a_j F_{\chi^2_{\nu+2j}} \left(\frac{x}{\beta} \right) \right| \leq \left| 1 - \sum_{j=0}^{J-1} a_j F_{\chi^2_{\nu+2j}} \left(\frac{x}{\beta} \right) \right|. \tag{18.62}$$

If some a_j 's are negative, the truncation error will not necessarily satisfy (18.62).

Based on Ruben's formulas, Sheil and O'Muirheartaigh (1977) and Farebrother (1984a, b, c) have provided algorithms for determining the distribution of a linear combination of chi-square (not necessarily central) random variables. Following the lines of Imhof, Davies (1980) presented an algorithm for computing the distribution of a variable

$$Q = \sum_{i=1}^k c_i \chi_{\nu_i}^2(\delta_i^2) + \delta X_0, \quad (18.63)$$

where X_0 is an independent standard normal variable, by employing the method of numerical inversion of the characteristic function developed earlier by Davies (1973).

Field (1993) has recently used a uniform saddlepoint approximation to obtain extreme tail areas for a linear combination of independent chi-square variables. This approximation uses a transformation of the tail area coming out of the Fourier inversion of the characteristic function which yields a quadratic in the exponent. The Jacobian of the transformation, when expanded in a Taylor series, leads to this approximation. Field has displayed that the approximation is quite accurate in extreme tails.

Finally, mention should be made of the works of Charnet and Rathie (1985), Shirahata (1988), and Provost (1986), with the last author deriving the exact distribution of the ratio of a linear combination of χ^2 variables over the root of a product of χ^2 variables. Gordon and Ramig (1983) discussed the distribution of the sum of correlated χ^2 variables (components of a multivariate chi-square distribution), while Hanumara and Barry (1978) discussed the distribution of a difference between independent χ^2 variables.

9 RELATED DISTRIBUTIONS

As mentioned earlier in Section 1 and also in Chapter 17, χ_ν^2 distributions are special gamma distributions. In fact χ_ν^2 is distributed as gamma with shape parameter $\alpha = \nu/2$ and scale parameter $\beta = 2$. As pointed out in Sections 2 and 4, the chi-square distribution is also related to the Poisson distribution. Specifically, for even values of ν , the survival function of a χ_ν^2 distribution at x is same as the cumulative distribution function of a Poisson random variable (with mean $x/2$) at $(\nu/2) - 1$. It has also been seen earlier in Chapter 15 that chi-square distributions arise naturally in the decomposition of inverse Gaussian variates.

Just as the sum of squares of ν independent standard normal variables has a χ_ν^2 distribution, the sum of squares of ν independent $N(\mu_j, 1)$, $j =$

1, 2, ..., ν , variables has a *noncentral chi-square distribution with ν degrees of freedom and noncentrality parameter $\delta^2 = \sum_{j=1}^{\nu} \mu_j^2$* . Han (1975) has expressed the cdf of a noncentral chi-square distribution with **odd degrees** of freedom as functions of the cdf and pdf of the standard normal distribution. For more details and a discussion on this noncentral χ_{ν}^2 distribution, refer to Chapter 29. One may also similarly define noncentral chi distributions.

Dion and Fridshal (1982) published an interesting conjecture that relates the quantiles of two independent χ^2 random variables with the quantiles of an appropriate F distribution. Specifically, let $\chi_{\nu, (1+\gamma)/2}^2$ and $\chi_{\nu, (1-\gamma)/2}^2$ denote the lower $(1 + \gamma)/2$ and $(1 - \gamma)/2$ percentage points of χ_{ν}^2 distribution, that is, $\Pr[\chi_{\nu}^2 \leq \chi_{\nu, (1+\gamma)/2}^2] = (1 + \gamma)/2$ and $\Pr[\chi_{\nu}^2 \leq \chi_{\nu, (1-\gamma)/2}^2] = (1 - \gamma)/2$, for any $\gamma \in [0, 1)$. Similarly, let $\chi_{\nu', (1+\gamma)/2}^2$ and $\chi_{\nu', (1-\gamma)/2}^2$ denote the lower $(1 + \gamma)/2$ and $(1 - \gamma)/2$ percentage points of $\chi_{\nu'}^2$ distribution. Finally, let $F_{\nu', \nu, (1+\gamma)/2}$ and $F_{\nu', \nu, (1-\gamma)/2}$ denote the lower $(1 + \gamma)/2$ and $(1 - \gamma)/2$ percentage points of the F-distribution with (ν', ν) degrees of freedom. Then Dion and Fridshal (1982) conjectured the quantile inequalities

$$\begin{aligned}
 F_{\nu', \nu, (1-\gamma)/2} &\geq \frac{\chi_{\nu', (1-\gamma)/2}^2 / \nu'}{\chi_{\nu, (1+\gamma)/2}^2 / \nu}, \\
 F_{\nu', \nu, (1+\gamma)/2} &\leq \frac{\chi_{\nu', (1+\gamma)/2}^2 / \nu'}{\chi_{\nu, (1-\gamma)/2}^2 / \nu}.
 \end{aligned}
 \tag{18.63}'$$

Burk et al. (1984) proved the above conjecture for the case of equal degrees of freedom (i.e., $\nu = \nu'$). In this case they also proved that (18.63)' holds for a broader class of distributions than χ^2 and gave sufficient conditions on the density functions in order for (18.63)' to hold. It is also of interest to mention here that Burk et al., through numerical studies, showed that the conjecture in (18.63)' is false in some small interval $0 \leq \gamma < \gamma_0$ but holds in the interval $\gamma_0 \leq \gamma < 1$.

Ghosh (1973) proved some monotonicity theorems for χ^2 and related F-distributions. He then remarked that the adequacy of interpolation formulae for $\chi_{\nu, \epsilon}^2$ (discussed in Section 5) and $F_{\nu', \nu, \epsilon}$ can be judged by using his theorems regarding increasing or decreasing property of these quantities. Following this work, Sarkar (1983) proved that $\chi_{\nu, \epsilon}^2$ have the *log-concave* property in $\nu > 0$ for fixed $\epsilon \in (0, 1)$. He also proved that $F_{\nu', \nu, \epsilon}$ have the log-concave (*log-convex*) property in $\nu' > 0$ ($\nu > 0$) for fixed $\nu > 0$ ($\nu' > 0$) and $\epsilon \in (0, 1)$. Incidentally he also established that $\chi_{\nu, \epsilon}^2$ possess the *total positivity of order 2* property in (ν, ϵ) , and similarly the related $F_{\nu', \nu, \epsilon}$ possess the same property in both (ν, ϵ) and (ν', ϵ) . Sarkar (1980) has also derived similar results for the distribution functions of χ_{ν}^2 (central as well as **noncentral**) and $F_{\nu', \nu}$.

The distribution of the product (W) of two independent variables, distributed as $\chi_{\nu_1}^2$ and $\chi_{\nu_2}^2$ respectively, can be obtained from (17.110.b) as the

distribution of $4Y$ with $a_1 = \nu_1/2$ and $a_2 = \nu_2/2$. The resulting density of $W \stackrel{d}{=} \chi_{\nu_1}^2 \chi_{\nu_2}^2$ is given by

$$p_W(w) = \frac{1}{2^{\frac{1}{2}(\nu_1 + \nu_2) - 1} \Gamma(\nu_1/2) \Gamma(\nu_2/2)} y^{\frac{1}{2}(\nu_1 + \nu_2) - 1} K_{\frac{1}{2}(\nu_1 - \nu_2)}(\sqrt{w}),$$

$$w > 0, \quad (18.64)$$

where $K_g(h)$ is the modified Bessel function of the third kind.

The probability distribution of the distance from the origin to a point (Y_1, Y_2, \dots, Y_N) in N -dimensional Euclidean space, where the Y_i 's are normal variables gives rise to the generalized Rayleigh distribution. Specifically, when Y_i 's are i.i.d. $N(0, \sigma^2)$ variables, the probability density function of $X = \sqrt{\sum_{i=1}^N Y_i^2}$ is given by

$$p_X(x; N, \sigma) = \frac{2}{(2\sigma^2)^{N/2} \Gamma(N/2)} x^{N-1} e^{-x^2/(2\sigma^2)}, \quad x > 0, \sigma > 0.$$

$$(18.65)$$

This generalized form of the Rayleigh distribution is also referred in literature as the "chi distribution with N degrees of freedom and scale parameter σ ." The density function in (18.5) thus corresponds to the standard chi distribution ($\sigma = 1$) with ν degrees of freedom. The density function in (18.65) is unimodal and the mode is easily seen to be at $\sqrt{N-1}\sigma$. The k th moment of X is given by

$$E[X^k] = \frac{2}{(2\sigma^2)^{N/2} \Gamma(N/2)} \int_0^\infty e^{-x^2/(2\sigma^2)} x^{N+k-1} dx$$

$$= \frac{2^{k/2} \sigma^k \Gamma[(N+k)/2]}{\Gamma(N/2)}.$$

$$(18.66)$$

From the expression of the raw moment in (18.66), one may easily obtain the mean, variance, and the coefficients of skewness and kurtosis of the distribution in (18.65) for any specified value of N , the degrees of freedom. It is also clear from the form of the density function in (18.65) that for a fixed value of N , the distribution belongs to the one-parameter exponential family of distributions; further, based on a sample of size n , namely X_1, X_2, \dots, X_n , a sufficient statistic for σ is $\sum_{i=1}^n X_i^2$. The likelihood function based on this

sample is

$$L = \frac{2^n}{2^{Nn/2} \{\Gamma(N/2)\}^n \sigma^{Nn}} \left\{ \prod_{i=1}^n X_i^{N-1} \right\} e^{-\sum_{i=1}^n X_i^2 / (2\sigma^2)} \quad (18.67)$$

which immediately yields the maximum likelihood estimator of σ to be

$$\hat{\sigma} = \left\{ \frac{1}{Nn} \sum_{i=1}^n X_i^2 \right\}^{1/2}. \quad (18.68)$$

The special case of $N = 2$ in (18.65) is the Rayleigh density function, which has been studied quite extensively in the statistical and engineering literature. Due to its importance and also the great deal of attention it has received over the years, specific developments with regard to the Rayleigh distribution are described in some length in Section 10 of this chapter.

It should also be mentioned here that the function in (18.65), for the special case of $N = 1$, reduces to

$$\frac{1}{\sigma} \sqrt{\frac{2}{\pi}} e^{-x^2/(2\sigma^2)}, \quad x > 0, \sigma > 0,$$

which is the density function of a half-normal or folded normal random variable. This distribution is discussed in Chapter 13. Furthermore, for the special case of $N = 3$, (18.65) reduces to

$$\frac{2^{3/2}}{\sigma^3 \sqrt{\pi}} x^2 e^{-x^2/(2\sigma^2)}, \quad x > 0, \sigma > 0,$$

which is the density function known in the statistics and physics literatures as "Maxwell-Boltzmann density function." This distribution arises as the distribution of the magnitude of the velocity of a randomly chosen molecule of a gas in a closed container under the assumption that the gas is not flowing and that the pressure in the gas is the same in all directions. Classical estimation and tests of hypotheses for the parameter σ have been discussed by Iliescu and Vodă (1974). Tyagi and Bhattacharya (1989) have developed a Bayesian estimator of the average velocity and of the distribution function, under the squared error loss function.

It should be mentioned here that for the chi distribution in (18.65), with N being assumed to be known, estimation of the parameter σ has been considered by several authors. For example, Stacy and Mihram (1965) dis-

cussed the estimation based on a complete sample while Dyer (1973) considered the BLU estimation of \mathbf{a} based on k optimally selected quantiles for various choices of N . By considering the two-parameter form of the chi distribution with probability density function

$$p_X(x; N, \mu, \sigma) = \frac{2}{(2\sigma^2)^{N/2} \Gamma(N/2)} (x - \mu)^{N-1} e^{-(x-\mu)^2/(2\sigma^2)},$$

$$x > \mu, \sigma > 0, \quad (18.69)$$

Harter (1970) dealt with the maximum likelihood estimation of the parameters μ and \mathbf{a} based on complete and **Type II** censored samples. For this two-parameter chi distribution with N degrees of freedom, Hassanein, Saleh, and Brown (1989) worked out the asymptotic best linear unbiased estimators of μ and σ based on k optimally selected sample quantiles and presented the necessary tables of optimum spacings and the corresponding coefficients and the variances and covariance of these estimates for $N = 3(1)30$ and $k = 2(1)6$. Ali, Umbach, and Saleh (1992) recently carried out a similar study on the asymptotic linear estimation of life functions such as the quantile, survival and hazard functions.

Azzalini (1985) considered a random variable Z with density function

$$\phi(z; \lambda) = 2\Phi(\lambda z)\phi(z), \quad -\infty < z < \infty, \quad (18.70)$$

where $\phi(\cdot)$ and $\Phi(\cdot)$ are standard normal density and distribution functions, respectively. He called Z as a *skew-normal random variable with parameter A* . This density is related to the chi density in (18.5) as it can be shown that (18.70), in the limiting case of $A \rightarrow \infty$, tends to the half-normal density function which, as mentioned earlier, is a chi distribution with $\nu = 1$ degree of freedom.

Chi-bar-square distributions are simply mixtures of chi-square distributions, mixed over their degrees of freedom. They often arise when testing hypotheses that involve inequality constraints [Barlow et al. (1972)]. Suppose that $\{P_n\}$ is a sequence of probability distributions, each of which has support contained in the nonnegative integers and has nonzero finite mean μ_n and finite variance σ_n^2 . Then Y_n , the random variable having the chi-bar-square distribution associated with P_n , has its survival function to be

$$\Pr[Y_n > x] = \sum_{j=0}^{\infty} p_{n,j} \Pr[\chi_j^2 > x], \quad (18.71)$$

where $p_{n,j} = P_n(j)$. It may then be easily verified that

$$E[Y_n] = \sum_{j=0}^{\infty} p_{n,j} E[\chi_j^2] = \sum_{j=0}^{\infty} j p_{n,j} = \mu_n, \tag{18.72}$$

$$\begin{aligned} E[Y_n^2] &= \sum_{j=0}^{\infty} p_{n,j} E[(\chi_j^2)^2] = \sum_{j=0}^{\infty} (j^2 + 2j) p_{n,j} \\ &= \sigma_n^2 + \mu_n^2 + 2\mu_n, \end{aligned} \tag{18.73}$$

and consequently

$$\text{Var}(Y_n) = \sigma_n^2 + 2\mu_n. \tag{18.74}$$

Recently Dykstra (1991) has determined necessary and sufficient conditions on the distributions $\{P_n\}_{n=1}^{\infty}$ that will ensure that $Z_n = (Y_n - \mu_n)/(\sigma_n^2 + 2\mu_n)^{1/2}$ converges in distribution to the standard normal. Specifically, he has shown that the asymptotic normality occurs for the chi-bar-square distribution if either the ratio of the mean to the variance of the mixing distribution goes to ∞ or the weighting distribution itself is asymptotically normal; these are the only ways for asymptotic normality to hold, other than a combination of the two phenomena. As an example, if we consider the earlier described (see also Chapter 29) noncentral chi-square random variable $\chi_{\nu}^2(\delta^2)$, with ν degrees of freedom and δ^2 as **noncentrality** parameter, then we can write

$$\Pr[\chi_{\nu}^2(\delta^2) > x] = \sum_{i=0}^{\infty} p_i \left(\frac{\delta^2}{2} \right) \Pr[\chi_{2i+\nu}^2 > x], \tag{18.75}$$

where $p_i(\lambda)$ is the probability that a Poisson (λ) random variable takes on the value i (see Chapter 4). The weight distribution in (18.71) for this distribution will be that of $2X + \nu$ when X has a Poisson ($\delta^2/2$) distribution. Of course this weighting distribution has mean $S^2 + \nu$ and variance $2\delta^2$; also $2X + \nu$ is asymptotically normal as $\delta^2 \rightarrow \infty$. Hence we have the asymptotic normality of a noncentral chi-square distribution in the case when ν is fixed and $\delta^2 \rightarrow \infty$. This result will continue to hold even when ν is allowed to vary.

By considering the one-parameter exponential family of distributions with pdf [Barndorff-Nielsen (1978)]

$$f(x; \theta) = \exp[a(x)b(\theta) + c(\theta) + h(x)],$$

Rahman and Gupta (1993) called the subfamily, having $-2a(X)b(\theta)$ to be distributed as chi-square with appropriate degrees of freedom, as the family of *transformed* chi-square distributions. They show that a necessary and

sufficient condition for belonging to this subfamily is

$$\frac{2c'(\theta)b(\theta)}{b'(\theta)} = k,$$

where k is positive and free from θ . It may be easily verified that distributions like the normal, log-normal, gamma, exponential, Rayleigh, Pareto, **Weibull**, Erlang, inverse Gaussian, and Maxwell all (discussed in this volume) belong to this transformed chi-square family. Rahman and Gupta (1993) have also discussed some inference problems with regard to this family of distributions.'

10 SPECIFIC DEVELOPMENTS IN THE RAYLEIGH DISTRIBUTION

10.1 Historical Remarks

The Rayleigh distribution was originally derived by Lord Rayleigh (J. W. **Strutt**) (1880, 1919) in connection with a problem in the field of acoustics. Miller (1964) derived the Rayleigh distribution as the probability distribution of the distance from the origin to a point (Y_1, Y_2, \dots, Y_N) in N -dimensional Euclidean space, where the Y_i 's are independent and identically distributed $N(0, \sigma^2)$ variables. Siddiqui (1962) showed that the Rayleigh amplitude distribution (the distribution of the power or amplitude of electronic waves received through a scattering medium) is the asymptotic distribution of a two-dimensional random walk. Polovko (1968) noted that some types of electrovacuum devices have the feature that they age rapidly with time even though they may have no manufacturing defects. The **Rayleigh distribution** is quite appropriate for modeling the lifetimes of such units as it possesses a linearly increasing hazard rate [see (18.79)]. Quoting the early works of Hertz (1909) and Skellam (1952), Cliff and Ord (1975) point out the remarkable property that the Rayleigh distribution arises as the distribution of the distance between an individual and its nearest neighbor when the spatial pattern is generated by a Poisson process. Hirano (1986) has presented a brief account of the history and properties of this distribution.

10.2 Basic Properties

A Rayleigh random variable X has probability density function [with $N = 2$ from (18.65)]

$$p_X(x) = \frac{x}{\sigma^2} e^{-x^2/(2\sigma^2)}, \quad 0 \leq x < \infty, \sigma > 0, \quad (18.76)$$

cumulative distribution function

$$F_X(x) = 1 - e^{-x^2/(2\sigma^2)}, \quad 0 \leq x < \infty, \sigma > 0, \quad (18.77)$$

survival or reliability function

$$R_X(x) = 1 - F_X(x) = e^{-x^2/(2\sigma^2)}, \quad 0 \leq x < \infty, \sigma > 0, \quad (18.78)$$

and hazard function

$$h_X(x) = \frac{p_X(x)}{R_X(x)} = \frac{x}{\sigma^2}, \quad 0 \leq x < \infty, \sigma > 0. \quad (18.79)$$

The mean residual life or the life expectancy of a Rayleigh component is obtained from (18.78) as

$$e_x = \int_x^\infty \frac{R_X(u)}{R_X(x)} du = e^{x^2/(2\sigma^2)} \int_x^\infty e^{-u^2/(2\sigma^2)} du.$$

Raja Rao and Talwalker (1989) derived lower and upper bounds for this function e_x .

As mentioned earlier, it is the linearly increasing hazard or failure rate in (18.79) that makes the Rayleigh distribution a possible model for the lifetimes of components that age rapidly with time. From (18.78) we observe that for small enough values of x the reliability of a component having the Rayleigh distribution decreases with time more slowly than the reliability of a component having an exponential distribution (whose hazard rate is constant); see Chapter 19. However, for larger values of x the reliability of the Rayleigh component decreases with time more rapidly than in the case of an exponential component [see Kodlin (1967)].

It should be mentioned here that the Rayleigh survival function in (18.78) has been generalized by Bradley, Bradley, and Naftel (1984) who have studied a survival function of the form

$$R(t) = \exp\left\{-\mu(1 - e^{-\beta t})^v - \alpha_0 t - \alpha_1 t^2\right\}$$

which is appropriately referred to as the generalized Gompertz-Rayleigh model. This general model includes the Makeham-Gompertz model studied earlier by Bailey, Homer, and Summe (1977) and Bailey (1978) as a special case.

Plots of the density function $p_X(x)$ are presented for $\alpha = 0.5(0.5)3.0$ in Figure 18.5 and for $\alpha = 4.0(1.0)8.0$ in Figure 18.6. The case when $\alpha = 1$ is referred to as the standard Rayleigh density function.

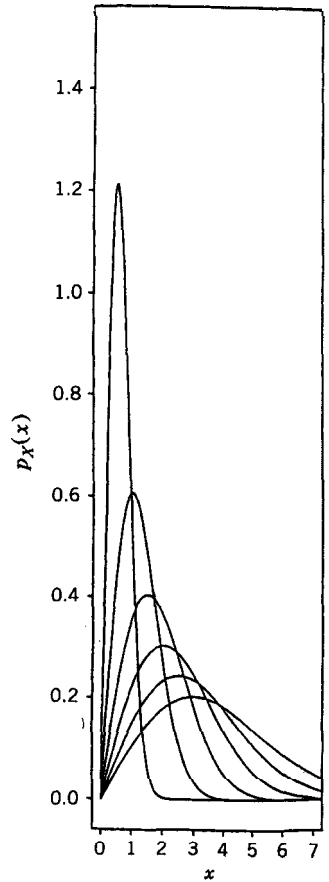


Figure 18.5 Rayleigh Densities for $a = 0.5(0.5)3.0$

From (18.76) and (18.77), it is readily noted that the mode of the distribution is at u [also see the comment after (18.65)] and that the p th percentile of the distribution is

$$x = F_X^{-1}(p) = \sigma \{-2 \log(1 - p)\}^{1/2}, \quad 0 < p < 1. \quad (18.80)$$

Further, the coefficient of variation of this distribution is $\sqrt{4\pi - 1}$ and the median of the distribution is $\sigma\sqrt{\log 4} \doteq 1.17741\sigma$. Furthermore we obtain immediately from (18.66) the r th raw moment of X to be

$$\mu'_r = E[X^r] = \sigma^r 2^{r/2} \Gamma\left(\frac{r}{2} + 1\right), \quad (18.81)$$

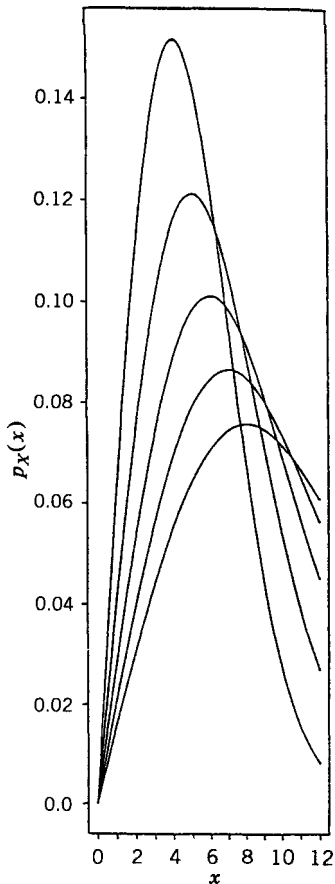


Figure 18.6 Rayleigh Densities for $\sigma = 4.0(1.0)8.0$

Equation (18.81) yields specifically the mean, variance and the coefficients of skewness and kurtosis of X to be

$$\text{Mean} = E[X] = \sigma\sqrt{\pi/2} \quad 1.25331\sigma,$$

$$\text{Variance} = \text{Var}(X) = \sigma^2(4 - \pi)/2 \doteq 0.42920\sigma^2,$$

$$\text{Skewness} = \sqrt{\beta_1(X)} = 2(\pi - 3)\sqrt{\pi}/(4 - \pi)^{3/2} = 0.63111,$$

$$\text{Kurtosis} = \beta_2(X) = (32 - 3\pi^2)/(4 - \pi)^2 \doteq 3.24509.$$

10.3 Order Statistics and Properties

Let X_1, X_2, \dots, X_n be random variables each having the Rayleigh distribution in (18.76). Let $X'_1 \leq X'_2 \leq \dots \leq X'_n$ denote the order statistics ob-

tained by arranging the above sample in increasing order of magnitude. Then Lieblein (1955) has shown that for $1 \leq r \leq n$,

$$\begin{aligned} E[X_r'] &= \frac{n!}{(r-1)!(n-r)!} \int_0^\infty \{1 - e^{-x^2/(2\sigma^2)}\}^{r-1} \{e^{-x^2/(2\sigma^2)}\}^{n-r+1} \frac{x^2}{\sigma^2} dx \\ &= \sigma \sqrt{\frac{\pi}{2}} \frac{n!}{(r-1)!(n-r)!} \sum_{i=0}^{r-1} \frac{(-1)^{r-1-i} \binom{r-1}{i}}{(n-i)^{3/2}} \end{aligned} \quad (18.82)$$

and

$$\begin{aligned} E[X_r'^2] &= \frac{n!}{(r-1)!(n-r)!} \int_0^\infty \{1 - e^{-x^2/(2\sigma^2)}\}^{r-1} \{e^{-x^2/(2\sigma^2)}\}^{n-r+1} \frac{x^3}{\sigma^2} dx \\ &= 2\sigma^2 \frac{n!}{(r-1)!(n-r)!} \sum_{i=0}^{r-1} \frac{(-1)^{r-1-i} \binom{r-1}{i}}{(n-i)^2}. \end{aligned} \quad (18.83)$$

Similarly Dyer and Whisenand (1973a) have shown that for $1 \leq r < s \leq n$,

$$\begin{aligned} E[X_r' X_s'] &= \frac{n!}{(r-1)!(s-r-1)!(n-s)!} \int_0^\infty \int_0^y \{1 - e^{-x^2/(2\sigma^2)}\}^{r-1} \\ &\quad \times \{e^{-x^2/(2\sigma^2)} - e^{-y^2/(2\sigma^2)}\}^{s-r-1} \{e^{-y^2/(2\sigma^2)}\}^{n-s+1} \frac{x^2 y^2}{\sigma^4} e^{-x^2/(2\sigma^2)} dx dy \\ &= \sigma^2 \frac{n!}{(r-1)!(s-r-1)!(n-s)!} \sum_{i=0}^{s-r-1} \sum_{j=0}^r (-1)^{i+j} \binom{s-r-1}{i} \binom{r-1}{j} \\ &\quad \times H(s-r-i+j, n-s+i+1), \end{aligned} \quad (18.84)$$

where the function $H(a, b)$ is defined as

$$H(a, b) = \int_0^\infty \int_0^y x^2 y^2 e^{-ax^2/2} e^{-by^2/2} dx dy, \quad a, b > 0. \quad (18.85)$$

Integration by parts immediately yields

$$H(a, b) = \int_0^\infty y^2 e^{-by^2/2} \left\{ -\frac{y}{a} e^{-ay^2/2} + \sqrt{\frac{\pi}{2a^3}} \operatorname{Erf} \left(\sqrt{\frac{a}{2}} y \right) \right\} dy,$$

where $\operatorname{Erf}(\cdot)$ denotes the error function (see Chapter 13). Now upon using the integral formulas

$$\int_0^\infty y^3 e^{-(a+b)y^2/2} dy = \frac{2}{(a+b)^2},$$

$$\int_0^\infty \operatorname{Erf} \left(\sqrt{\frac{a}{2}} y \right) e^{-by^2/2} y^2 dy = \sqrt{\frac{2}{\pi b^3}} \left\{ \frac{\pi}{2} - \tan^{-1} \sqrt{\frac{b}{a}} + \frac{\sqrt{ab}}{a+b} \right\}$$

[see Ng and Geller (1969)], we obtain

$$H(a, b) = \frac{1}{(ab)^{3/2}} \left\{ \frac{\pi}{2} - \tan^{-1} \sqrt{\frac{b}{a}} + \frac{\sqrt{ab}(a-b)}{(a+b)^2} \right\}. \quad (18.86)$$

As pointed out by Dyer and Whisenand (1973a), formula (18.84) can effectively be used along with formula (18.86) in computing the product moments of order statistics. It should be mentioned here that an alternate formula for the product moments in terms of the incomplete beta function was derived by Lieblein (1955); reference may also be made to Shoukri (1982).

10.4 Inference

Let X_1, X_2, \dots, X_n be a random sample from the Rayleigh population with probability density function as in (18.76). Let $X'_1 \leq \dots \leq X'_n$ be the corresponding order statistics. In this section we present the various results on inference for the parameter σ .

Best Linear Unbiased Estimation

Suppose that $X'_{r+1} \leq X'_{r+2} \leq \dots \leq X'_{n-s}$ is the available Type II censored sample, where the smallest r and the largest s observations were not observed due to experimental restrictions. Then, by using the generalized least-squares approach originally due to Aitken (1934) and Lloyd (1952), one may obtain the best linear unbiased estimator (BLUE) of the scale parameter

a of the Rayleigh distribution in (18.77) as

$$\sigma^* = \frac{\alpha^T \Sigma^{-1}}{\alpha^T \Sigma^{-1} \alpha} \mathbf{X} = \sum_{i=r+1}^{n-s} a_i X'_i, \quad (18.87)$$

where

$$\mathbf{X} = (X'_{r+1}, X'_{r+2}, \dots, X'_{n-s})^T,$$

$$\alpha = \frac{1}{\sigma} E[\mathbf{X}] \quad \text{and} \quad \Sigma = \frac{1}{\sigma^2} \text{Var}(\mathbf{X}).$$

Further the variance of the BLUE in (18.87) is

$$\text{Var}(\sigma^*) = \frac{\sigma^2}{\alpha^T \Sigma^{-1} \alpha}. \quad (18.88)$$

For details, one may refer to David (1981) and Balakrishnan and Cohen (1991). Dyer and Whisenand (1973a) have computed the coefficients a_i and $\text{Var}(\sigma^*)$ for n up to 15 and all possible choices of r and s (i.e., $r + s \leq n - 1$). Balakrishnan and Ambagaspitiya (1993) have recently tabulated the coefficients a_i and values of $\text{Var}(\sigma^*)/\sigma^2$ for n up to 30 for the case of right-censored samples ($r = 0$). These values are presented in Table 18.8 for sample sizes up to 10 with $r = 0$; the efficiency of a^* based on censored samples relative to the complete sample are also reported. More elaborate tables have also been presented by Adatia (1994).

It should be mentioned here that Hirai (1972) has used Downton's (1966) general approach to derive quadratic coefficients estimators for the two-parameter Rayleigh distribution. This method, applicable only for complete samples, is shown to yield highly efficient estimators even in the case of small sample sizes [also see Hirai (1976)].

Asymptotic Best Linear Unbiased Estimation

The asymptotic best linear unbiased estimate (ABLUE) of σ based on k optimally selected order statistics has been discussed by Dyer and Whisenand (1973b), Dyer (1973), and Cheng (1980). By following the steps of Ogawa (1951) [also see Balakrishnan and Cohen (1991)], these authors have shown that the ABLUE of σ based on the spacing $\{A_1, A_2, \dots, A_k\}$ is

$$\sigma^{**} = \sum_{i=1}^k b_i X'_{[n\lambda_i]+1}, \quad (18.89)$$

where

$$b_i = \frac{f_i}{K_2} \left\{ \frac{f_i \xi_i - f_{i-1} \xi_{i-1}}{\lambda_i - \lambda_{i-1}} - \frac{f_{i+1} \xi_{i+1} - f_i \xi_i}{\lambda_{i+1} - \lambda_i} \right\}, \quad i = 1, \dots, k,$$

$$K_2 = \sum_{i=1}^{k+1} \frac{(f_i \xi_i - f_{i-1} \xi_{i-1})^2}{\lambda_i - \lambda_{i-1}},$$

$$\xi_i = \{-2 \log(1 - \lambda_i)\}^{1/2} \quad \text{and} \quad f_i = \xi_i(1 - \lambda_i), \quad i = 1, 2, \dots, k,$$

with

$$\lambda_0 = 0, \lambda_{k+1} = 1, \quad \text{and} \quad f_0 \xi_0 = 0 = f_{k+1} \xi_{k+1}.$$

(Note that the λ_i 's do not depend on n .) Further the asymptotic variance of the ABLUE in (18.89) is

$$A \text{Var}(\sigma^{**}) = \frac{\sigma^2}{nK_2}. \quad (18.90)$$

From (18.90) it is readily seen that the spacing which maximizes K_2 is the optimal spacing. These optimal spacings have been numerically determined by Dyer and Whisenand (1973b), Dyer (1973), and Cheng (1980). It should be mentioned here that Cheng has shown that the optimal spacing $\{\lambda_i\}$ satisfies the relation

$$\lambda_i = 1 - \lambda_{k-i+1}^*, \quad i = 1, 2, \dots, k,$$

where $\{\lambda_i^*\}$ is the optimal spacing for the ABLUE μ^{**} (when \mathbf{a} is known) for the extreme-value distribution of the largest values determined earlier by Chan and Kabir (1969). An optimal t-test [based on σ^{**} in (18.89)] has also been proposed by Cheng (1980) for testing hypotheses regarding \mathbf{a} . In Table 18.9, the values of the optimal λ_i , the corresponding coefficients b_i , and K_2 are presented for k up to 10; Adatia (1994) has recently prepared tables of optimal BLUE based on k selected order statistics for sample sizes $n = 20(1)40$ and $k = 2(1)4$.

It is also of interest to mention here that D'Agostino and Lee (1975) have used the technique of Chernoff, Gastwirth and Johns (1967) to derive the ABLUE of \mathbf{a} based on Type II censored samples. They show that this estimator, in addition to having a simple closed form, possesses good efficiency even for samples as small as 5.

Table 18.8 Coefficients a_i of the BLUE of σ and Efficiency Relative to the BLUE Based on Complete Sample for $n = 2(1)10$, $r = 0$, and $s = 0(1)n - 2$

n	s	a_i	n	s	a_i	n	s	a_i	n	s	a_i	n	s	a_i	n	s	a_i						
2	0	0.24097			79.7%			32.3%			1.27394	8	4	0.05933			0.04781	10	0	0.02149			0.05739
		0.48534	5	2	0.09957	7	0	0.03655			27.7%			0.08793			0.06103			0.03171			0.06872
		100.0%			0.15151			0.05485	8	0	0.02996			0.11216			0.07351			0.04034			0.07982
3	0	0.13004			0.67477			0.07110			0.04464			0.74509			0.08604			0.04841			0.09114
		0.21305			59.3%			0.08739			0.05739			49.4%			0.09924			0.05641			0.44466
		0.35498	5	3	0.14600			0.10537			0.06977	8	5	0.07820			0.36983			0.06475			69.8%
		100.0%			1.03016			0.12799			0.08274			0.11540			77.6%			0.07388	10	4	0.03570
3	1	0.19180			39.0%			0.17785			0.09746			0.99106	9	3	0.03762			0.08457			0.05256
		0.71088	6	0	0.04599			100.0%			0.11634			36.8%			0.05565			0.09865			0.06668
		65.8%			0.06969	7	1	0.04261			0.15894	8	6	0.11440			0.07094			0.13149			0.07971
4	0	0.08434			0.09142			0.06390			100.0%			1.38007			0.08529			100.0%			0.09237
		0.13250			0.11434			0.08272	8	1	0.03422			24.1%			0.09952	10	1	0.02387			0.56855
		0.18370			0.14236			0.10145			0.05097	9	0	0.02514			0.49590			0.03522			59.7%
		0.28212			0.20229			0.12177			0.06549			0.03725			66.4%			0.04479	10	5	0.04268
		100.0%			100.0%			0.31934			0.07953			0.04761	9	4	0.04500			0.05373			0.06276

4	1	0.11181	6	1	0.05512	85.6%	0.09412	0.05745	0.06647	0.06258	0.07948					
		0.17429			0.08341	7	2	0.05103	0.11041	0.06743	0.08456	0.07176	0.09477			
		0.53470			0.10912	0.07640		0.28344	0.07816	0.10137	0.08174	0.08174	0.71543			
		<u>74.5%</u>			0.13579	0.09867		<u>87.4%</u>	0.09057	<u>0.64294</u>	0.09325		<u>49.5%</u>			
4	2	0.16426			0.36696	0.12049	8	2	0.03988	0.10672	<u>55.1%</u>	<u>0.23258</u>	10	6	0.05301	
		0.88430			83.1%	0.47254		0.05935	0.14384	9	5	0.05590	<u>90.0%</u>		0.07777	
		<u>49.0%</u>			0.06864	<u>71.1%</u>		0.07615	<u>100.0%</u>	0.08238	10	2	0.02685		0.09821	
5	0	0.06038			0.10354	7	3	0.06348	0.09228	9	1	0.02827	0.10448		0.03959	0.90085
		0.09279			0.13477	0.09478		0.10882	0.04189	<u>0.82629</u>		0.05033			<u>39.4%</u>	
		0.12404			0.55338	0.12187		0.41420	0.05351	<u>43.9%</u>		0.06033	10	7	0.06980	
		0.16048			<u>66.2%</u>	0.65522		<u>74.8%</u>	0.06453	9	6	0.07364	0.07019		0.10207	
		0.23520	6	3	0.09063	<u>56.6%</u>	8	3	0.04773	0.07566	0.10812	0.08036			<u>1.15721</u>	
		<u>100.0%</u>			0.13594	7	4	0.08373	0.07092	0.08755	<u>1.07720</u>	0.09127			<u>29.5%</u>	
5	1	0.07530			0.79308	0.12440		0.09079	0.10106	<u>32.6%</u>		0.33479	10	8	0.10203	
		0.11534			<u>49.3%</u>	0.89716		0.10964	0.25529	9	7	0.10768	<u>79.9%</u>		<u>1.57120</u>	
		0.15324	6	4	0.13274	<u>42.1%</u>		0.56289	<u>88.8%</u>	<u>1.47869</u>	10	3	0.03066		<u>19.3%</u>	
		0.43358			1.15833	7	5	0.12255	62.1%	9	2	0.03229	<u>21.4%</u>		0.04518	

Table 18.9 Optimum Spacings $\{\lambda_i\}$, Corresponding Coefficients b_i , and the Value of K_2 for the ABLUE σ^{**} (Complete Samples)

$k =$	2	3	4	5	6	7	8	9	10
λ_1	0.63853	0.52953	0.45143	0.39306	0.34790	0.31198	0.28274	0.25848	0.23805
λ_2	0.92655	0.82994	0.74192	0.66705	0.60421	0.55134	0.50651	0.46814	0.43500
λ_3		0.96545	0.90671	0.84336	0.78288	0.72769	0.67820	0.63407	0.59475
λ_4			0.98105	0.94338	0.89785	0.85062	0.80469	0.76138	0.72118
λ_5				0.98850	0.96308	0.92972	0.89286	0.85517	0.81818
λ_6					0.99250	0.97460	0.94959	0.92055	0.88965
λ_7						0.99484	0.98178	0.96262	0.93946
λ_8							0.99630	0.98649	0.97152
λ_9								0.99726	0.98971
λ_{10}									0.99791
b_1	0.37319	0.27489	0.21407	0.17305	0.14374	0.12191	0.10512	0.09187	0.08120
b_2	0.20462	0.21326	0.19429	0.17201	0.15167	0.13419	0.11942	0.10696	0.09640
b_3		0.10061	0.13013	0.13495	0.13040	0.12251	0.11376	0.10517	0.09714
b_4			0.05759	0.08501	0.09630	0.09920	0.09784	0.09440	0.09002
b_5				0.03628	0.05861	0.07084	0.07664	0.07856	0.07819
b_6					0.02443	0.04217	0.05356	0.06024	0.06371
b_7						0.01728	0.03139	0.04147	0.04814
b_8							0.01270	0.02402	0.03276
b_9								0.00962	0.01881
b_{10}									0.00747
K_2	3.28105	3.56419	3.70764	3.79029	3.84224	3.87702	3.90144	3.91924	3.93263

Maximum Likelihood Estimation

Based on a complete sample X_1, X_2, \dots, X_n of size n from the Rayleigh population with pdf as in (18.76), the likelihood function is [see (18.67)]

$$L(X_1, \dots, X_n; \sigma) = \frac{1}{\sigma^{2n}} \left\{ \prod_{i=1}^n X_i \right\} e^{-\sum_{i=1}^n X_i^2 / (2\sigma^2)} \quad (18.91)$$

from which we immediately obtain the maximum likelihood estimator (MLE) of σ as [see (18.68)]

$$\hat{\sigma} = \left\{ \frac{1}{2n} \sum_{i=1}^n X_i^2 \right\}^{1/2}. \quad (18.92)$$

Of course from (18.81) we can also propose a simple moment estimator for σ as $\bar{X}\sqrt{2/\pi}$. As Cohen and Whitten (1988) and Balakrishnan and Cohen (1991) point out, since $X_i^2 \sim \sigma^2 \chi_2^2$ ($i = 1, \dots, n$), $2n\hat{\sigma}^2/\sigma^2$ has a chi-square distribution with $2n$ degrees of freedom. By making use of this exact

distributional result, we can construct a $100(1 - \alpha)\%$ confidence interval for σ as

$$\left(\sqrt{\frac{2n\hat{\sigma}^2}{\chi_{2n, 1-\frac{\alpha}{2}}^2}}, \sqrt{\frac{2n\hat{\sigma}^2}{\chi_{2n, \frac{\alpha}{2}}^2}} \right), \tag{18.93}$$

where $\chi_{2n, \frac{\alpha}{2}}^2$ and $\chi_{2n, 1-\frac{\alpha}{2}}^2$ are respectively the lower and upper $\frac{\alpha}{2}$ percentage points of the chi-square distribution with $2n$ degrees of freedom. Further, since the Rayleigh density in (18.76) belongs to the general exponential family of distributions, it immediately follows from (18.91) that $\sum_{i=1}^n X_i^2$ is both complete and sufficient, and that the MLE of σ^2 given by $\sum_{i=1}^n X_i^2 / (2n)$ is unbiased and also the uniformly minimum variance unbiased estimator (UMVUE) of σ^2 . Now upon using the fact that $2n\hat{\sigma}^2 / \sigma^2 \sim \chi_{2n}^2$ and the asymptotic expansion $\Gamma(x + a) / \Gamma(x) \approx x^a [1 + (a^2 + a) / (2x)]$, as done by Sinha and Howlader (1983), the MLE $\hat{\sigma}$ in (18.92) can be shown to be asymptotically unbiased for σ . This fact can alternatively be verified by using Kendall, Stuart, and Ord's (1991) series expression for the mean of the chi distribution; for example, refer to Balakrishnan and Cohen (1991, p. 143).

Furthermore it is easily observed that the MLE of the reliability function $R_X(t)$ in (18.78) is given by

$$\hat{R}_X(t) = \exp \left\{ \frac{-nt^2}{\sum_{i=1}^n X_i^2} \right\}.$$

Also, following Basu (1964), we have the UMVUE of $R_X(t)$ as

$$\tilde{R}_X(t) = \begin{cases} \left(1 - \frac{t^2}{\sum_{i=1}^n X_i^2} \right)^{n-1} & \text{for } 0 \leq t < \sqrt{\sum_{i=1}^n X_i^2}, \\ 0 & \text{for } t \geq \sqrt{\sum_{i=1}^n X_i^2}. \end{cases}$$

It is of interest to note here that

$$\lim_{n \rightarrow \infty} \tilde{R}_X(t) = \lim_{n \rightarrow \infty} \left(1 - \frac{t^2}{\sum_{i=1}^n X_i^2} \right)^{n-1} = \exp \left\{ \frac{-nt^2}{\sum_{i=1}^n X_i^2} \right\} = \hat{R}_X(t).$$

Hence the UMVUE of the reliability function $R_X(t)$ tends asymptotically to the MLE.

Suppose that the available sample is singly right censored at time T . That is, out of a total of N items placed on test n are completely observed ($\leq T$) and c are censored ($> T$) so that $N = n + c$. Note that T is a fixed constant

in the case of Type I censoring and that $T = X'_n$ in the case of **Type II** censoring. For samples of this type the MLE of σ may be explicitly derived to be [Cohen and **Whitten (1988)**]

$$\hat{\sigma} = \left\{ \frac{\sum_{i=1}^n X_i'^2 + cT^2}{2n} \right\}^{1/2}. \quad (18.94)$$

Suppose that the independent sample X_i , $i = 1, 2, \dots, n$, arises from a singly right-truncated Rayleigh distribution (truncated at $x = T$). That is, the sample consists of n random observations each of which is in the time interval $[0, T]$. Then, by introducing the unknown parameter $T_0 = T/\sigma$, Cohen and **Whitten (1988)** have shown that the MLE of T_0 satisfies the equation

$$J_2(\hat{T}_0) = \frac{1}{nT^2} \sum_{i=1}^n X_i^2, \quad (18.95)$$

where

$$J_2(z) = \frac{2}{z^2} - \frac{\phi(z)}{\phi(0) - \phi(z)}; \quad (18.96)$$

$\phi(\cdot)$ is the pdf of the standard normal distribution. To facilitate the calculation of \hat{T}_0 and hence of $\hat{\sigma}$ ($= T/\hat{T}_0$), Cohen and **Whitten (1988)** presented tables and a graph of the function $J_2(z)$ [see also Balakrishnan and Cohen (1991, p. 142)]. A graph of the function $J_2(z)$ is presented here in Figure 18.7. To use this method of estimation in a practical situation, we first need

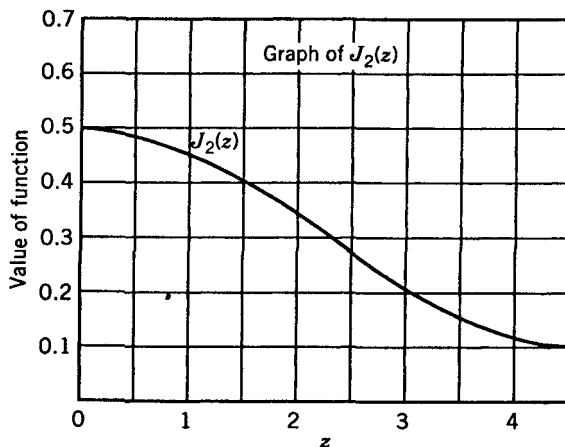


Figure 18.7 Graph of the Function $J_2(z)$ in (18.96) for the Determination of the MLE of σ in the Singly Right-Truncated Rayleigh Distribution

to find the value of $J_2(\hat{T}_0)$ in (18.95) from the observed data, read the corresponding value of \hat{T}_0 from Figure 18.7, and then determine the MLE of σ as $\hat{\sigma} = T/\hat{T}_0$.

It should be mentioned here that by considering a doubly Type II censored sample $X'_{r+1} \leq X'_{r+s} \leq \dots \leq X'_{n-s}$ from (18.76) (with r smallest and s largest observations censored from a sample of size n), Lee, Kapadia, and Brock (1980) derived the modified maximum likelihood estimator of the parameter u . Specifically, by considering the likelihood function

$$L = \frac{n!}{r!s!\sigma^{n-r-s}} \{F(z_{r+1})\}^r \{1 - F(z_{n-s})\}^s \prod_{i=r+1}^{n-s} p(z_i) \quad (18.97)$$

and the likelihood equation for σ given by

$$\frac{d \log L}{d\sigma} = -\frac{1}{\sigma} \left[2(n - r - s) + rz_{r+1} \frac{p(z_{r+1})}{F(z_{r+1})} - sz_{n-s} \frac{p(z_{n-s})}{1 - F(z_{n-s})} - \sum_{i=r+1}^{n-s} z_i^2 \right] = 0, \quad (18.98)$$

where $z_i = X'_i/\sigma$ are the standardized order statistics and $p(z)$ and $F(z)$ are the standard pdf and cdf given by

$$p(z) = ze^{-z^2/2} \quad \text{for } z > 0,$$

$$F(z) = 1 - e^{-z^2/2} \quad \text{for } z > 0,$$

Lee, Kapadia, and Brock (1980) derived a modified maximum likelihood estimator for a by approximating the likelihood equation in (18.98). Upon using the linear approximation

$$g(z_{r+1}) = \frac{p(z_{r+1})}{F(z_{r+1})} = \frac{z_{r+1}e^{-z_{r+1}^2/2}}{1 - e^{-z_{r+1}^2/2}} \approx \alpha + \beta z_{r+1}, \quad (18.99)$$

where α and β are such that

$$\beta = \frac{g(h_2) - g(h_1)}{h_2 - h_1} \quad \text{and} \quad \alpha = g(h_1) - h_1\beta, \quad (18.100)$$

with h_1 and h_2 being chosen so that

$$h_1 = F^{-1} \left\{ \frac{r}{n} - \sqrt{\frac{1}{n} \binom{r}{n} \binom{n-r}{n}} \right\},$$

$$h_2 = F^{-1} \left\{ \frac{r}{n} + \sqrt{\frac{1}{n} \binom{r}{n} \binom{n-r}{n}} \right\},$$

Lee, Kapadia, and Brock (1980) derived the modified maximum likelihood estimator for α to be

$$\hat{\sigma} = \frac{1}{2G} \left\{ -D + \sqrt{D^2 + 4GB} \right\}, \quad (18.101)$$

where

$$G = 2(n - r - s),$$

$$D = r\alpha X'_{r+1},$$

$$B = r\beta X'^2_{r+1} + X'^2_{n-s} + \sum_{i=r+1}^{n-s} X_i'^2.$$

These results have been reported by Tiku, Tan, and Balakrishnan (1986) (with an algebraic error). It is of interest to mention here that Lee, Kapadia, and Brock (1980) also suggested an estimator based on linear approximation twice in order to achieve greater accuracy in the approximation in case of small sample sizes.

Based on a complete sample X_1, X_2, \dots, X_n from a two-parameter Rayleigh population with pdf,

$$p_X(x) = \frac{x - \mu}{\sigma^2} e^{-(x-\mu)^2/(2\sigma^2)}, \quad x \geq \mu, \sigma > 0, \quad (18.102)$$

we have the likelihood function as

$$L(X_1, \dots, X_n; \mu, \sigma) = \frac{1}{\sigma^{2n}} \prod_{i=1}^n (X_i - \mu) e^{-\sum_{i=1}^n (X_i - \mu)^2 / (2\sigma^2)}, \quad (18.103)$$

from which the likelihood equations for σ and μ are immediately obtained as

$$\frac{\partial \log L}{\partial \sigma} = -\frac{2n}{\sigma} + \frac{1}{\sigma^3} \sum_{i=1}^n (X_i - \mu)^2 = 0 \quad (18.104)$$

and

$$\frac{\partial \log L}{\partial \mu} = -\sum_{i=1}^n \left\{ \frac{1}{X_i - \mu} \right\} + \frac{1}{\sigma^2} \sum_{i=1}^n (X_i - \mu) = 0. \quad (18.105)$$

Upon writing (18.104) as

$$\hat{\sigma}^2 = \frac{1}{2n} \sum_{i=1}^n (X_i - \hat{\mu})^2 \quad (18.106)$$

and then eliminating σ^2 from (18.105), we obtain the likelihood equation for μ as

$$\frac{n(\bar{X} - \hat{\mu})}{\sum_{i=1}^n [1/(X_i - \hat{\mu})]} - \frac{1}{2n} \sum_{i=1}^n (X_i - \hat{\mu})^2 = 0. \tag{18.107}$$

As mentioned by Balakrishnan and Cohen (1991, pp. 140-141), one may solve for $\hat{\mu}$ iteratively from (18.107) and then determine $\hat{\sigma}$ from (18.106).

From (18.81) we can also employ the estimating equations $E[X] = \bar{X}$ (the sample mean) and $\text{Var}(X) = s^2$ (the sample variance) and derive simple moment estimators for α and μ as $\hat{\sigma} = s\sqrt{2/(4 - \pi)}$ and $\hat{\mu} = \bar{X} - \hat{\sigma}\sqrt{\pi}/2$. Alternatively, we can employ the estimating equations $E[X'_1] = X'_1$ and $E[X] = \bar{X}$ and derive the following modified moment estimators [see Balakrishnan and Cohen (1991) for more details] for α and μ as

$$\hat{\sigma} = \frac{\bar{X} - X'_1}{\sqrt{\pi/2} - \sqrt{\pi/2n}} \quad \text{and} \quad \hat{\mu} = \bar{X} - \hat{\sigma} \sqrt{\frac{\pi}{2}}. \tag{18.108}$$

Bayesian Estimation

Let us consider the one-parameter Rayleigh distribution with pdf as in (18.76). In situations where very little is known about the parameter α of interest, it is customary to use Jeffreys's (1961) noninformative (or vague) prior

$$g(\sigma) \propto |I(\sigma)|^{1/2} = \frac{1}{\sigma} \tag{18.109}$$

[since $I(\sigma) = E\{- (d^2/d\sigma^2)\log p_X(x|\sigma)\} = 1/\sigma^2$ is the Fisher's information based on a single observation] due to its invariance under parametric transformations [see Box and Tiao (1973)]. Combining the likelihood function in (18.91) with the vague prior in (18.109), we obtain the posterior density of σ as

$$\Pi(\sigma|\mathbf{X}) = \frac{2(\frac{1}{2}\sum_{i=1}^n X_i^2)^n}{\Gamma(n)\sigma^{2n+1}} e^{-\sum_{i=1}^n X_i^2/(2\sigma^2)} \tag{18.110}$$

In estimating a parameter, the squared-error loss function can be used when decisions become gradually more damaging for larger error. Under this squared-error loss function, as shown by Sinha and Howlader (1983), the Bayesian estimator of α is the mean of the posterior density in (18.110) and

is given by

$$\hat{\sigma}_B = E[\sigma|\mathbf{X}] = \frac{\Gamma(n - \frac{1}{2})}{\sqrt{2}\Gamma(n)} \left\{ \sum_{i=1}^n X_i^2 \right\}^{1/2}. \quad (18.111)$$

Note that the Bayesian estimator $\hat{\sigma}_B$ in (18.111) tends to the MLE $\hat{\sigma}$ in (18.92) as $n \rightarrow \infty$.

Similarly the posterior density of σ^2 is

$$\Pi(\sigma^2|\mathbf{X}) = \frac{\left(\frac{1}{2}\sum_{i=1}^n X_i^2\right)^n}{\Gamma(n)(\sigma^2)^{n+1}} e^{-\sum_{i=1}^n X_i^2/(2\sigma^2)} \quad (18.112)$$

from which the Bayesian estimator of σ^2 , under the squared-error loss function, may be obtained as

$$(\hat{\sigma}^2)_B = \frac{1}{2n - 2} \sum_{i=1}^n X_i^2. \quad (18.113)$$

For large n , the Bayesian estimator of σ^2 in (18.113) becomes $\sum_{i=1}^n X_i^2/(2n)$, which is the MLE of σ^2 .

Next, upon substituting $\sigma^2 = t^2/\{-2\log(R_X(t))\}$ in (18.112), we obtain the posterior density of the reliability function $R_X(t)$ as

$$\begin{aligned} \Pi(R_X(t)|\mathbf{X}) &= \frac{\left[(1/t^2)\sum_{i=1}^n X_i^2\right]^n}{\Gamma(n)} (R_X(t))^{(1/t^2)\sum_{i=1}^n X_i^2 - 1} \\ &\times \{-\log(R_X(t))\}^{(n-1)/2}, \quad 0 < R_X(t) < 1, \quad (18.114) \end{aligned}$$

from which the Bayesian estimator of $R_X(t)$, under the squared-error loss function, is obtained as

$$\overline{(R_X(t))}_B = E[R_X(t)|\mathbf{X}] = \left(1 + \frac{t^2}{\sum_{i=1}^n X_i^2}\right)^{-n/2}. \quad (18.115)$$

It is easy to note that the Bayesian estimator $\overline{(R_X(t))}_B$ in (18.115) tends to the MLE $\hat{R}_X(t) = \exp\{-nt^2/\sum_{i=1}^n X_i^2\}$.

Proceeding in a similar manner, **Sinha** and Howlader (1983) obtained the posterior density of the hazard function $h_X(t)$ in (18.79) to be

$$\Pi(h_X(t)|\mathbf{X}) = \frac{(\frac{1}{2}\sum_{i=1}^n X_i^2)^n}{\Gamma(n)t^n} (h_X(t))^{n-1} e^{-(1/2t)h_X(t)\sum_{i=1}^n X_i^2}, \quad 0 < h_X(t) < \infty, \tag{18.116}$$

and the Bayesian estimator of $h_X(t)$, under the squared-error loss function, to be

$$\widehat{(h_X(t))}_B = E[h_X(t)|\mathbf{X}] = \frac{2nt}{\sum_{i=1}^n X_i^2} \tag{18.117}$$

which is exactly the same as the MLE of $h_X(t)$.

Sinha and Howlader (1983) also developed Bayesian intervals for the parameter α . Since $\sum_{i=1}^n X_i^2/\sigma^2$ has a chi-square distribution with $2n$ degrees of freedom, the interval in (18.93) simply becomes the $100(1 - \alpha)\%$ equal-tail credible interval for α [Edwards, Lindman, and Savage (1963)]. After observing that the posterior density of α in (18.110) is unimodal, the highest posterior density interval (H_L, H_U) of α satisfies the following two equations simultaneously:

$$\Pr\left[\frac{\sum_{i=1}^n X_i^2}{H_U^2} \leq \chi_{2n}^2 \leq \frac{\sum_{i=1}^n X_i^2}{H_L^2}\right] = 1 - \alpha, \tag{18.118}$$

$$e^{-\sum_{i=1}^n X_i^2[(1/H_L^2) - (1/H_U^2)]/2} = \left(\frac{H_L}{H_U}\right)^{2n+1}. \tag{18.119}$$

Similarly, by noting from the posterior density of $R_X(t)$ in (18.114) that $-2\sum_{i=1}^n X_i^2 \log(R_X(t))/t^2$ has a chi-square distribution with $2n$ degrees of freedom, the highest posterior density interval $(H_L(t), H_U(t))$ of the reliability $R_X(t)$ satisfies the following two equations simultaneously:

$$\Pr\left[-\frac{2}{t^2} \sum_{i=1}^n X_i^2 \log(H_U(t)) \leq \chi_{2n}^2 \leq -\frac{2}{t^2} \sum_{i=1}^n X_i^2 \log(H_L(t))\right] = 1 - \alpha, \tag{18.120}$$

$$\left\{\frac{\log(H_U(t))}{\log(H_L(t))}\right\}^{n-1} = \left\{\frac{H_L(t)}{H_U(t)}\right\}^{(1/t^2)\sum_{i=1}^n X_i^2 - 1}. \tag{18.121}$$

Mention has to be made of the work of Ariyawansa and Templeton (1984) who considered the problem of statistical inference on the parameter α

based on a doubly Type II censored sample using **Fraser's** (1968) structural inference approach. Mention should also be made to **Bühler** (1983), **Corotis**, **Sigl**, and **Klein** (1978), and **Barros and Estevan** (1983) who have implemented methods of estimation and fitted Rayleigh distributions in some practical situations. While the first paper introduced the Rayleigh distribution in the analysis of blurred photographs due to camera shake, the last two papers make use of the Rayleigh distribution in the evaluation of wind power from short wind records.

10.5 Prediction

When X has a one-parameter Rayleigh distribution with density as in (18.761), then it is easy to see that X^2 has a one-parameter exponential distribution (since $X^2 \sim \sigma^2 \chi_2^2$). Due to this fact, some of the known results on the prediction limits and prediction intervals in the one-parameter exponential distribution can be suitably adopted for the Rayleigh distribution. Specifically the prediction problems that are of interest are of the following types [**Aitchison and Dunsmore** (1975)]:

1. After observing the first r failure times out of n items placed on a lifetest, one wants to construct a prediction interval for X'_s , the s th failure time, for $r < s \leq n$.
2. After observing a sample size n (or even a Type II censored sample), one may be interested in constructing a prediction interval for failure times from a "future sample" of items to be placed on a life test.

Balakrishnan and Ambagaspitiya (1993) and **Raqab** (1992) discussed the prediction problems for the Rayleigh distribution in great detail. While the former discusses prediction based on the BLUE discussed in Section 10.4.1, the latter discusses predictors based on maximum likelihood method, conditional median approach, and linear method; it also compares these various predictors through Monte Carlo simulations.

Howlader (1985) constructed prediction intervals for problem (2) from the Bayesian viewpoint. Given the data X , with the posterior density of σ as in (18.110), we have the conditional joint density of a future independent observation y and σ as

$$\begin{aligned} h(y, \sigma | \mathbf{X}) &= f(y | \sigma, \mathbf{X}) \Pi(\sigma | \mathbf{X}) \\ &= f(y | \sigma) \Pi(\sigma | \mathbf{X}) \quad \text{since } y \text{ is independent of } X \\ &= \frac{y}{\sigma^2} e^{-y^2/(2\sigma^2)} \frac{2 \left(\frac{1}{2} \sum_{i=1}^n X_i^2 \right)^n}{\Gamma(n) \sigma^{2n+1}} e^{-\sum_{i=1}^n X_i^2 / (2\sigma^2)}. \end{aligned} \quad (18.122)$$

Integrating out σ in (18.122), we obtain the predictive density of y to be

$$\Pi(y|\mathbf{X}) = \frac{2ny(\sum_{i=1}^n X_i^2)^n}{(y^2 + \sum_{i=1}^n X_i^2)^{n+1}}, \quad (18.123)$$

from which it is easy to see that y^2 has a beta distribution of the second kind. Under the squared-error loss function, the Bayesian predictive estimator of y is simply

$$\hat{y}_B = E[y|\mathbf{X}] = \frac{\sqrt{\pi}\Gamma(n - \frac{1}{2})}{2\Gamma(n)} \left(\sum_{i=1}^n X_i^2 \right)^{1/2}. \quad (18.124)$$

From (18.93), Howlader (1985) also derived the $100(1 - \alpha)\%$ highest posterior density prediction interval (c_1, c_2) for y to be the simultaneous solution of

$$\left(\frac{\sum_{i=1}^n X_i^2}{c_1^2 + \sum_{i=1}^n X_i^2} \right)^n - \left(\frac{\sum_{i=1}^n X_i^2}{c_2^2 + \sum_{i=1}^n X_i^2} \right)^n = 1 - \alpha, \quad (18.125)$$

$$\left(\frac{c_2^2 + \sum_{i=1}^n X_i^2}{c_1^2 + \sum_{i=1}^n X_i^2} \right)^{n+1} = \frac{c_2}{c_1}. \quad (18.126)$$

It should also be added here that Howlader (1985) further discussed the prediction of the k th order statistic y'_k from a future sample of m observations. Sinha (1990) developed Bayesian prediction limits for a future independent observation y under the asymptotically locally invariant prior due to Hartigan (1964) which assigns a prior distribution for σ as $g(\sigma)$ and satisfies the equation

$$\frac{d}{d\sigma} \log g(\sigma) = - \frac{E(I_1 I_2)}{E(I_2)}, \quad (18.127)$$

where $I_i = (d^i/d\sigma^i) \log f(x|\sigma)$ if $E(I_1) = 0$ and $E(I_1^2) + E(I_2) = 0$; for the case of the Rayleigh distribution in (18.76), it yields the prior $g(\sigma)$ a $1/\sigma^3$.

10.6 Record Values and Related Issues

Distributions and Moments

Let $X_{U(1)}, X_{U(2)}, \dots$ be the upper record values arising from a sequence $\{X_i\}$ of independent and identically distributed Rayleigh random variables with pdf and cdf as in (18.76) and (18.77), respectively. Balakrishnan and Chan (1993) have studied the properties of record values and also discussed some related issues. Let us denote $E[X_{U(n)}^k]$ by $\alpha_n^{(k)}$, $E[X_{U(m)}X_{U(n)}]$ by $\alpha_{m,n}$,

$\text{Var}(X_{U(n)})$ by $\Sigma_{n,n}$, and $\text{Cov}(X_{U(m)}, X_{U(n)})$ by $\Sigma_{m,n}$. Then for $n \geq 1$ and $k \geq 0$ we obtain

$$\begin{aligned} \alpha_n^{(k)} &= \frac{1}{\Gamma(n)} \int_0^\infty x^k \{-\log(1 - F_X(x))\}^{n-1} p_X(x) dx \\ &= \frac{1}{\Gamma(n)} \int_0^\infty x^k \left(\frac{x^2}{2\sigma^2}\right)^{n-1} \times \frac{x}{\sigma^2} e^{-x^2/(2\sigma^2)} \\ &= \frac{\sigma^k 2^{k/2} \Gamma\left[n + \frac{k}{2}\right]}{\Gamma(n)}. \end{aligned} \quad (18.128)$$

Similarly we obtain for $1 \leq m < n$,

$$\begin{aligned} \alpha_{m,n} &= \frac{1}{\Gamma(m)\Gamma(n-m)} \int_0^\infty \int_0^y xy \left(\frac{x^2}{2\sigma^2}\right)^{m-1} \frac{x}{\sigma^2} \left(\frac{y^2}{2\sigma^2} - \frac{x^2}{2\sigma^2}\right)^{n-m-1} \\ &\quad \times \frac{y}{\sigma^2} e^{-y^2/(2\sigma^2)} dx dy \\ &= 2\sigma^2 \frac{\Gamma(m + \frac{1}{2})\Gamma(n+1)}{\Gamma(m)\Gamma(n + \frac{1}{2})}. \end{aligned} \quad (18.129)$$

From (18.128) and (18.129), for example, we get

$$\alpha_n = E[X_{U(n)}] = \frac{\sigma\sqrt{2}\Gamma(n + \frac{1}{2})}{\Gamma(n)}, \quad (18.130)$$

$$\Sigma_{n,n} = \text{Var}(X_{U(n)}) = 2\sigma^2 \left\{ n - \left(\frac{\Gamma(n + \frac{1}{2})}{\Gamma(n)} \right)^2 \right\}, \quad (18.131)$$

$$\Sigma_{m,n} = \text{Cov}(X_{U(m)}, X_{U(n)}) = 2\sigma^2 \frac{\Gamma(m + \frac{1}{2})}{\Gamma(m)} \left\{ \frac{\Gamma(n+1)}{\Gamma(n + \frac{1}{2})} - \frac{\Gamma(n + \frac{1}{2})}{\Gamma(n)} \right\}. \quad (18.132)$$

These results can be used to develop some inference procedures based on record values, as demonstrated by Balakrishnan and Chan (1993).

Estimation

Suppose the first n upper record values from the Rayleigh population are available. Then, by proceeding along the lines in Section 10.4 and denoting

$$\mathbf{X} = (X_{U(1)}, X_{U(2)}, \dots, X_{U(n)})^T,$$

$$\mathbf{a} = \frac{1}{\sigma}(\alpha_1, \alpha_2, \dots, \alpha_n)^T \quad \text{and} \quad \Sigma = \frac{1}{\sigma^2}(\alpha_i \alpha_j)_{i,j=1}^n,$$

we derive the best linear unbiased estimator (BLUE) of the scale parameter σ of the Rayleigh distribution as

$$\sigma^* = \frac{\mathbf{a}^T \Sigma^{-1}}{\mathbf{a}^T \Sigma^{-1} \mathbf{a}} \mathbf{X} = \sum_{i=1}^n c_i X_{U(i)} \quad (18.133)$$

and its variance as

$$\text{Var}(\sigma^*) = \frac{\sigma^2}{\mathbf{a}^T \Sigma^{-1} \mathbf{a}}. \quad (18.134)$$

By noting that $\Sigma_{i,j}$ is of the specific form $p_i q_j$ (for $i \leq j$), and that therefore the matrix Σ is invertible and its inverse a simple tridiagonal matrix, **Balakrishnan** and Chan (1993) have simplified the expression in (18.133) in order to derive the BLUE as

$$\sigma^* = \frac{\Gamma(n)}{\sqrt{2} \Gamma(n + \frac{1}{2})} X_{U(n)} \quad (18.135)$$

and its variance to be

$$\text{Var}(\sigma^*) = \sigma^2 \left\{ \frac{n \Gamma^2(n)}{\Gamma^2(n + \frac{1}{2})} - 1 \right\}. \quad (18.136)$$

Based on the first n upper record values, the likelihood function is then given by

$$L = \frac{p_X(x_1)}{1 - F_X(x_1)} \frac{p_X(x_2)}{1 - F_X(x_2)} \cdots \frac{p_X(x_{n-1})}{1 - F_X(x_{n-1})} p_X(x_n)$$

$$= \left(\prod_{i=1}^n x_i \right) \sigma^{-2n} e^{-x_i^2/(2\sigma^2)}, \quad 0 \leq x_1 < x_2 < \cdots < x_n < \infty. \quad (18.137)$$

Equation (18.137) yields the maximum likelihood estimator of σ as

$$\hat{\sigma} = \frac{1}{\sqrt{2n}} X_{U(n)} \quad (18.138)$$

and its variance is given by

$$\text{Var}(\hat{\sigma}) = \sigma^2 \left\{ 1 - \frac{\Gamma^2(n + \frac{1}{2})}{n\Gamma^2(n)} \right\}. \quad (18.139)$$

Since $\lim_{n \rightarrow \infty} n^{-1/2}[\Gamma(n + \frac{1}{2})/\Gamma(n)] = 1$ [e.g., Abramowitz and Stegun (1973, p. 257)], it is quite clear from (18.135) and (18.138) that the BLUE and the MLE are asymptotically identical.

Prediction

Suppose the first m upper records $X_{U(1)}, \dots, X_{U(m)}$ have been observed. Then the BLU predicted value of the n th record $X_{U(n)}$, $n \geq m + 1$, is given by

$$X_{U(n)}^* = \frac{\Gamma(m)}{\Gamma(m + \frac{1}{2})} \frac{\Gamma(n + \frac{1}{2})}{\Gamma(n)} X_{U(m)}. \quad (18.140)$$

We can also construct a prediction interval for $X_{U(n)}$ by considering the pivotal quantity

$$T_{m,n} = \sqrt{2} \frac{\Gamma(m + \frac{1}{2})}{\Gamma(m)} \left\{ \frac{X_{U(n)}}{X_{U(m)}} - 1 \right\} \quad (18.141)$$

Since $X^2/(2\sigma^2) \sim \chi_2^2/2$ is distributed as a standard exponential random variable, we can show that $X_{U(m)}^2/X_{U(n)}^2$ is distributed as a **beta**($m, n - m$) variate [see Chapter 25 and Dunsmore (1983)]. Using this property, the $100(1 - \alpha)\%$ prediction interval for $X_{U(n)}$ has been derived by Balakrishnan and Chan (1993) to be

$$\left[X_{U(m)}, \frac{X_{U(m)}}{\sqrt{b_\alpha(m, n - m)}} \right], \quad (18.142)$$

where $b_\alpha(m, n - m)$ is the lower α percentage point of the **beta**($m, n - m$) distribution. Balakrishnan and Chan (1993) have extended all these results to the case where the upper record values arise from a sequence of **i.i.d.** variables from a two-parameter Rayleigh distribution with density function as in (18.102). For more details on related work, interested readers should refer to **Ahsanullah** (1988), Arnold and Balakrishnan (1989), and Arnold, Balakrishnan, and Nagaraja (1992).

10.7 Related Distributions

As indicated earlier in Section 9, the Rayleigh distribution is simply the chi distribution with two degrees of freedom and scale parameter σ . The inverse Rayleigh distribution with probability density function

$$\frac{2\theta}{x^3} e^{-\theta/x^2}, \quad x > 0, \theta > 0,$$

has been considered by Iliescu and VodI (1973) and VodI (1972). Similarly the log-Rayleigh distribution has been discussed by Shepherd (1975).

It is of interest to point out here that Vodă (1976a) considered a distribution with probability density function

$$p_X(x; k, \theta) = \frac{2\theta^{k+1}}{\Gamma(k+1)} x^{2k+1} e^{-\theta x^2}, \quad x > 0, \theta > 0, k \geq 0, \quad (18.143)$$

and termed it the "generalized Rayleigh distribution." The Rayleigh density in (18.76) is obtained as a special case of (18.143) when $k = 0$. One should bear in mind that while the chi distribution in (18.65) is defined for positive integral values of the parameter N , the generalized Rayleigh distribution in (18.143) is defined for nonnegative real values of the parameter k . Vodă (1976a) has discussed some properties of this generalized distribution and also studied the maximum likelihood estimate and the best linear estimate of the parameter θ under complete and censored samples [also see Vodă (1977)]. Further Vodă (1975, 1976a) considered the left-truncated form of the distribution in (18.143) given by

$$p_X(x; k, \theta) = \frac{p_{X_T}(x; k, \theta)}{1 - F_X(x_T; k, \theta)}, \quad x \geq x_T, \theta > 0, k \geq 0,$$

where x_T is the truncation point, and discussed the maximum likelihood estimation of the parameter θ . VodI (1976b) also considered a two-component mixture of generalized Rayleigh distributions of the form $\pi p_X(x; k, \theta_1) + (1 - \pi) p_X(x; k, \theta_2)$ and discussed the method of moments estimation of the parameters θ_1 , θ_2 , and π . This work is an extension of the work by Krysicki (1963) who had earlier discussed the problem of estimation for a two-component mixture of Rayleigh distributions.

The Rayleigh density function in (18.76) is also a special case of the Weibull distribution with density function

$$p_X(x) = \frac{c}{\sigma^c} x^{c-1} e^{-x^c/\sigma^c}, \quad 0 \leq x < \infty, c > 0, \sigma > 0.$$

This distribution is discussed at great length in Chapter 21.

Many suggestions have been made regarding the use of a distribution with its hazard function being a lower-order polynomial in the fields of life testing and reliability; for example, see Bain (1974), Gross and Clark (1975), and Lawless (1982). The linear-exponential distribution with density

$$p_X(x) = (\lambda + vx)e^{-(\lambda x + vx^2/2)}, \quad x \geq 0, \quad (18.144)$$

and its hazard function varying as a linear function is one such distribution. This distribution and its applications have been discussed in detail by Broadbent (1958), Carbone, Kellerhouse and Gehan (1967), Gehan and Siddiqui (1973), and Balakrishnan and Malik (1986).

Balakrishnan and Kocherlakota (1985) considered the double Rayleigh distribution with probability density function

$$p_X(x) = \frac{|x - \mu|}{2\sigma^2} e^{-(x-\mu)^2/2\sigma^2}, \quad -\infty < x < \infty, -\infty < \mu < \infty, \sigma > 0 \quad (18.145)$$

[the two-parameter Rayleigh distribution in (18.102) is simply the density function in (18.145) folded at $x = \mu$, and hence the distribution in (18.145) is appropriately termed as the double Rayleigh]. They studied the order statistics from this distribution and constructed the best linear unbiased estimators of the parameters μ and σ . Balakrishnan and Kocherlakota also carried out a similar work on a more general double **Weibull** distribution.

Another interesting distribution to which Rayleigh is related is the Rice distribution. In the data transmission theory the Rice distribution function plays a fundamental role in topics concerned with normally derived processes as the first-order statistics of the envelope of additive narrowband signal and normal noise processes [e.g., see Rice (1944, 1945, 1948); Middleton (1960); Levin (1973); and Dozio, Taute, and Hein (1991)]. The Rice density function of kind (μ, σ) is the two-parameter density function given by

$$\frac{x}{\sigma^2} e^{-(x^2 + \mu^2)/(2\sigma^2)} I_0\left(\frac{\mu x}{\sigma^2}\right) H(x), \quad -\infty < \mu < \infty, \sigma > 0, \quad (18.146)$$

where H is the **Heaviside** unit step and I_0 is the modified Bessel function of the first kind and order zero [Watson (1944)]. It is clear that (18.146) reduces to the Rayleigh density in (18.76) in the particular case when $\mu = 0$. In the context of statistical properties of additive narrowband signal and normal noise processes, σ^2 in (18.146) represents the mean-squared value of the cosine and sine components of the real stationary normal narrowband noise process, while μ in (18.146) represents the amplitude of the narrowband signal ensemble. When μ/σ is small, the Rice density function in (18.146) is very close to the Rayleigh density function, and when x is far out on the tail

of the curve or when μ is large, the Rice density function in (18.146) behaves like a normal density with mean μ and variance σ^2 [see Dozio, Taute and Hein (1991)].

Barnett, Clough, and Kedem (1993) have considered the fitting of Rayleigh and left-truncated Rayleigh distributions to model high peak distributions while studying the phenomenon of acoustic emission. It was Ono (1976) who earlier studied the peak distribution of continuous and burst-type acoustic emission signals and displayed that the Rayleigh distribution serves as an adequate model for the peak magnitude observed in continuous-type acoustic emission regardless of bandwidth.

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CHAPTER 19

Exponential Distributions

1 DEFINITION

The random variable X has an *exponential* (or *negative exponential*) *distribution* if it has a probability density function of form

$$p_X(x) = \sigma^{-1} \exp\left[-\frac{(x - \theta)}{\sigma}\right], \quad x > \theta; \sigma > 0. \quad (19.1)$$

Figure 19.1 gives a graphical representation of this function, with $\theta > 0$. This is a special case of the gamma distribution, the subject of Chapter 17. The exponential distribution has a separate chapter because of its considerable importance and widespread use in statistical procedures.

Very often it is reasonable to take $\theta = 0$. The special case of (19.1) so obtained is called the *one-parameter* exponential distribution. If $\theta = 0$ and $\sigma = 1$, the distribution is called the *standard* exponential distribution. The pdf is

$$p_X(x) = \exp(-x), \quad x > 0. \quad (19.2)$$

The mathematics associated with the exponential distribution is often of a simple nature, and so it is possible to obtain explicit formulas in terms of elementary functions, without troublesome quadratures. For this reason models constructed from exponential variables are sometimes used as an approximate representation of other models that are more appropriate for a particular application.

2 GENESIS

There are many situations in which one would expect an exponential distribution to give a useful description of observed variation. One of the most widely quoted is that of events recurring "at random in time." In particular, suppose that the future lifetime of an individual has the same distribution, no matter

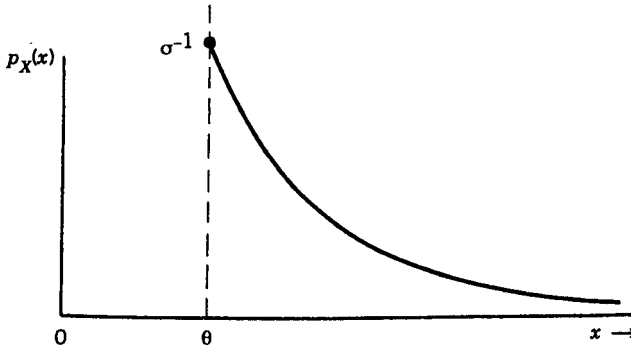


Figure 19.1 Exponential Density Function

how old it is at present. This can be written formally (X representing lifetime)

$$\Pr[X \leq x_0 + x | X > x_0] = \Pr[X \leq x] \quad \text{for all } x_0 > 0, x > 0.$$

X must be a continuous positive random variable. If it has a probability density function $p_X(x)$, then the conditional probability density function, given that X is greater than x_0 , is

$$\frac{p_X(x)}{1 - F_X(x_0)}, \quad x > x_0 > 0.$$

Since the conditional distribution of the future lifetime ($X - x_0$) is the same as the (unconditional) distribution of X , we have, say,

$$\frac{p_X(x_0)}{1 - F_X(x_0)} = p_X(0) = p_0.$$

It follows that if $F_X(x_0) \neq 1$, $p_0 > 0$ and $F_X(x)$ satisfy the differential equation

$$\frac{dF_X(x)}{dx} = p_0[1 - F_X(x)],$$

whence $1 - F_X(x)$ is e^{-p_0x} . Introducing the condition $\lim_{x \rightarrow 0} F_X(x) = 0$, we find that

$$1 - F_X(x) = e^{-p_0x}, \tag{19.3}$$

that is,

$$F_X(x) = 1 - e^{-p_0x} = p_0 \int_0^x e^{-p_0t} dt.$$

This shows that the probability density function of X is of form (19.1) with $\theta = 0$, $a = p_0^{-1}$.

There are other situations in which exponential distributions appear to be the most natural. Many of these do, however, have as an essential feature the random recurrence (often in time) of an event.

In applying the Monte Carlo method it is often required to transform random variables from a standard rectangular distribution to exponential random variables. An ingenious method was suggested at an early date by von Neumann (1951). Let $\{X_i; i = 0, 1, \dots\}$ be a sequence of independent random variables from the standard rectangular distribution, and define a random variable N taking positive integer values through $\{X_i\}$ by the inequalities

$$X_1 < X_0, \quad \sum_{j=1}^2 X_j < X_0, \dots, \quad \sum_{j=1}^{N-1} X_j < X_0, \quad \sum_{j=1}^N X_j > X_0.$$

We "accept" the sequence $\{X_i\}$ if N is odd, otherwise we "reject" it and repeat the process until N turns out odd. Let T be the number of sequences rejected before an odd N appears ($T = 0, 1, \dots$) and X_0 be the value of the first variable in the accepted sequence. Then $Y = T + X_0$ is an exponential random variable with the standard density e^{-x} .

A rather more convenient method was suggested by Marsaglia (1961). Let N be a nonnegative random integer with the geometric distribution [Chapter 5, Section 2, equation (5.8)]

$$\Pr[N = n] = (1 - e^{-\lambda})e^{-n\lambda}, \quad n = 0, 1, \dots,$$

and let M be a positive random integer with the zero-truncated Poisson distribution [Chapter 4, Section 10, equation (4.73)]

$$\Pr[M = m] = (1 - e^{-\lambda})^{-1} \frac{e^{-\lambda}\lambda^m}{m!}, \quad m = 1, 2, \dots$$

Finally let $\{X_i; i = 1, 2, \dots\}$ be a sequence of independent random variables each having a standard rectangular distribution (Chapter 26). Then

$$Y = \lambda\{N + \min(X_1, \dots, X_M)\}$$

has the standard exponential distribution.

Sibuya (1962) gave a statistical interpretation of the procedure, recommended that the value of the parameter A be taken as 0.5 or $\log 2$, and extended the technique to the chi-square distribution. **Bánkövi** (1964) investigated a similar technique. A table of 10,000 exponential random numbers is given by **Barnett** (1965).

3 SOME REMARKS ON HISTORY

Over the last 40 years the study of estimators based on samples from an exponential population has been closely associated with the study of order statistics. Lloyd (1952) described a method for obtaining the best linear unbiased estimators (**BLUEs**) of the parameters of a distribution, using order statistics. Epstein and **Sobel** (1953) presented the maximum likelihood estimator of the scale parameter a , of the one-parameter exponential distribution in the case of censoring from the right. Epstein and **Sobel** (1954) extended the foregoing analysis to the two-parameter exponential distribution. Sarhan (1954) employed the method derived by Lloyd to obtain the **BLUEs** of a and θ for the two-parameter exponential distribution in the case of no censoring. Sarhan (1955) extended his results to censoring. Sarhan noted that in the special case of the one-parameter exponential distribution, his results agreed with those of Epstein and **Sobel**, and therefore his estimator of a was not only the best linear unbiased estimator but also the maximum likelihood estimator of a . Epstein (1960) extended his own results to estimators of a and θ for the one- and two-parameter exponential distributions in the cases of censoring from the right and/or left. For the two-parameter exponential distribution his maximum likelihood estimators coincided with the **BLUEs** of Sarhan (1960), but for the one-parameter exponential distribution there was agreement only in the case of censoring from the right. Many other contributions by Epstein and **Sobel** are included in the references.

In the light of the applicability of order statistics to the exponential distribution it became quite natural to attempt estimation of the parameter by use of the sample quasi-ranges. Rider (1959) derived the probability density function and the cumulants of the quasi-range of the standardized exponential distribution and Fukuta (1960) derived "best" linear estimators of a and θ by two sample quasi-ranges. The next step would quite reasonably be that of determining the two order statistics that would supply the best linear unbiased estimator of σ and θ for the two-parameter distribution; this was in fact done numerically by Sarhan, Greenberg, and Ogawa (1963). They employed the method of Lloyd to obtain the best linear estimators of a and θ based on the two-order statistics $X'_{l:n}$ and $X'_{m:n}$, and then compared numerically the relative efficiencies of the estimators for various pairs of values (l, m) . Harter (1961), using a similar approach to that of Sarhan and his coworkers, presented the best linear estimators of σ for the one-

parameter distribution based on one- and two-order statistics. Harter mentioned in this paper that he was not aware of any analytical process by which the optimum pair of order statistics $X'_{l:n}$ and $X'_{m:n}$ can be determined. Siddiqui (1963) presented an analytical method based on the Euler-MacLaurin formula for obtaining the optimum pair of BLUE order statistics. Since 1963 a considerable number of additional, more refined, results have been obtained. Some of these results are presented in Section 7.

4 MOMENTS AND GENERATING FUNCTIONS

The moment generating function of a random variable X with probability density function (19.1) is

$$E[e^{tX}] = (1 - \sigma t)^{-1} e^{t\theta} \quad (= (1 - \sigma t)^{-1} \text{ if } \theta = 0). \quad (19.4)$$

The characteristic function is $(1 - i\sigma t)^{-1} e^{it\theta}$.

The central moment generating function is

$$E[e^{t(X-\theta-\sigma)}] = (1 - \sigma t)^{-1} e^{-t\sigma}.$$

The cumulant generating function is $\log E[e^{tX}] = t\theta - \log(1 - \sigma t)$. Hence the cumulants are

$$\begin{aligned} \kappa_1 &= \theta + \sigma & (= E[X]) \\ \kappa_r &= (r-1)! \sigma^r, & r > 1. \end{aligned} \quad (19.5)$$

Setting $r = 2, 3, 4$, we find that

$$\begin{aligned} \text{Var}(X) &= \mu_2 = \sigma^2 \\ \mu_3 &= 2\sigma^3 \\ \mu_4 &= 9\sigma^4. \end{aligned}$$

Note that if $\theta = 0$ and $\sigma = 1$, then $E[X] = 1 = \text{Var}(X)$.

The first two moment ratios are

$$\sqrt{\beta_1} = 2, \quad \beta_2 = 9.$$

The mean deviation is

$$2\sigma \int_1^\infty (x-1)e^{-x} dx = 2e^{-1}\sigma. \quad (19.6)$$

Note that

$$\frac{\text{Mean deviation}}{\text{Standard deviation}} = \frac{2}{e} = 0.736. \quad (19.7)$$

The median of the distribution is $\theta + \sigma \log 2$. The mode of this distribution is at the lowest value θ of the range of variation.

The information generating function [($u - 1$)-th frequency moment] is $\sigma^{1-u} u^{-1}$. The entropy is $1 + \log \sigma$. The hazard rate (σ^{-1}) is constant. This is an important property of exponential distributions.

5 APPLICATIONS

As has already been mentioned in Section 1, the exponential distribution is applied in a very wide variety of statistical procedures. Currently among the most prominent applications are in the field of life-testing. The lifetime (or life characteristic, as it is often called) can be usefully represented by an exponential random variable, with (usually) a relatively simple associated theory. Sometimes the representation is not adequate; in such cases a modification of the exponential distribution [often a **Weibull** distribution (Chapter 21) is used].

Another application is producing usable approximate solutions to difficult distributional problems. An ingenious application of the exponential distribution to approximate a sequential procedure is due to Ray (1957). He wished to calculate the distribution of the smallest n for which $\sum_{i=1}^n U_i^2 < K_n$, where U_1, U_2, \dots are independent unit normal variables and K_1, K_2, \dots are specified positive constants. By replacing this by the distribution of the smallest even n , he obtained a problem in which the sums $\sum_{i=1}^n U_i^2$ are replaced by sums of independent exponential variables (actually χ^2 's with two degrees of freedom each).

Vardeman and Ray (1985) investigated the average sum lengths for CUSUM schemes when observations are exponentially distributed. They show that in this case the Page (1954) integral equation whose solution gives average sum lengths for one-sided CUSUM schemes can be solved without resorting to approximation. They provide tables of average run lengths for the exponential case.

6 ORDER STATISTICS

Let $X'_1 \leq X'_2 \leq \dots \leq X'_n$ be the order statistics obtained from a sample of size n from the standard exponential distribution in (19.2). Then, the joint

density of all n order statistics is

$$p_{X'_1, \dots, X'_n}(x_1, \dots, x_n) = n! e^{-\sum_{i=1}^n x_i}, \quad 0 \leq x_1 \leq \dots \leq x_n < \infty. \quad (19.8)$$

By making the transformation

$$Y_i = (n - i + 1)(X'_i - X'_{i-1}), \quad i = 1, 2, \dots, n \text{ (with } X'_0 \equiv 0), \quad (19.9)$$

we obtain from (19.8) the joint density function of Y_1, Y_2, \dots, Y_n to be

$$p_{Y_1, \dots, Y_n}(y_1, \dots, y_n) = e^{-\sum_{i=1}^n y_i}, \quad 0 \leq y_1, \dots, y_n < \infty. \quad (19.10)$$

That is, the Y_i 's (termed normalized spacings) are independent and identically distributed standard exponential random variables. This result is originally due to Sukhatme (1937). Also from (19.9),

$$X'_i \triangleq \sum_{j=1}^i \left\{ \frac{Y_j}{n - j + 1} \right\}, \quad i = 1, 2, \dots, n. \quad (19.11)$$

From (19.11) it is clear that the exponential order statistics form an additive Markov chain as shown originally by Rényi (1953).

The additive Markov chain representation in (19.11) makes it possible to write down explicit expressions for the single and product moments of X'_i . For example, we have

$$E[X'_i] = \sum_{j=1}^i \frac{E[Y_j]}{n - j + 1} = \sum_{j=1}^i \frac{1}{n - j + 1}, \quad i = 1, 2, \dots, n, \quad (19.12)$$

$$\text{Var}(X'_i) = \sum_{j=1}^i \frac{\text{Var}(Y_j)}{(n - j + 1)^2} = \sum_{j=1}^i \frac{1}{(n - j + 1)^2}, \quad i = 1, 2, \dots, n, \quad (19.13)$$

$$\begin{aligned} \text{Cov}(X'_i, X'_k) &= \sum_{j=1}^i \frac{\text{Var}(Y_j)}{(n - j + 1)^2} = \sum_{j=1}^i \frac{1}{(n - j + 1)^2} \\ &= \text{Var}(X'_i) \quad \text{for } 1 \leq i < k \leq n. \end{aligned} \quad (19.14)$$

This special structure of the variance-covariance matrix of exponential order statistics makes it possible to derive the best linear unbiased estimators of the parameters in an explicit form (see Section 7).

Interestingly the result that the normalized spacings Y_i 's defined in (19.9) are i.i.d. standard exponential random variables has been generalized by

Viveros and Balakrishnan (1994) to the case of a Type **II** progressively censored sample. To be precise, let m be the number of failures observed before termination of a life test of n individuals and $X'_1 \leq X'_2 \leq \dots \leq X'_m$ be the observed ordered life lengths. Let R_i designate the number of units removed at the time of the i th failure (Type **II** censoring),

$$0 \leq R_i \leq n - \sum_{j=1}^{i-1} (R_j + 1) - 1, \quad i = 2, 3, \dots, m - 1,$$

with

$$0 \leq R_1 \leq n - 1,$$

$$R_n = n - \sum_{j=1}^{m-1} (R_j + 1) - 1.$$

The resulting data are referred to as a Type **II** progressively censored sample [e.g., see Nelson (1982); Lawless (1982); Cohen and Whitten (1988); Balakrishnan and Cohen (1991); Cohen (1991)]. Defining the i th normalized spacing between X'_1, X'_2, \dots, X'_m as

$$Y_i = \left\{ n - \sum_{j=1}^{i-1} (R_j + 1) \right\} (X'_i - X'_{i-1}), \quad i = 1, 2, \dots, m, \text{ (with } X'_0 \equiv 0),$$

(19.15)

Viveros and Balakrishnan (1994) have proved that Y_i 's are i.i.d. exponential random variables. Sukhatme's result, presented earlier, is a particular case of this general result corresponding to $R_1 = R_2 = \dots = R_m = 0$. In this general case an additive Markov chain representation for X'_i similar to the one in (19.11) is possible; it can then be used in writing down explicit expressions for the means, variances, and covariances of X'_i that are similar to those in (19.12)–(19.14). The special structure of the variance-covariance matrix of exponential order statistics observed earlier in (19.13)–(19.14) occurs in this general case of Type **II** progressively censored sample and enables the best linear unbiased estimators of the parameters to be derived in an explicit form (as described in Section 7c).

Due to the close relationship between the geometric and the exponential distributions, there also exists a close relationship between the dependence structure of order statistics from the geometric distribution and those from the exponential distribution. Steutel and Thiemann (1989) showed some of these similarities. For example, by introducing a second subscript to denote

sample size, (19.11) can be written as

$$X'_{i:n} \stackrel{d}{=} \sum_{j=1}^i \frac{I_j}{(n-j+1)} \stackrel{d}{=} \sum_{j=1}^i X'_{1:n-j+1}, \quad (19.16)$$

where the $X'_{1:n-j+1}$'s are independent. Steutel and Thiemann (1989) established the following parallel relationship for the geometric order statistics:

$$Z'_{i:n} \stackrel{d}{=} \sum_{j=1}^i Z'_{1:n-j+1} + \left[\sum_{j=1}^i \left\langle \frac{Y_j}{n-j+1} \right\rangle \right], \quad (19.17)$$

where $Z'_{i:n}$ denotes the i th order statistic from a random sample of size n from a geometric (p) distribution, the Y_j 's are independent exponential (σ) random variables with $\sigma = 1/[-\log(1-p)]$, $[Y]$ denotes the integer part of Y , and $\langle Y \rangle$ denotes the fractional part of Y . Further, all the random variables on the right-hand side of (19.17) are independent.

Arnold and Villaseñor (1989) and Arnold and Nagaraja (1991) discussed the Lorenz order relationships among order statistics from exponential samples. The Lorenz curve associated with X is

$$L_X(u) = \frac{\int_0^u F_X^{-1}(t) dt}{\int_0^1 F_X^{-1}(t) dt}, \quad 0 \leq u \leq 1 \quad (19.18)$$

(see Chapter 12, Section 1). Given two nonnegative random variables X and Y (with finite positive mean), we say X exhibits less inequality (or variability) than Y in the Lorenz sense, and write $X <_L Y$, if $L_X(u) \geq L_Y(u)$ for all $u \in [0, 1]$; if the inequality is an equality, we write $X =_L Y$. If $L_X(u)$ and $L_Y(u)$ cross, X and Y are not comparable in the Lorenz sense. Arnold and Nagaraja (1991) proved that for $i \leq j$,

$$X'_{j:m} <_L X'_{i:n} \quad \text{iff} \quad (n-i+1)E[X'_{i:n}] \mathbf{I} (m-j+1)E[X'_{j:m}]. \quad (19.19)$$

As direct consequences of this result, they established for the exponential order statistics that

1. $X'_{i:n+1} <_L X'_{i:n}$,
2. $X'_{i+1:n+1} <_L X'_{i:n}$,
3. $X'_{i+1:n} <_L X'_{i:n}$ iff $E[X'_{i:n}] \mathbf{I} 1$; otherwise, $X'_{i:n}$ and $X'_{i+1:n}$ are not Lorenz ordered.

These authors have also discussed the Lorenz ordering of linear functions of exponential order statistics.

By making use of the underlying differential equation of a standard exponential distribution, given by $p_X(x) = 1 - F_X(x)$, Joshi (1978, 1982) derived the following recurrence relations:

$$E[X'_{1:n}] = \frac{m}{n} E[X'^{m-1}_{1:n}], \quad n \geq 1, \quad m = 1, 2, \dots, \quad (19.20a)$$

$$E[X'^m_{i:n}] = E[X'^m_{i-1:n-1}] + \frac{m}{n} E[X'^{m-1}_{i:n}],$$

and

$$2 \leq i \leq n, \quad m = 1, 2, \dots, \quad (19.20b)$$

$$E[X'_{i:n} X'_{i+1:n}] = E[X'^2_{i:n}] + \frac{1}{n-i} E[X'_{i:n}], \quad 1 \leq i \leq n-1, \quad (19.20c)$$

and

$$E[X'_{i:n} X'_{j:n}] = E[X'_{i:n} X'_{j-1:n}] + \frac{1}{n-j+1} E[X'_{i:n}],$$

$$1 \leq i < j \leq n, \quad j-i \geq 2. \quad (19.20d)$$

These recurrence relations can be used in a simple recursive manner in order to compute all the single and product moments (in particular, the means, variances, and covariances) of all order statistics. Balakrishnan and Gupta (1992) extended these results and derived relations that will enable one to find the moments and cross-moments (of order up to 4) of order statistics. They then used these results to determine the mean, variance, and the coefficients of skewness and kurtosis of a general linear function of exponential order statistics and approximate its distribution. Through this approach Balakrishnan and Gupta (1992) justify a chi-square approximation for the distribution of the best linear unbiased estimator of the mean lifetime based on doubly Type II censored samples (see Section 7). Interestingly the relations in (19.20a)–(19.20d), under certain conditions, can also be shown to be characterizations of the exponential distribution [Lin (1988, 1989) (see Section 8). Balakrishnan and Malik (1986) derived similar recurrence relations for the single and product moments of order statistics from a linear-exponential distribution with increasing hazard rate. Sen and Bhattacharyya (1994) have discussed inferential issues relating to this distribution.

By making use of the facts that $X = -\log U$ has a standard exponential distribution, when U has a uniform $(0, 1)$ distribution (see Chapter 26), and that $-\log U$ is a monotonic decreasing function of U , we have

$$X'_{i:n} \stackrel{d}{=} -\log U'_{n-i+1:n}, \quad 1 \leq i \leq n,$$

and hence

$$V_i = \left(\frac{U'_{i:n}}{U'_{i+1:n}} \right)^i \stackrel{d}{=} \exp\{-i(X'_{n-i+1:n} - X'_{n-i:n})\} \stackrel{d}{=} e^{-Y'_n{}_{i+1}}, \quad (19.21)$$

where Y'_i 's are the normalized exponential spacings defined in (19.9). Since Y'_i 's are i.i.d. exponential, as seen earlier, it immediately follows from (19.21) that

$$V_1 = \frac{U'_{1:n}}{U'_{2:n}}, \quad V_2 = \left(\frac{U'_{2:n}}{U'_{3:n}} \right)^2, \dots, V_{n-1} = \left(\frac{U'_{n-1:n}}{U'_{n:n}} \right)^{n-1}, \quad V_n = U'_{n:n}{}^m \quad (19.22)$$

are i.i.d. uniform $(0, 1)$ random variables. This result was derived originally by Malmquist (1950) and is now used effectively to simulate order statistics from uniform distribution without resorting to any ordering.

Joshi (1978, 1982) also considered order statistics from a right-truncated exponential population with density

$$p_X(x) = \begin{cases} \frac{1}{P}e^{-x}, & 0 \leq x \leq P_1, \\ 0, & \text{otherwise,} \end{cases} \quad (19.23)$$

where $P_1 = -\log(1 - P)$ and $1 - P$ ($0 < P < 1$) is the proportion of truncation on the right of the standard exponential distribution. By making use of the underlying differential equation given by

$$p_X(x) = [1 - F_X(x)] + \left(\frac{1 - P}{P} \right)$$

and proceeding along the lines used to prove relations (19.20a)–(19.20d), Joshi (1978, 1982) established the following recurrence relations:

$$E[X'_{1:n}{}^m] = \frac{m}{n} E[X'_{1:n}{}^{m-1}] - \left(\frac{1 - P}{P} \right) E[X'_{1:n-1}{}^m], \quad n \geq 2, m = 1, 2, \dots, \quad (19.24a)$$

$$E[X'_{i:n}{}^m] = \frac{1}{P} E[X'_{i-1:n-1}{}^m] + \frac{m}{n} E[X'_{i:n}{}^{m-1}] - \left(\frac{1 - P}{P} \right) E[X'_{i:n-1}{}^m], \quad 2 \leq i \leq n - 1, m = 1, 2, \dots, \quad (19.24b)$$

$$E[X'_{n:n}] = \frac{1}{P}E[X'^{m}_{n-1:n-1}] + \frac{m}{n}E[X'^{m-1}_{n:n}] - \left(\frac{1-P}{P}\right)P_1^m, \quad n \geq 2, m = 1, 2, \dots, \quad (19.24c)$$

$$E[X'_{n-1:n}X'_{n:n}] = E[X'^2_{n-1:n}] + E[X'_{n-1:n}] - n\left(\frac{1-P}{P}\right)\{P_1E[X'_{n-1:n-1}] - E[X'^2_{n-1:n-1}]\},$$

$n \geq 2, \quad (19.24d)$

$$E[X'_{i:n}X'_{i+1:n}] = E[X'^2_{i:n}] + \frac{1}{n-i} \times \left\{ E[X'_{i:n}] - n\left(\frac{1-P}{P}\right)\{E[X'_{i:n-1}X'_{i+1:n-1}] - E[X'^2_{i:n-1}]\} \right\}, \quad 1 \leq i \leq n-2, \quad (19.24e)$$

$$E[X'_{i:n}X'_{j:n}] = E[X'_{i:n}X'_{j-1:n}] + \frac{1}{n-j+1} \times \left\{ E[X'_{i:n}] - n\left(\frac{1-P}{P}\right)\{E[X'_{i:n-1}X'_{j:n-1}] - E[X'_{i:n-1}X'_{j-1:n-1}]\} \right\},$$

$1 \leq i < j \leq n-1; j-i \geq 2, \quad (19.24f)$

and

$$E[X'_{i:n}X'_{n:n}] = E[X'_{i:n}X'_{n-1:n}] + E[X'_{i:n}] - n\left(\frac{1-P}{P}\right)\{P_1E[X'_{i:n-1}] - E[X'_{i:n-1}X'_{n-1:n-1}]\},$$

$1 \leq i \leq n-2. \quad (19.24g)$

Saleh, Scott, and **Junkins** (1975) derived exact (but somewhat cumbersome) explicit expressions for the first two single moments and the product moments of order statistics in this right-truncated exponential case. Balakrishnan and Gupta (1992) extended the results of Joshi and established recurrence relations that will enable one to find the moments and cross-moments (of order up to four) of order statistics.

By considering the doubly truncated exponential distribution with density

$$p_X(x) = \begin{cases} \frac{1}{P-Q} e^{-x}, & Q_1 \leq x \leq P_1, \\ 0, & \text{otherwise,} \end{cases} \quad (19.25)$$

where Q and $1 - P$ ($0 < Q < P < 1$) are the proportions of truncation on the left and right of the standard exponential distribution, respectively, and $Q_1 = -\log(1 - Q)$ and $P_1 = -\log(1 - P)$, Joshi (1979) and Balakrishnan and Joshi (1984) derived several recurrence relations satisfied by the single and the product moments of order statistics. Khan, Yaqub, and Parvez (1983) tabulated these quantities for some value of P , Q , and n . Distributions of some systematic statistics like the sample range and quasi-range were derived in this case by Joshi and Balakrishnan (1984).

7 ESTIMATION

Before 1959 a considerable amount of work had been done on inference procedures for the exponential distribution with both censored and uncensored data. (See numerous references at the end of this chapter.) It was realized, in the 1960s and 1970s, that although the exponential distribution can be handled rather easily, the consequent analysis is often poorly robust [e.g., see Zelen and Dannemiller (1961)]. Nevertheless, the study of properties of this distribution, and especially construction of estimation and testing procedures has continued steadily, during the last 30 years, with some emphasis on Bayesian analysis and order statistics methodology, and an explosion of results on characterizations. To keep this chapter within reasonable bounds, it was necessary to be very selective in our citations and descriptions of results. We first discuss classical estimators.

7.1 Classical Estimation

If X_1, X_2, \dots, X_n are independent random variables each having the probability density function (19.1), then the maximum likelihood estimators of θ and a are

$$\begin{aligned} \hat{\theta} &= \min(X_1, X_2, \dots, X_n), \\ \hat{a} &= n^{-1} \sum_{i=1}^n (X_i - \hat{\theta}) = \bar{X} - \hat{\theta}. \end{aligned} \quad (19.26)$$

If θ is known, the maximum likelihood estimator of a is $(\bar{X} - \theta)$. Even with a known, $\hat{\theta}$ above is still the maximum likelihood estimator of θ .

The probability density function of $\hat{\theta}$ is

$$p_{\hat{\theta}}(t) = \left(\frac{n}{\sigma}\right) \exp\left[-\frac{n(t-\theta)}{\sigma}\right], \quad t > \theta, \quad (19.27)$$

which is of the same form as (19.1) but with σ replaced by σ/n . The variance of $\hat{\theta}$ is therefore σ^2/n^2 , and its expected value is $\theta + \sigma/n$. It is interesting to note that the variance is proportional to n^{-2} and not to n^{-1} .

The expected value of $\hat{\sigma} [= \bar{X} - \hat{\theta}]$ is $\sigma(1 - n^{-1})$, and its variance is

$$\sigma^2[n^{-1} + n^{-2} - 2n^{-3}].$$

The expected value of $(\bar{X} - \theta)$ is σ and its variance is $\sigma^2 n^{-1}$.

A function of special interest in some applications is the value of the probability that X exceeds a value x_0 ; the reliability function $R(x_0)$. If $\theta = 0$ so that (19.1) becomes

$$p_X(x) = \sigma^{-1} \exp\left(-\frac{x}{\sigma}\right), \quad x > 0, \sigma > 0, \quad (19.28)$$

then

$$R(x_0) = e^{-x_0/\sigma}. \quad (19.29)$$

Inserting the **maximum** likelihood estimator, $\hat{\sigma} = n^{-1} \sum_{i=1}^n X_i$ in place of σ , would give the estimator $\exp(-x_0 n / \sum_{i=1}^n X_i)$. This is the maximum likelihood estimator of the reliability $R(x_0)$. It is biased, but a minimum variance unbiased estimator can be obtained by using the Blackwell-Rao theorem.

The statistic

$$T = \begin{cases} 1 & \text{if } X_1 > x_0, \\ 0 & \text{if } X_1 \leq x_0, \end{cases}$$

is an unbiased estimator of $\exp(-x_0/\sigma)$. Since $\sum_{i=1}^n X_i$ is a complete sufficient statistic for σ [and so also for $\exp(-x_0/\sigma)$], the required minimum variance unbiased estimator is

$$E\left[T \mid \sum_{i=1}^n X_i\right] = \Pr\left[X_1 > x_0 \mid \sum_{i=1}^n X_i\right].$$

The ratio $X_1/\sum_{i=1}^n X_i$ has a beta distribution with parameters 1, $n - 1$, and

is independent of $\sum_{i=1}^n X_i$ (Chapter 17, Section 6). Hence

$$E\left[T \left| \sum_{i=1}^n X_i \right.\right] = (n-1) \int_{x_0/\sum_{i=1}^n X_i}^1 (1-z)^{n-2} dz$$

$$= \begin{cases} \left(1 - \frac{x_0}{\sum_{i=1}^n X_i}\right)^{n-1}, & x_0 < \sum_{i=1}^n X_i \\ 0, & x_0 \geq \sum_{i=1}^n X_i \end{cases} \quad (19.30)$$

which is the required minimum variance unbiased estimator. This formula was obtained by Pugh (1963). (Pugh claims this is the "best" estimator but does not compare its mean square error with that of competing estimators.) The sampling distribution of the maximum likelihood estimator of parameter σ in (19.28), based on a "time-censored" sample, was derived by Bartholomew (1963).

Moment estimators $(\tilde{\theta}, \tilde{\sigma})$ of (θ, σ) can be obtained by equating sample and population values of the mean and variance. They are

$$\tilde{\theta} = \bar{X} - \tilde{\sigma} \quad (19.31a)$$

$$\tilde{\sigma} = \text{sample standard deviation.} \quad (19.31b)$$

Cohen and Helm (1973) discuss modified moment estimators obtained by replacing (19.31b) by an equation that puts the first-order statistic X'_1 equal to its expected value. This gives

$$\tilde{\theta}^* + n^{-1}\tilde{\sigma}^* = X'_1, \quad (19.31c)$$

which leads to

$$\tilde{\theta}^* = \frac{nX'_1 - \bar{X}}{n-1}, \quad (19.31d)$$

and

$$\tilde{\sigma}^* = \frac{n(\bar{X} - X'_1)}{n-1} \quad (19.31e)$$

They show that these are minimum variance unbiased estimators (and

a fortiori BLUEs). Also

$$\text{Var}(\tilde{\theta}^*) = \frac{\sigma^2}{n(n-1)}, \quad (19.32a)$$

$$\text{Var}(\tilde{\sigma}^*) = \frac{\sigma^2}{n-1}, \quad (19.32b)$$

$$\text{Cov}(\tilde{\theta}^*, \tilde{\sigma}^*) = \frac{\sigma^2}{n(n-1)}, \quad (19.32c)$$

so that $\text{Corr}(\tilde{\theta}^*, \tilde{\sigma}^*) = 1/\sqrt{n}$. Further, since $\tilde{\sigma}^*$ is distributed as $\frac{1}{2}(n-1)^{-1}\chi_{2(n-1)}^2$, a $100(1-\alpha)\%$ confidence interval for σ is (in the obvious notation)

$$\left(\frac{2(n-1)}{\chi_{2(n-1), 1-\frac{\alpha}{2}}^2} \tilde{\sigma}^*, \frac{2(n-1)}{\chi_{2(n-1), \frac{\alpha}{2}}^2} \tilde{\sigma}^* \right). \quad (19.33)$$

72 Grouped Data

In a monograph **Kulldorff** (1961) discussed a general theory of estimation based on grouped or partially grouped samples. By *grouped* we mean that in disjoint intervals of the distribution range, only the numbers of observed values that have fallen in the intervals are available, and not the individual sample values. The distribution of the observed numbers is a **multinomial** distribution with probabilities that are functions of the parameter. If individual observations are available in *some* intervals, the sample is *partially grouped*.

Kulldorff devoted a large part of his book to the estimation of the exponential distribution because of its simplicity. The cases studied included completely or partially grouped data, θ unknown, a unknown, both θ and a unknown, a finite number of intervals, an infinite number of intervals, intervals of equal length, and intervals of unequal length. Here we describe only the maximum likelihood estimator of a when θ is known, the intervals are not of equal length, and the number of intervals is finite.

Let $0 = x_0 < x_1 < \dots < x_{k-1} < \infty$ be the dividing points and N_1, \dots, N_k , ($\sum_{i=1}^k N_i = n$) the numbers of observed values in the respective intervals. Then the maximum likelihood estimator $\hat{\theta}$ is the unique solution of

$$\sum_{i=1}^{k-1} \frac{N_i(x_i - x_{i-1})}{e^{(x_i - x_{i-1})/\hat{\theta}} - 1} - \sum_{i=2}^k N_i x_{i-1} = 0 \quad (19.34)$$

which exists if and only if $N_1 < n$ and $N_k < n$. For large n ,

$$n \text{Var}(\hat{\sigma}^{-1}) \doteq \left(\sum_{i=1}^{k-1} \frac{(x_i - x_{i-1})^2}{e^{x_i/\sigma} - e^{x_{i-1}/\sigma}} \right)^{-1}. \quad (19.35)$$

For a given k , the dividing points that minimize the asymptotic variance are

$$\frac{x_i}{\sigma} = \sum_{j=k-i}^{k-1} \delta_j, \quad (19.36)$$

where

$$\delta_1 = g^{-1}(2), \quad \delta_i = g^{-1}\{2 + \delta_{i-1} - g(\delta_{i-1})\},$$

$$g(x) = x(1 - e^{-x})^{-1}.$$

For example,

$$k = 2, \quad \frac{x_1}{\sigma} = 1.5936;$$

$$k = 3, \quad \frac{x_1}{\sigma} = 1.0176, \quad \frac{x_2}{\sigma} = 2.6112.$$

The simplicity of mathematical analysis for the exponential distribution permits us to construct convenient Bayesian estimators of parameters of (19.1). Some initial results in this area (for censored samples) are presented in Varde (1969), who also compared their performance with more natural (at least in this case) and efficient maximum likelihood and minimum variance unbiased estimators.

7.3 Estimators Using Selected Quantiles

In life-test analysis it is often supported that lifetime can be represented by a random variable with probability density function

$$p_X(x) = \sigma^{-1} \exp\left(-\frac{x}{\sigma}\right), \quad x > 0, \sigma > 0. \quad (19.28)'$$

If a number n of items are observed with lifetimes commencing simultaneously, then, as each life concludes, observations of lifetime become available sequentially, starting with the shortest lifetime X'_1 of the n items, followed by the 2nd, 3rd... shortest lifetimes X'_2, X'_3, \dots , respectively. Clearly it will be advantageous if useful inferences can be made at a relatively early stage, without waiting for completion of the longer lifetimes. This means that

inference must be based on observed values of the k , say, shortest lifetimes, or in more general terms, the first k -order statistics (see Section 6). On account of the practical importance of these analyses, statistical techniques have been worked out in considerable detail. Here we will describe only methods of estimation, but a considerable range of test procedures is also available.

From (19.8) we find that if

$$V_2 = X'_2 - X'_1, \quad V_3 = X'_3 - X'_2, \dots, V_n = X'_n - X'_{n-1},$$

then

1. $X'_1, V_2, V_3, \dots, V_n$ are mutually independent,
2. the distribution of X'_1 is exponential (19.1) with $\theta = 0$, $\sigma = n^{-1}$,
3. the distribution of V_j is exponential (19.1) with $\theta = 0$, $\sigma = (n - j + 1)^{-1}$, $j = 2, \dots, n$.

Since $X'_j = X'_1 + V_2 + \dots + V_j$ ($j \geq 2$), it follows that all linear functions of the order statistics can be expressed as linear functions of the independent random variables X'_1, V_2, \dots, V_n . This form of representation [suggested by **Sukhatme (1937)** and **Rényi (1953)**; see also **Epstein and Sobel (1954)** for a similar result] is very helpful in solving distribution problems associated with methods described in the remainder of this section. A similar kind of representation can be applied to gamma distributions, though the results are not so simple.

It is necessary to distinguish between censoring (often referred as Type II censoring), in which the order statistics that will be used (**e.g.**, the r smallest values) are decided in advance, and truncation (or Type I censoring) in which the range of values that will be used (**e.g.**, all observations less than T_0) is decided in advance (regardless of how many observations fall within the specific limits). Truncation (or Type I censoring) by omission of all observations less than a fixed value T_0 (> 0) has the effect that observed values may be represented by a random variable with probability density function

$$\sigma^{-1} \exp\left[-\frac{x - T_0}{\sigma}\right], \quad x > T_0, \sigma > 0, \quad (19.37)$$

which is again of form (19.1) [with T_0 (known) replacing θ], and so presents no special difficulties. However, if (as is more commonly the case) truncation is by omission of all values greater than T_0 (> 0), then the corresponding probability density function is

$$p_X(x) = \left[1 - \exp\left(-\frac{T_0}{\sigma}\right)\right]^{-1} \sigma^{-1} \exp\left(-\frac{x}{\sigma}\right), \quad 0 < x < T_0, \sigma > 0. \quad (19.38)$$

If m observations are obtained, they can be represented by independent random variables X_1, X_2, \dots, X_m , each with distribution (19.38). The maximum likelihood equation for an estimator $\hat{\sigma}_{T_0}$ of σ is

$$\hat{\sigma}_{T_0} = m^{-1} \sum_{j=1}^m x_j + T_0 \left[\exp\left(\frac{T_0}{\hat{\sigma}_{T_0}}\right) - 1 \right]^{-1}. \quad (19.39)$$

This equation may be solved by an iterative process. In this work the table of Barton, David, and Merrington (1963) is useful.

Wright, Engelhardt, and Bain (1978) and Piegorsch (1987) studied inference on θ and σ for distribution (19.1) under Type I censoring. Wright, Engelhardt, and Bain (1978) presented procedures based on the conditional distribution of "failure" times, given the number D of failures occurring before the censoring time τ . They distinguished between testing with and without replacement. In the first case X'_1 and D are sufficient statistics, and in the second D and $S = \sum_{j=1}^D X'_j$ are sufficient.

Assuming testing without replacement, they utilized the facts that given $D = d$, the conditional distribution of $[(X - X'_1)/(X - \theta)]^d$ is uniform on $(0, 1)$, and that for fixed σ , D is sufficient and complete for θ , while for fixed θ , X'_1 is sufficient and complete for σ .

Assuming testing without replacement leads to a rather complicated conditional density for X_i , given D and S . However, Wright, Engelhardt, and Bain (1978) provide a table of exact percentage points of X'_1 for small and moderate D and an approximation for large D . [In the case where $\sigma = 0$, Bartholomew (1963) developed confidence intervals based on the maximum likelihood estimator

$$\hat{\sigma} = \frac{\sum_{i=1}^D X'_i + (n - D)\tau}{D} = \frac{T_{D:n}}{D} \quad (19.40)$$

where τ is the termination time, (provided that $D > 0$).

Piegorsch (1987) uses somewhat simpler methods, based on the approximate distribution of the likelihood ratio (LR) test statistic and some other approximations reviewed in Lawless (1982, Sec. 3.5.2). He discusses small sample performance of these procedures, based on Monte Carlo evaluation. He introduces the sets

$$A = \{i: \min(t_i, \tau) = t_i, i = 1, \dots, n\}$$

and

$$\Gamma = \{i: \min(t_i, \tau) = \tau, i = 1, \dots, n\}$$

and proposes estimators

$$\tilde{\theta} = X'_1 \quad (19.41a)$$

and

$$\tilde{\sigma} = \left[\sum_{\Delta} (X_i - \tilde{\theta}) + \sum_{\Gamma} \max(\tau - \tilde{\theta}, 0) \right], \quad D > 0, \quad (19.41b)$$

and observed lifetimes t_i and fixed censoring time at τ .

The LR statistic for testing $\sigma = \sigma_0$ is

$$2D \{ \tilde{\sigma} \sigma_0^{-1} - \log(\tilde{\sigma} \sigma_0^{-1}) - 1 \}. \quad (19.42)$$

The asymptotic distribution of this statistic is χ^2 with one degree of freedom if $\theta = \theta_0$. To construct approximate $100(1 - \alpha)\%$ confidence limits for σ , Piegorsch (1987) suggests solving the equations

$$\tilde{\sigma} \sigma^{-1} - \log(\tilde{\sigma} \sigma^{-1}) = 1 + \chi_{1, 1-\alpha}^2 (2D)^{-1}.$$

This equation always has two solutions, one for $\tilde{\sigma}/\sigma < 1$ and the other for $\tilde{\sigma}/\sigma > 1$. These solutions L_σ and U_σ are then used to construct an asymptotic $100(1 - \alpha)\%$ confidence interval on σ of the form

$$\frac{\tilde{\sigma}}{U_\sigma} \leq \sigma \leq \frac{\tilde{\sigma}}{L_\sigma}. \quad (19.43)$$

A similar approach yields asymptotic $100(1 - \alpha)\%$ confidence limits for θ . For smaller sample sizes ($n \leq 10$), the conditional inference on σ given by Wright, Engelhardt, and Bain (1978) may be preferred. However, Piegorsch's method for σ performs well even for $n = 5$ with an F-based approximation providing errors closer to nominal than the LR-based values particularly at $\alpha = 0.05$.

Joint regions for (σ, θ) can be constructed using Bonferroni's approach, with a rectangular region corresponding to the cross-product of univariate $1 - \frac{\alpha}{2}$ confidence intervals on θ and σ (the elliptic procedure using the asymptotic normality of the MLEs breaks down, yielding a hyperbolic rather than an elliptic region). Ranking and subset selection procedures for exponential population with Type I (and Type II) censored data are discussed in Berger and Kim (1985).

We will now restrict ourselves to Type II censored samples only. We will give details only for the case where $\theta = 0$ [so that the probability density function is as in (19.28)] and where censoring results in omission of the largest $n - k$ values (i.e., observation of the k smallest values, where k is specified prior to obtaining the observations). The joint probability density

function of the k (> 1) smallest observations in a random sample of size n is

$$p_{X_1, \dots, X_k}(x_1, \dots, x_k) = \frac{n!}{(n-k)! \sigma^k} \exp\left(-\frac{\sum_{j=1}^{k-1} x_j + (n-k+1)x_k}{\sigma}\right),$$

$$0 \leq x_1 \leq x_2 \leq \dots \leq x_k. \quad (19.44)$$

The maximum likelihood estimator of σ is

$$Y'_k = k^{-1} \left\{ \sum_{j=1}^{k-1} X'_j + (n-k+1)X'_k \right\} = k^{-1} T_{k:n}. \quad (19.45)$$

This statistic is distributed as $(\frac{1}{2}\sigma/k) \times (\chi^2$ with $2k$ degrees of freedom). The expected value of Y'_k is therefore σ , and its variance is σ^2/k . The limits

$$\frac{2kY'_k}{\chi^2_{2k, 1-\frac{1}{2}\alpha}} \quad \text{and} \quad \frac{2kY'_k}{\chi^2_{2k, \frac{1}{2}\alpha}}$$

define a confidence interval for σ with confidence coefficient $100(1-\alpha)\%$.

A wide variety of estimators of σ and θ based on order statistics is available. Many references at the end of this chapter contain discussions of such estimators. Among the problems discussed are estimation

1. by linear functions of a limited number (usually not more than about five) of order statistics—this includes both the choice of coefficients in the linear function, and of the order statistics to be used;
2. when only the k *largest* values are observed;
3. when predetermined numbers of both the smallest and largest values are omitted;
4. conversely, when only these values are known—that is, the middle group of observations is omitted.

In all cases formulas have been obtained appropriate to estimation of σ , knowing θ ; of θ , knowing σ ; and of both θ and σ , neither being known. We now discuss some of the more useful of these formulas.

The variance-covariance matrix of the order statistics $X'_1 \leq X'_2 \leq \dots < X'_n$ has elements

$$\text{Var}(X'_r) = \sigma^2 \sum_{j=1}^r (n-j+1)^{-2} = \text{Cov}(X'_r, X'_s), \quad r < s. \quad (19.46)$$

Also

$$E[X'_r] = \theta + \sigma \sum_{j=1}^r (n-j+1)^{-1}. \quad (19.47)$$

From these relationships it is straightforward to construct best linear unbiased estimators based on k -selected order statistics $X'_{n_1}, X'_{n_2}, \dots, X'_{n_k}$ with

$$n_1 < n_2 < \dots < n_k.$$

It will be convenient to use the notation

$$w_{mi} = \sum_{j=n_{i-1}}^{n_i-1} (n-j)^{-m}, \quad (19.48)$$

with $n_0 = 0$, and $w_{10}/w_{20}, w_{1,k+1}/w_{2,k+1}$ each defined to be zero.

If θ is known, the best linear unbiased estimator of α is

$$\tilde{\sigma} = \left[\sum_{i=1}^k \left(\frac{w_{1i}}{w_{2i}} - \frac{w_{1,i+1}}{w_{2,i+1}} \right) X'_{n_i} - \frac{w_{11}}{w_{21}} \theta \right] \left[\sum_{i=1}^k \frac{w_{1i}^2}{w_{2i}} \right]^{-1}. \quad (19.49)$$

The variance of $\tilde{\sigma}$ is $\sigma^2(\sum_{i=1}^k w_{1i}^2 w_{2i}^{-1})^{-1}$. Some special cases are

1. $n_i = i, k = n$ (complete sample):

$$\tilde{\sigma} = n^{-1} \sum_{i=1}^n X_i,$$

$$\text{Var}(\tilde{\sigma}) = \frac{\sigma^2}{n}.$$

2. $n_i = r_1 + i, k = n - r_1 - r_2$ (censoring r_1 smallest and r_2 largest values):

$$\tilde{\sigma} = K^{-1} \left[\frac{\sum_{i=1}^{r_1+1} (n-i+1)^{-1}}{\sum_{i=1}^{r_1+1} (n-i+1)^{-2}} (X'_{r_1+1} - \theta) - (n-r_1) X'_{r_1+1} \right. \\ \left. + (n-r_1-k) X'_{r_1+k} + \sum_{i=r_1+1}^{r_1+k} X'_i \right] \quad (19.50)$$

(1963)]. Epstein (1962) has noted that the efficiency of the unbiased estimator based on $X'_r - 8$ is never less than 96% if $r/n \leq \frac{1}{2}$, or 90% if $r/n \leq \frac{2}{3}$.

- 5. $k = 2$ (estimation from two order statistics X'_{n_1}, X'_{n_2}). The variance of $\bar{\sigma}$ is a minimum when n_1 is the nearest integer to $0.6386(n + \frac{1}{2})$ and n_2 is the nearest integer to $0.9266(n + \frac{1}{2})$ [Siddiqui (1963)].

For small samples Sarhan and Greenberg (1958) give the following optimal choices:

Sample Size (n)	2-4	5-7	8-11	12-15	16-18	19-21
n_1	$n - 1$	$n - 2$	$n - 3$	$n - 4$	$n - 6$	$n - 7$
n_2	n	n	n	n	$n - 1$	$n - 1$

If θ is not known, the optimal choices are different. Sarhan and Greenberg (1958) give the following optimal choices for n_1 and n_2 (with $k = 2$):

Sample Size (n)	2-6	7-10	11-15	16-20	21
n_1	1	1	1	1	1
n_2	n	$n - 1$	$n - 2$	$n - 3$	$n - 4$

The best (in fact only) linear unbiased estimator of \mathbf{a} , using only X'_{n_1} and X'_{n_2} is

$$(X'_{n_2} - X'_{n_1}) \left[\sum_{j=n_1}^{n_2-1} (n-j)^{-1} \right]^{-1} \tag{19.53}$$

and its variance is

$$\left(\sum_{j=n_1}^{n_2-1} (n-j)^{-1} \right)^{-2} \left(\sum_{j=n_1}^{n_2-1} (n-j)^{-1} \right)^{-1} \sigma^2 \tag{19.54}$$

The optimal value of n_1 is always 1, whatever the values of n and n_2 .

Kulldorff (1962) considered the problem of choosing n_1, n_2, \dots, n_k to minimize $\text{Var}(\bar{\sigma})$ or $\text{Var}(\hat{\theta})$ for k fixed. He tabulated the optimal n_i 's and coefficients for small values of k and n . Earlier, Sarhan and Greenberg (1958) treated the asymptotic (large n) case (for θ known) giving the optimal percentiles $n_1/n, n_2/n, \dots, n_k/n$, for k fixed. These tables are reproduced by Ogawa (1962). Saleh and Ali (1966) and Saleh (1966) proved the uniqueness of the optimal selection and extended the results to censored cases.

The table of Zabransky, Sibuya, and Saleh (1966) is most exhaustive and covers uncensored and censored samples, finite and asymptotic cases for a wide range. Sibuya (1969) gave the algorithms for computing their tables, and unified previous results in simpler form.

(1963)]. Epstein (1962) has noted that the efficiency of the unbiased estimator based on $X'_r - \theta$ is never less than 96% if $r/n \leq \frac{1}{2}$, or 90% if $r/n \leq \frac{2}{3}$.

- 5. $k = 2$ (estimation from two order statistics X'_{n_1}, X'_{n_2}). The variance of $\hat{\sigma}$ is a minimum when n , is the nearest integer to $0.6386(n + \frac{1}{2})$ and n_2 is the nearest integer to $0.9266(n + \frac{1}{2})$ [Siddiqui (1963)].

For small samples Sarhan and Greenberg (1958) give the following optimal choices:

Sample Size (n)	2-4	5-7	8-11	12-15	16-18	19-21
n_1	$n - 1$	$n - 2$	$n - 3$	$n - 4$	$n - 6$	$n - 7$
n_2	n	n	n	n	$n - 1$	$n - 1$

If θ is not known, the optimal choices are different. Sarhan and Greenberg (1958) give the following optimal choices for n , and n_2 (with $k = 2$):

Sample Size (n)	2-6	7-10	11-15	16-20	21
n_1	1	1	1	1	1
n_2	n	$n - 1$	$n - 2$	$n - 3$	$n - 4$

The best (in fact only) linear unbiased estimator of a , using only X'_{n_1} and X'_{n_2} is

$$(X'_{n_2} - X'_{n_1}) \left[\sum_{j=n_1}^{n_2-1} (n - j)^{-1} \right]^{-1} \tag{19.53}$$

and its variance is

$$\left[\sum_{j=n_1}^{n_2-1} (n - j)^{-2} \right] \left[\sum_{j=n_1}^{n_2-1} (n - j)^{-1} \right]^{-2} \sigma^2. \tag{19.54}$$

The optimal value of n , is always 1, whatever the values of n and n_2 .

Kulldorff (1962) considered the problem of choosing n, n_2, \dots, n_k to minimize $\text{Var}(\hat{\sigma})$ or $\text{Var}(\hat{\theta})$ for k fixed. He tabulated the optimal n_i 's and coefficients for small values of k and n . Earlier, Sarhan and Greenberg (1958) treated the asymptotic (large n) case (for 8 known) giving the optimal percentiles $n_1/n, n_2/n, \dots, n_k/n$, for k fixed. These tables are reproduced by Ogawa (1962). Saleh and Ali (1966) and Saleh (1966) proved the uniqueness of the optimal selection and extended the results to censored cases.

The table of Zabransky, Sibuya, and Saleh (1966) is most exhaustive and covers uncensored and censored samples, finite and asymptotic cases for a wide range. Sibuya (1969) gave the algorithms for computing their tables, and unified previous results in simpler form.

Epstein (1962) gave a number of useful results. He pointed out that $X'_r - \theta$ is approximately distributed as $\frac{1}{2}(\sigma/r) \times (\chi^2$ with $2r$ degrees of freedom). Approximate confidence intervals for σ can be constructed on this basis. Epstein also gave formulas for the minimum variance unbiased estimators of θ and σ for the two-parameter distribution (19.1), based on X'_1, X'_2, \dots, X'_k . These are

$$\sigma^* = (k-1)^{-1} \sum_{j=1}^{k-1} (n-j)(X'_{j+1} - X'_j), \quad (19.55a)$$

$$\theta^* = X'_1 - n^{-1}\sigma^*; \quad (19.55b)$$

σ^* is distributed as $\frac{1}{2}\sigma(k-1)^{-1} \times [\chi^2$ with $2(k-1)$ degrees of freedom]. $100(1-a)\%$ confidence limits for σ are

$$\frac{2(k-1)\sigma^*}{\chi_{2(k-1), 1-\frac{a}{2}}^2} \quad \text{and} \quad \frac{2(k-1)\sigma^*}{\chi_{2(k-1), \frac{a}{2}}^2}.$$

$100(1-a)\%$ confidence limits for θ are

$$X'_1 - F_{2, 2(k-1), 1-\alpha} \sigma^* n^{-1} \quad \text{and} \quad X'_1 \quad (19.56)$$

(using the notation of Chapter 27, Section 1).

If only $X'_{k_1+1}, \dots, X'_{n-k_2}$ are to be used, the minimum variance unbiased estimators are

$$\sigma^* = (n - k_1 - k_2 - 1)^{-1} \sum_{j=k_1+1}^{n-k_2-1} (n-j+1)(X'_{j+1} - X'_j), \quad (19.57a)$$

$$\theta^* = X'_{k_1+1} - \sigma^* \sum_{j=0}^{k_1} (n-j)^{-1}; \quad (19.57b)$$

σ^* is distributed as $\frac{1}{2}\sigma(n - k_1 - k_2 - 1)^{-1} \times [\chi^2$ with $2(n - k_1 - k_2 - 1)$ degrees of freedom] and

$$\text{Var}(\theta^*) = \sigma^2 \left[\sum_{j=0}^{k_1} (n-j)^{-2} + (n - k_1 - k_2 - 1)^{-1} \left\{ \sum_{j=0}^{k_1} (n-j)^{-1} \right\}^2 \right]. \quad (19.58)$$

The minimum variance unbiased estimator (MVUE) of the reliability func-

tion based on X'_1, \dots, X'_k is

$$\hat{R}(t) = \begin{cases} \left(1 - \frac{t}{T_{k:n}}\right)^{k-1} & \text{if } t \leq T_{k:n}, \\ 0 & \text{if } t \geq T_{k:n}. \end{cases} \quad (19.59)$$

$[T_{k:n}]$ is defined in (19.45).

The mean square error of $\hat{R}(t)$ is

$$MSE(\hat{R}(t)) = \int_c^\infty \left(1 - \frac{c}{u}\right)^{2r-2} \gamma(u; r) du$$

where

$$\gamma(u; r) = \frac{1}{\Gamma(r)} u^{r-1} e^{-u},$$

$$c = \frac{t}{\sigma}$$

[Basu (1964)]. Based on past data, one may have a prior (guessed) value of a , say, that can be utilized for statistical inference. The so-called shrinkage estimators arising in this situation perform better than the MVUE if the value σ_0 is close to a . A preliminary test can be conducted to check the closeness of σ_0 to a . Chiou (1987) proposes incorporating a preliminary test on a , using an estimator of type

$$R_{PT}(t) = \begin{cases} \exp\left(-\frac{t}{\sigma_0}\right) & \text{if } H_0: \sigma = \sigma_0 \text{ is not rejected,} \\ \hat{R}(t) & \text{otherwise.} \end{cases} \quad (19.60)$$

Since $2T_{k:n}/\sigma$ has a χ^2 distribution with $2k$ degrees of freedom, H_0 is not rejected if

$$C_1 \leq \frac{2T_{k:n}}{\sigma_0} \leq C_2,$$

where C_1 (C_2) are the $\frac{\alpha}{2}$ lower (upper) percentage points of χ_{2k}^2 . Thus

$$\hat{R}_{PT}(t) = \begin{cases} \exp\left(-\frac{t}{\sigma_0}\right) & \text{if } C_1 \leq \frac{2T_{k:n}}{\sigma_0} \leq C_2, \\ \hat{R}(t) & \text{otherwise.} \end{cases} \quad (19.61)$$

Chiou (1987) provides optimal critical values for the preliminary test and their corresponding level of significance, based on the minimax regret criterion.

Alternatively, Chiou (1992) proposes the "shrinkage estimator"

$$\hat{R}_2(t) = \begin{cases} \omega \exp\left(-\frac{t}{\sigma_0}\right) + (1 - \omega)\hat{R}(t) & \text{if } C_1 \leq \frac{2T_{k:n}}{\sigma_0} \leq C_2 \\ \hat{R}(t) & \text{otherwise,} \end{cases} \quad (19.62)$$

where ω is a shrinkage coefficient suitably specified. Chiou provides a table of optimum values of shrinkage coefficient ω for $t/\sigma_0 = 0.25(0.25)2.0$ and $k = 4(2)10$ as well as critical values C_1 and C_2 for the preliminary test.

Zacks and Even (1966) compared the performance of MVUE and the maximum likelihood estimator in terms of mean square error for small samples. The MLE is more efficient than MVUE over the interval $0.5 < t/\sigma < 3.5$. Over the "effective intervals where σ_0/σ is in the vicinity of 1 [(0.7, 1.4) for $r = 4$ and $t/\sigma_0 = 2$ as an example], Chiou's (1992) shrinkage estimators are more efficient, but none of the estimators for $R(t)$ investigated so far is uniformly better than others over the whole possible range of σ/σ_0 ."

Cohen and Whitten (1988) discuss estimation of parameters in the case of progressively censored samples. Censoring is progressively carried out in k stages at times $\tau_1 < \tau_2 < \dots < \tau_j < \dots < \tau_k$. At j th stage of censoring, C_j sample specimens, selected randomly from the survivors at time τ_j , are removed. In addition we have n full-term observations and our sample consists of (X_1, X_2, \dots, X_n) plus k partial term observations $\{C_j\tau_j\}$ ($j \geq 1, \dots, k$). Thus $N = n + r$, where $r = \sum_1^k C_j$ ($C_j \geq 1$ corresponds to censoring and $C_j = 0$ to noncensoring), and the sum total (ST) term of all N observations in the sample is

$$ST = \sum_{i=1}^n X_i + \sum_{j=1}^k C_j \tau_j.$$

The modified maximum likelihood estimators (MMLEs) of σ and θ in the case of progressive censoring, obtained by solving

$$\frac{\partial \ln L}{\partial \sigma} = 0 \quad \text{and} \quad E[X'_1] = X'_1$$

are given by

$$\begin{aligned} \tilde{\sigma} &= \frac{ST - N\tilde{\theta}}{n} \\ \tilde{\theta} &= \frac{ST - NX'_1}{n - 1}. \end{aligned} \quad (19.63a)$$

Explicitly

$$\begin{aligned}\tilde{\sigma} &= \frac{ST - NX'_1}{n - 1}, \\ \tilde{\theta} &= \frac{nX'_1 - N^{-1}ST}{n - 1}.\end{aligned}\quad (19.63b)$$

(For the uncensored case $C_j = 0$, $n = N$, and $ST = n\bar{X}$.)

Estimation of parameters from general location-scale **families** (of which the two-parameter exponential distribution is a member) under progressive censored sampling was studied by Viveros and Balakrishnan (1994). They follow the classical arguments for conditional inference for location and scale parameters as expounded, for example, in Lawless (1982).

A modified hybrid censoring model was investigated by Zacks (1986). Let τ_0 be the fixed time at which the (Type I) censoring occurs. Let $X'_{k:n}$ denote the k th-order statistic of a sample of n i.i.d. random variables from the one-parameter exponential distribution (19.28).

Let $X_k^* = \min(X'_{k:n}, \tau_0)$. The recorded random variable is the time-censored k th-order statistic. Let $X_{k1}^*, \dots, X_{km}^*$ denote m i.i.d. random variables distributed as X_k^* . Zacks (1986) shows the existence and uniqueness of a MLE of σ based on the sample $X_{k,m}^* = (X_{k1}^*, \dots, X_{km}^*)$.

He also investigates the properties of the moment estimator (ME) that is the root of the equation in σ

$$\sigma \sum_{j=0}^{k-1} \frac{1}{n-j} [1 - B(j; n; e^{-\tau_0/\sigma})] = \bar{X}_k^* = m^{-1} \sum_{j=1}^m X_{kj}^*, \quad (19.64)$$

where $B(j; n; p)$ is the cdf of the binomial distribution with parameters (n, p) .

Numerical comparisons show that in the case of MLE "censoring has a dramatic effect on the possibility of estimating σ efficiently. The efficiency of the MLE drops to almost zero when σ is in the neighborhood of τ_0 ." The asymptotic relative efficiency of ME relative to MLE is an increasing function of $\tau_0/\sigma \equiv q$. When $\eta = 1$, the ARE of the ME is about 62%, whereas at $\eta = 3$ it is 99%. On the other hand, under censoring, the MLE is considerably more efficient than the ME when η is close to 1.

7.4 Estimation of Quantiles

Robertson (1977), in an important paper, develops estimation procedures for quantiles of the exponential distribution (19.28) such that mean square errors in the predicted distribution function is minimized. For complete random samples of size n , a particular quantile, represented as $K\sigma$, has estimators of the form $K^*\bar{X}$. The optimal estimator of $K\sigma$ (with squared error loss) is in

fact $K_0 \bar{X}$, where

$$K_0 = n \left[\frac{\exp\{K/(n+1)\} - 1}{2 - \exp\{K/(n+1)\}} \right]. \quad (19.65)$$

Its mean square error is

$$e^{-2K} - e^{-K} \left[2 - \exp\left\{ \frac{K}{n+1} \right\} \right]^{n+1} \quad (19.66)$$

For a linear estimator $\sum_{i=1}^n a_i X_i$, the mean square error is

$$\begin{aligned} & \int_0^\infty \cdots \int_0^\infty \{e^{-K} - e^{-\sum a_i x_i}\}^2 e^{-\sum x_i} dx_1 dx_2 \cdots dx_n \\ &= e^{-2K} - 2e^{-K} \prod_{i=1}^n (1 + a_i)^{-1} + \prod_{i=1}^n (1 + 2a_i)^{-1} \end{aligned} \quad (19.67)$$

where $\sigma = 1$ for convenience, yielding minimizing values

$$a_i = \frac{[\exp\{K/(n+1)\} - 1]}{2 - \exp\{K/(n+1)\}} \quad \text{for all } i \quad (19.68)$$

For $n < (K/\log 2) - 1$, this estimator will break down, and the optimum choice will be $K_0 = \infty$. [Indeed one cannot reasonably expect to estimate the 99% point ($K = 4.605$) using a sample of size 5 [$< (K/\log 2) - 1$].] Comparison of $K_0 \bar{X}$ with $K \bar{X}$ (the natural K) and $K_2 \bar{X}$ [chosen to make $\exp(-K_2 \bar{X})$ an unbiased estimator of $\exp(-K\sigma)$] has been carried out by Robertson (1977). For small n or large K (extreme percentiles) there are considerable differences among the three estimators.

To estimate $K\sigma$ by means of a single order statistic the estimator is of the form $K_3 X'_r$, where the optimal choice for large n turns out to be $r \doteq an$ with $a = 0.79681213$ (the positive root of equation $e^{-2a} = 1 - a$) and

$$K_3 = \frac{K}{2a} + \frac{3K^2 - 2(1 - a)K}{16a^2(1 - a)n} + O(n^{-2}). \quad (19.69)$$

For large n , $K_3 X'_r$ has efficiency approximately 65% [$\doteq 4a(1 - a)\%$] relative to $K_0 \bar{X}$, the optimal estimator based on the complete sample.

7.5 Bayesian Estimation

One-Parameter Exponential Distributions

In Bayesian estimation prior distributions are often assigned to the hazard rate ($A = \sigma^{-1}$) rather than to the expected value (σ). We therefore use the

pdf

$$p_X(x|\lambda) = \lambda e^{-\lambda x} \quad (x > 0; \lambda > 0). \quad (19.28)''$$

If the prior on A is uniform over $(0, M)$, then the posterior density of λ , given a random sample X_1, X_2, \dots, X_n is

$$\frac{\lambda^n \exp(-\lambda \sum_{i=1}^n X_i)}{\int_0^M \lambda^n \exp(-\lambda \sum_{i=1}^n X_i) d\lambda}, \quad 0 < \lambda < M. \quad (19.70)$$

For large M this is approximately a gamma $(n + 1, \{\sum_{i=1}^n X_i\}^{-1})$ distribution with pdf

$$\frac{(\sum_{i=1}^n X_i)^{n+1} \lambda^n}{\Gamma(n+1)} \exp\left(-\lambda \sum_{i=1}^n X_i\right). \quad (19.71)$$

If this posterior pdf is used as a new prior, and a random sample Y_1, Y_2, \dots, Y_m obtained, the new posterior is of the same form as (19.71), with n increased to $(n + m)$ and $\sum_{i=1}^n X_i$ increased by $\sum_{j=1}^m Y_j$. Thus the gamma prior is a "natural conjugate" prior for A [see Barlow and Proschan (1979)].

Waller et al. (1977) develop an interesting and potentially fruitful approach to determination of the parameters of a gamma (a, β) prior on A in the pdf (19.28)'', based on values of

$$\Pr[\lambda < \lambda_j] = p_j, \quad j = 1, 2; \lambda_1 < \lambda_2,$$

decided upon by a researcher. Extensive tables and graphs are provided giving values of a and β for selected values A , and p_0 for which

$$\Pr[\lambda < A] = p_0. \quad (19.72)$$

By overlapping transparencies of graphs for (A, p_1) and (A, p_2) , appropriate values of a and β can be determined. If (19.72) is satisfied then λ_0/β is constant for given a . For small values of a , Waller et al. (1977) recommended the approximation $A \sim \beta p^{1/\alpha}$.

For situations where only the first k "failures" are observed, with k specified in advance (Type II censoring), the MLE of A is

$$\hat{\lambda} = kT_k^{-1}, \quad (19.73)$$

with $T_k = \sum_{i=1}^k X_i + (n - k)X'_k$. With a gamma (a, b^{-1}) prior on A , we arrive at a posterior gamma $(a + k, (b + T_k)^{-1})$ distribution of A . Similar results are obtained for truncated sampling (Type I censoring), and also for inverse binomial sampling (when a failed or truncated unit is replaced).

If λ^{-1} ($= \sigma$) is ascribed a "uniform" distribution, the posterior distribution for σ would have pdf

$$\frac{(\sum_{i=1}^n X_i)^{n-1}}{\Gamma(n-1)} \left(\frac{1}{\sigma}\right)^n \exp\left(-\frac{1}{\sigma} \sum_{i=1}^n X_i\right), \quad \sigma > 0, \quad (19.74)$$

which is called the inverted gamma distribution.

Since an inverted gamma prior on σ also results in an inverted gamma posterior distribution for σ , it is a natural conjugate in this situation. This is not surprising since, if A has a gamma distribution, σ ($= \lambda^{-1}$) has an inverted gamma distribution.

Bayesian estimation of the reliability function

$$R(t) = \Pr[X > t] = \exp\left(-\frac{t}{\sigma}\right) \quad (19.29)'$$

has been studied by **Sinha** and **Guttman (1976)**. Assuming a so-called vague Jeffreys's prior density (proportional to σ^{-1}) on σ , and using only the first k order statistics, they show that the posterior density of $R(t)$ is

$$\frac{S_k^k}{\Gamma(k)} \{-\log R(t)\} \{R(t)\}^{S_k-1}, \quad R(t) \geq 0, \quad (19.75)$$

where $S_k = T_k/t$, which can be regarded as the "cumulative life per unit time" up to time t . The posterior density for σ in this situation is

$$\frac{T_k^k}{\Gamma(k)} \sigma^{-(k+1)} \exp\left(-\frac{T_k}{\sigma}\right). \quad (19.76)$$

See also **Shoukri (1983)** for further discussions.

Villén-Altamizano (1990) used a gamma (p, a^{-1}) prior for A ($= \sigma^{-1}$), obtaining the posterior density of $R(\mathbf{1}) = \exp(-\sigma^{-1})$ given the results (W_j, I_j) ($j = 1, \dots, n$) from a randomly censored sample of size n with lifetimes $\{X_j\}$ and censoring times $\{Y_j\}$, where

$$W_j = \min(X_j, Y_j)$$

and

$$I_j = I(X_j \leq Y_j) = \begin{cases} 1 & \text{if } X_j \leq Y_j, \\ 0 & \text{if } X_j > Y_j, \end{cases}$$

in the form

$$p_R(r|W, I) = \frac{(a + W)^{p+I}}{\Gamma(p + 1)} r^{a+W-1} (-\log r)^{p+I-1}, \quad 0 < r < 1, \quad (19.77)$$

where $W = \sum_{j=1}^n W_j$ and $I = \sum_{j=1}^n I_j$.

The posterior expected value is

$$\tilde{R}_2 = E[R|W, I] = \left(\frac{a + W}{a + W + 1} \right)^{p+I}. \quad (19.78)$$

This is the Bayesian estimator (optimal for quadratic loss). The mode of the posterior distribution is

$$\tilde{R}_3 = \begin{cases} \exp\left(-\frac{p + I - 1}{a + W - 1}\right) & \text{if } W > 1 - a, \\ 0 & \text{otherwise.} \end{cases} \quad (19.79)$$

Two-Parameter Exponential Distributions

For the two-parameter distribution

$$p_X(x) = \sigma^{-1} \exp\left\{-\frac{x - \theta}{\sigma}\right\}, \quad x \geq \theta > 0; \sigma > 0, \quad (19.1)'$$

Sinha and Guttman (1976) ascribed a joint prior to θ and σ that is proportional to σ^{-a} ($a > 0$), and obtained the following results for Type I censoring using the first k order statistics in a random sample of size n . The posterior expected values (Bayes estimators) of θ and σ are

$$E[\theta|\mathbf{X}] = \frac{C_k \{n(k + a - 3)X'_1 - C_{k-1}^{-1}S'_k\}}{n(k + a - 3)}, \quad (19.80)$$

$$E[\sigma|\mathbf{X}] = \frac{C_k S'_k}{C_{k-1}(k + a - 3)}, \quad (19.81)$$

where

$$S'_k = \sum_{i=1}^k (X'_i - X'_1) + (n - k)(X'_k - X'_1),$$

$$C_k = \left\{ 1 - \left(1 + \frac{nX'_1}{S'_k} \right)^{-(k+a-2)} \right\}^{-1}.$$

For the reliability function

$$R(t) = \exp\left\{-\frac{t - \theta}{\sigma}\right\},$$

we have

$$E[R(t)|\mathbf{X}] = \frac{n}{n+1} C_k \left\{ \left(1 + \frac{t - X'_1}{S_k} \right)^{-(k+a-2)} - \left(1 + \frac{t + nX'_1}{S_k} \right)^{-(k+a-2)} \right\}, \quad t > X'_1. \quad (19.82)$$

This estimator was found to be reasonably robust with respect to a . The posterior distribution of $R(t)$ is quite complicated [see also Pierce (1973)]. Trader (1985) used a truncated normal prior.

7.6 Miscellaneous

Maximum probability estimation (MPE) is a method of estimation proposed by Weiss and Wolfowitz (1967) [see also Weiss (1985)]. The essential idea is to seek an interval of predetermined length 1, say, that maximizes the integral of the likelihood function over the interval. In the case of the two-parameter exponential distribution (19.1), the analysis for estimation of δ takes an especially simple form. Given a random sample of size n with values X_1, \dots, X_n , the likelihood function is

$$L(\mathbf{X}|\theta, a) = \begin{cases} \exp\left\{-\frac{\sum_{i=1}^n (X_i - \theta)}{\sigma}\right\} & \sigma > 0, \theta \leq \min X_i = X'_1, \\ 0, & \theta > X'_1. \end{cases} \quad (19.83)$$

Since $L = 0$ for $8 > X'_1$ and L is an increasing function of θ for $8 \leq X'_1$, the MPE interval of length l is

$$(X'_1 - l, X'_1) \tag{19.84}$$

(whatever the value of a). Blyth (1982) followed this analysis by considering choice of attractive values for l , if $(X'_1 - \frac{1}{2}l)$ is used as a point estimator of 8 . He found that

1. for minimum mean square error, $\frac{1}{2}l = n^{-1}\sigma$,
2. for minimum absolute error, $\frac{1}{2}l = n^{-1}a \log 2$.

Introducing a quadratic loss function, Arnold (1970), and independently Zidek (1973) and Brewster (1974), derived optimal estimators of a for cases where θ is unknown. The MLE of a , $\hat{\sigma} = \bar{X} - X'_1$, is also the best affine equivariant estimator (BAEE) of a . However, the estimator is inadmissible for a wide class of loss functions satisfying conditions of differentiability and bowl-shapedness. Modified estimators, aimed at reducing this drawback, were suggested by the above authors.

Estimators of the ratio ($\delta = \sigma_2/\sigma_1$) of scale parameters of two distributions π_1, π_2 of form (19.1) with values (σ_j, θ_j) ($j = 1, 2$) for the parameters (σ, θ) , respectively, were investigated by Madi and Tsui (1990). Suppose that there are two independent ordered random sample values

$$X'_{11} \mathbf{I} X'_{12} \leq \dots \leq X'_{1n_1} \text{ from } \pi_1$$

and

$$X'_{21} \mathbf{I} X'_{22} \leq \dots \leq X'_{2n_2} \text{ from } \pi_2.$$

With loss function $W(\delta, \delta^*)$ whence δ^* is an estimator of δ , the statistics

$$(\bar{X}_1 - X'_{11}, \bar{X}_2 - X'_{21}) \left(\frac{X'_{11}}{\bar{X}_1 - X'_{11}}, \frac{X'_{21}}{\bar{X}_2 - X'_{21}} \right)$$

are sufficient for the four parameters a_1, a_2, θ_1 , and θ_2 . Assuming that $W(\delta, \delta^*) = W(\delta^*/\delta)$, the BAEE estimator is

$$\delta^* = \begin{cases} \frac{\bar{X}_1 - X'_{11}}{\bar{X}_2 - X'_{21}} \min \left[c_0, c_1 \frac{\bar{X}_1}{\bar{X}_1 - X'_{11}} \right] & \text{if } X'_{11} > 0, \\ \frac{\bar{X}'_1 - X'_{11}}{\bar{X}_2 - X'_{21}} c_0 & \text{if } X'_{11} \leq 0, \end{cases} \tag{19.85}$$

where c_0 minimizes $\int_0^\infty t^{n_1-2} W(ct) (1 + n_1 t/n_2)^{-(n_1+n_2-2)} dt$ and c_1 minimizes $\int_0^\infty t^{n_1-1} W(ct) (1 + n_1 t/n_2)^{-(n_1+n_2-1)} dt$ provided that

1. W is differentiable,
2. $W(y)$ is bowl-shaped [i.e., $W(y)$ decreases with y for $y \leq y_0$, increases for $y > y_0$], attaining its minimum value at $y = 1$,
3. if $\sigma_1 = \sigma_2 = 1$, then

$$E \left[\left| W' \left(c \frac{\bar{X}_1 - X'_{11}}{\bar{X}_2 - X'_{21}} \right) \right| \right] \text{ is finite for all } c > 1.$$

A "smooth" version of δ^* can be obtained by replacing the multiplier of $(\bar{X}_1 - X'_{11})/(\bar{X}_2 - X'_{21})$ by a more refined function. The resulting estimator has

$$c_0 = 1 - 3n_2^{-1},$$

$$c_1 = n_2^{-1}(n_1 + 1)^{-1} n_1(n_2 - 3) \quad \text{for } n_2 > 3 \quad \text{and } W\left(\frac{\delta^*}{\delta}\right) = 1 - \left(\frac{\delta^*}{\delta}\right)^2; \quad (19.86a)$$

$$c_0 = n_2^{-1}(n_1 - 1)^{-1} n_1(n_2 - 2),$$

$$c_1 = 1 - 2n_2^{-1} \quad \text{for } W\left(\frac{\delta^*}{\delta}\right) = \left(\frac{\delta^*}{\delta}\right) - \log\left(\frac{\delta^*}{\delta}\right) - 1. \quad (19.86b)$$

Effects of Outliers

The effects of outliers on the estimation of α in the one-parameter case (19.28) has received considerable attention in the literature since the early 1970s. Among the first studies were those of Kale and Sinha (1971) and Joshi (1972). They initially studied situations where $n - 1$ independent random variables each had distribution (19.28), while one further random variable (the "outlier") has a pdf of the same form, but with α replaced by σ/α .

For situations where the identity of the outlier is not known (and the probability that X_j is the outlier is n^{-1} for $j = 1, \dots, n$), Kale and Sinha (1971) suggest consideration of the class of estimators (for σ):

$$\tilde{\sigma}_k = \frac{T_k}{k + 1}, \quad (19.87)$$

where T_k is defined as in (19.73). Joshi (1972) tabulates optimum values for k , minimizing the mean square error. If $k = n$ [with $\tilde{\sigma}_n = \sum_{i=1}^n X_i / (n + 1)$], we have

$$\text{MSE}(\tilde{\sigma}_n/\sigma) = (n + 1)^{-1} + 2(\alpha^{-1} - 1)^2(n + 1)^{-2}, \quad (19.88)$$

where σ/α is the mean of the outlier.

Generally, the optimum k has to be found numerically. Joshi (1972) found that for $0.55 \leq a \leq 1$ the optimal value of k is n . Later [Joshi (1988)] he found that the optimal value of k is fairly stable over wide ranges of values of a and suggested, as a rule of thumb,

Take $k = n$ for $0.5 \leq a < 1.0$

Take $k = n - 1$ for $0.25 \leq a < 0.5$

Take $k = n - 2$ for $0.05 \leq a \leq 0.25$.

Chikkagoudar and Kunchur (1980) suggest the estimator

$$V = \sum_{j=1}^n \left(\frac{1}{n} - \frac{2j}{n^2(n+1)} \right) X_j' \quad (19.89)$$

Comparison between $\tilde{\sigma}_k$ and V shows that neither estimator dominates the other (in terms of mean square error loss). [T_k (for optimal k) is superior for values of a near 0 or 1.] Balakrishnan and Barnett (1994) have recently proposed some generalized estimators of this form and discussed their properties.

From (1991) has studied robust estimators that are general linear functions of order statistics, aiming to obtain optimal (or near-optimal) values for the coefficients c_j in $\sum_{j=1}^n c_j X_j'$, for various values of α and n . Optimal choice calls for rather complicated calculations, so From advocates use of simplified estimators with very nearly optimal mean square error, which is always less than those of $\tilde{\sigma}_k$ and V . This estimator uses

$$c_j = \begin{cases} d_1 & \text{for } 1 \leq j \leq m, \\ d_2 & \text{for } m+1 \leq j \leq n, \end{cases}$$

with $d_1 > d_2$ and appropriate integer m . Tables are provided giving optimal values of (d_1, d_2, m) for $n = 2(1)15(5)30(10)50$ and $a = 0.05, 0.15$.

If the value of a is known, Joshi (1972) suggests using the estimator

$$(n-1 + \alpha^{-1})\tilde{\sigma}_{n-1}/n. \quad (19.90)$$

He also suggests estimating a (if it is unknown) by an iterative procedure, solving the equation

$$n\tilde{\sigma}_n = (n-1 + \alpha^{-1})\tilde{\sigma}_{n-1} \quad (19.91)$$

to estimate a , and then using optimal k to get a new estimator $\tilde{\sigma}_n$ of a , and so on; see also Jevanand and Nair (1993).

Through a systematic study of order statistics from independent and non-identically distributed exponential random variables, Balakrishnan (1994)

has established several recurrence relations for the single and the product moments of order statistics. These results will enable the computation of all the single and product moments of order statistics arising from a sample containing p outliers (recursively in p by starting with $p = 0$ or the i.i.d. case). Through this recursive computational process, Balakrishnan (1994) has extended the work of Joshi (1972) to the p -outlier case and determined the optimal trimmed and Winsorized estimators. The robustness properties of various linear estimators, including the Chikkagoudar–Kunchur estimator in (19.89), have also been examined by Balakrishnan (1994).

Veale (1981) has investigated cases where the identity of the outlier is known. This of course leads to much simpler analysis.

Returning to uncontaminated (no-outliers) data, the estimation of a in the standard (one-parameter) case (19.28), subject to the condition that a is no less than a_0 , was studied by Gupta and Basu (1980). [Related cases $\sigma < a_0$, or a in (a_0, a_1) can be analyzed similarly by using appropriate transformations.]

Natural estimators of a (given $\sigma > \sigma_0$) are

$$\hat{a} = \max(\bar{X}, \sigma_0) \quad (\text{the MLE}) \quad (19.92)$$

or

$$\hat{a}^* = n^{-1} \sum_{j=1}^n \max(X_j, \sigma_0). \quad (19.93)$$

Numerical studies show that the mean square error (MSE) of \hat{a}^* is less than that of \hat{a} for small n , when σ_0/σ is small. Indeed, even for $n = 30$, \hat{a}^* has the smaller MSE if $\sigma_0/\sigma \leq 0.3$.

Estimation of the probability $P = \Pr\{Y < X\}$, where X and Y are independent exponential variables, has received prominent attention in the literature. The common interpretations of this probability is a measure of the reliability or performance of an item of strength Y subject to a stress X , or probability that one component fails prior to another component of some device.

Tong (1974, 1975) obtained the uniformly minimum variance unbiased estimator (UMVUE) of P when X and Y are independent one-parameter exponential (19.28) variables. Kelley, Kelley, and Schucany (1976) derived the variance of the UMVUE of P . Beg (1980) obtained the UMVUE of P when X and Y have two-parameter exponential (19.1) distributions with unequal scale and location parameters. Gupta and Gupta (1988) obtained the MLE, the UMVUE, and a Bayesian estimator of P when the location parameters are unequal but there is a common scale parameter. Bartoszewicz (1977) tackled the problem in the exponential case for different types of censoring. Reiser, Faraggi, and Guttman (1993) discuss the choice of sample sizes for the experiments dealing with inference on $\Pr\{Y < X\}$ in an acceptance

sampling theory framework with exponential variables. Most recently Bai and Hong (1992) revisited the problem, obtaining the UMWE of P with unequal sample sizes when X and Y are independent two-parameter exponential random variables with an unknown common location parameter. Kocherlakota and Balakrishnan (1986) have discussed one-sided as well as two-sided acceptance sampling plans based on Type-II censored samples.

If X and Y are independent one-parameter exponential (19.28) random variables with hazard rates (σ^{-1}) λ and μ , respectively, then

$$P = \Pr[Y < X] = \mu(\lambda + \mu)^{-1}. \tag{19.94}$$

Given two independent random samples X_1, \dots, X_m and Y_1, \dots, Y_n , the MVUE of P is

$$P^* = \begin{cases} \sum_{j=0}^{m-1} (-1)^j \frac{(m-1)^{(j)}}{n^{[j]}} \left(\frac{n\bar{Y}}{m\bar{X}}\right)^j & \text{if } n\bar{Y} \leq m\bar{X}, \\ 1 - \sum_{j=0}^{n-1} (-1)^j \frac{(n-1)^{(j)}}{m^{[j]}} \left(\frac{m\bar{X}}{n\bar{Y}}\right)^j & \text{if } n\bar{Y} > m\bar{X}. \end{cases} \tag{19.95}$$

[Tong (1974)] where $a^{(b)} = a(a-1)\dots(a-b+1)$, $a^{[b]} = a(a+1)\dots(a+b-1)$.

If μ is known so that there is no need to sample for Y values, the MVUE is

$$P^{**} = \sum_{j=0}^{m-1} (-1)^j (m-1)^{(j)} (m\mu\bar{X})^{-j} + (-1)^m (m\mu\bar{X})^{-m+1} \exp(-m\mu\bar{X}). \tag{19.96}$$

If there is Type II censoring, with only the first g order statistics X'_1, \dots, X'_g of X and the first h order statistics Y'_1, \dots, Y'_h of Y being available, the UMVUE of P is

$$\hat{P}^* = \begin{cases} \sum_{j=0}^{g-1} (-1)^j \frac{(g-1)^{(j)}}{h^{[j]}} \left(\frac{H}{G}\right)^j & \text{if } H \leq G, \\ 1 - \sum_{j=0}^{h-1} (-1)^j \frac{(h-1)^{(j)}}{g^{[j]}} \left(\frac{G}{H}\right)^j & \text{if } H > G, \end{cases} \tag{19.97}$$

where $G = \sum_{j=1}^g X'_j + (m-g)X'_g$, $H = \sum_{j=1}^h Y'_j + (n-h)Y'_h$. For $g = m$ and $h = n$, (19.97) reduces to (19.95). If each failed item is replaced immediately

by a new item having the same lifetime distribution, the UMVUE of P is obtained from (19.97) by replacing G by mX'_g and H by nY'_h .

The maximum likelihood estimator of P (given complete sample values) is

$$\hat{P} = \frac{\bar{X}}{\bar{X} + \bar{Y}}. \quad (19.98)$$

If $m = n$ the MLE is unbiased ($E[\hat{P}] = \mu(\lambda + \mu)^{-1}$), and hence it is also the UMVUE of P , as noted by Chious and Cohen (1984). Expressions for the UMVUE of P for the general case of two-parameter exponential random variables are complex, even in the case of common (unknown) location parameter.

However, the MLE of P is given by

$$\hat{P} = \frac{\bar{X} - T}{\bar{X} + \bar{Y} - 2T}, \quad (19.99)$$

where $T = \min(\mathbf{X}, \mathbf{Y}) = \min(X'_1, Y'_1)$ is the maximum likelihood estimator of the common location parameter. As $m, n \rightarrow \infty$, with $m/n \rightarrow \gamma$, asymptotically

$$\sqrt{n}(\hat{P} - P) \xrightarrow{d} N(0, \sigma^2), \quad (19.100)$$

where $\sigma^2 = P^2(1 - P)^2\{\gamma(1 - \gamma)\}$ and the \hat{P} and the UMVUE are asymptotically equivalent in this case.

In view of (19.94), the problem of choice of sample sizes for estimating P with specified accuracy is equivalent to the solution to the sample size problem provided by Reiser, Faraggi, and Guttman (1993) for the ratio of two exponential scale parameters. Given P_1, a, P_2, β with $0 < P_2 < P_1 < 1$, $0 < a < 1$, $0 < \beta < 1$, it is required to find an acceptance rule of the form $P > P_c$, with m and n such that (1) if $P = P_1$, the probability of acceptance is $1 - a$, and (2) if $P = P_2$, the probability of acceptance is β . In this case m and n must satisfy

$$\frac{F_{2n, 2m; \alpha}}{F_{2n, 2m; (1 - \beta)}} = \frac{P_2}{P_1}, \quad (19.101)$$

where $F_{2n, 2m; \alpha}$ is the α percentage point of the $F_{2n, 2m}$ distribution.

When a random sample of size n has been censored by omission of the greatest $n - k$ observed values, it may be of interest to estimate (predict) the

value of a specific one of the omitted values X'_r , say ($r > k$). Lawless (1971) used the pivotal variable

$$G_1 = \frac{X'_r - X'_k}{T_k} \quad [T_k \text{ as defined in (19.73)}] \quad (19.102)$$

to obtain the upper $100(1 - \alpha)\%$ prediction limit (UPL),

$$\text{UPL}(X'_r) = X'_k + g_{1,1-\alpha} T_k \quad (19.103)$$

where $\text{Pr}[G_1 \leq g_{1,1-\alpha}] = 1 - \alpha$. The cdf of G_1 is

$$\begin{aligned} \text{Pr}[G_1 \leq g] &= \frac{k}{B(r-k, n-r+1)} \\ &\times \sum_{i=1}^{r-k-1} \binom{r-k-1}{i} (-1)^i (n-r+i+1)^{-1} \\ &\times \{1 + (n-r+i+1)g\}^{-k}. \end{aligned} \quad (19.104)$$

Lingappaiah (1973) suggested using

$$G_2 = \frac{X'_r - X'_k}{X'_k} \quad (19.105)$$

in place of G_1 , noting that these would lead to simpler calculations and that X'_k contains "all the prior information" about X'_r . However, Kaminsky (1977) pointed out that this is only true if σ is known. He also noted that the probability that the UPL based on G_1 exceeds that based on G_2 is close to (but below) 0.5 in a number of representative cases. Furthermore he showed that the asymptotic probability (as $n \rightarrow \infty$) that the length of predictor interval based on G_2 exceeds that based on G_1 is zero.

For the two-parameter distribution (19.1) similar procedures can be followed, noting that the variables $X'_i - X'_1$ are distributed as order statistics from a random sample of size $n - 1$ from the distribution (19.28). Likeš (1974) extends Lawless's (1971) treatment to this case, using the statistic

$$G'_1 = \frac{X'_r - X'_k}{T'_k} \quad (19.106)$$

with $T'_k = \sum_{i=2}^k X'_i + (n-k)X'_k - (n-1)X'_1$. Tables of quantiles of G'_1 were constructed by Likeš and Nedělka (1973). Further results on these lines were obtained by Lawless (1977), and later incorporated in his important textbook,

Lawless (1982). Prediction intervals under "hybrid censoring"—termination when either k "failures" have occurred, or at a fixed time T , whichever comes first—have been studied by Ebrahimi (1992).

Sometimes, it is desired to "predict" statistics based on a *future* random sample from the same exponential population. If all observed values in the original sample $(X'_1 \leq \dots \leq X'_{n_1})$ are available the (minimum variance unbiased) estimator of the s th order statistic (Y'_s) in a future sample of size n_2 is in fact the best linear unbiased estimator.

A predicted interval for the range of a future sample has been constructed by Colangelo and Patel (1992), using the cdf of the ratio (W_2/W_1) of ranges of independent random samples of sizes n_1 and n_2 . We have

$$\begin{aligned} \Pr \left[\frac{W_2}{W_1} \leq y \right] &= (n_1 - 1) \int_0^\infty e^{-x} (1 - e^{-x})^{n_1 - 2} (1 - e^{-yx})^{n_2 - 1} dx \\ &= (n_1 - 1) \sum_{i=0}^{n_1 - 2} \sum_{j=0}^{n_2 - 1} \binom{n_1 - 2}{i} \binom{n_2 - 1}{j} (-1)^{i+j} (1 + i + jy)^{-1}. \end{aligned} \tag{19.107}$$

The authors provide tables of value K_γ such that $\Pr\{(W_2/W_1) \leq K_\gamma\} = \gamma$ for $n_1, n_2 = 5(5)25$ and $y = 0.005, 0.001, 0.025, 0.05, 0.1, 0.9, 0.95, 0.975, 0.99, 0.995$. From these tables $100(1 - \alpha_1 - \alpha_2)\%$ prediction intervals $(K_{\alpha_1}W, K_{1-\alpha_2}W)$ can be constructed.

Evans and Nigm (1980) [see also Dunsmore (1974)] use Bayesian methods to obtain a predicted interval for X'_s , based on a Type I censored data (X'_1, \dots, X'_k) ($k < s$). They point out that with the Bayesian approach it is easy to take into account prior information on the value of θ [in (19.1)] such as $\theta > 0$.

Dunsmore's (1974) **result**, which does not allow for the condition $8 > 0$, may serve as a reasonably good approximation even when the true underlying distribution is the left-truncated **exponential**, since in typical life-testing situations the amount of probability given to negative X 's using Dunsmore's approach is small. Dunsmore's (1974) **results**, which do not impose positivity constraint, can be used as starting values in an iterative solution and in many cases may provide an adequate approximation.

8 CHARACTERIZATIONS

In the preparation of this **section**, some 200 works published on this subject during the last 35 years [from Fisz (1958) onward] have been studied. These include three monographs—Galambos and Kotz (1978), Azlarov and Volodin

(1986) and Kakosyan, Klebanov, and Melamed (1984)—and the survey of Kotz (1974). The stream of publications shows no signs of drying up. We are highly impressed by the ingenuity displayed in much of the work on this topic, though we must admit to having some doubts on adequate justification for publishing some of it. It is of course impossible to mention all the published results, and the inevitable choices presented considerable difficulties. We would like to make it clear that lack of citation of a result is not necessarily indicative of assessment of lesser value, on our part, and certainly not in any objective sense.

The main criteria for inclusion were chronological novelty (post 1978) and evidence of development of the four basic types of characterization delineated in the Galambos and Kotz (1978) monograph. We believe the latter is the clearest (most "transparent") available system of classification, enabling us to distinguish, in many cases, among overlapping, albeit independent, results. Our sincere apologies go to researchers whose names are not mentioned or whose contributions are included only in part.

We have also attempted to include new types of characterizations, developed since 1978, although, in our opinion, these constitute only a minority in the flood of recently published results. For readers' convenience we produce here—with minor modifications—the four distinct **types** of characterizations presented in Galambos and Kotz (1978), ignoring some mathematical niceties. See Table 19.1.

Table 19.1 A Dictionary of Characterizations of the Exponential Distribution

Mathematical Properties	Statistical Interpretation
I. $\bar{F}(x_1 + x_2) = \bar{F}(x_1)\bar{F}(x_2)$ for $x_1, x_2 > 0$	Lack of memory property
II. $\bar{F}(nx) = \{\bar{F}(x)\}^n$ for $n \geq 1, x \geq 0$	$nX_1 \stackrel{d}{=} X$ (characterization in terms of the minimum value in random sample of size n)
III. $\int_z^\infty \bar{F}(x) dx = \bar{F}(z)$ for $z \geq 0$ and successive iterations of this integral equation	Characterizations in terms of truncated distributions, the constancy of conditional expectations, conditional variances, and conditional higher moments
IV. $\bar{F}'(x) = c\bar{F}(x)$ for $x \geq 0$	Constancy of the hazard rate

Remark

In a substantial number of papers, characterizations in terms of independence of order statistics and some other relations between them are directly

reduced to property I in Table 19.1 via the property

$$\left\{ \frac{\bar{F}(x+u)}{\bar{F}(x)} \right\}^n \quad \text{is independent of } x \text{ for all } n \geq 1, u \geq 0.$$

The underlying tool (in many cases) is the logarithmic version of the celebrated Cauchy functional equation

$$f(x+y) = f(x)f(y), \quad \forall x, y \geq 0 \quad (19.108)$$

or its more abstract equivalent, the Choquet-Deny equation. This is especially true in type I characterizations.

The major part of the edifice of characterizations of exponential distributions is rooted, in the final analysis, in this equation, or in its integral form, although very often in a hardly recognizable guise. Once again we note that what follows is a condensed account of a selective catalog of characterizations, motivated by two (occasionally conflicting) aims—emphasizing the more recent results and assessing the (potential) applicability of these results in practical situations.

There are quite severe restraints on size, since this is just one section of a volume containing ten chapters. We have also kept in mind the aim of reflecting, and reporting objectively on, the "state of the art" in statistical distribution theory in the last decade of the twentieth century. The results are presented, more or less, in chronological order, and we have tried to hint at mathematical tools used in their derivation. The close relationship between exponential and Poisson distributions is glossed over in this section. Some relevant characterizations are sited in Chapter 4 (on Poisson distributions), and other results relating to exponential distributions appear in Chapter 6 (on negative binomial, including geometric, distributions).

8.1 Characterizations Based on Lack of Memory and on Distributions of Order Statistics

The lack of memory property is identical with the constancy of hazard rate property (group IV) provided that the existence of a density [absolute continuity of $F_X(x)$] is assumed, so we will not treat the latter separately. We will, however, include in this subsection characterizations based on distributions of order statistics. We now consider extensions of the simple lack of memory property as characterizations of exponential distributions.

We first discuss conditions in terms of *relevation* functions. The earliest concept of this kind introduced by Krakowski (1973) in order to represent the distribution of the time T to failure of the *second* component in a system, where each item is replaced on failure by an item of the *same age*. If the lifetime cdf of each item is $F_X(x)$, with $F_X(0) = 0$, and the density $p_X(x) = F'_X(x)$ exists, the relevation cdf is

$$F_T(t) = \Pr[T \leq t] = \int_0^t p_X(x) \left\{ 1 - \frac{\bar{F}_X(t)}{\bar{F}_X(x)} \right\} dx. \quad (19.109)$$

The similarity is apparent to the cdf of the convolution of two X 's (corresponding to replacement by a *new* item), which is

$$\int_0^t p_X(x) \{1 - \bar{F}_X(t - x)\} dx. \quad (19.110)$$

The two cdfs are in fact identical if $F_X(x)$ is of form (19.28). Under certain mild assumptions on $F_X(x)$, the converse is also true.

In fact, if (19.109) and (19.110) are identical, or equivalently if

$$\bar{F}_X(t) \int_0^t p_X(x) \{ \bar{F}_X(x) \}^{-1} dx = \int_0^t p_X(x) \bar{F}_X(t - x) dx, \quad (19.111)$$

then provided that $F_X(x)$ is absolutely continuous $F_X(x) = 1 - e^{-x/\sigma}$.

For the case where the replacement item has lifetimes X_2 with a cdf $F_{X_2}(x)$ differing from $F_{X_1}(x)$, Grosswald, Kotz, and Johnson (1980) and Westcott (1981), among others, extend (19.111) to

$$\bar{F}_{X_1}(t) \int_0^t p_X(x) \{ \bar{F}_{X_2}(x) \}^{-1} dx = \int_0^t p_X(x) \bar{F}_{X_2}(t - x) dx. \quad (19.112)$$

If $F_{X_2}(x)$ is continuous and $F_{X_1}(x)$ is absolutely continuous, then $F_{X_2}(x) = 1 - e^{-x/\sigma}$ whatever $F_{X_1}(x)$ may be. Rao and Shanbhag (1986) show that this result holds even under less stringent conditions than continuity of $F_{X_2}(x)$.

Ahsanullah (1976, 1977, 1978a, b) considers the following equation:

$$\int_0^\infty p_X(x) \left[\left\{ \frac{\bar{F}_X(x+z)}{\bar{F}_X(x)} \right\} - \bar{F}(z) \right] dx = 0. \quad (19.113)$$

This can be regarded as an "integrated" lack of memory condition. It is

clearly satisfied for exponential distributions of type (19.28) since $\bar{F}_X(x) = e^{-x/\sigma}$ results in $\bar{F}_X(x+z)/\bar{F}_X(x) = e^{-z/\sigma} = \bar{F}_X(z)$. Conditions under which the converse also holds are more difficult to establish than those sufficing for (19.111) and (19.112). Grosswald and Kotz (1981), and also Shimizu (1978), found that satisfaction of the condition

$$\lim_{x \rightarrow \infty} e^{-bx} \bar{F}''(x) = 0 \quad \text{for some } b > 0$$

is sufficient. Further refinements were obtained by Yanushkyavichyus (1989).

A theorem of Lau and Rao (1982, 1984) reveals that integrated lack of memory properties generally lead to solutions of type

$$\bar{F}_X(x) = g(x)e^{-\lambda x}, \quad (19.114)$$

where

$$g(x+w) = g(x) \quad \text{for some } w.$$

[This generally does reduce to $e^{-\lambda x}$ provided the support of w is not a lattice.]

In this subsection it will be convenient, in our study of characterizations using order statistics, to denote the r th order statistic in a random sample of size n by the symbol $X'_{r:n}$ because we will need to refer to different sample sizes in the same equation. Puri and Rubin (1970) showed that the condition

$$X'_{2:2} - X'_{1:2} \stackrel{d}{=} X, \quad (19.115)$$

which is equivalent to

$$2 \int_0^\infty \bar{F}(x+y) p_X(y) dy = \bar{F}(x), \quad (19.115)'$$

characterizes a (**nonlattice**) exponential distribution. Ahsanullah (1976) claimed that the conditions

$$X'_{s_i:n} - X'_{r:n} \stackrel{d}{=} X'_{s_i-r:n-r}, \quad i = 1, 2, \quad 1 < r < s_1 < s_2 < n \quad (19.116)$$

characterize exponential distribution (provided the distribution is absolutely continuous). [Gather (1989) points out that Ahsanullah's proof involves the assumption that $\bar{F}(x+u)/\{\bar{F}(u)\bar{F}(x)\} - 1$ has the same sign (always positive or always negative) for all $u > 0$ and any fixed $x > 0$.]

Another result of Ahsanullah's (1977)—that

$$(n - 1)(X'_{i+1:n} - X'_{i:n}) \stackrel{d}{=} X \quad \text{for some } i \text{ and } n \quad (19.117)$$

characterizes an exponential distribution—is effectively based on the functional equation

$$\bar{F}(mx) = \{\bar{F}(x)\}^m. \quad (19.118)$$

In fact property II of Table 19.2 can be derived from I. Since

$$\bar{F}(s_1 + s_2 + s_3) = \bar{F}(s_1 + s_2)\bar{F}(s_3) = \bar{F}(s_1)\bar{F}(s_2)\bar{F}(s_3)$$

and generally

$$\bar{F}\left(\sum_{j=1}^m s_j\right) = \prod_{j=1}^m \bar{F}(s_j), \quad (19.119a)$$

by taking $s_1 = s_2 = \dots = s_m = x$, we have

$$\bar{F}(mx) = \{\bar{F}(x)\}^m. \quad (19.119b)$$

We therefore do not assign a separate subsection to property II, and proceed to property III.

Recently, Liang and Balakrishnan (1992) proved a characterization result for exponential distributions with possibly different scale parameters. Their result is as follows: "Let X_1, X_2, \dots, X_n be mutually independent nonnegative random variables having absolutely continuous distribution functions $F_i(x)$ over its support $[0, \infty)$ and the corresponding density function $p_i(x) > 0$ for $x > 0$. Let A denote the event that $X_i - X_{i+1} > 0$ for all $i = 1, 2, \dots, n - 1$. Then, conditional on the event A , $X_i - X_{i+1}$ and X_{i+1} are independent for all $i = 1, 2, \dots, k$ if and only if X_i ($i = 1, 2, \dots, k$) are exponentially distributed random variables (possibly with different scale parameters), where $1 \leq k \leq n - 1$."

A similar characterization of geometric distributions has also been established by Liang and Balakrishnan (1993). Fosam and Shanbhag (1994) have shown that these characterization results can be proved through Lau and Rao's (1982, 1984) theorem mentioned above under weaker assumptions.

8.2 Characterizations Based on Conditional Expectation (Regression)

If X is a nonnegative random variable, and $h(z)$ is a real-valued measurable function for $z > 0$, such that the expected value of $|h(X)|$ is finite, we have the following characterizations based on the condition

$$E[h(X - y)|X \geq y] = E[h(X)] \quad (19.120)$$

for all nonnegative values of y . If $h(z)$ is linear, the corresponding condition

$$E[X|X \geq y] = y + E[X] \quad (19.121)$$

characterizes the exponential distributions [Shanbhag (1970); Dallas (1973)].

With $h(z)$ a polynomial in z the same result was derived by Sahobov and Geshev (1974). An even more general result was obtained by Klebanov (1980). His characterization of exponential distributions is set out formally below.

The cdf $F_X(x)$ is of form (19.28) if and only if for some absolutely continuous $h(z)$ and for some value of σ ,

$$g(z) = \begin{cases} h'(z)\exp(-\sigma z) & \text{for } z \geq 0, \\ 0 & \text{for } z < 0, \end{cases} \quad (19.122)$$

is integrable in Lebesgue measure, and also

1. $\lim_{x \rightarrow \infty} \{\bar{F}_X(x)\exp(\sigma x)\} = 0$,
2. $-\left(\frac{1}{2\pi}\right) \log\left\{1 - \frac{1}{E[h(X)] - h(0)}\right\} \int_{-\infty}^{\infty} g(-z)e^{itz} dz \leq 1$.

We have the following characterizations as corollaries:

1. $E[e^{-X}|X \geq y] = e^{-y}E[X]$ for all $y \geq 0$.
2. $E[\exp\{-\frac{1}{2}(X - y)^2\}|X \geq y] = E[\exp\{-\frac{1}{2}X^2\}]$ for all $y \geq 0$.
3. $E[(X - y)^a|X \geq y] = E[X^a]$ for all $y \geq 0$ and for $0 < a \leq 4$ provided that $\lim_{x \rightarrow \infty} e^{\delta x}\{1 - F_X(x)\} = 0$ for some $\delta > 0$.

Introducing the further condition on $F_X(x)$ [in addition to $F_X(0) = 0$] that $E[X^2]$ is finite, we have

$$\text{Var}(X|X > y) = c \quad \text{for all } y \geq 0 \quad (19.123)$$

which characterizes distribution (19.28), as does

$$E[(X - y)^2|X > y] = c \quad \text{for all } y \geq 0. \quad (19.124)$$

[Azlarov, Dzimirzaev, and Sultanova (1972); Laurent (1974)].

Dallas (1979) showed that if $F_X(0) = 0$ and $E[X^r]$ is finite for some positive integer r , then

$$E[(X - y)^r | X > y] = c \quad \text{for all } y \geq 0 \quad (19.125)$$

characterizes (19.28). Nagaraja's (1975) characterization avoids introducing constancy of conditional expectation directly. The condition is

$$\{E[X - y | X > y]\}^2 = \text{Var}(X | X > y) \quad \text{for all } y > 0. \quad (19.126)$$

The condition

$$E[\{h(X) - h(y)\}^m | X > y] = c, \quad (19.127)$$

where $h(\cdot)$ is strictly increasing and differentiable characterizes

$$F_X(x) = 1 - \exp\left(-\frac{h(x)}{c}\right),$$

as does the condition

$$E[h(X) | X > y] = h(y) + c. \quad (19.128)$$

Kotlarski (1972) obtained a generalization of this case.

Characterizations due to Guerrieri (1965), Reinhardt (1968), Hoang (1968), Shanbhag (1970), Obretenov (1970), Azlarov, Dzamirzaev, and Sultanova (1972), Laurent (1974), Vartak (1974), Dallas (1974), Deryagin and Polesitskaya (1975), and Gupta (1975) are all equivalent to, or included in Sahobov and Geshev's (1974) result (see the following paragraph).

As an indication of the mathematical tools employed in Sahobov and Geshev's (1974) work, note that their equation [see also Dallas (1974)]

$$E[(X - y)^r | X > y] = E[X^r] \quad (19.129)$$

for all $y \geq 0$ and some integer $r > 0$ is mathematically equivalent to the functional equation

$$\int_y^\infty (u - y)^{r-1} \bar{F}(u) du = c_r \bar{F}(y), \quad (19.129')$$

which leads to an equation of form

$$\frac{d^r \bar{F}(y)}{dy^r} = c_r^* \bar{F}(y). \quad (19.130)$$

The general solution of this equation is

$$\bar{F}(y) = c_0 e^{-y/\sigma_n} + \sum_{i=1}^{n-1} c_i \exp(z_i y) \quad (19.131)$$

where $\sigma_n > 0$ and the z_i 's are (possibly) complex numbers.

The conditions that $\bar{F}(y)$ is bounded, nonincreasing, and nonnegative ensure that $c_i \equiv 0$ for $i = 1, \dots, n - 1$ so that

$$\bar{F}(y) = c_0 \exp(-y/\sigma_n)$$

—that is, it is the survivor function of an exponential distribution. Similarly the condition $\text{Var}(X - y | X \geq y) = c$ for all $y \geq 0$ is equivalent to

$$\frac{2}{\bar{F}(y)} \int_y^\infty (x - y)^2 \bar{F}(x) dx - \left\{ \frac{1}{\bar{F}(y)} \int_y^\infty \bar{F}(x) dx \right\}^2 = c,$$

leading to

$$\frac{2\psi(y)}{\psi''(y)} = \left[\frac{\psi'(y)}{\psi''(y)} \right]^2, \quad (19.132)$$

where $\psi(y) = \int_y^\infty (x - y) \bar{F}(x) dx$, and $\psi''(y) = \bar{F}(y)$. Solutions of (19.132) are

1. $\psi(y) = c_0 \exp(\pm \sqrt{y}/K)$,
2. $\psi(y) \equiv$ quadratic function of y .

However only $\psi(y) = \psi_0 \exp(-\sqrt{y}/K)$ satisfies the boundary conditions.

Wang and Srivastava (1980) obtained a characterization in terms of order statistics. If X has a continuous cdf and has finite expected value, then

$$E \left[(n - k)^{-1} \sum_{i=k+1}^n (X'_{i:n} - X'_{k:n}) | X'_{k:n} = y \right] = c \quad \text{for all } y \geq 0$$

characterizes an exponential distribution. Mukherjee and Roy (1986) noted that since

$$E \left[(n - k)^{-1} \sum_{i=k+1}^n (X'_{i:n} - X'_{k:n}) | X'_{k:n} = y \right] = E[X - y | X > y],$$

this result is equivalent to the results of Reinhardt (1968) and Shanbhag (1970). They also showed that the exponential distribution is characterized by constancy of the conditional coefficient of variation of $(n - k)^{-1} \sum_{i=k+1}^n (X'_{i:n} - X'_{k:n})$, given $X'_{k:n}$.

In a later paper Roy and Mukherjee (1991) show that among distributions with finite variance and monotone $E[\sum_{j=2}^n (X'_{j:n} - X'_{1:n}) | X'_{1:n} = x] = r(x)$, the condition $\text{Cov}(X'_{1:n}, \sum_{j=2}^n (X'_{j:n} - X'_{1:n})) = 0$ characterizes exponential (19.1) distributions [see also Swanepoel (1991)]. Kotz and Shanbhag (1980) pointed out that any distribution with $F_X(0) = 0$ —as is typical for lifetime distributions—is uniquely determined by its mean residual life function $E[X - u | X > u]$, and many of the results cited above can be derived from this fact.

The following example of a stable characterization is appealing. Van Beek and Braat (1973) showed that if $E[X] = 1$ and the residual lifetime at a randomly chosen "age" is distributed as X/q , then if $q = 1$,

$$F_X(x) = 1 - e^{-x},$$

while if $0 < q < 1$,

$$F_X(x) = 1 - \frac{\int_{-\infty}^{\infty} q^{u^2/2} \exp(-xq^{u-(1/2)}) \nu(du)}{\int_{-\infty}^{\infty} q^{u^2/2} \nu(du)}$$

for any periodic measure ν of period 1. [It is straightforward to allow for $E[X] \neq 1$.]

All distributions of the above class have the same moments

$$\mu'_r = rq^{-r(r-1)/2}.$$

Although the moments do not determine ("characterize") the distributions, Vardi, Shepp, and Logan (1981) have shown that they differ little unless q is very small. In fact for $q > e^{-2\pi} = 0.001867$, the maximum absolute difference between the cdfs of any two distributions in the class is less than'

$$\frac{\sqrt{2\pi\alpha^{-1}} \exp\left(\frac{1}{8}\pi^2\alpha^{-1}\right)}{(\sqrt{2\pi\alpha^{-1}}) \sinh(\pi^2\alpha^{-1})} \sim 8 \exp\left(-\frac{7}{8}\pi^2\alpha^{-1}\right),$$

where $\alpha = -\log q$.

Vardi, Shepp, and Logan (1981) note that for $q > 0.8$, the absolute difference cannot exceed 10^{-15} . This may be regarded as a remarkable example of "stability" in a characterization. Vardi and his coworkers also showed that it is not possible to have $q > 1$.

Suppose X_i , $i = 1, 2, 3$, are i.i.d., nonnegative continuous random variables that are square-integrable such that $E[X_i] = \text{Var}(X_i) = 1$ for $i = 1, 2, 3$. Let

$$U = \frac{1}{b}X_2 - \frac{1}{a}X_1 \quad \text{and} \quad W = \frac{1}{b}X_3 - \frac{1}{a}X_1.$$

Then, Pusz (1993) has proved that X_i 's are exponentially distributed if and only if

$$E[U|W] = \begin{cases} \frac{a}{(a+b)b} & \text{if } W \leq 0 \\ \frac{a}{(a+b)b} & \text{if } W > 0 \end{cases} \quad \text{and} \quad \text{Var}(U|W) = \frac{(a+b)^2 + b^2}{(a+b)^2 b^2}$$

8.3 Record Values

Characterization based on record values has been a fashionable topic during the last 15 years. A record value in a sequence X_1, X_2, \dots is defined as any X_j that is greater than the preceding values (X_1, \dots, X_{j-1}). [Lower record values (e.g., time to run 100 m.) may similarly be defined as any X_j that is smaller than the preceding values (X_1, \dots, X_{j-1}).]

The record times are the values of j for which X_j is a record value. In terms of order statistics ($X'_{1:n} \leq X'_{2:n} \leq \dots \leq X'_{n:n}$), if the u th record time is $n_{(u)}$, then

$$n_{(1)} = 1, \quad n_{(u)} = \min(m > n_{(u-1)}; X_m > X'_{n_{(u-1)}:n_{(u-1)}}), \quad (19.133)$$

and the u th record value is

$$R_{(u)} = X'_{n_{(u)}:n_{(u)}}. \quad (19.134)$$

The starting point of much research in this field was Tata's (1969) theorem, which states that if $F_X(x)$ is absolutely continuous, it is an exponential cdf if and only if $R_{(1)}$ and $R_{(2)} - R_{(1)}$ are mutually independent. [Galambos and Kotz (1978) provide a detailed discussion.] A flood of generalizations, extensions, and variants followed the original work. These are well summarized in Deheuvels (1984).

8.4 Miscellaneous

Another line of development started from results obtained by Ferguson (1964) and Crawford (1966), stating that quite generally if $X'_{1:2}$ and $X'_{2:2} - X'_{1:2}$ are mutually independent, then either $F_X(x)$ is a geometric cdf (see Chapter 5) or

$$F_X(x) = 1 - \exp\{-b(x-a)\}, \quad x \geq a, b > 0.$$

An independent flood of generalizations followed, the most notable being due to Rossberg (1972a, b). Among his results, we quote the following:

1. If $\bar{F}_X(x)$ is neither degenerate nor a lattice distribution, the condition

$$\Pr[X'_{k+1:n} - X'_{k:n} > x] = \{\bar{F}(x)\}^{n-k} \tag{19.135}$$

characterizes distributions of form (19.28).

2. If $F(x)$ and $G(x)$ are cdfs, such that $\lim_{x \rightarrow 0+} F(x) = 0$ and $\lim_{x \rightarrow 0+} G(x) = 1$, $F(x)$ not being a lattice distribution, then the condition

$$\alpha F(x) + \beta G(x) = F(x) * G(x) \tag{19.136}$$

[the convolution of independent variables with cdfs $F(x), G(x)$, respectively] is equivalent to $F(x)$ being of form (19.28) and $G(x)$ being the cdf of the negative of a variable of the same form (19.28), with the ratio of the parameters (σ_F/σ_G) being β/α .

85 Stability

The "stability" of certain characterizations of the exponential distribution—namely the closeness of a distribution to an exponential distribution consequent upon near (but not exact) satisfaction of a characterization condition—has been studied by Shimizu (1980, 1981). He showed, among other things, that if X_1, \dots, X_n are i.i.d. with survival function $\bar{F}(x)$, and

$$\Pr[\min(a_1 X_1, \dots, a_n X_n) < x] = [1 - R(x)]\bar{F}(x) \tag{19.137}$$

for $0 < x < x_0$ with $x_0 > 0, a_j > 0, \sum_{j=1}^n a_j^{-1} < \infty$ where

$$R(x) = \begin{cases} \varepsilon \zeta x^2, & x \leq 1, \\ \delta \zeta, & x > 1, \quad |\zeta| < 1, \quad 0 < \varepsilon, \delta < \frac{1}{2}, \end{cases}$$

then

$$\bar{F}(x) = \begin{cases} e^{-x/\sigma}(1 + \varepsilon_1 \zeta x^2), & 0 \leq x \leq 1, \\ e^{-x/\sigma}\{1 + \phi \zeta x \exp(\phi x)\}, & 1 < x < x_0, \end{cases} \tag{19.138}$$

where $\lim_{x \rightarrow 0+} \{F(x)/x\} = \sigma^{-1}, \varepsilon_1 = 2\varepsilon(1 - a)^{-1}, \phi = 2(\varepsilon + \delta)(1 - a)^{-1}$, and $a = \max(a_1^{-1}, \dots, a_n^{-1})$. [See also Yanushkyevichene (1983).]

From Yanushkyevichene (1983) and Yanushkyevichyus (1989) we have another stability theorem: If $F_X(x)$ is continuous and strictly monotone over the domain $0 < F_X(x) < 1$ and has a finite first moment, and if for some $\varepsilon > 0$, there exists a positive constant γ such that for F -almost all $t > 0$,

then for all $x \geq 0$,

$$\left| \bar{F}_X(x) - \exp(-\lambda_* x) \right| \leq C \varepsilon^{1/(n-j)} \exp(-\lambda x),$$

where λ_* , A , and C depend only on γ and $n - j$.

The following result gives stability theorem for record value characterizations. Let $\{R_j\}$ be record values of a sequence of **i.i.d.** nonnegative random variables with a continuous distribution function $F(x)$, possessing a finite first moment and also strictly monotonic over $0 < F(x) < 1$. If for some fixed j there exists a positive constant γ such that for all $x \geq 0$,

$$\left| E[R_{j+1} - R_j | R_j = x] - \gamma \right| \leq \varepsilon,$$

then

$$\left| \bar{F}(x) - \exp(-\lambda_0 x) \right| \leq C \varepsilon \exp(\lambda x), \quad x \geq 0,$$

where $A = \gamma^{-1} - 6 > 0$, 6 a fixed positive constant, and C and A , depend only on γ and 6 .

Before leaving the topic of characterizations we note the following simple transformations [for distribution (19.2)] that relate the exponential distribution to other commonly employed distributions.

Transformation	$\bar{F}_Y(y) = 1 - F_Y(y)$	Distribution
$Y = \log X$	$\exp(-e^y)$	Extreme value (Chapter 22)
$Y = \exp(X/\tau)$	$(1/y)^\tau$ ($y \geq 1$)	Pareto (Chapter 20)
$Y = 1 - e^{-X}$	$1 - y$ ($0 \leq y \leq 1$)	Uniform (Chapter 26)
$Y = X^{1/c}$ ($c > 0$)	$\exp(-y^c)$ ($y > 0$)	Weibull (Chapter 21)

Characterizations of these distributions can be used (with appropriate transformation) to characterize exponential distributions, and conversely.

9 MIXTURES OF EXPONENTIAL DISTRIBUTIONS

Mixtures of exponential distributions have important life-testing applications. A batch of electronic tubes may consist of two subpopulations, with each subpopulation having its own characteristic mean life and the two **subpopulations** being in proportions ω_1 and $\omega_2 = 1 - \omega_1$. (Each unit of the population may be regarded as if it contains a "tag" that indicates the subpopulation to which it belongs and hence defines the way in which that particular item will fail.) Finally, the failure times for the i th subpopulation are assumed to be independently distributed with probability density function (19.28) with $\sigma = \sigma_i$ ($i = 1, 2$).

If ω_1 is the proportion of units belonging to subpopulation $i = 1$, then the cumulative distribution function of T , the time to failure, is

$$\omega_1 \left[1 - \exp\left(\frac{-t}{\sigma_1}\right) \right] + (1 - \omega_1) \left[1 - \exp\left(\frac{-t}{\sigma_2}\right) \right], \quad t \geq 0, \quad (19.139a)$$

and the density function is

$$\omega_1 \sigma_1^{-1} e^{-t/\sigma_1} + (1 - \omega_1) \sigma_2^{-1} e^{-t/\sigma_2}, \quad t \geq 0. \quad (19.139b)$$

This distribution has also been applied (under the name *Schuhl* distribution) to the distances between elements in traffic [Petigny (1966)]. Mixtures of exponential distributions have been found to represent some demographic distributions [Susarla and Pathala (1965)].

Gumbel (1939) gave a method for fitting a mixture of two exponential distributions, using the first two sample moments. Cases where a has a continuous distribution have been studied by Bhattacharya and Holla (1965) and Bhattacharya (1966). In the latter paper it is shown that if σ has an exponential distribution (with parameters $\mathbf{0}, \boldsymbol{\beta}$) the probability density function of T is $2\boldsymbol{\beta}^{-1} K_0(2(t/\boldsymbol{\beta})^{1/2})$ ($0 < t$), where $K_0(\cdot)$ is a modified Bessel function of the third kind of zero order (see Chapter 1, Section A12). If a has a beta distribution (Chapter 25) over the range $(\mathbf{0}, \boldsymbol{\theta})$ the probability density function can be expressed in terms of a Whittaker function. In the earlier paper the special case where a has a uniform distribution is considered.

We now consider methods of estimating the parameters w , a , and σ_2 in (19.139a) and (19.139b).

Case A: Relative Magnitude of Subpopulation Parameters Not Known

Mendenhall and Hader (1958) derived the following equations for the maximum likelihood estimators, expressed in terms of

$$\hat{\omega}_1 = \frac{R_1}{n} + \hat{k} \frac{(n - R)}{n}, \quad (19.140a)$$

$$\hat{\beta}_1 = \bar{X}_1 + \hat{k} \frac{(n - R)}{R_1}, \quad (19.140b)$$

$$\hat{\beta}_2 = \bar{X}_2 + \frac{(1 - \hat{k})(n - R)}{R_2}, \quad (19.140c)$$

where

$$\bar{X}_i = \frac{\sum_{j=1}^{R_i} X_{ij}}{R_i}, \quad i = 1, 2,$$

and

$$\hat{k} = \frac{1}{1 + \left(\frac{1 - \hat{\omega}_1}{\hat{\omega}_1} \right) \exp[(1/\hat{\beta}_1) - (1/\hat{\beta}_2)]}$$

Here

n = the number of units on test,

t_0 = the time at which test is terminated,

R = the total number of failures during test,

R_1 = the number of failures from subpopulation 1,

R_2 = the number of failures from subpopulation 2 (note that $R = R_1 + R_2$),

$X_{ij} = T_{ij}/t_0$, T_{ij} being the time at which the j th failure from the i th population occurs,

$\hat{\beta}_i$ is the estimator of $\beta_i = \sigma_i/t_0$ ($i = 1, 2$).

The estimators of β_1 , β_2 , and ω_1 must be obtained by solving the simultaneous equations (19.140). A method of solving these approximately was given by Mendenhall and Hader (1958).

Case B: Relative Magnitude of Subpopulation Parameters Known

In the special case $\beta_1 = \beta_2 = \beta$ the maximum likelihood estimators become

$$\hat{\omega}_1 = \frac{r_1}{r}. \quad (19.140a)'$$

$$\hat{\beta} = \frac{r_1 \bar{X}_1 + r_2 \bar{X}_2 + (n - r)}{r} \quad (19.140b)'$$

In general, we have to use the method in case A to obtain estimators, but if we have crossover, that is,

$$\hat{\beta}_1 > \hat{\beta}_2 \quad \text{while} \quad \beta_1 \leq \beta_2$$

or

$$\hat{\beta}_1 < \hat{\beta}_2 \quad \text{while} \quad \beta_1 \geq \beta_2,$$

we use case B estimators corresponding to the special case $\beta_1 = \beta_2 = \beta$.

Rider (1961) used the "method of moments" to obtain rather involved estimators of mixture exponential parameters. Proschan (1963) also discussed the problem of mixture of several exponential distributions and derived some

interesting results concerning the resulting mixed population. For the case of mixture distributions with pdf

$$(1 - \omega)\sigma^{-1} \exp\left(-\frac{x}{\sigma}\right) + \omega\left(\frac{\sigma}{\alpha}\right)^{-1} \exp\left(-\frac{\alpha x}{\sigma}\right),$$

$$x > 0, \sigma > 0, \alpha > 0, 0 \leq \omega \leq 1$$

(the *number* of "outliers" in the sample not being specified), **Willemain et al.** (1992) carried out extensive Monte Carlo comparisons of seven estimators of α , using the relative closeness (difference of absolute values of errors of estimation) as a criterion. More details on mixtures of exponential distributions can be found in books by Everitt and Hand (1981) and Titterton, Smith, and Makov (1985).

Mixed distributions with

$$F_X(x) = \omega + (1 - \omega)(1 - e^{-t/\sigma}), \quad t \geq 0, 0 < \omega < 1, \sigma > 0, \quad (19.141)$$

can arise in clinical trial situations where there is a probability ω of immediate failure but survivors have a lifetime distribution as in (19.28). **Kleyle and Dahiya** (1975) have considered estimation of the parameters ω and α .

McClellan (1986) studied estimation for the mixed exponential distribution where the failure time data is grouped. The problem originated from the data of job status of university graduates in the Northern Ireland collected quarterly for various grades over $5\frac{1}{4}$ year period on whether or not they were still in service. **Bartholomew** (1982) has shown that a mixed exponential distribution provides a good fit to these data.

Mixtures of generalized exponential distributions have also found application in "mine dust" analysis [**Tallis and Light** (1968)]. In particular, a problem that arises is that of estimating the parameters α , β , and γ of the distribution with density function

$$p_X(x) = \gamma A e^{-\alpha\sqrt{x}} + (1 - \gamma) B e^{-\beta\sqrt{x}}, \quad x > a,$$

where A , B , and a are known constants.

The method of maximum likelihood is often regarded as the standard method of estimating parameters. In this case, however, we would obtain rather complicated equations, and methods using *half-moment* equations have been developed [**Joffe** (1964)]. Half-moment equations are less complicated. Although they must be solved iteratively, they can be handled on a pocket calculator. The three half-moment equations are

$$m'_{\frac{r}{2}} = \tilde{\gamma} \mu'_{\frac{r}{2}, \alpha} + (1 - \tilde{\gamma}) \mu'_{\frac{r}{2}, \beta}, \quad r = 1, 2, 3, \quad (19.142)$$

where

$$\bar{m}'_2 = \frac{1}{n} \sum_{i=1}^n X_i^{r/2} \quad (n \text{ is the number of elements})$$

and

$$\mu'_{\frac{r}{2}, \tilde{\alpha}} = \frac{\tilde{\alpha}^2 e^{\tilde{\alpha}\sqrt{a}}}{2(1 + \tilde{\alpha}\sqrt{a})} \int_a^\infty x^{r/2} e^{-\alpha\sqrt{x}} dx.$$

Use may be made of the recurrence relationship

$$\int_a^\infty x^{r/2} e^{-\alpha\sqrt{x}} dx = \frac{2a^{(r+1)/2} e^{-\alpha\sqrt{a}}}{\alpha} + \frac{r+1}{\alpha} \int_a^\infty x^{(r-1)/2} e^{-\alpha\sqrt{x}} dx.$$

One can express $\tilde{\beta}$ as a function of $\tilde{\alpha}$ and $\tilde{\gamma}$, and the three half-moments as follows:

$$\tilde{\beta} = \frac{P - \tilde{\gamma}Q}{R - (\tilde{\gamma}/\tilde{\alpha})Q}, \quad (19.143a)$$

where

$$P = 4m'_1 - 3\sqrt{am'_1},$$

$$Q = 4\mu'_{1, \tilde{\alpha}} - 3\sqrt{a\mu'_{\frac{1}{2}, \tilde{\alpha}}},$$

$$R = m'_{\frac{3}{2}} - \sqrt{am'_1}.$$

$\tilde{\gamma}$ may be written as a function of $\tilde{\alpha}$, and the three half-moments as

$$\tilde{\gamma} = \frac{PU - SR}{Q[U - (S/\tilde{\alpha})] - \tau[R - (P/\tilde{\alpha})]}, \quad (19.143b)$$

where

$$U = m'_1 - \sqrt{am'_1}$$

$$S = 3m'_{\frac{1}{2}} - 2\sqrt{a}$$

$$\tau = 3\mu'_{\frac{1}{2}, \tilde{\alpha}} - 2\sqrt{a}.$$

A solution of these equations can be obtained iteratively by choosing a value of $\tilde{\alpha}$ and consequent values $\tilde{\beta}$ and $\tilde{\gamma}$ from (19.143a) and (19.143b).

Considerable work has also been done on the generalized mixed exponential form (often denoted by GH) in the last decade; for example, see Botta and Harris (1986), Botta, Marchal, and Harris (1987), Harris and Sykes (1987), Harris and Botta (1988), and Harris, Marchal, and Botta (1992). These generalized mixed exponential forms are linear but not necessarily convex combinations of negative exponential distribution functions (unlike the mixture form). The cumulative distribution function is given by

$$F(x) = 1 - \sum_{i=1}^k p_i e^{-\theta_i x},$$

with $\theta_i > 0$, $\sum_{i=1}^k p_i = 1$, $-\infty < p_i < \infty$, and $\theta_1 < \theta_2 < \dots < \theta_k$ (without loss of any generality). Botta and Harris (1986) showed that the above class is dense in the set of all distribution functions relative to an appropriate metric. Harris, Marchal, and Botta (1992) have recently reviewed the relationship of these generalized hyperexponential distributions to other types of distribution functions in the Coxian family, particularly the phase types. Interestingly, by assuming the claim amount distribution to be of the generalized hyperexponential form given above, Gerber, Goovaerts, and Kaas (1987) have considered the probability and the severity of ruin in terms of the usual model of the collective risk theory in insurance.

10 RELATED DISTRIBUTIONS

There are many important distributions closely related to the exponential distribution. (See also the end of Section 8.)

If a variable X ($> \theta$) is such that $Y = (X - \theta)^c$ has the exponential distribution (19.281), then X is said to have a *Weibull distribution* with shape parameter c . It is necessary that c be greater than -1 , for otherwise the integral of

$$p_X(x) = \sigma^{-1} c (x - \theta)^{c-1} \exp\left[\frac{-(x - \theta)^c}{\sigma}\right], \quad x > \theta, \quad (19.144)$$

between $x = \theta$ and $x = \theta' > \theta$ will be infinite. (See Chapter 21 for a detailed discussion of this distribution.) If c and σ are known (and often θ is known to be zero) the transformed variable $Y = (X - \theta)^c$ may be used, and the well-developed techniques associated with the exponential distribution become applicable. If c is not known, special techniques are needed; these techniques are discussed in Chapter 21.

If $Y = e^{-X}$ has an exponential distribution of form (19.28), then X has a distribution of *extreme value* form (Chapter 22).

Another distribution of theoretical, and some practical, importance is the double (or bilateral) exponential distribution. This is the distribution of a random variable X with probability density function

$$p_X(x) = (2\sigma)^{-1} \exp\left(\frac{-|x - \theta|}{\sigma}\right), \quad \sigma > 0. \quad (19.145)$$

It is also known as Laplace's *first* law of error. (*Laplace's* second law of error is the normal distribution.) The exponential distribution might be regarded as a double exponential "folded" about $x = \theta$. The double exponential distribution is the subject of Chapter 24.

The fact that the exponential distribution belongs to the class of gamma distributions has been mentioned in Section 1. Taking $\theta = 0$ and $\sigma = 2$ in (19.1), we obtain the distribution of χ^2 with **two** degrees of freedom. From this it can be seen that if X_1, X_2, \dots, X_n are independent random variables each with probability density function (19.1), then their arithmetic mean is distributed as $\theta + \frac{1}{2}n^{-1}\sigma \times (\chi^2$ with $2n$ degrees of freedom). We further note that if the quadratic form $\sum_{i,j=1}^n a_{ij}U_iU_j$ in independent unit normal variables U_1, U_2, \dots, U_n has a matrix A with eigenvalues $\lambda_1, \lambda_2, \dots, \lambda_n$, then applying an appropriate linear transformation of the U 's,

$$\sum_{i,j=1}^n a_{ij}U_iU_j = \sum_{j=1}^n \lambda_j U_j^{*2}, \quad (19.146)$$

where $U_1^*, U_2^*, \dots, U_n^*$ are independent unit normal variables. If the nonzero λ 's are equal in pairs, then $\sum_{j=1}^n \lambda_j U_j^{*2}$ can be expressed as a linear function of independent variables each distributed as χ^2 with **two** degrees of freedom, and so exponentially. The distribution theory of such a variable is much simpler than that of a general quadratic form in normal variables.

In fact, if X_1, \dots, X_n are independent standard exponential variables, then the linear form

$$Y = \sum_{j=1}^n \lambda_j X_j, \quad \lambda_j \neq \lambda_k$$

has the probability density function

$$p_Y(y) = \sum_{j=1}^n \left(\prod_{k \neq j} (\lambda_j - \lambda_k)^{-1} \right) \lambda_j^{n-2} e^{-y/\lambda_j}, \quad y > 0. \quad (19.147)$$

This is a special type of mixture of exponential distributions and called the general gamma or the general Erlang distribution. It is used in queueing theory, reliability theory, and psychology. Some special patterns of λ 's have been discussed by Likes (1967, 1968), McGill and Gibbon (1965), and others.

Kaminsky, Luks, and Nelson (1984) derived a recursive formula that is easily programmable for the evaluation of the distribution function of ratios of linear combinations of independent exponential random variables. The result is based on a generalization of the lack of memory property for the exponential distribution.

Let $\mathbf{a} = (a_1, \dots, a_m)$, $\mathbf{b} = (b_1, \dots, b_n)$ be vectors of positive constants, and let $\mathbf{X} = (X_1, X_2, \dots, X_m)$, $\mathbf{Y} = (Y_1, Y_2, \dots, Y_n)$ be independent vectors of independent exponential random variables, each with density $p_X(x) = e^{-x}$, $x > 0$. For any vector $\mathbf{U} = (U_1, \dots, U_m)$, let $\mathbf{U}^* = (U_2, \dots, U_m)$. Then the functions $G_{m,n}: ((R^+)^m \times (R^+)^n) \rightarrow [0, 1]$ given by

$$G_{m,n}(\mathbf{a}, \mathbf{b}) = \Pr[\mathbf{a}'\mathbf{X} \geq \mathbf{b}'\mathbf{Y}]$$

satisfy

$$G_{m,n}(\mathbf{a}, \mathbf{b}) = \left(\frac{b_1}{a_1 + b_1} \right) G_{m-1,n}(\mathbf{a}^*, \mathbf{b}) + \left(\frac{a_1}{a_1 + b_1} \right) G_{m,n-1}(\mathbf{a}, \mathbf{b}^*), \tag{19.148}$$

with boundary conditions,

$$G_{0,n}(\mathbf{0}, \mathbf{b}) = 0,$$

$$G_{m,0}(\mathbf{a}, \mathbf{0}) = 1.$$

The relationship between the exponential and rectangular distributions is discussed in more detail in Chapter 26. Here we note only the following property: If X_1, X_2, \dots, X_n , each have probability density function (19.28), then $Y_j = \sum_{i=1}^j X_i / [\sum_{i=1}^n X_i]$ for $j = 1, \dots, (n - 1)$ are distributed as the order statistics of a random sample of size $n - 1$ from a rectangular distribution over the range 0 to 1.

The following relation between Poisson and exponential distributions is of importance in applications (see also Chapter 4, Sections 2 and 9): If T_1, T_2, \dots are a succession of independent random variables each having the same density function (19.28) and the random variable N is defined by the inequalities

$$T_1 + T_2 + \dots + T_N \leq \tau < T_1 + T_2 + \dots + T_{N+1},$$

then N has a Poisson distribution with expected value τ/σ .

An exponential distribution truncated from below is still an exponential distribution with the same scale parameter.

An exponential distribution truncated by exclusion of values exceeding x_0 has the density function

$$p_X(x) = \sigma^{-1} \left\{ 1 - \exp \left[-\frac{x_0 - \theta}{\sigma} \right] \right\}^{-1} \exp \left[-\frac{x - \theta}{\sigma} \right], \quad x_0 > x > \theta. \quad (19.149)$$

The expected value of this distribution is

$$\theta + \sigma \left[1 - \frac{x_0 - \theta}{\sigma} \left\{ \exp \left[\frac{x_0 - \theta}{\sigma} \right] - 1 \right\}^{-1} \right].$$

If X_1, X_2, \dots, X_n are independent random variables, each having the distribution (19.149), then the statistic $\sum_{j=1}^n X_j$ is sufficient for σ , if θ be known. Bain and Weeks (1964) have shown that the density function of $Y = \sum_{j=1}^n X_j - n\theta$ is

$$p_Y(y) = \left[\sigma \left\{ 1 - \exp \left[-\frac{x_0 - \theta}{\sigma} \right] \right\} \right]^{-n} e^{-y/\sigma} [(n-1)!]^{-1} \\ \times \sum_{j=0}^{j_0} (-1)^j \binom{n}{j} [y - j(x_0 - \theta)]^{n-1} \quad (19.150a)$$

for $j_0(x_0 - \theta) < y < (j_0 + 1)(x_0 - \theta)$, $j_0 = 0, 1, 2, \dots, (n-1)$. The cumulative distribution function is

$$F_Y(y) = \left\{ 1 - \exp \left[-\frac{x_0 - \theta}{\sigma} \right] \right\}^{-n} \sum_{j=0}^{j_0} (-1)^j \binom{n}{j} e^{-j(x_0 - \theta)/\sigma} \\ \times \Pr \left[\chi_{2n}^2 < \frac{2(j_0 + d - j)(x_0 - \theta)}{\sigma} \right], \quad (19.150b)$$

where $y = (x_0 - \theta)(j_0 + d)$, j_0 being an integer and $0 \leq d \leq 1$.

Deemer and Votaw (1955) showed that if θ be known to be zero, then the maximum likelihood estimator $\hat{\sigma}$ of σ is the solution of the equation

$$\bar{X}x_0^{-1} = \hat{\sigma}x_0^{-1} - (e^{x_0/\hat{\sigma}} - 1)^{-1} \quad (19.151)$$

provided that $\bar{X} < \frac{1}{2}x_0$. If $\bar{X} > \frac{1}{2}x_0$, then $\hat{\sigma}$ is infinite; this result may be taken to mean that a truncated exponential distribution is inappropriate. [Formally, it indicates that a rectangular distribution (Chapter 26) over the range 0 to x_0 should be used.] In Deemer and Votaw (1955) there is a table of \bar{X}/x_0 to four decimal places as a function of $\hat{\sigma}^{-1}$ for $\hat{\sigma}^{-1} = 0.01(0.01)0.89$. For n large,

$$n \text{Var}(\hat{\sigma}^{-1}) \doteq \left[\sigma^2 \frac{x_0^2 e^{-x_0/\sigma} (1 - e^{-x_0/\sigma})^{-2}}{\sigma^2} \right]^{-1}. \quad (19.152)$$

Estimation of 8 for the cumulative distribution function

$$1 - e^{-x/\theta} \{1 - F(x)\},$$

[where $F(x)$ is the cumulative distribution function of a non-negative random variable] was treated by Gerčbah (1967). He suggested an estimator based on a random sample of size $n = km$. Divide the sample into m groups at random, with $X'_{1(j)}$ the smallest value in the j th group. Then under certain monotonicity conditions on $F(x)$

$$\hat{\theta} = km^{-1} \sum_{j=1}^m X'_{1(j)}$$

is a consistent estimator of 8 as k and m tend to infinity.

In extending the Marshall–Olkin bivariate exponential distribution to an absolutely continuous and not necessarily possessing memoryless property model, Ryu (1993) has recently presented a generalization of the exponential distribution derived as a marginal distribution of this generalized bivariate model. The new generalized distribution with density function

$$p_X(x) = \{\lambda_1 + \lambda_{12}(1 - e^{-sx})\} e^{-\lambda_1 x - \lambda_{12} x + \frac{\lambda_{12}}{s}(1 - e^{-sx})} \quad (19.153)$$

has an increasing failure rate in general. Note that when $s \rightarrow \infty$, the density in (19.153) becomes the exponential density function with constant hazard rate of $\lambda_1 + \lambda_{12}$. In Figure 19.2, plots of the exponential density function and the generalized exponential density function are presented. While the exponential density function is monotonically decreasing, the density in (19.153) is initially increasing and then decreasing.

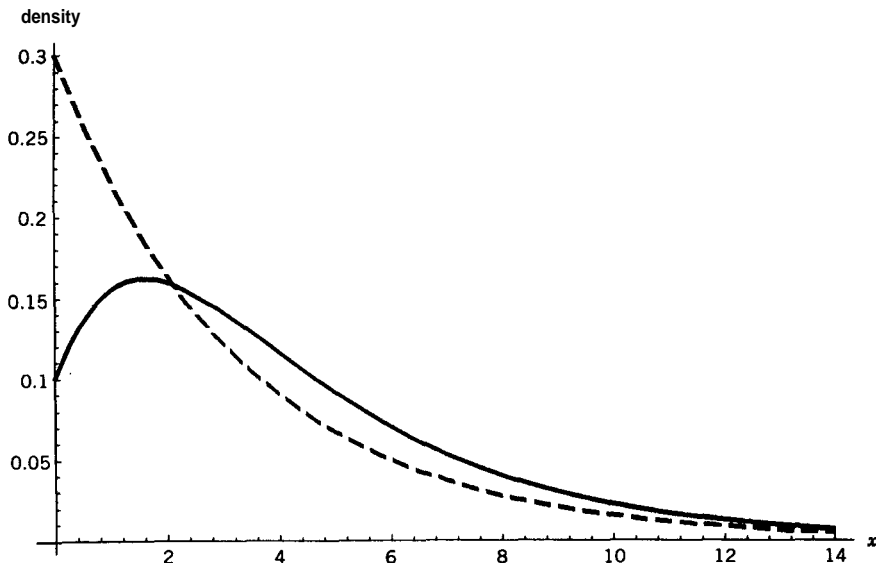


Figure 19.2 Plots of the Generalized Exponential Density in (19.153) and the Exponential Density for the Case $\lambda = 0.1$, $\lambda_{12} = 0.2$ and $s = 0.5$, and $\lambda = 0.1$, $\lambda_{12} = 0.2$ and $s = \infty$, Respectively. The Dashed Line Is the Exponential Density and the Solid Line Is the Generalized Exponential Density.

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CHAPTER 20

Pareto Distributions

1 INTRODUCTION

Since the publication of the first edition of this book, the literature on Pareto distributions has grown, perhaps faster than for any other continuous **univariate** distribution. To survey comprehensively the new material would require much more space than is available for this distribution. Fortunately, the availability of an excellent text by B. C. Arnold (1983), devoted solely (except for the last chapter) to the univariate Pareto and related distributions allows us to concentrate on topics that are only briefly discussed in that text (e.g., estimation using order statistics) and also to emphasize developments since 1982. Besides a thorough discussion of characterization and measures of inequality that are closely associated with Pareto distributions, Arnold's monograph provides a comprehensive historical overview.

2 GENESIS

The Pareto distribution is named after an Italian-born Swiss professor of economics, Vilfredo Pareto (1848–1923). Pareto's law, as formulated by him (1897), dealt with the distribution of income over a population and can be stated as follows:

$$N = Ax^{-a}$$

where N is the number of persons having income $\geq x$, and A, a are parameters (a is known both as Pareto's constant and as a shape parameter). It was felt by Pareto that this law was universal and inevitable—regardless of taxation and social and political conditions. “**Refutations**” of the law have been made by several well-known economists over the past 60 years [e.g., Pigou (1932); Shirras (1935); Hayakawa (1951)]. More recently attempts have been made to explain many empirical phenomena using the Pareto

distribution or some closely related form [e.g., Steindl (1965); Mandelbrot (1960, 1963, 1967); Hagstroem (1960); Ord (1975)].

Harris (1968) has pointed out that a mixture of exponential distributions, with parameter θ^{-1} having a gamma distribution, and with origin at zero, gives rise to a Pareto distribution. [See also Maguire, Pearson, and Wynn (1952).] In fact, if

$$\Pr[X \leq x | \theta] = 1 - e^{-x/\theta}$$

and $\mu = \theta^{-1}$ has a gamma distribution [(17.2) of Chapter 17], then

$$\begin{aligned} \Pr[X \leq x] &= \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^\infty t^{\alpha-1} e^{-t/\beta} (1 - e^{-tx}) dt \\ &= 1 - \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^\infty t^{\alpha-1} e^{-t(x+\beta^{-1})} dt \\ &= 1 - (\beta x + 1)^{-\alpha}, \end{aligned}$$

which is of the form (20.4) below.

3 DEFINITIONS

The Pareto distribution has survived in its original form as

$$\bar{F}_X(x) = \Pr[X \geq x] = \left(\frac{k}{x}\right)^a, \quad k > 0, a > 0, x \geq k, \quad (20.1)$$

where $\bar{F}_X(x)$ is the probability that the income is equal to or greater than x and k represents some minimum income. As a consequence of (20.1), the cumulative distribution function of X , representing income, may be written as

$$F_X(x) = 1 - \left(\frac{k}{x}\right)^a, \quad k > 0, a > 0, x \geq k, \quad (20.2)$$

and the corresponding pdf is

$$p_X(x) = ak^a x^{-(a+1)}, \quad k > 0, a > 0, x \geq k. \quad (20.3)$$

This is a special form of **Pearson** Type VI distribution; we will denote it by $X \sim P(I)(k, a)$. The relation given by (20.2) is now more properly known as the Pareto *distribution* of the first kind.

For Bayesian analysis a slightly different parametrization is sometimes found to be convenient (see Section 6). In economic literature, special

attention is given to determination of an appropriate value of the parameter a . For income distributions, the assumption that $a > 1$ seems to be quite realistic. In Bresciani-Turroni (1939) we find the comment:

The actual values of "a"... fall within comparatively narrow limits. They oscillate about 1.5, and deviations from this value appear to be caused [more] by imperfections of statistical material than by the real cause.

Some 30 years later, Cramer (1971, p. 57) remarked

The values of "a" have increased from between 1.6 and 1.8 in the nineteenth century to between 1.9 and 2.1 in the developed countries at the present time.

Two other forms of this distribution were proposed by Pareto. One, now referred to as the Pareto distribution of the second kind (sometimes Lomax distribution), is given by

$$F_X(x) = 1 - \frac{C^a}{(x + C)^a}, \quad x \geq 0. \quad (20.4)$$

This is also a Pearson Type VI distribution. It will be denoted by $X \sim \text{P(II)}(C, a)$. Lomax (1954) used this distribution in the analysis of business failure data.

The standard P(II) distribution has $C = 1$; its pdf is

$$p_X(x) = a(1 + x)^{-a-1}, \quad x > 0, a > 0, \quad (20.5a)$$

and the survival function is

$$\bar{F}_X(x) = (1 + x)^{-a}, \quad x > 0, a > 0. \quad (20.5b)$$

Introducing a location parameter μ , the P(II) distribution's survival function can be represented as

$$\bar{F}_X(x) = \left\{ 1 + \frac{x - \mu}{C} \right\}^{-a}, \quad x > \mu; C, a > 0. \quad (20.4)'$$

In most applications μ is nonnegative. The shape parameter a is often assumed to exceed 1, so as to ensure that the expected value is finite. We will denote this distribution by $\text{P(II)}(\mu, C, a)$.

The third distribution proposed by Pareto—the Pareto distribution of the first kind—has the cdf

$$F_X(x) = 1 - \frac{Ce^{-bx}}{(x + C)^a}, \quad x > 0. \quad (20.6)$$

It can be denoted $\mathbf{P(III)}(a, b; C)$.

In this chapter we will concentrate mainly on the simple Pareto $\mathbf{(I)}$ and Pareto $\mathbf{(II)}$ distributions. Arnold (1983) defines a Pareto distribution by the cdf

$$F_X(x) = \left[1 + \left(\frac{x - \mu}{\sigma} \right)^{1/\gamma} \right]^{-\alpha}, \quad x > \mu; \alpha, \gamma, \sigma > 0. \quad (20.7)$$

We will denote this distribution as $\mathbf{P(IV)}(\mu, u, y, a)$. Note that

$$\begin{aligned} \mathbf{P(I)}(\sigma, \alpha) &\equiv \mathbf{P(IV)}(\sigma, \sigma, 1, \alpha) \quad \text{and} \\ \mathbf{P(II)}(\mu, \sigma, \alpha) &\equiv \mathbf{P(IV)}(\mu, \sigma, 1, a). \end{aligned}$$

Feller (1971) defines a Pareto distribution as the distribution of $W = Y^{-1} - 1$ when Y has a standard beta (γ_1, γ_2) distribution. The pdf of Y is

$$p_Y(y) = \{B(\gamma_1, \gamma_2)\}^{-1} y^{\gamma_1-1} (1-y)^{\gamma_2-1}, \quad 0 < y < 1; \gamma_1, \gamma_2 > 0. \quad (20.8)$$

If $\gamma_2 = 1$ the distribution of W is a **Lomax** distribution (20.4). Arnold (1983) pointed out that the variable

$$\mu + \sigma(Y^{-1} - 1)^\gamma$$

is a generalization of the Pareto $\mathbf{(IV)}$ variable. This in turn is called a generalized F variable if $\mu = 0$ [Kalbfleisch and Prentice (1980)]; see Chapter 27.

A basic property of a standard $\mathbf{(P(I))}(k, a)$ Pareto variable X is that

$$X = k \exp\left(\frac{V}{a}\right), \quad (20.9)$$

where V is a standard exponential variable ($p_V(v) = \exp(-v)$, $v > 0$). [Equivalently $2a \log(X/k)$ has a χ^2 distribution with two degrees of freedom.]

This intimate relationship between $\mathbf{P(I)}$ and exponential distributions permits us to obtain a wide range of properties of the former—in particular, characterizations—from properties of the latter. (See Chapter 19, Section 8, for characterizations of exponential distributions.) Takano (1992) has discussed recently a relationship between the Pareto distribution and a differential equation. An expression for the U -measure of the Pareto density has also been given by Takano (1992), where it is considered as a generalized gamma convolution (see Chapter 17, Section 8.4).

4 MOMENTS AND OTHER INDICES

4.1 Moments

Provided that r is less than a , the r th moment about zero of a $\mathbf{P}(\mathbf{I})(k, a)$ variable is

$$\mu'_r = ak^r(a-r)^{-1} = k^r \left(1 - \frac{r}{a}\right)^{-1}, \quad r < a. \quad (20.10)$$

In particular the expected value is

$$E[X] = ak(a-1)^{-1}, \quad a > 1, \quad (20.11a)$$

and the variance is

$$\text{Var}(X) = ak^2(a-1)^{-2}(a-2)^{-1}, \quad a > 2. \quad (20.11b)$$

Also

$$\alpha_3(X) = \sqrt{\beta_1(X)} = 2 \frac{a+1}{a-3} \sqrt{\frac{a-2}{a}}, \quad a > 3, \quad (20.11c)$$

$$\alpha_4(X) = \beta_2(X) = \frac{3(a-2)(3a^2+a+2)}{a(a-3)(a-4)}, \quad a > 4. \quad (20.11d)$$

As $a \rightarrow \infty$, $\alpha_3(x) \rightarrow 2$, and $\alpha_4(X) \rightarrow 9$. The mean deviation is $2k(a-1)^{-1}(1-a^{-1})^{a-1}$ ($a > 1$) and

$$\frac{\text{Mean deviation}}{\text{Standard deviation}} = 2(1-2a^{-1})^{1/2}(1-a^{-1})^{a-1}, \quad a > 2. \quad (20.12)$$

The value of this ratio is *0.513* when $a = 3$, and *0.597* when $a = 4$. As a tends to infinity, the ratio tends to $2e^{-1} = 0.736$. Cohen and Whitten (1988) provide tables of the skewness [$\alpha_3(X)$] and kurtosis [$\alpha_4(X)$] of $\mathbf{P}(\mathbf{I})(k, a)$ as functions of a for $a = 4.1, 4.2(0.2)19.0, 20, 30, 50, 100$, and the expected value and variance as functions of a and k .

4.2 Alternative Measures of Location

Although the expected value does not always exist, the following alternative measures of location do exist. The population geometric mean is

$$g = k \exp\left(\frac{1}{a}\right). \quad (20.13)$$

The population harmonic mean ($\{E[X^{-1}]\}^{-1}$) is

$$h = k(1 + a^{-1}). \quad (20.14)$$

The population median is

$$m = 2^{1/a}k. \quad (20.15)$$

One might also use the mode k , though this index does not take into account the value of a . [The mode of $P(\Pi)(\mu, C, a)$ is at μ .]

4.3 Measures of Inequality

Arnold (1983) emphasizes that the value of the variance is of little importance in the context of modeling income distributions, as compared with some other measures of inequality. We note the Gini index, which for $P(I)(k, a)$ is

$$G = (2a - 1)^{-1}, \quad a > 1. \quad (20.16)$$

Also the Lorenz curve is

$$L(u) = 1 - (1 - u)^{(a-1)/a}, \quad a > 1. \quad (20.17)$$

An alternative expression for G is

$$1 - \frac{E[X'_{1:2}]}{E[X]}, \quad (20.16)'$$

from which an extension to a generalized *n*th-order Gini index

$$G_n = 1 - \frac{E[X'_{1:n+1}]}{E[X'_{1:n}]}, \quad (20.16)''$$

has been made. [Here $X'_{1:m}$ denotes the first order statistic (least value) in a

random sample of size m .] For the $P(I)(k, a)$ distribution

$$G_n = \{n(n+1)a - n\}^{-1}. \quad (20.18)$$

Other classical measures of inequality are the average income of poorer-than-average individuals

$$m_L = \frac{1}{F_X(E[X])} \int_k^{E[X]} x dF_X(x) \\ \left(= \left(\frac{a}{a-1} \right) \left\{ 1 - \left(\frac{a}{a-1} \right)^{1-a} \right\} \left\{ 1 - \left(\frac{a}{a-1} \right)^{-a} \right\}^{-1} \right. \\ \left. \text{for } P(I)(k, a) \right) \quad (20.19)$$

and the average income of richer-than-average individuals

$$m_U = \frac{1}{1 - F_X(E[X])} \int_{E[X]}^{\infty} x dF_X(x) \\ \left(= \left(\frac{a}{a-1} \right)^2 \text{ for } P(I)(k, a) \right). \quad (20.20)$$

The hazard rate is

$$r(x) = ax^{-1}, \quad (20.21)$$

and the cumulative hazard rate is

$$R(x) = \int_k^x r(t) dt = a \log \left(\frac{x}{k} \right). \quad (20.22)$$

Note that the hazard rate is a decreasing function of x . However, the elasticity [$d \log F(x) / d \log x$] is constant (equal to a).

Ahmed, Haq, and Khurshid (1990) have discussed the peakedness of the Pareto distribution through a slight modification of a measure of peakedness given by Horn (1983). The modification has been made in order to take into account the skewness of the Pareto distribution.

5 ESTIMATION OF PARAMETERS

In this section we will suppose (unless otherwise explicitly stated) that X_1, X_2, \dots, X_n are independent random variables each distributed as in (20.2).

5.1 Least-Squares Estimators

Rearranging (20.2) and taking logarithms of both sides, we obtain

$$\log[1 - F_X(x)] = a \log k - a \log x. \quad (20.23)$$

The parameters a and k may be estimated by least-squares from sample estimates of $F_X(x)$, using as the dependent variable the logarithm of 1 minus the cumulative distribution of the sample. The least-squares estimator of a is then

$$\tilde{a} = \frac{-n \sum_{i=1}^n \log X_i \log[1 - F_X(X_i)] + (\sum_{i=1}^n \log X_i)(\sum_{i=1}^n \log[1 - F_X(X_i)])}{n \sum_{i=1}^n (\log X_i)^2 - (\sum_{i=1}^n \log X_i)^2} \quad (20.24)$$

The corresponding least-squares estimator of k may be obtained by substituting into (20.23) the arithmetic mean values of the dependent and independent variables along with the estimator \tilde{a} and solving for k . Estimators of the parameters obtained by least-squares methods have been shown to be consistent [Quandt (1966)].

5.2 Estimators from Moments

Provided that $a > 1$, the mean of the Pareto distribution exists and is given by (20.11a). By equating this to the sample mean \bar{X} and rearranging, we obtain the relation

$$a^* = \frac{\bar{X}}{\bar{X} - k^*} \quad (20.25)$$

between estimators a^* , k^* of a and k . A formula for k^* may be found by the following argument [Quandt (1966)]: The probability that all n of the X_i 's are greater than a particular value x is $(k/x)^{an}$. Let $F_{X_1'}(x)$ be the cumulative distribution function of the smallest sample value. Then

$$F_{X_1'}(x) = 1 - \left(\frac{k}{x}\right)^{an}, \quad x \geq k. \quad (20.26)$$

The corresponding density function is

$$p_{X_1'}(x) = \frac{ank^{an}}{x^{an+1}} \quad (20.27)$$

From (20.27) the expected value of X'_1 (the smallest sample value) is

$$E[X'_1] = \frac{ank}{an - 1}, \quad (20.28)$$

Equating X'_1 to $E[X'_1]$ in (20.28), the estimator of k is found to be

$$k^* = \frac{(a^*n - 1)X'_1}{a^*n}, \quad (20.29)$$

and substituting this in (20.25), we obtain

$$a^* = \frac{n\bar{X} - X'_1}{n(\bar{X} - X'_1)}. \quad (20.30)$$

The estimators a^* and k^* are consistent [Quandt (1966)].

5.3 Maximum Likelihood Estimation

The likelihood function for a sample (X_1, \dots, X_n) from a Pareto distribution is

$$L = \prod_{j=1}^n \frac{ak^a}{X_j^{a+1}}. \quad (20.31)$$

Taking logarithms of both sides, differentiating partially with respect to the parameter a , and setting the result to zero we find the relation

$$\hat{a} = n \left[\sum_{j=1}^n \log \left(\frac{X_j}{\hat{k}} \right) \right]^{-1} \quad (20.32)$$

between the maximum likelihood estimators \hat{a} , \hat{k} of a , k , respectively.

A second equation (corresponding to $\partial \log L / \partial k = 0$) cannot be obtained in the usual way, since $\log L$ is unbounded with respect to k . Since k is a lower bound on the random variable X , $\log L$ must be maximized subject to the constraint

$$\hat{k} \leq \min_i X_i. \quad (20.33)$$

By inspection, the value of \hat{k} that minimizes (20.31) subject to (20.33) is

$$\hat{k} = \min_i X_i = X'_1; \quad (20.34)$$

\hat{a} may be expressed as a function of \hat{k} and the geometric mean by substituting $\hat{g} = (\prod_{i=1}^n X_i)^{1/n}$ into (20.32) to yield

$$\hat{a} = \left[\log \left(\frac{\hat{g}}{\hat{k}} \right) \right]^{-1}. \quad (20.35)$$

We have

$$E[\hat{k}] = \frac{nka}{na - 1}, \quad n > \frac{1}{a}, \quad (20.36a)$$

$$\text{Var}(\hat{k}) = \frac{nka^2}{(na - 1)^2(na - 2)}, \quad n > \frac{2}{a}; \quad (20.36b)$$

hence

$$\text{MSE}(\hat{k}) = \frac{2k^2}{(na - 1)(na - 2)}, \quad n > \frac{2}{a}. \quad (20.36c)$$

Also

$$E[\hat{a}] = \frac{na}{n - 2}, \quad n > 2, \quad (20.37a)$$

$$\text{Var}(\hat{a}) = \frac{n^2 a^2}{(n - 2)^2(n - 3)}, \quad n > 3; \quad (20.37b)$$

hence

$$\text{MSE}(\hat{a}) = \frac{a^2(n^2 + 4n - 12)}{(n - 2)(n - 3)}, \quad n > 3. \quad (20.37c)$$

It has been shown by Quandt (1966) that both \hat{a} and \hat{k} are consistent estimators of a and k , respectively.

Note that $2na/\hat{a}$ is distributed as χ^2 with $2(n - 1)$ degrees of freedom. A $100(1 - \alpha)\%$ confidence interval for a is given by

$$\left(\hat{a} \chi_{2(n-1), \frac{\alpha}{2}}^2 (2n)^{-1}, \hat{a} \chi_{2(n-1), 1-\frac{\alpha}{2}}^2 (2n)^{-1} \right). \quad (20.38)$$

The pdf of \hat{k} is

$$p_{\hat{k}}(y) = nak^{na} y^{-na-1}, \quad y > 0.$$

The set (\hat{k}, \hat{a}) is jointly sufficient for (k, a) , and \hat{k} and \hat{a} are mutually independent [Malik (1970)]. Also \hat{k} is sufficient for k when a is known and \hat{a} is sufficient for a when k is known.

From (20.37a) and (20.37b),

$$a^* = (1 - 2n^{-1})\hat{a} \quad (20.39)$$

and

$$k^* = \{1 - (n - 1)^{-1}\hat{a}^{-1}\}\hat{k} \quad (20.40)$$

are unbiased estimators of a and k , respectively. The variance of k^* is

$$\text{Var}(k^*) = a^{-1}(n - 1)^{-1}(na - 2)^{-1}k^2, \quad n > \frac{2}{a}. \quad (20.41)$$

Since (\hat{a}, \hat{k}) is a sufficient statistic for (a, k) , and (a^*, k^*) is a function of (\hat{a}, \hat{k}) , (a^*, k^*) is the uniform minimum variance estimator of (a, k) . Its ellipse of concentration is contained within the ellipse of concentration of every other unbiased estimator of (a, k) . From this point of view it may be called the "best" unbiased estimator of (a, k) , though some biased estimators might be "better" in terms of appropriate loss functions.

If k is known the maximum likelihood estimator of a is

$$\hat{a}' = \left[\log \left(\frac{\hat{g}}{k} \right) \right]^{-1}. \quad (20.42)$$

Note that $2na/\hat{a}'$ is distributed as χ^2 with $2n$ degrees of freedom. A $100(1 - \alpha)\%$ confidence interval for a is given by

$$\left(\hat{a}'\chi_{2n, \frac{\alpha}{2}}^2(2n)^{-1}, \hat{a}'\chi_{2n, 1 - \frac{\alpha}{2}}^2(2n)^{-1} \right). \quad (20.43)$$

[Compare with (20.38) to assess the greater accuracy accruing from knowledge of the value of k .] Also

$$E[\hat{a}'] = \frac{na}{n - 1}, \quad (20.44a)$$

$$\text{Var}(\hat{a}') = \frac{n^2a^2}{(n - 1)^2(n - 2)}. \quad (20.44b)$$

Maximum likelihood estimation from grouped data for $\mathbf{P}(\mathbf{I})(k, a)$ when k is known (i.e., estimation of a when k is known) has been discussed by Fisk (1961) and Aigner and Goldberger (1970). Aigner and Goldberger apply a general method of Kulldorff (1961) for maximum likelihood estimation from grouped data, to estimation of a from $\mathbf{P}(\mathbf{I})$ distributions with $k = 1$ [$\mathbf{P}(\mathbf{I})(1, a)$ distributions].

Let $x_0 = 1 < x_1 < x_2 < \dots < x_T < x_{T+1} = \infty$ be the boundaries of the $(T + 1)$ groups, and denote the number of observations, in a random sample of size n , falling into the group bounded by x_t and x_{t+1} , by N_t ($t = 0, 1, \dots, T$; $\sum_{t=0}^T N_t = n$). The maximum likelihood estimator of a is the solution of the equation

$$\sum_{t=0}^{T-1} N_t \left(\frac{x_{t+1}^{-a} \log x_{t+1} - x_t^{-a} \log x_t}{x_{t+1}^{-a} - x_t^{-a}} \right) + N_T \log x_T = 0. \quad (20.45)$$

Although the left-hand side of (20.45) is highly nonlinear in a , Aigner and Goldberger (1970) assert that it is usually amenable to iterative solution, or simply to trial-and-error search over a relevant range of values for a . It should be noted, however, that zero values of N_t pose problems for maximum likelihood estimation. It is recommended that such group intervals be disregarded (though this is likely to lead to bias in the estimator).

If the group boundaries are in equal ratios, with $x_t = cx_{t-1}$ for $t = 1, \dots, T$ (and $x_0 = k$), then the maximum likelihood estimator of a is

$$\frac{1}{\log c} \log \left(1 + \frac{n}{\sum_{t=0}^{T-1} t N_t} \right) \quad (20.46)$$

(The grouped data have a truncated log-geometric distribution; see Chapter 5, Section 11).

5.4 Estimation Based on Order Statistics

For $P(I)(k, a)$ distribution both the moment estimation (Section 5.2) and the maximum likelihood estimation (Section 5.3) may be modified by using the equation

$$X'_1 (= E[X'_1]) = nak(na - 1)^{-1} \quad (20.47)$$

together with (20.25) or (20.32), respectively. Estimation of k and a , using estimators of two quantiles, is simple to apply, in the way described below.

Select two numbers P_1 and P_2 between 0 and 1 and obtain estimators of the respective quantiles \hat{X}_{P_1} and \hat{X}_{P_2} . [In large samples it is possible to take $\hat{X}_{P_j} = X'_{(n+1)P_j}$.] Estimators of a and k are then obtained by solving the two simultaneous equations

$$P_j = 1 - \left(\frac{k}{\hat{X}_{P_j}} \right)^a, \quad j = 1, 2. \quad (20.48)$$

The estimator of a is

$$\frac{\log[(1 - P_1)/(1 - P_2)]}{\log(\hat{X}_{P_2}/\hat{X}_{P_1})} \quad (20.49)$$

The corresponding estimator of k can be obtained from (20.48). It has been shown that the estimators of a and k obtained by this method are consistent [Quandt (1966)] (see also Section 5.8).

Koutrouvelis (1981) extends the quantile method of estimation to the use of suitably chosen order statistics $X'_{n_1}, X'_{n_2}, \dots, X'_{n_k}$ from a random sample of (large) size n from a $\mathbf{P}(\mathbf{I})(k, a)$ distribution (see also Section 5.8). The idea is to reduce the problem to an exponential distribution by noting that $Y'_{n_i} = \log X'_{n_i}$ is an order statistic from a population with cdf $F_Y(y) = 1 - \exp(-(y - \eta)/\sigma)$, where $\eta = \log k$ and $\sigma = 1/a$. The estimators $\hat{\eta}$ and $\hat{\sigma}$ are obtained from the weighted linear regression fit to $E[\log X'_{n_i}] = \eta - a \log(1 - t_i)$ ($i = 1, \dots, k$), where $t_i = n_i/n$. They are given by

$$\hat{\sigma} = \sum_{i=1}^n b_i \log X'_{n_i}, \quad (20.50a)$$

$$\hat{\eta} = \log X'_{n_1} - \hat{\sigma} u_1, \quad (20.50b)$$

where

$$b_1 = -\frac{(u_2 - u_1)/\{\exp(u_2) - \exp(u_1)\}}{L},$$

$$b_i = \frac{\{(u_i - u_{i-1})/[\exp(u_i) - \exp(u_{i-1})]\} - \{(u_{i+1} - u_i)/[\exp(u_{i+1}) - \exp(u_i)]\}}{L},$$

$$i = 2, 3, \dots, k - 1,$$

$$b_k = \frac{(u_k - u_{k-1})/\{\exp(u_k) - \exp(u_{k-1})\}}{L},$$

with

$$u_i = -\log(1 - t_i), \quad i = 1, 2, \dots, k,$$

$$L = \sum_{i=2}^k \frac{(u_i - u_{i-1})^2}{\exp(u_i) - \exp(u_{i-1})}.$$

These estimators are asymptotically BLUEs of η and a , respectively [Ogawa (1962)], while the estimators $\hat{k} = \exp(\hat{\eta})$ and $\hat{a} = 1/\hat{\sigma}$ (with $\hat{\eta}$ and $\hat{\sigma}$ given above) remain asymptotically unbiased but no longer linear. Koutrouvelis

(1981) has shown that \tilde{k} and \tilde{a} are consistent and asymptotically normal with means k and a and variances

$$\text{Var}(\tilde{k}) \sim \frac{k^2(u_1^2 L^{-1} + \exp(u_1) - 1)}{na^2}, \quad (20.51a)$$

$$\text{Var}(\tilde{a}) \sim a^2/(nL). \quad (20.51b)$$

Since the determinant of the variance-covariance matrix of \hat{k} and \hat{a} is $k^2\{\exp(u_1) - 1\}/(n^2L)$, the optimal values for u_1, \dots, u_k are obtained by maximizing the function $\{\exp(u_1) - 1\}^{-1}L$ with respect to u_1, u_2, \dots, u_k subject to the constraint $0 < u_1 < u_2 < \dots < u_k < \infty$. The values of t_1 and of $u_1 = -\log(1 - t_1)$ must be positive. Saleh and Ali (1966) propose to first take the optimal $n_1^0 = 1$ and $t_1^0 = n_1^0/(n + \frac{1}{2})$ for fixed t_2, \dots, t_k . Thus $u_1^0 = \log\{1 - 1/(n + \frac{1}{2})\}^{-1}$. The optimal choice of u_2, \dots, u_k is determined after replacing u_1 by u_1^0 . Koutrouvelis (1981) provides additional details. Simulation investigations carried out by Koutrouvelis (1981) show that for parameter k , his method using two optimal sample quantiles performs almost as well as using five optimal quantiles (for $n = 25, 100$, and **500**), while for parameter a the estimator based on five sample quantiles is substantially more efficient than the two quantile procedure, and competes in efficiency with the maximum likelihood estimator. For all the cases considered $\text{RE}(\tilde{a}) \geq 0.697$ for the five quantile procedure and $\text{RE}(\tilde{a}) \geq 0.584$ for two quantile procedure ($n = 25, 100, 500$, $k = 1$, and $a = 0.5, 1.5$, and 4.5). He also discovered that even a slight change of the definition of sample quantile has a significant effect on the values of moments of a .

For the three-parameter $\mathbf{P}(\text{II})(\mu, C, a)$ distribution (20.4), the construction of BLUEs for μ and C , when a is known has received much attention. **Kulldorff** and Vannman (1973) and Vannman (1976) pioneered this work. Charek, Moore, and Coleman (1988) compared BLUEs with six minimum distance estimators of μ and C [based on Kolmogorov (D) distance, **Cramér-von Mises** distance and the Anderson-Darling statistic, each applied with two different minimization routines]. They found that for the values $a = 1(1)4$ and sample sizes $n = 6(3)18$, the BLUE for C had the smallest mean square error, and that the BLUE for μ also has advantageous properties.

The BLUEs developed by **Kulldorff** and Vannman (1973) for the case $a > 2$, are calculated from the equations

$$\tilde{\mu} = X'_1 - Y[(na - 1)(na - 2) - naD]^{-1}, \quad (20.52a)$$

$$\tilde{C} = (X'_1 - \tilde{\mu})(na - 1), \quad (20.52b)$$

where

$$\begin{aligned}
 B_0 &= 1, B_i = \{1 - 2a^{-1}(n - i + 1)^{-1}\}B_{i-1}, \quad i = 1, 2, \dots, n, \\
 D &= (a + 1) \sum_{i=1}^n B_i + (a - 1)B_n, \\
 Y &= (a + 1) \sum_{i=1}^n B_i X'_i + (a - 1)B_n X'_n - DX'_1. \quad (20.52c)
 \end{aligned}$$

Vannman's (1976) estimators, developed for the case $a < 2$, are given by

$$\tilde{\mu} = X'_2 - \frac{\tilde{C}}{na - 1}, \quad (20.53a)$$

$$\begin{aligned}
 \tilde{C} &= \frac{1}{U} \left[(a + 1) \sum_{i=1}^{n-2} B_i X'_i + (2a - 1)B_{n-1} X'_{n-1} \right. \\
 &\quad \left. - \left(\frac{na - 1}{na} \right) (na - 2 - U) X'_1 \right], \quad (20.53b)
 \end{aligned}$$

where

$$U = \frac{(na - 2)(na - a - 2) - na(a - 2)B_{n-1}}{(na - 1)(a + 2)}$$

and the B_i 's are as defined in (20.52c). For $2/n < a \leq 2$, with $2/a$ an integer, Vannman's estimators simplify to

$$\tilde{C} = (na - 1)(X'_1 - \hat{\mu}), \quad (20.53a)'$$

$$\tilde{\mu} = X'_1 - \frac{(a + 1)(a + 2)}{(na - 2)(na - a - 2)} \left[\sum_{i=1}^{n-(2/a)} B_i X'_i + \frac{na - 2}{a + 2} X'_1 \right]. \quad (20.53b)'$$

Note that in (20.53b)' only the first $n - (2/a)$ order statistics are used. Asymptotically BLUEs of C, when a is known, have been considered by Chan and Cheng (1973), who also dealt with censored cases.

For small sample sizes, calculation of BLUEs is fairly simple, but it becomes tedious as n increases. Vannman (1976) suggests using BLUEs based on the first k order statistics, with k considerably less than n. Arnold (1983) notes that the latter order statistics may be unstable.

5.5 Sequential Estimation

Hamdy and Pallotta (1987) constructed a three-stage procedure for estimating the parameters of $\mathbf{P}(\mathbf{I}(k, a))$. From a random sample X_1, X_2, \dots, X_n of size n , we have estimators

$$k_n^* = X'_1 = \min(X_1, \dots, X_n), \quad (20.54a)$$

$$a_n^* = (n - 1) \left\{ \sum_{i=1}^n \log \left(\frac{X_i}{X'_1} \right) \right\}^{-1}, \quad (20.54b)$$

of k and a , respectively. Hamdy and Pallotta (1987) assume that the optimal sample size needed to estimate k is of the form

$$n_0 = \beta a^{-\gamma}, \quad \beta, \gamma > 0, \quad (20.55)$$

where β and γ are known constants. If a also were known, then n_0 would be determined. If a is not known, the following three-stage procedure is proposed: Start with a sample of size m (≥ 2), and take an "appropriate" constant δ . If $[\delta \beta a_m^{*\gamma}] + 1 > m$ take an additional sample of size $[\delta \beta a_m^{*\gamma}] + 1 - m$ so that the total sample size is $R^* = \max(m, [\delta \beta a_m^{*\gamma}] + 1)$. In the third stage we make the final sample size to be

$$N^* = \max(R^*, [\delta \beta a_{R^*}^{*\gamma}] + 1)$$

by taking $N^* - R^*$ additional observations. Hamdy and Pallotta suggest taking $\delta = \frac{1}{2}$, and assert that their method is a practical alternative to one-at-a-time sequential sampling.

5.6 Minimax Estimation

Kaluszka (1986) has shown that for the $\mathbf{P}(\mathbf{I}(k, a))$ distribution, a minimax and admissible estimator (with mean square error loss function) of a^r , if k is known, is

$$\frac{\Gamma(n - r)}{\Gamma(n - 2r)} \left(-n \log k + \sum_{i=1}^n \log X_i \right)^{-r}, \quad r < \frac{n}{2}. \quad (20.56)$$

[See also Iliescu and Vodă (1979).] The result is obtained by noting that the distribution of $\sum_{i=1}^n \log(X_i/k)$ is gamma (n, a^{-1}) and then applying a general method of Kaluszka (1986). [See also Chapter 17, Section 8.]

5.7 Estimation of Pareto Densities

Asrabadi (1990) discusses estimation of the $P(I)(k, a)$ pdf

$$p_X(x) = \frac{ak^a}{x^{a+1}}, \quad x \geq k > 0, a > 0, \quad (20.57)$$

using the popular method of finding the UMVUE of this simple function of the parameters. If k is known, then $T = \prod_{i=1}^n X_i$ is a complete sufficient statistic for the parameter a . Thus the conditional pdf of X_1 , given T , is a function of T only, $p_X^*(x|T)$, say, and this is the UMVUE of $p_X(x)$. We have

$$p_X^*(x) = \frac{(n-1)\{\log T - \log x - (n-1)\log k\}^{n-2}}{x(\log T - n \log k)^{n-1}}, \quad k \leq x \leq Tk^{-n+1}. \quad (20.58)$$

The corresponding estimate of the cdf

$$F_X(x) = 1 - \left(\frac{k}{x}\right)^a, \quad x \geq k > 0, \quad (20.2')$$

is

$$F_X^*(x) = \begin{cases} 0 & \text{for } x < k, \\ 1 - \frac{\{\log T - \log x - (n-1)\log k\}^{n-1}}{(\log T - n \log k)^{n-1}} & \text{for } k \leq x \leq Tk^{-n+1}, \\ 1 & \text{for } x \geq Tk^{-n+1}. \end{cases} \quad (20.59)$$

This is the UMVUE of $F_X(x)$. Similarly the r th moment of $p_X^*(x)$ is the UMVUE of the r th moment of the $P(I)(k, a)$ distribution.

After successive integrations by parts we find

$$(E[X^r])^* = \frac{(n-1)!k^r r^{n-1}}{(\log T - n \log k)^{-n+1}} \times \left\{ Tk^{-rn} - 1 - \sum_{i=1}^{r-2} \frac{(\log T - n \log k)^i r^i}{i!} \right\}. \quad (20.60)$$

We emphasize that these simple expressions are due to the especially simple form of the pdf and cdf of the classical $P(I)(k, a)$ distribution (see analogous results for the exponential distribution in Chapter 19).

Both $p_X(x)$ and $p_X^*(x)$ are decreasing functions of x for $x \geq k$ (and equal to zero for $x < k$). The value of $p_X^*(x)$ at $x = k$ is $(n-1)k^{-1}\{\log T - n \log k\}^{-1}$, which is the UMVUE of $k^{-1}a$, the value of $p_X(x)$ at $x = k$. Note that

$$a^* = \frac{n-1}{n \log k} \quad (20.61)$$

is the UMWE of a and that the distribution of a^{*-1} is gamma $(n, a^{-1}(n-1)^{-1})$, so $2(n-1)a/a^*$ has a χ_{2n}^2 distribution (see Chapter 18). Also

$$\text{Var}(a^*) = a^2(n-2)^{-1} \quad (20.62)$$

and $a^{*2}(n-1)^{-1}$ is an unbiased estimator of $\text{Var}(a^*)$.

Reduction to a problem involving exponentially distributed variables is employed by Hassanein, Saleh, and Brown (1991) to estimate the survivor function

$$\bar{F}_X(x) = \left(\frac{k}{x}\right)^a, \quad x \geq k, \quad (20.63)$$

for $\mathbf{P(I)}(k, a)$ using just m ($\leq n$) of the order statistics from a random sample of size n . Choice of the appropriate order statistics is discussed in their paper.

5.8 Estimation of Pareto Quantiles

Umbach, Ali, and Hassanein (1981) consider the $\mathbf{P(III)}(\mu, C, a)$ distribution (20.4), with known shape parameter a . They wish to estimate x_ξ , the ξ -quantile of $\mathbf{P(III)}(\mu, C, a)$ by the estimator

$$\bar{x}_\xi(l, u) = b_l X'_l + b_u X'_u, \quad (20.64)$$

where X_i, X'_u are the i th and u th order statistics ($i < u$) in a random sample of size n , and b_l and b_u are chosen so that $\bar{x}_\xi(l, u)$ will be asymptotically unbiased and minimum variance.

Suppose that $1 = [np_l] + 1$, $u = [np_u] + 1$ ($p_l < p_u$). The asymptotic expected values of X_i and X'_u are

$$\begin{aligned} E[X'_l] &\doteq x_{p_l} = \mu + z_{p_l}k, \\ E[X'_u] &\doteq x_{p_u} = \mu + z_{p_u}k, \end{aligned} \quad (20.65)$$

where z_ξ is the ξ -quantile of $\mathbf{P(I)}(1, a)$.

Table 20.1 Values of $\begin{pmatrix} p_l & p_u \\ b_l & b_u \end{pmatrix}$ for Specific Estimator of x_ξ of the Form (20.64)

	$\xi = 0.1$	$\xi = 0.5$	$\xi = 0.75$
$a = 0.5$	0, 0.3596 0.8369, 0.1631	0.4374, 0.6397 0.8151, 0.1849	0, 0.3596 -9.4279, 10.4279
$a = 1$	0, 0.5000 0.8889, 0.1111	0.4000, 0.7000 0.8000, 0.2000	0, 0.5000 -3.0000, 4.0000
$a = 2$	0, 0.6180 0.9125, 0.0875	0.3572, 0.7545 0.7835, 0.2165	0.6786, 0.8772 0.7835, 0.2165
$a = 3$	0, 0.6695 0.9199, 0.0801	0.3333, 0.7796 0.7745, 0.2255	0.6667, 0.8898 0.7745, 0.2255

The asymptotic variance of $\tilde{x}_\xi(l, u)$ is

$$\begin{aligned} \text{Var}(\tilde{x}_\xi(l, u)) = & \frac{k^2}{na^2(z_{p_u} - z_{p_l})^2} \left\{ (z_{p_u} - z_\xi)^2 z_{p_l}^2 (z_{p_l}^a - 1) \right. \\ & + 2z_{p_l} z_{p_u} (z_{p_u} - z_\xi)(z_{p_l} - z_\xi)(z_{p_l}^a - 1) \\ & \left. + (z_\xi - z_{p_l})^2 z_{p_u}^2 (z_{p_u}^a - 1) \right\}. \quad (20.66) \end{aligned}$$

If optimal values of l and u (minimizing the asymptotic variance) include $p_l = 0$, then $p_u = 1 - k_a^{-a}$, $b_l = (k_a - z_\xi)/(k_a - 1)$, and $b_u = (z_\xi - 1)/(k_a - 1)$, where

$$ak_a^a(k_a - 1) = 2(k_a^a - 1). \quad (20.67)$$

Expressions for the optimal values of p_l , p_u , b_l , and b_u are more complex in the general case. Optimal sets of values are shown in Table 20.1 for a few special cases. Of course one needs to have a good idea of the value of a to use these tables. Values of the ARE of \tilde{x}_ξ , compared to the nonparametric estimator $X'_{[n\xi]+1}$, is presented in Table 20.2 which indicates that \tilde{x}_ξ performs far better than $X'_{[n\xi]+1}$ especially for values of ξ close to 0 or 1.

A different approach to estimation of quantiles was adopted by Asrabadi (1990), using formula (20.59) for the UMVUE, $F_X^*(x)$ of $F_X(x)$. The ξ -quantile of $F_X^*(x)$, viz., $X_\xi^* = F_X^{*-1}(\xi)$ is not a UMVUE of x_ξ , the ξ -quantile of $P(\mathbf{I})(k, a)$. However, from the distribution of X_ξ^* an approximate $100(1 - \alpha)\%$

Table 20.2 ARE for x_ξ Compared to $X'_{[n\xi]^{+1}}$

$a = 0.5$	191%	111%	5288%
$v = 1$	Z77	117	133
$a = 2$	380	Z26	116
$a = 3$	438	ED	167
$\xi = 0.1$	$\xi = 0.5$	$\xi = 0.75$	

confidence interval for x_ξ is given by

$$(20.68) \left[1 - \left\{ \frac{\chi^2_{2n, 1-\frac{\xi}{a}}}{2a \log(X^*/k)} \right\}^{n-1}, 1 - \left\{ 1 - \frac{\chi^2_{2n, \frac{\xi}{a}}}{2a \log(X^*/k)} \right\}^{n-1} \right].$$

Salah, Ali, and Umbach (1985) investigated *nonlinear* estimators of the quantiles of $P(I)(k, v)$ based on a few selected order statistics, using the approach developed by Koutrouvelis (1981) (see Section 5.4). The quantile

$$(20.69) x_\xi = F_{-1}^{X'}(\xi) = k(1 - \xi)^{-1/a}$$

is estimated by exploiting the relationship between Pareto and exponential distributions [see (20.9)]. If X'_r is the r th-order statistic in a random sample of size n from a $P(I)(k, a)$ distribution, then $Z'_r = \log(X'_r/k)$ is the corresponding order statistic in a sample from the exponential distribution with pdf

$$(20.70) a^{-1} \exp(-a^{-1}z), \quad z \geq 0.$$

Asymptotic BLUEs $\log k$ and a^{-1} , for $\log y$ and v^{-1} , respectively, for the latter situation have been thoroughly investigated [e.g., see Saleh and Ali (1966) and Koutrouvelis (1981) for a corrected version]. The corresponding estimator of x_ξ is

$$(20.71) x_\xi = \exp\{\log k - a^{-1} \log(1 - \xi)\}.$$

The estimator is quite efficient even for a small number (2-4) of selected order statistics and highly efficient for moderate numbers (≥ 8). It is superior to the nonparametric estimator $X'_{[n\xi]^{+1}}$, and far superior if ξ is near 0 or 1.

5.9 Censored Data

For censored samples of size n , with only values less than a (known) value τ recorded, suppose that exact values X_1, \dots, X_{n-c} are known for only $n - c$ individuals, while for the other c individuals it is only known that the value

exceeds τ . If k is known, the MLE of a is

$$\hat{a} = (n - c) \left(\sum_{i=1}^{n-c} \log X_i - n \log k + c \log \tau \right)^{-1}. \quad (20.72)$$

If k is not known, Cohen and Whitten (1988) recommend modified maximum likelihood estimators, obtained by solving the equations

$$X'_1 = E[X'_1] = \hat{k} \hat{a} n (\hat{a} n - 1)^{-1}, \quad (20.73a)$$

$$\hat{a} = (n - c) \left(\sum_{i=1}^{n-c} \log X_i - n \log \hat{k} + c \log \tau \right)^{-1}, \quad (20.73b)$$

iteratively, starting with \hat{k} slightly less than X'_1 .

Rohatgi and Saleh (1987) discuss the case where τ is not known, but only the least $n - c$ among the n sample values ($X'_1 \mathbf{I} X'_2 \mathbf{I} \dots \mathbf{I} X'_{n-c}$) are known. All that is known of the remaining c values is that they are not less than X'_{n-c} . Extending results of Saksena and Johnson (1984), they obtain the maximum likelihood estimators

$$\hat{k} = X'_1, \quad (20.74a)$$

$$\hat{a} = (n - c) \left(\sum_{i=1}^{n-c} \log X'_i + c \log X'_{n-c} - n \log X'_1 \right)^{-1}. \quad (20.74b)$$

The UMVUEs are

$$k^* = \left(1 - \frac{n - c}{n(n - c - 1)} \frac{1}{\hat{a}} \right) \hat{k}, \quad (20.75a)$$

$$a^* = \frac{n - c - \frac{2}{\hat{a}}}{n - c} \hat{a} \quad (20.75b)$$

If we have independent samples of sizes n_1, n_2 from $P(\mathbf{I}(k, \mathbf{a},))$ and $P(\mathbf{I}(k, \mathbf{a},))$, respectively, of which only the $n_1 - c_1, n_2 - c_2$ least values are known, UMVUE of the common value of k is

$$\hat{k} = \left[1 - \left\{ \sum_{j=1}^2 \frac{n_j(n_j - c_j - 1) \hat{a}_j}{n_j - c_j} \right\}^{-1} \right] \hat{k}, \quad (20.76)$$

where subscripts refer to estimators based on the j th sample values, and

$\hat{k} = \min(\hat{k}_1, \hat{k}_2)$. The variance of this UMVUE of k is estimated by

$$\hat{k}^2 \left\{ \sum_{j=1}^2 \frac{n_j(n_j - c_j - 1)\hat{a}_j}{n_j - c_j} \right\}^2. \tag{20.77}$$

5.10 Bayesian Estimation

The following prior distributions for the parameters a and k in $P(\mathbf{I}(k, a))$ have been studied [* denotes natural conjugate, and (Pareto)⁻¹ signifies distribution of the reciprocal of a $P(\mathbf{I}(k, a))$ variable]:

Reference	k	a
Lwin (1972)	Known	Gamma*
	Known	$a a^{-1}$
	Power Function	Known
	$\frac{m(m-1)^m(-\log n)^m}{\Gamma(m)}$	$\frac{k^{ma-1}a^m}{n^a}$
Nigm and Hamdy (1987)	αk^{-1}	Gamma*
	αk^{-1}	$a a^{-1}$ (independent)
Arnold and Press	(1983) Power function*	Gamma*
	(1989) (Pareto) ⁻¹	Known
	(1989) (Pareto) ⁻¹	Gamma*

Gamma distributions are natural conjugates for a ; power-function distributions are natural conjugates for k .

Geisser (1984, 1985) has provided extensive analysis of the application of Bayesian methods in predicting future values of $P(\mathbf{I}(k, a))$ distributed random variables from observed values in a complete random sample. Nigm and Hamdy (1987) have considered a similar problem where only the r least values (first r order statistics) in a random sample of size n are available, and it is desired to predict the remaining $n - r$ values. Geisser (1985) and Arnold and Press (1989) are of the opinion that it is more natural to assess prior belief about k first and then to consider the conditional prior distribution of a , given k , than conversely. Arnold and Press (1989) also point out that Nigm and Hamdy's (1987) analysis can be performed for the case where for the $P(\mathbf{I}(k, a))$ distribution

$$\Pr[X'_{r+1} > x | X'_i = x_i, i = 1, \dots, r; k, a] = \left(\frac{x}{x_r} \right)^{-(n-r)a}. \tag{20.78}$$

By considering the Pareto density function in (20.3) when the shape parameter a is known and the scale parameter k is unknown, Liang (1993) has discussed the problem of estimating the scale parameter k under a squared-error loss through the nonparametric empirical Bayes approach. He has then derived an empirical Bayes estimator of k and discussed the corresponding asymptotic optimality. Under some mild conditions, Liang (1993) has shown that this empirical Bayes estimator is asymptotically optimal and that the associated rate of convergence is of order $O(n^{-2/3})$.

6 ESTIMATION OF LORENZ CURVE AND GINI INDEX

The Lorenz curve is

$$L(p, a) = 1 - (1 - p)^{1-a^{-1}}, \quad (20.79)$$

and the Gini index is

$$G(a) = (2a - 1)^{-1}$$

(see Section 4.3).

The maximum likelihood estimators of these two quantities are obtained by replacing a by \hat{a} (if k is known) or by \hat{a}' (if k is unknown) and then introducing the condition $L(p, a) > 0$. Moothathu (1985, 1990) has investigated the sampling distributions of the estimators (\hat{L}) of $L(p, a)$, showing them to be asymptotically consistent. The distribution is mixed, with

$$\Pr[\hat{L} = 1] = \Pr[(\text{MLE of } a) \leq 1] \quad (20.80a)$$

and density

$$p_{\hat{L}}(w) = - \frac{\eta^{n-s+1}}{\Gamma(n-s+1)(1-p)^\eta} (1-w)^{n-1} (\log w)^{n-s}, \quad (20.80b)$$

with $\eta = na/\log(1-p)$, and $s = 1$ (2) according as k is (is not) known.

An unbiased estimator of $L(p, a)$ is

$$\begin{aligned} \tilde{L} &= 1 - (1-p) \left[1 + \sum_{j=1}^{\infty} \frac{\{-S_1 \log(1-p)\}^j}{n^{[j]} j!} \right] \\ &= 1 - (1-p) {}_0F_1(-; n; -S_1 \log(1-p)), \end{aligned} \quad (20.81a)$$

Note that

$$E[M] = \frac{\Gamma(n+1)\Gamma[\frac{1}{2}(n+1) - a^{-1}]}{\Gamma[\frac{1}{2}(n+1)]\Gamma(n+1 - a^{-1})} \times k. \quad (20.92)$$

[Note also from (20.15) that the population median value is $2^{1/a}k$.]

Applying Stirling's formula to (20.92), using logarithmic expansion, and retaining terms to the order of $1/n$, we obtain

$$\begin{aligned} E[M] &\doteq k2^{1/a} \left(1 + \frac{a+1}{2na^2} \right), \\ \text{Var}(M) &= k^2 2^{2/a} a^{-2} n^{-1}. \end{aligned} \quad (20.93)$$

It is apparent from (20.93) that

$$\lim_{n \rightarrow \infty} E[M] = 2^{1/a}k = m; \quad [\text{cf (20.15)}]$$

Further, we see that

$$\frac{V(\hat{m})}{V(M)} \doteq 1,$$

where $\hat{m} = 2^{1/\hat{a}}\hat{k}$ is the MLE of the median (m).

On setting the parameter k in (20.2) equal to 1, we obtain

$$F_X(x) = 1 - x^{-a}, \quad x \geq 1. \quad (20.94)$$

This may be regarded as a standard **form** of the Pareto distribution. A location parameter ε can be introduced to yield

$$F_X(x) = 1 - (x - \varepsilon)^{-a}, \quad x \geq 1 + \varepsilon. \quad (20.95)$$

It can be shown [Gumbel (1958)] that if T has an **exponential** distribution with scale parameter θ , then $X = \exp(T) + \varepsilon$ has the Pareto distribution (20.95) with

$$\begin{aligned} a &= \frac{1}{\theta}, \quad a \geq 1, \\ x &> 1 + \varepsilon, \quad \varepsilon \geq 0. \end{aligned}$$

A single-order statistic estimator using only X'_m of a , given ε , is

$$\tilde{a}|\varepsilon = \frac{1}{\tilde{\theta}} = \frac{1}{C_{mn} \log(X'_m - \varepsilon)}, \quad (20.96)$$

where

$$C_{mn} = \frac{1}{\sum_{i=1}^m (n - i + 1)^{-1}}$$

[Moore and Harter (1967)]. $\tilde{a}|\varepsilon$ and $\tilde{\theta}$ are consistent estimators of the shape parameter of the Pareto distribution and the scale parameter of the exponential distribution, respectively [Moore and Harter (1967)].

It can be shown [Moore and Harter (1967)] that an exact confidence interval for ε based on X'_m alone, if ε is known, is

$$\{D_{l,m,n} \log(X'_m - \varepsilon)\}^{-1} > a > \{D_{u,m,n} \log(X'_m - \varepsilon)\}^{-1}, \quad (20.97)$$

where the coefficients $D_{l,m,n}$ and $D_{u,m,n}$ have been tabulated [Harter (1964)] when $n = 1(1)20(2)40$ for m optimal. (In the sense that the value of m selected maximizes the efficiency of the confidence interval.)

8 ORDER STATISTICS AND RECORD VALUES

8.1 Order Statistics

We have already noted the distribution of the median of $n (= 2p + 1)$ independent random variables, each having the Pareto distribution. The j th smallest order statistic X'_j has density function

$$p_{X'_j}(x) = \frac{n!}{(j-1)!(n-j)!} \left(\frac{a}{x}\right) \left(\frac{k}{x}\right)^{a(n-j+1)} \left\{1 - \left(\frac{k}{x}\right)^a\right\}^{j-1}, \quad k \leq x, \quad (20.98)$$

and its r th moment about zero is

$$\mu'_r(X'_j) = \frac{\Gamma(n+1)\Gamma(n-j+1-ra^{-1})}{\Gamma(n+1-ra^{-1})\Gamma(n-j+1)} k^r. \quad (20.99)$$

[see (20.91) which is obtained by putting $j = \frac{1}{2}(n+1)$ in (20.99).] The joint probability density function of two order statistics X'_r, X'_s ($r < s$) is

$$p_{X'_r, X'_s}(x_r, x_s) = \frac{n! a^2 k^{2a}}{(r-1)!(s-r-1)!(n-s)!} \times \left[1 - \left(\frac{k}{x_r}\right)^a\right]^{r-1} \left[\left(\frac{k}{x_s}\right)^a - \left(\frac{k}{x_r}\right)^a\right]^{s-r-1} \times \left(\frac{k}{x_s}\right)^{a(n-s)} (x_r x_s)^{-(a+1)}, \quad k \leq x_r \leq x_s, \quad (20.100)$$

and their covariance can be calculated from

$$E[X'_r X'_s] = \frac{\Gamma(n+1)\Gamma(n-r-2a^{-1}+1)\Gamma(n-s-a^{-1}+1)}{\Gamma(n-s+1)\Gamma(n-r-a^{-1}+1)\Gamma(n-2a^{-1}+1)} k^2. \quad (20.101)$$

Malik (1966) showed that the characteristic function of the k th smallest order statistic X'_k in a random sample of size n is

$$\frac{\Gamma(n+1)}{\Gamma(k)} \sum_{j=0}^{\infty} \frac{\Gamma(k+ja^{-1})}{\Gamma(n+ja^{-1}+1)} \frac{(it)^j}{j!},$$

and obtained the interesting recurrence relationships

$$(k-1)E[(X'_k)^r] = (k+ra^{-1}-1)E[(X'_{k-1})^r] \quad (k > 1) \quad (20.102a)$$

$$(2a^{-1}+l-1)E[X'_k X'_l] = (a^{-1}+l-1)E[X'_k X'_{l-1}] \quad (k < l). \quad (20.102b)$$

He has provided tables of:

1. $E[X'_j]$ for $n \leq 12$,
2. $E[X'_r X'_s]$ for $n \leq 12$,
3. $\text{Var}(X'_j)$ and $\text{Cov}(X'_r, X'_s)$ for $n \leq 8$

to four decimal places.

Huang (1975) showed that for $P(I)(k, a)$

$$E[X'_i]^r = \frac{k^{(r)} n^{(r)}}{(n-ia^{-1})^{(r)}} \quad \text{for } a > i(n-r+1)^{-1}. \quad (20.103)$$

Balakrishnan and Joshi (1982) derived further recurrence relations among single and product moments of order statistics for different sample sizes, with $\mu_{r:n}^{(t)} = E[(X'_{r:n})^t]$ and $\mu_{r,s:n} = E[X'_{r:n} X'_{s:n}]$, namely

$$(na-t)\mu_{1:n}^{(t)} = nak^t, \quad n \geq 1, \quad (20.104a)$$

$$(na-t)\mu_{r:n}^{(t)} = na\mu_{r-1:n-1}^{(t)}, \quad 2 \leq r \leq n, \quad (20.104b)$$

$$\{a(n-r)-1\}\mu_{r,r+1:n} = a(n-r)\mu_{r:n}^{(2)}, \quad 1 \leq r \leq n-1, \quad (20.104c)$$

and

$$\{a(n-s+1) - 1\} \mu_{r,s:n} = a(n-s+1) \mu_{r,s-1:n},$$

$$1 \leq r < s \leq n, s-r \geq 2. \quad (20.104d)$$

8.2 Record Values

Pareto distributions arise as limiting distributions of the waiting time W_1 , the number of new observations needed to obtain a value exceeding the a th greatest among n observations already available. Formally,

$$W = \min(h; h \geq 1, X_{n+h} > X'_{n-a+1:n}). \quad (20.105)$$

It can be shown that if the parent distribution is continuous

$$\lim_{n \rightarrow \infty} \Pr[W_n^{-1} > x] = (1+x)^{-a}, \quad x \geq 0. \quad (20.106)$$

This is the $P(I)(1, a)$ distribution. This is a general result for any continuous parent distribution.

For cases where the parent distribution itself is Pareto, **Ahsanullah** and **Houchens** (1989) and **Balakrishnan** and **Ahsanullah** (1994a, b) have obtained several results: Let X_n ($n \geq 1$) be a sequence of i.i.d. random variables, possessing a pdf. Define

$$Y_n = \max(X_1, \dots, X_n), \quad n \geq 1.$$

Then X_j is a (upper) *record* value of the sequence $\{X_n\}$ if $X_j > Y_{j-1}$ ($j > 1$). (By definition, X_1 is a record value.)

The indices T_n at which the record values occur are the *record times*. Formally,

$$T_n = \min(j: X_j > X_{T_{n-1}}), \quad (20.107)$$

with $T_0 = 1$. A characteristic property of the Pareto distribution is that the ratios $X_{T_n}/X_{T_{n-1}}$ are independent and identically distributed as $P(I)(1, a)$. The pdf of X_{T_n} is

$$p_{X_{T_n}}(x) = \frac{\{R(x)\}^n}{n!} p_X(x), \quad (20.108)$$

where $R(x)$ is the cumulative hazard rate a $\log(x/k)$ (see Section 4.3). It follows that X_{T_n} is the product of $n-1$ mutually independent $P(I)(k, a)$ variables.

Ahsanullah and Houchens (1989) provide tables of the variances and covariances of X_{T_m} and X_{T_n} for $a = 2.5(0.5)5.0$, $0 < m < n \leq 3$. Balakrishnan and Ahsanullah (1994a) derive recurrence relations for single and product moments of (upper) record values for standardized Lomax, P(II), distributions with cdf

$$F_X(x) = 1 - (1 + x)^{-a}, \quad x \geq 0, a > 0. \quad (20.109)$$

They show that the pdf of X_{T_n} is

$$p_{X_{T_n}}(x) = \frac{1}{n!} [-\log\{1 - F_X(x)\}]^n p_X(x). \quad (20.110)$$

Using direct calculations, they show that

$$E[X_{T_{n+1}}^{r+1}] = \frac{(r+1)E[X_{T_{n+1}}^r] + aE[X_{T_n}^{r+1}]}{a-r-1}, \quad r < a-1. \quad (20.111a)$$

In particular,

$$E[X_{T_{n+1}}] = \frac{1 + aE[X_{T_n}]}{a-1} \quad (20.111b)$$

Also

$$\text{Cov}(X_{T_m}, X_{T_n}) = \left(\frac{a}{a-1}\right)^{n-m} \text{Var}(X_{T_m}), \quad 0 \leq m \leq n-1. \quad (20.111c)$$

Ahsanullah (1991) has carried out a detailed study of a *generalized* Pareto (II) (Lomax) distribution, with pdf

$$p_X(x) = \frac{1}{K} \left\{ 1 + \beta \frac{x - \xi}{K} \right\}^{-(1+\beta^{-1})}, \quad \begin{cases} x \geq \xi & \text{if } \beta \geq 0 \\ 0 < x < \xi - \frac{1}{\beta} & \text{if } \beta < 0 \end{cases}. \quad (20.112)$$

In this case X_{T_n} is distributed as

$$\xi - \frac{K}{\beta} + \frac{K}{\beta} \prod_{i=0}^{n-1} V_i, \quad (20.113)$$

where the V_i 's are i.i.d. as $P(1, \beta^{-1})$. For this case, Balakrishnan and Ahsanullah (1994b) have established recurrence relations for single and product moments of upper record values generalizing the results given above [equations (20.111)] for the Lomax distribution.

9 CHARACTERIZATIONS

The close relationship between the exponential and Pareto distributions emphasized in Section 3 allows us to simply translate various characterizations of the exponential distribution to Pareto. These characterizations are however of limited intrinsic value for understanding the models that can be generated by and/or admit a Pareto distribution fit. Galambos and Kotz (1978) provide a detailed discussion of characterizations of the exponential and Pareto distributions; some of these characterizations are presented in Chapter 19. Most characterizations of Pareto distribution are essentially based on the mean residual life property (Hagstroem (1925)). More rigorous proofs have been developed by Arnold (1971) and Huang (1974).

A typical, more recent, result along these lines, due to Morrison (1978), states that the Pareto distribution of the second kind (with range $x > 0$) is the unique gamma mixture of exponential distributions that yields a linearly increasing mean residual lifetime $E\{X|X > t\}$ regardless of the mixing process. (Recall that Pareto is generated by a gamma mixing of exponentials—see Section 2). There is an extensive discussion of characterizations based on mean residual lifetime in Kotz and Shanbhag (1980). A second class of characterizations is based on the property connecting truncation to **rescaling**. A typical result, due to Bhattacharya (1963), is that under certain conditions on the support of the distribution, the relationship

$$\Pr\{X > y|X > x_0\} = \Pr\left(\frac{x_0}{k}X > y\right), \quad \text{for all } y > x_0 \geq k, \quad (20.114)$$

characterizes $P(\text{I})(k, a)$ distributions with scale parameter k .

Under the assumption of the existence of moments, this characterization is equivalent to the linearity of the mean residual lifetime as a function of x_0 [Kotz and Shanbhag (1980), Dallas (1976)].

The property (20.114) can be interpreted in the following ("underreported income property") way:

If the distribution of $Y = \theta X$, where $0 < \theta \leq 1$, truncated from below at k , is the same as the distribution of X , then X must have a $P(\text{II})$ distribution with scale parameter k [Krishnaji (1970, 1971)]. Y may be regarded as reported and X as actual income.

Refinements of this interpretation have been provided by Huang (1978) and Marsaglia and Tubilla (1975). However, the assumption that underreported income has this relation to actual income is very doubtful.

Characterizations based on truncation invariance of the Gini index [Ord, Patil, and Taillie (1981)] and on a linear relation between $\log x$ and $\log\{1 - F_x(x)\}$ [Moothathu (1984)] have similar bases.

Schmittlein and Morrison (1981) claimed that the median residual lifetime

$$M(x_0) = \text{median}(X - x_0 | X > x_0) \quad (20.115)$$

is of form $a + bx_0$ if and only if X has a **P(II)** distribution. However, Gupta and Langford (1984) showed that non-Paretian distributions with cdf of form

$$F_X(x) = 1 - \left(\frac{a}{a + bx} \right)^c g(\log(a + bx))$$

with $g(\cdot)$ a periodic function of period $\log(b + 1)$ such that

$$g(\log(a + bk)) = \left(\frac{a + bk}{a} \right)^c,$$

where $c = (\log 2) / \{\log(b + 1)\}$, also have $M(x_0)$ of this form.

Many characterizations are based on distributions of order statistics, usually involving the least observed value, X'_1 .

A typical result is

Let $X'_1 \leq X'_2 \leq \dots \leq X'_n$ be the order statistics from an absolutely continuous distribution function $F_X(x)$ where the lower bound on the random variable X is given by k , that is, $F_X(k) = 0$. It can then be shown for a sample of size n from this distribution that the statistics X'_1 and $(X'_1 + \dots + X'_n) / X'_1$, or equivalently X'_1 and $(X'_2 + \dots + X'_n) / X'_1$, are independent if and only if the random variable X has the Pareto distribution. [Srivastava (1965)]

Dallas (1976) provides an essentially equivalent theorem "Under the assumption of existence of the r -th moment

$$E \left[\prod_{i=1}^n X'_i | X'_1 = x \right] = cx^r \text{ implies that } X \text{ is Pareto (I)."} \quad (20.116)$$

Characterizations of the type:

$$E[X'_{s+1} | X'_s = x] = cx^r \text{ for } 1 \leq s < n \quad (20.117)$$

[Beg and Kirmani (1974), Khan and Khan (1987)] are simply restatements of the characterizing equation

$$\frac{p_X(x)}{1 - F_X(x)} = \frac{a}{x} \quad (20.118)$$

of the Pareto distribution (see Section 4).

James's (1979) characterization based on the independence $(X_1/X'_1, X_2/X'_1, \dots, X_n/X'_1)$ and X'_1 , falls within the general framework of shape-size analysis in Mosimann (1970).

Arnold (1983) provides an alternative, very illuminating interpretation of these results. The reader is referred to his book for further characterizations of Pareto distributions of various kinds. In our opinion most of the characterizations of Pareto (and exponential) distributions are in essence variants of the *memoryless* property of the *exponential* and are eventually reduced to solving a Cauchy-type functional equation or its integral variants (see Chapter 19).

10 PRODUCT AND RATIOS OF PARETO RANDOM VARIABLES

The product of n independent Pareto random variables X_i , distributed as $P(I)(k_i, a_i)$ ($i = 1, \dots, n$) can be expressed in the form

$$\left(\prod_{i=1}^n k_i \right) \exp \left\{ \sum_{i=1}^n (V_i/a_i) \right\} \tag{20.119}$$

where the V_i 's are independent standard exponential variables.

If the a_i 's are all distinct but $k_i = k$ for all i , the distribution of $V = \prod_{i=1}^n X_i$ is given in terms of the survival function as

$$\bar{F}_Y(y) = \Pr[Y > y] = \sum_{i=1}^n \left\{ \left(\frac{y}{k} \right)^{-a_i} \prod_{\substack{l=1 \\ l \neq i}}^n \left(\frac{a_l}{a_l - a_i} \right) \right\}, \quad y > k. \tag{20.120}$$

Pederzoli and Rathie (1980), using the method of Mellin transforms, obtained an expression for the distribution of Y when the a_i 's are not all distinct.

Castellani (1950) and Malik (1970a) have analyzed the special case when $a_1 = a_2 = \dots = a_n = a$.

In this case,

$$\sum_{i=1}^n (V_i/a)$$

is distributed as a gamma (n, a^{-1}) variable, and the distribution of the product has pdf

$$p_Y(y) = \frac{\{m \log(y/m)\}^{n-1} (y/m)^{-a} (a/y)}{\Gamma(n)} \quad (y \geq m), \tag{20.121}$$

where $m = \prod_{i=1}^n k_i$.

The distribution of the quotient $Z = X_1/X_2$ of two independent Pareto random variables with parameters (k_1, a_1) and (k_2, a_2) respectively, was also tackled by Pederzoli and Rathie (1980). The corresponding pdf is

$$p_Z(z) = \begin{cases} \frac{a_1 a_2}{k_1 k_2^{-1} (a_1 + a_2)} \left(\frac{z}{k_1 k_2^{-1}} \right)^{a_2 - 1} & \text{for } z \leq k_1 k_2^{-1} \\ \frac{a_1 a_2}{k_1 k_2^{-1} (a_1 + a_2)} \left(\frac{z}{k_1 k_2^{-1}} \right)^{-a_1 - 1} & \text{for } z \geq k_1 k_2^{-1} \end{cases} \quad (20.122)$$

The cdf is

$$F_Z(z) = \begin{cases} \frac{a_1}{a_1 + a_2} \left(\frac{z}{k_1 k_2^{-1}} \right)^{a_2} & \text{for } z \leq k_1 k_2^{-1} \\ 1 - \frac{a_2}{a_1 + a_2} \left(\frac{k_1 k_2^{-1}}{z} \right)^{a_1} & \text{for } z > k_1 k_2^{-1}. \end{cases} \quad (20.123)$$

Given a random sample of size n from $\mathbf{P}(\mathbf{I})(k, a)$ with order statistics $X'_1 \leq X'_2 \leq \dots \leq X'_n$, the pdf of the ratio

$$W \equiv \frac{X'_i}{X'_j} \quad (i < j)$$

is

$$p_W(w) = \frac{k}{a^k B(n-j+1, j-1)} w^{k(n-j+1)} (1-w^k)^{j-i-1} \quad (0 < w < 1) \quad (20.124)$$

[see, e.g., Springer (1979)].

The pdf of the product $T = X'_i X'_j$ was also obtained in a closed, albeit cumbersome, form, using the Mellin transform. The exact expression involves summations with respect to r and s of terms of the type:

$$\frac{n! a k^{2a(r+n-j+1)}}{(i-1)!(j-i-1)!(n-j)!(2r+n+i-2j-s+1)} t^{a(j-r-n-1)-1} \cdot \left[1 - \left(\frac{k}{\sqrt{t}} \right)^{-a(2r+n+i-2j-s+1)} \right] = h(t, a, k; i, j, s, r), \quad (20.125)$$

with appropriate weights.

Explicitly:

$$p_T(t) = \sum_{r=0}^{j-i-1} \sum_{s=0}^{i-1} (-1)^{r+s-1} \binom{j-i-1}{r} \binom{i-1}{s} h(t, a, k; i, j, s, r) \quad (0 < t) \quad (20.126)$$

where $1 \leq i < j \leq n$, [see, e.g., Springer (1979)].

Distribution of products of independent Pareto (IV) variables can be derived from the distribution of products of powers of independent gamma variables (generalized gamma variables)—see Chapter 17, Section 8.7. Blum (1970) has discussed the distribution of the sum of independent Pareto variables.

If X has a $P(\text{I})(k, a)$ distribution, then $Y = X^{-1}$ has the density function

$$p_Y(y) = ak^a y^{a-1} \quad (0 < y < k^{-1}). \quad (20.127)$$

This distribution, which is a special **Pearson** Type I distribution, is called the power-function distribution. Its moments are, of course, simply the negative moments of the corresponding Pareto distribution, so that

$$\mu'_r(Y) = \frac{ak^{-r}}{a+r} \quad (20.128)$$

Moments of order statistics for this distribution were calculated by Malik (1967), while recurrence relations for these quantities have been derived by Balakrishnan and Joshi (1981). Rider (1964) has obtained the distribution of products and quotients of maximum values of sets of independent random variables having distribution (20.127). He suggests such distributions might be used in approximate **representation** of the lower tail of the distribution of a random variable having a fixed lower bound (as in a gamma distribution, for example).

11 APPLICATIONS AND RELATED DISTRIBUTIONS

The discrete form of the Pareto distribution (**Zipf–Estoup's law**) has been discussed in Chapter 11. In many cases the Pareto distribution may be used as an approximation to the Zipf distribution. Xekalaki and Panaretos (1988) consider the Yule distribution discussed in Chapter 6, Section 10.3 to be the discrete analog of the Pareto distribution and provide a mutual characterization of these distributions. Many socioeconomic and other naturally occurring quantities are distributed according to certain statistical distributions with very long right tails. Examples of some of these empirical phenomena are distributions of city population sizes, occurrence of natural resources, stock

price fluctuations, size of firms, personal incomes, and error clustering in communication circuits. Many distributions have been developed in an attempt to explain these empirical data. As Arnold (1985) points out:

The bald fact remains that in the upper tail, income distributions are reasonably well approximated by Pareto distributions and, certainly for predictive purposes, the lack of a compelling explanatory model should not deter one from capitalizing on the appealing simplicity of Pareto's distribution.

The lognormal distribution has emerged as the main competitor for Pareto. It has been observed that while the fit of the Pareto curve may be rather good at the extremities of the income range, the fit over the whole range is often rather poor. On the other hand, the lognormal (**Gibrat**) distribution (Chapter 14) fits well over a large part of the income range but diverges markedly at the extremities [**Fisk (1961)**].

Ferguson (1962) and James (1979) discuss the Pareto distributions as limiting distributions of the generalized gamma distribution (Chapter 17) when the parameter $c \rightarrow -\infty$.

Truncated Pareto distributions, with an upper limit (k') as well as a lower limit (k), have been found by **Goldberg** (1967) to fit the distribution of oil fields, in a specified area, by size. A truncated **P(I)(k, a)** distribution has density function of the form

$$p_X(x) = \frac{a}{k} [1 - (k/k')^a]^{-1} (k/x)^{a+1} \quad (k \leq x \leq k') \quad (20.129)$$

and cumulative distribution function

$$F_X(x) = \begin{cases} 0 & (x < k) \\ [1 - (k/k')^a]^{-1} [1 - (k/x)^a] & (k \leq x \leq k') \\ 1 & (x > k'), \end{cases} \quad (20.130a)$$

or equivalently

$$F_X(x) = \begin{cases} 0 & (x < K(1 - Q)^{-1/a}) \\ (1 - Q - k^a x^{-a}) / (P - Q) & (K(1 - Q)^{-1/a} \leq x \leq K(1 - P)^{-1/a}) \\ 1 & (x > K(1 - P)^{-1/a}) \end{cases} \quad (20.130b)$$

with $K = k(1 - Q)^{1/a}$, where Q and $1 - P$ ($Q < P$) are the proportions truncated on the left and right, respectively. Moments of order statistics $E[X_{r:n}^{(i)}] \equiv \mu_{r:n}^{(i)}$ from this distribution exist for all r, n and i because the range of the distribution is finite.

Balakrishnan and Joshi (1982) derived recurrence relations for these moments. Taking, without loss of generality, the scale parameter $k = 1$, a typical relation is:

For $n \geq 2, 1 \leq r \leq n - 1$ and $i = 1, 2, \dots$

$$\begin{aligned} & \{(n - r + 1)a - i\} \mu_{r:n}^{(i)} \\ &= a[(n - r + 1)\mu_{r-1:n}^{(i)} + nP_2\{\mu_{r:n-1}^{(i)} - \mu_{r-1:n-1}^{(i)}\}] \end{aligned} \quad (20.131)$$

where

$$P_2 = \frac{P - 1}{P - Q}.$$

(Compare with similar relationship for the nontruncated case in Section 8.)

Similar relations were obtained by Khurana and Jha (1985) based on expressions for $\mu_{r:n}^{(i)}$ in terms of hypergeometric functions ${}_2F_1(a, b; c; t)$. A typical relation is

$$\left(\frac{i}{a} - r\right) \mu_{r:n}^{(i)} = \frac{i}{a} \frac{1 - Q}{k^a} \mu_{r:n}^{(i+a)} - r \mu_{r+1:n}^{(i)}, \quad (20.132)$$

which follows from

$$\mu_{r:n}^{(i)} = k^i (1 - Q)^{-i/a} {}_2F_1\left(i/a, r; n + 1; \frac{P - Q}{1 - Q}\right),$$

since $(a - b) {}_2F_1(a, b; c; z) = a {}_2F_1(a + 1, b; c; z) - b {}_2F_1(a, b + 1; c; z)$.

Cohen and Whitten (1988) discuss estimation of parameters for distributions truncated on the right (at point x_0). When k is known, the MLE of a is the solution (in \hat{a}) of the equation

$$\frac{1}{\hat{a}} + \frac{(k/x_0)^{\hat{a}} \log(k/x_0)}{1 - (k/x_0)^{\hat{a}}} = \frac{1}{n} \sum_{i=1}^n \log X_i - \log k. \quad (20.133)$$

Cohen and Whitten recommend the use of

$$\hat{a}_1 = n \left/ \sum_{i=1}^n \log\left(\frac{X_i}{K}\right) \right.$$

as the initial value in an iterative procedure, which would be the MLE of a if the distribution were not truncated.

A mixture of two Pareto distributions is sometimes called a double Pareto distribution.

Modifications of the Pareto distribution have been developed to give better representation of income distributions.

One of the best known income distributions is the Champernowne distribution [Champernowne (1952)]. It is supposed that the random variable X , termed "income-power," and defined by $X = \log T$, where T is the actual

income, has a density function of the form

$$p_X(x) = \frac{n}{\cosh\{\alpha(x - x_0)\} + \lambda}, \quad (20.134)$$

where n , α , x_0 and λ are parameters (n is, of course, a function of α and λ). This is included in Perks's family of distributions, described in Chapter 23. We have retained the unusual notation (n) used by Champernowne. This symbol does not have anything to do with "sample size" in the present context.

The curve given by (20.134) is symmetrical and x_0 is the median value of the income-power. If we let $\log t_0 = x_0$ then the density function of income ($T = e^X$) is

$$p_T(t) = \frac{n}{t \left[\frac{1}{2} (t/t_0)^{-\alpha} + \lambda + \frac{1}{2} (t/t_0)^\alpha \right]} \quad (20.135)$$

and t_0 is the median value of the income.

In order to find the proportion of persons with income greater than t , we integrate (20.135). The form that the integral takes will depend on the value of λ . For $-1 < \lambda < 1$ the cumulative distribution function is

$$F_T(t) = 1 - \frac{1}{\theta} \tan^{-1} \left\{ \frac{\sin \theta}{\cos \theta + (t/t_0)^\alpha} \right\} \quad (t > 0), \quad (20.136)$$

where

$$0 < \theta < \pi \quad \text{and} \quad \cos \theta = \lambda.$$

For $\lambda = 1$

$$F_T(t) = 1 - \frac{t_0^\alpha}{t_0^\alpha + t^\alpha} \quad (t > 0) \quad (20.137)$$

For $\lambda > 1$

$$F_T(t) = 1 - \frac{1}{2\eta} \log \left\{ \frac{t^\alpha + e^\eta t_0^\alpha}{t^\alpha + e^{-\eta} t_0^\alpha} \right\} \quad (t > 0), \quad (20.138)$$

where

$$\cosh \eta = \lambda.$$

In (20.136)–(20.138) α is equal to Pareto's constant (Section 2), and t_0 is the median value of the income. No simple interpretation exists for the parameters θ and η . The latter may be regarded as a parameter used for adjusting the kurtosis of the fitted density function (20.134) along the income power scale [Champernowne (1952)].

The three forms of the density function corresponding to (20.136)–(20.138) may be obtained by differentiation and are, respectively

$$\frac{a \sin \theta}{\theta t \left\{ (t/t_0)^\alpha + 2 \cos \theta + (t_0/t)^\alpha \right\}}; \quad (20.139)$$

$$\frac{\alpha}{t \left\{ (t/t_0)^{\alpha/2} + (t_0/t)^{\alpha/2} \right\}^2}; \quad (20.140)$$

$$\frac{a \sinh \eta}{\eta t \left\{ (t/t_0)^\alpha + 2 \cosh \eta + (t_0/t)^\alpha \right\}}. \quad (20.141)$$

[These are all of form (20.135), of course.] Methods of fitting are described in Champernowne (1952).

In general, it is possible to improve the fit of a distribution by the incorporation of extra parameters. To this end Champernowne (1952) proposed a five parameter model of the form:

$$F_T(t) = \begin{cases} 1 - \frac{1}{(1 + \sigma)\theta} \left[(\sigma - 1)\theta + 2 \tan^{-1} \left\{ \frac{\sin \theta}{\cos \theta + (t/t_0)^\alpha} \right\} \right] & \text{for } 0 \leq t \leq t_0, \\ 1 - \frac{2\sigma}{(1 + \sigma)\theta} \tan^{-1} \left\{ \frac{\sin \theta}{\cos \theta + (t/t_0)^\alpha} \right\} & \text{for } t \geq t_0. \end{cases} \quad (20.142)$$

The fifth parameter σ may be considered as a measure of skewness, in that when $\sigma > 1$ the curve exhibits positive skewness, and when $\sigma < 1$ the curve is negatively skewed. When $\sigma = 1$, the distribution (20.136) is obtained.

The limiting form of the density function of the Champernowne distribution as $\theta \rightarrow 0$ is

$$\frac{(t/t_0)^{\alpha-1}}{t_0 \left[1 + (t/t_0)^\alpha \right]^2}. \quad (20.143)$$

On making the transformation $(T/t_0)^\alpha = e^t$, the logistic or sech square density *function*

$$p_\phi(t) = \frac{e^t}{[1 + e^t]^2} = \frac{e^{-t}}{[1 + e^{-t}]^2} \quad (20.144)$$

is obtained [see Chapter 23] [Fisk (1961)]. The shape of this distribution is quite similar to that of the normal density function. However, in the tails the sech square density is greater than the normal. For economists concerned

with the upper tails of distributions, the Pareto, Champernowne, and sech square distributions are probably more useful than the lognormal, which generally gives a poor fit in the tails [Aitchison and Brown (1957)].

The cumulative distribution function corresponding to (20.143) is

$$F_T(t) = \frac{(t/t_0)^\alpha}{1 + (t/t_0)^\alpha}, \quad (20.145)$$

that is,

$$F_T(t) = 1 - \frac{(t/t_0)^{-\alpha}}{1 + (t/t_0)^{-\alpha}}. \quad (20.146)$$

For small t , (20.146) is close to the Pareto distribution (20.2).

A number of papers [Mandelbrot (1960, 1963, 1967)] discuss a class of distributions that has been termed "stable Paretian." In the development of the theory, two forms of the Pareto law are distinguished [Mandelbrot (1960)]:

Strong Law of Pareto. The distribution is of the form given by (20.2); that is,

$$\begin{aligned} 1 - F_X(x) &= \left(\frac{x}{k}\right)^{-\alpha} & x \geq k; \\ &= 1 & x < k. \end{aligned}$$

Weak or Asymptotic form of the law of Pareto. The form of this distribution is

$$1 - F_X(x) \sim \left(\frac{x}{k}\right)^{-\alpha} \quad \text{as } x \rightarrow \infty. \quad (20.147)$$

This implies that if $\log[1 - F_X(x)]$ is plotted against $\log x$, the resulting curve should be asymptotic to a straight line with slope equal to $-\alpha$ as x approaches infinity (see Section 9). It has been shown [Lévy (1925)] that there is a class of distributions that follow the asymptotic form of the law of Pareto and are characterized by the fact that $0 < \alpha < 2$. These are known as the stable *Paretian* or stable non-Gaussian distributions. The normal distribution ($\alpha = 2$) is also a member of the family of stable laws and has the property that it is the only one with a finite variance. A further property of the non-Gaussian stable laws when $1 < \alpha < 2$ is that the expected value is finite.

It has been shown by Lévy (1925) that the logarithm of the characteristic function of the stable *Paretian* distribution is

$$\log \phi(t) = i \delta t - \gamma |t|^\alpha [1 - i\beta(t/|t|)\tan(\alpha\pi/2)]. \quad (20.148)$$

The parameters of (20.148) are α , β , γ and δ . The location parameter is δ ; and if $\alpha > 1$, then δ is the mean of the distribution. β is an index of

skewness such that when equal to zero the curve is symmetric; when $\beta > 0$ the curve is skewed to the right, and when $\beta < 0$ it is skewed to the left. The scale parameter is γ ; a is intimately related to the Pareto exponent (in the sense that the limit of $x^{\alpha-1} \Pr[X > x]$ is finite and non-zero) and controls the amount of probability found in the tails of the distribution. When $0 < a < 2$, the extreme tails of the stable distributions are higher than those of the normal, with the total probability in the tails increasing as a moves from 2 to 0. Explicit expressions for the density functions of stable **Paretian** distributions are known for only three cases; the Cauchy ($a = 1, \beta = 0$), the normal ($a = 2$), and the "coin tossing" (Bernoulli) case ($\alpha = \frac{1}{2}, \beta = 1, \delta = 0, \gamma = 1$) [Fama (1963)].

Putting $\beta = 0$ in (20.148), we have

$$\log \phi(t) = i \delta t - \gamma |t|^\alpha$$

For the variable $Y = (X - \delta)\gamma^{-1/\alpha}$ we have the "standard form" of symmetric stable distribution with

$$\log \phi_Y(t) = -|t|^\alpha.$$

Bergstrom (1952) has shown that, for $a > 1$,

$$p_Y(y) = \frac{1}{\pi \alpha} \sum_{j=0}^{\infty} (-1)^j \frac{\Gamma[(2j+1)\alpha^{-1}]}{(2j)!} y^{2j} \quad (20.149)$$

so that

$$F_Y(y) = \frac{1}{2} + \sum_{j=1}^{\infty} (-1)^{j-1} \frac{\Gamma[(2j-1)\alpha^{-1}]}{(2j-1)!} y^{2j-1}. \quad (20.150)$$

For large y , the asymptotic series

$$1 + \frac{1}{\pi} \sum_{j=1}^{\infty} (-1)^j \frac{\Gamma(j\alpha)}{j! y^{\alpha j}} \sin(\frac{1}{2}j\alpha\pi) \quad (20.151)$$

is useful for calculating $F_Y(y)$, when $a > 1$.

Fama and Roll (1968) give tables of values of $F_Y(y)$, to four decimal places, for

$$a = 1.0(0.1)1.9(0.05)2.00$$

and

$$y = 0.05(0.05)1.00(0.1)2.0(0.2)4.0(0.4)6.0(1)8, 10, 15, 20.$$

They also give values of y_P satisfying $F_Y(y_P) = P$, to three decimal places, for the same values of a and $P = 0.52(0.02)0.94(0.01)0.97(0.005)0.995, 0.9995$. It is notable that $y_{0.72}$ varies but little with a . Its value increases from 0.827 when $a = 1$ (Cauchy) to about 0.830 ($\alpha = 1.3 - 1.6$) and then decreases to 0.824 for $a = 2$ (normal).

Fama and Roll (1968) suggest that this stability may be used to construct an estimator of $\gamma^{1/\alpha}$ as

$$(0.827)^{-1} \times [\text{upper 28\% order statistic} - \text{lower 28\% order statistic}],$$

which should be robust with respect to changes in a .

The Pareto distribution has been applied by astronomers to model the brightness (equivalent to magnitude) distribution of comets. Donnison (1990) used the Pareto power-law model for the distribution of the long-period comets (those that take more than 200 years to complete an orbit) and the short-period comets (those that take less than 15 years to complete an orbit). Donnison analyzed some data by assuming a Pareto distribution for the distribution of brightness. By hypothesizing that brightness indices have increased with discovery date, Donnison and Peers (1992) subsequently analyzed the same data in terms of trend analysis. Pettit (1993) has recently provided an alternative Bayesian solution to the problem by using Gibbs sampling.

12 GENERALIZED PARETO DISTRIBUTIONS

1. A class of "generalized Pareto" distributions was described by Ljubo (1965). The cumulative distribution function is

$$F_X(x) = \begin{cases} 1 - \left(\frac{k + \alpha}{x + \alpha} \right)^a e^{-\beta(x-k)} & (x \geq k) \\ 0 & (x < k) \end{cases} \quad (20.152)$$

with $\beta > 0$.

2. A class more extensively studied within the framework of extreme-value distributions and used in applications is originally due to Pickands (1975) but more recently propagated by Hosking and his co-workers.

Hosking and Wallis (1987) and Dargahi-Noubary (1989), among others, investigate a generalized Pareto distribution (GPD) with the cdf

$$F_X(x; c, k) = 1 - (1 - cx/k)^{1/c}. \quad (20.153)$$

Special cases, $c = 0$ and $c = 1$, correspond respectively to exponential distribution with mean k and the uniform distribution on $(0, k)$, while Pareto distributions correspond to negative values of c . This distribution is extensively used in the analysis of extreme events (Pickands (1975) was apparently the first to use this distribution in this context), especially in hydrology [van Montfort and Witter (1985)], as well as in reliability studies when

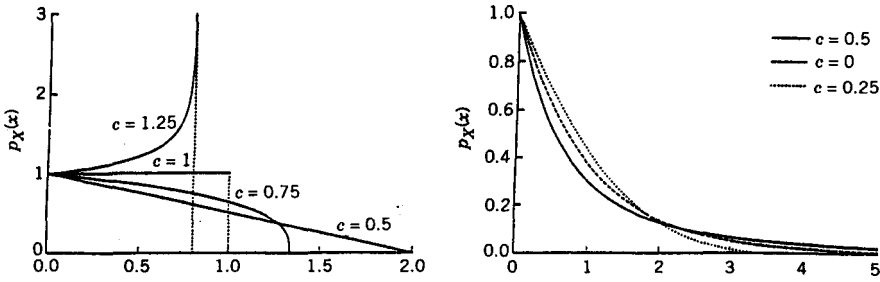


Figure 20.1 Probability Density Function of the Generalized Pareto Distribution for Different Values of the Shape Parameter c [Source: Hosking and Wallis (1987)]

robustness is required against heavier tailed or lighter tailed alternatives to an exponential distribution, **Typical** forms of these distributions are depicted in Figure 20.1.

The pdf is

$$p_X(x) = k^{-1}(1 - cx/k)^{c-1} \quad (c \neq 0), \quad (20.154a)$$

or

$$p_X(x) = k^{-1} \exp(-x/k) \quad (c = 0). \quad (20.154b)$$

The support of the distribution is $x > 0$ for $c \leq 0$ and $0 < x < k/c$ for $c > 0$.

Dargahi-Noubary (1989) recommends GPD for use as the distribution of the excess of **observed** values over an arbitrarily chosen "threshold." He points out that, "the GPD arises as a class of limit distribution for the excess over a threshold, as the threshold increases toward the right-hand end of the distribution (tail)."

Moreover, "Direct connection between the GPD and extreme value distributions is as follows: If N is a Poisson random variable with mean λ and Y_1, Y_2, \dots, Y_N are independent excesses with the distribution function [(20.153)], then

$$\Pr[\max(Y_1, Y_2, \dots, Y_N) \leq x] = \exp[-\lambda(1 - cx/k)^{1/c}] \quad (20.155)$$

(an extreme value distribution; see Chapter 22).

If X has a GPD with parameters (k, c) then the conditional distribution of $X - y'$ given $X > y'$ is GPD with parameters $k - cy', c$ provided $k - cy' > 0$. (Compare with the memoryless property of the exponential distribution.)

This property of GPD is called "threshold stability." Dargahi-Noubary (1989) also advocates use of GPD (and threshold methods) for fitting a

distribution of annual maxima of the wind speed (gusts) using the data provided by Cook (1982), and that of maximum floods of the Feather River for the years (1962–1980). He finds the fit based on GPD to be much better than one using classical extreme value methods.

The hazard rate $r_x(x) = p_x(x)/\{1 - F_x(x)\}$ of the GPD is $1/(k - cx)$, which is a monotonic function of x , decreasing for $c < 0$, constant for $c = 0$, and increasing for $c > 0$ [see Xekalaki (1983), who characterizes this distribution by its hazard rate].

Generalized Pareto distributions with $c > \frac{1}{2}$ have finite endpoints with $p_x(x) > 0$ at each end (see Figure 20.1). Such distributions seldom occur in statistical application. (The variance of generalized Pareto for $c \geq \frac{1}{2}$ is infinite.)

With $E[(1 - cX/k)^r] = (1 + rc)^{-1}$ for $1 + rc > 0$, we have

$$\mu = E[X] = k/(1 + c) \quad (20.156a)$$

and

$$\text{Var}(X) = \sigma^2 = k^2/\{(1 + c)^2(1 + 2c)\}. \quad (20.156b)$$

The skewness is

$$\sqrt{\beta_1} = \alpha_3 = 2(1 - c)(1 + 2c)^{1/2}/(1 + 3c), \quad (20.156c)$$

and the kurtosis is

$$\beta_2 = \alpha_4 = \frac{3(1 + 2c)(3 - c + 2c^2)}{(1 + 3c)(1 + 4c)}. \quad (20.156d)$$

In general the r -th moment exists if $c > -1/r$.

Also, since $-c^{-1} \log(1 - cX/k)$ has a standard exponential distribution,

$$E\left[\left\{-\log\left(1 - \frac{cX}{k}\right)\right\}^s\right] = c^s \Gamma(s + 1) \quad \text{for integer } s. \quad (20.156e)$$

Davison (1984) has observed that if X has a GPD (k, c) distribution, then

$$E[X - u | X > u] = \frac{k - cu}{1 + c}, \quad \text{for all } u > 0$$

if $c > -1$. Thus the plot of mean "excess" over u , versus u , should be roughly linear with the slope $-c/(1 + c)$ and intercept $k/(1 + c)$.

Hosking and Wallis (1987) provide a detailed investigation of estimation procedures for the GPD. Their general conclusion is that "maximum likeli-

hood estimation, although asymptotically the most efficient method, does not clearly display its efficiency even in samples as large as 500, while the method of moments is generally reliable except when $c < -2$."

The **maximum** likelihood equations are:

$$\left[1 + n^{-1} \sum_{i=1}^n \log(1 - \hat{c}\hat{k}^{-1}X_i) \right] \left[n^{-1} \sum_{i=1}^n (1 + \hat{c}\hat{k}^{-1}X_i)^{-1} \right] = 1; \quad (20.157a)$$

$$\hat{c} = -n^{-1} \sum_{i=1}^n \log(1 - \hat{c}\hat{k}^{-1}X_i). \quad (20.157b)$$

Since $\log L$ approaches infinity when $c > 1$ and k/c approaches $\max(X_i) = X'_n$, the **MLEs** are taken as the values \hat{k} and \hat{c} which yield a local **maximum** of $\log L$ (unless the Giesbrecht and Kempthorne (1976) approach of maximizing grouped-data likelihood function is used—as described in Chapter 14 for the lognormal distribution).

Maximum likelihood estimation of parameters works well if $c < \frac{1}{2}$, but not otherwise. For $c < \frac{1}{2}$ the asymptotic normal distribution of the **maximum** likelihood estimates based on a sample of size n has the mean value (c, k) and variance-covariance **matrix**

$$\frac{1}{n} \begin{pmatrix} (1-c)^2 & k(1-c) \\ k(1-c) & 2k^2(1-c) \end{pmatrix}. \quad (20.158)$$

The estimators are consistent, asymptotically normal, and asymptotically efficient for $c < \frac{1}{2}$. The nonregular case is discussed by Smith (1985).

Grimshaw (1993) describes an algorithm for solution of equations (20.157). He points out that $\hat{c}\hat{k}^{-1}$ can be determined from (20.157a), and this value can then be inserted in (20.157b) to obtain \hat{c} . If no local minimum is found in the space

$$\{c < 0, k > 0\} \cup \{0 < c \leq 1, k/c > X'_n\},$$

there is no **maximum** likelihood estimator. In such cases, Grimshaw (1993) recommends using "alternative estimators given by Hosking and Wallis (1987)."

The moment estimators are easily computed from the formulas

$$\tilde{k} = \frac{1}{2}\bar{X}(\bar{X}^2S^{-2} + 1) \quad (20.159a)$$

$$\text{and } \tilde{c} = \frac{1}{2}(\bar{X}^2/S^2 - 1) \quad (20.159b)$$

where \bar{X} and S^2 are the sample mean and variance respectively.

Since $\text{Var}(S^2)$ is infinite for $c \leq -1/4$, these estimators are not asymptotically normal (of order n^{-1}). For $c = 0$, we have exponential distributions and the moment estimators coincide with the maximum likelihood ones. For $c > -1/4$, (\tilde{k}, \tilde{c}) is asymptotically bivariate normal with variance-covariance matrix

$$n \text{ var} \begin{bmatrix} \tilde{k} \\ \tilde{c} \end{bmatrix} \sim \frac{(1+c)^2}{(1+2c)(1+3c)(1+4c)} \times \begin{bmatrix} 2k^2(1+6c+12c^2) & k(1+2c)(1+4c+12c^2) \\ k(1+2c)(1+4c+12c^2) & (1+2c)^2(1+c+6c^2) \end{bmatrix}. \quad (20.160)$$

Hosking and Wallis (1987) also suggest use of probability-weighted moments (PWM)

$$M_{p,r,s} = E[X^p \{F_X(X)\}^r \{1 - F_X(X)\}^s]$$

for estimation of GPD parameters. In particular,

$$a_s = M_{1,0,s} = E[X\{1 - F(X)\}^s] = \frac{k}{(s+1)(s+1+k)} \quad (20.161)$$

exists for $c > -1$ and the identities

$$k = \frac{2a_0 a_1}{a_0 - 2a_1}, \quad c = \frac{a_0}{a_0 - 2a_1} - 2, \quad (20.162)$$

are valid. They recommend substituting \tilde{a}_r and \tilde{a}_1 in (20.162) by the estimators

$$\tilde{a}_r = n^{-1} \sum_{j=1}^n \frac{(n-j)(n-j-1)\dots(n-j-r+1)}{(n-1)(n-2)\dots(n-r)} X_{(j)}, \quad r = 0, 1, \quad (20.163a)$$

or

$$\tilde{a}_r = n^{-1} \sum_{j=1}^n (1 - p_{j:n})^r X'_j, \quad r = 0, 1, \quad (20.163b)$$

where $p_{j:n} = (j + \gamma)/(n + \delta)$, where γ and δ are suitable constants (often $\gamma = -0.375$ and $\delta = 0.25$).

The estimators \tilde{a}_r and \tilde{a}_1 are asymptotically equivalent.

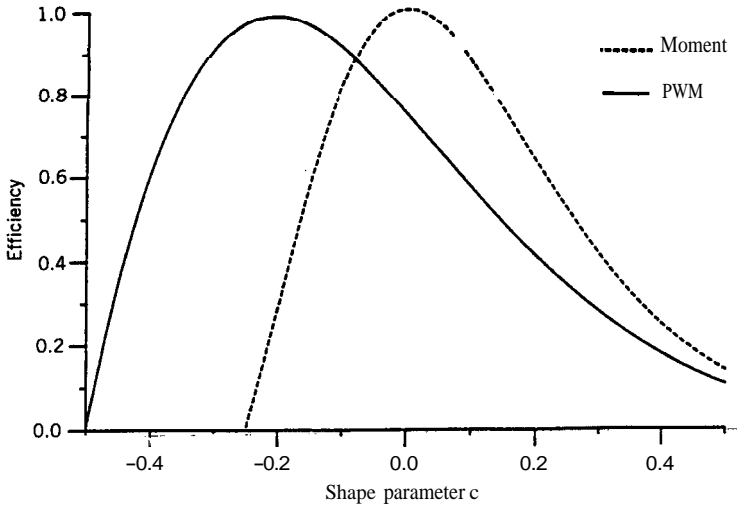


Figure 20.2 Asymptotic Efficiency, Relative to the Maximum Likelihood Estimator, of Moment and PWM Estimators' of the Shape Parameter of the Generalized Pareto Distribution

Asymptotic efficiency of moment and probability-weighted moment estimators of the shape parameter of the GPD are presented in Figure 20.2.

Simulations carried out by Hosking and Wallis (1987) have shown that the estimators with the smallest mean squared error (MSE) are moment estimators when $c > 0$ and PWM estimators when $c < -0.2$, while PWM have overall lower bias. The theoretical and simulated standard deviations of the estimators differed by less than 10% provided $n \geq 50$ and $c > 0.4$.

Quantile estimators of GPD are easily obtained from the relation

$$\begin{aligned} x(F) &= k\{1 - (1 - F)^c\}/c, & c \neq 0 \\ &= -k \log(1 - F), & c = 0 \end{aligned} \tag{20.164}$$

by substituting k and c by their estimators \hat{k} and \hat{c} .

Since

$$x(F) = kF\{1 + \frac{1}{2}(1 - c)F + O(F^2)\} \text{ as } F \rightarrow 0,$$

the accuracy of $\hat{x}(F)$, for small F , is essentially determined by the accuracy of \hat{k} .

Smith (1987) estimates the tail of a distribution that covers all three limit laws of classical extreme value theory. Given a large number of independent observations X_1, \dots, X_n with a common density f , fix a high threshold u and let N denote the number of exceedance of u and let Y_1, \dots, Y_N be the excesses. Namely $Y_j = X_j - u$ when j is the index of the i -th exceedance.

Conditionally on N the excesses are i.i.d. with the definition

$$F_u(y) = \{F(u+y) - F(u)\} / \{1 - F(u)\}, \quad u < x_0, \quad 0 < y < x_0 - u, \quad (20.165)$$

where x_0 is the upper end point of F .

Smith (1987) proposes to estimate F_u by the GPD $G(\cdot; k, c)$, estimating k and c by maximum likelihood estimates. A similar approach has been taken by Hall (1982) and Joe (1987).

The justification of these approximations is based on Pickands's (1975) result stating

$$\lim_{u \rightarrow x_0} \sup_{0 < y < x_0 - u} |F_u(y) - G(u; k(u), c)| = 0 \quad (20.166)$$

for some fixed c and function $k(u)$ if and only if F is in the domain of attraction of one of the three limit extreme value laws. (See Chapter 22.)

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Weibull Distributions

1 HISTORICAL REMARKS

The Weibull distribution is named after the Swedish physicist, Waloddi Weibull, who (1939a, b) used it to represent the distribution of the breaking strength of materials and in 1951 for a wide variety of other applications. The close agreement that Weibull demonstrated between his observed data and those predicted with the fitted Weibull models was quite impressive. He used the distribution to model data secured from problems dealing with yield strength of Bofors' steel, fiber strength of Indian cotton, length of syrtoideas, fatigue life of an ST-37 steel, statures of adult males born in the British Isles, and breadth of beans of *Phaseolus vulgaris*. Interestingly Rosen and Rammler had used this distribution earlier in 1933 to describe the "laws governing the fineness of powdered coal." In the Russian statistical literature this distribution is often referred to as the Weibull-Gnedenko distribution, since it is one of the three types of limit distributions for the sample maximum established rigorously by Gnedenko (1943) [e.g., see Gnedenko, Belyaev, and Solov'ev (1965)]. The name *Frechét* distribution is also used sometimes due to the fact that it was **Frechét** (1927) who first identified this distribution to be an extremal distribution [later on shown to be one of three possible solutions by Fisher and Tippett (1928)].

The Weibull distribution includes the exponential and the Rayleigh distributions as special cases (see Chapters 19 and 18). Since the hazard function (or the failure rate) of this distribution is a decreasing function when the shape parameter c is less than 1, a constant when c equals 1 (the exponential case), and an increasing function when c is greater than 1, the use of the distribution in reliability and quality control work was advocated by many authors following Weibull (1951), Kao (1958, 1959), and Berrettoni (1964). Due to the nature of the hazard function described above, the distribution often becomes suitable where the conditions for "strict randomness" of the exponential distribution are not satisfied, with the shape parameter c having a characteristic or predictable value depending upon the fundamental nature of the problem being considered. Unlike in the case of the exponential

distribution, probabilistic bases for the Weibull distribution are not commonly encountered in situations where the distribution is actually employed. However, Malik (1975) and Franck (1988) have assigned some simple physical meanings and interpretations for the Weibull distribution, thus providing natural applications of this distribution in reliability problems particularly dealing with wearing styles [see also Harter (1986)]. The distribution, being a power transformation of the exponential, presents a convenient way of introducing some flexibility in the model through the power (or the shape parameter) c . Some situations where the Weibull distribution will likely arise have been mentioned by Gittus (1967). Hallinan (1993) has recently provided an excellent review of the Weibull distribution by presenting historical facts, and the many different forms of this distribution as used by practitioners and possible confusions and errors that arise due to this non-uniqueness.

The Weibull distribution is undeniably the distribution that has received maximum attention during the past 23 years since the first edition of this volume was published. This is clearly evident from the large number of references (most of which have been published since 1970) at the end of this chapter.

2 DEFINITION

A random variable X has a *Weibull distribution* if there are values of the parameters $c (> 0)$, $\alpha (> 0)$, and ξ_0 such that

$$Y = \left(\frac{X - \xi_0}{\alpha} \right)^c \quad (21.1)$$

has the standard exponential distribution with probability density function

$$p_Y(y) = e^{-y}, \quad y > 0. \quad (21.2)$$

The probability density function of the Weibull random variable X is then

$$p_X(x) = \frac{c}{\alpha} \left(\frac{x - \xi_0}{\alpha} \right)^{c-1} e^{-((x-\xi_0)/\alpha)^c}, \quad x > \xi_0. \quad (21.3)$$

The cumulative distribution function is

$$F_X(x) = 1 - e^{-((x-\xi_0)/\alpha)^c}, \quad x > \xi_0, \quad (21.4)$$

and the survival (or the reliability) function is

$$R_X(x) = 1 - F_X(x) = e^{-((x-\xi_0)/\alpha)^c}, \quad x > \xi_0. \quad (21.5)$$

From (21.3) and (21.5) we get the hazard function

$$h_X(x) = \frac{p_X(x)}{R_X(x)} = \frac{c}{\alpha} \left(\frac{x - \xi_0}{\alpha} \right)^{c-1}, \quad x > \xi_0. \quad (21.6)$$

As mentioned earlier, it is clear that the hazard function in (21.6) is decreasing for $c < 1$, constant for $c = 1$, and increasing for $c > 1$. The mean residual life or the life expectancy of a Weibull component is obtained from (21.5) as

$$e_x = \int_x^\infty \frac{R_X(u)}{R_X(x)} du = e^{[(x-\xi_0)/\alpha]^c} \int_x^\infty e^{-[(u-\xi_0)/\alpha]^c} du.$$

Raja Rao and Talwalker (1989) derived lower and upper bounds for this function.

For $c > 1$ the Weibull density function in (21.3) tends to 0 as $x \rightarrow \xi_0$, and there is a single mode at

$$x = \alpha \left(\frac{c-1}{c} \right)^{1/c} + \xi_0. \quad (21.7)$$

This value tends to $\alpha + \xi_0$ very rapidly as $c \rightarrow \infty$. For $0 < c \leq 1$ the mode is at ξ_0 and the density is a decreasing function of x for all $x > \xi_0$.

From (21.4) we observe that the median of the distribution is

$$a(\log 2)^{1/c} + \xi_0. \quad (21.8)$$

It is also of interest to note that for all values of c ,

$$F_X(\xi_0 + \alpha) = 1 - e^{-1} \doteq 0.63. \quad (21.9)$$

The standard form of the distribution will have $\xi_0 = 0$ and $a = 1$ so that the standard density function is

$$p_X(x) = cx^{c-1}e^{-x^c}, \quad x > 0, c > 0 \quad (21.10)$$

and the corresponding cumulative distribution function is

$$F_X(x) = 1 - e^{-x^c}, \quad x > 0, c > 0. \quad (21.11)$$

The distribution of X now depends on the shape parameter c alone. The plots of the standard density function in (21.10) for $c = 0.25, 0.5, 1, 1.5, 2, 3, 4, 5$ are presented in Figure 21.1. The moment ratios, coefficient of variation, and standardized **cumulants** $\kappa_r/\kappa_2^{r/2}$ of the standard distribution are of course the same as those of the distribution in (21.3), which depend only on c and not on ξ_0 or α (as they are location and scale parameters). Moments corresponding to the three-parameter distribution in (21.3) are easily derived from those corresponding to the standard distribution in (21.10) by using the transformation $X' = \xi_0 + \alpha X$.

Since X^c has the standard exponential distribution in (21.2), the r th raw moment of X is also the (r/c) th moment about zero of the standard

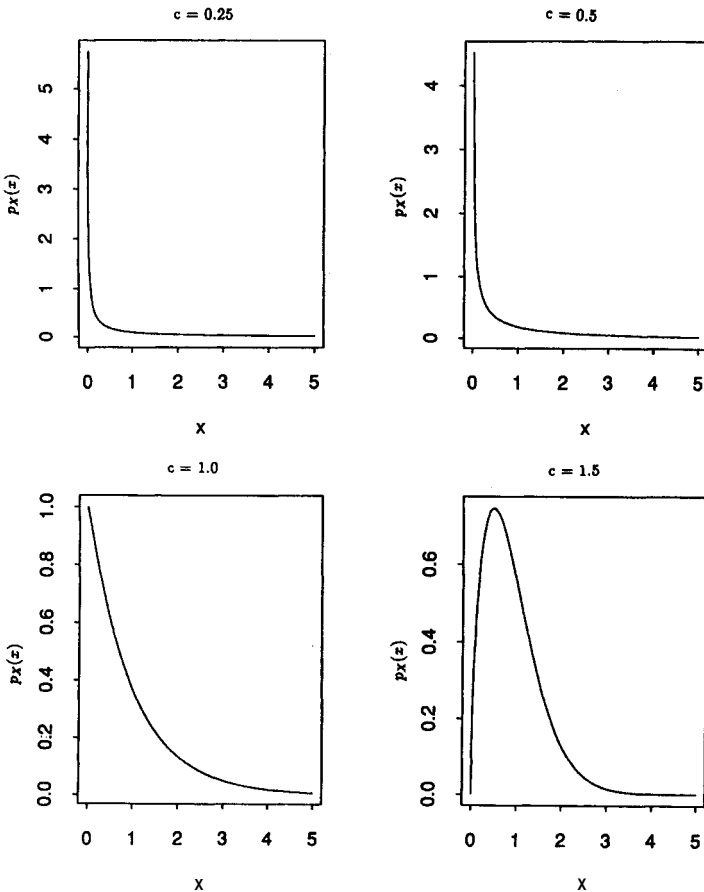


Figure 21.1 Plots of Standard Weibull Density Function in (21.10)

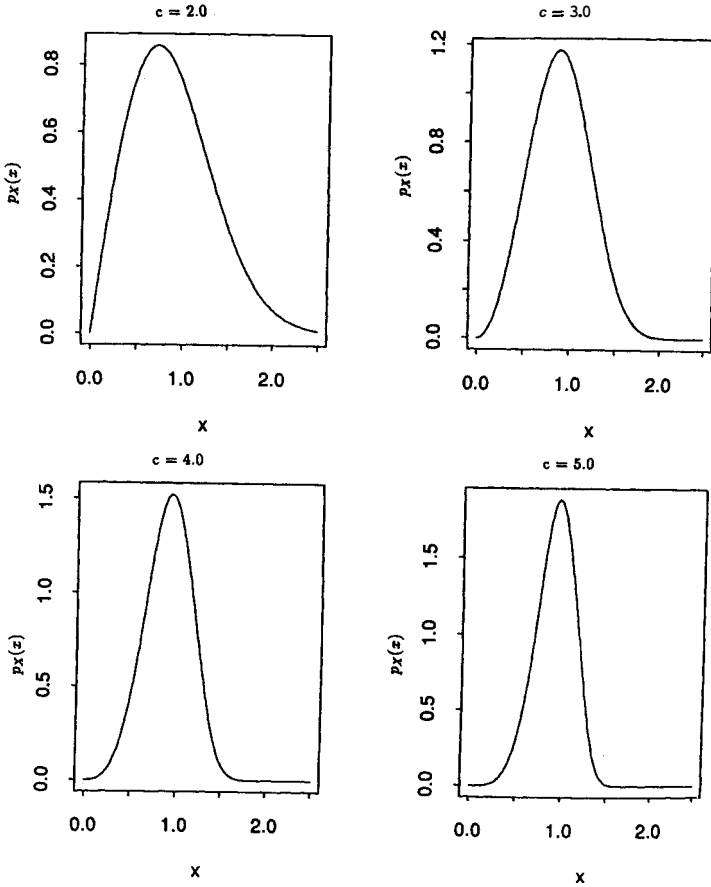


Figure 21.1 (Continued)

exponential random variable (see Chapter 19). Hence

$$\mu'_r = E[X^r] = \Gamma\left(\frac{r}{c} + 1\right) \quad (21.12)$$

from which we get

$$E[X] = \Gamma\left(\frac{1}{c} + 1\right)$$

$$\text{Var}(X) = \Gamma\left(\frac{2}{c} + 1\right) - \left\{\Gamma\left(\frac{1}{c} + 1\right)\right\}^2. \quad (21.13)$$

'similar expressions for the moment ratios can easily be written down explic-

itly. When c is large, we obtain from (21.13) that

$$E[X] \approx 1 - \frac{\gamma}{c} + \frac{1}{2c^2} \left(\frac{\pi^2}{6} + \gamma^2 \right) \approx 1 - \frac{0.57722}{c} + \frac{0.98905}{c^2},$$

$$\text{Var}(X) \approx \frac{\pi^2}{6c^2} \approx \frac{1.64493}{c^2}, \tag{21.14}$$

where γ is Euler's constant.

Table 21.1 gives some numerical values of the mean, standard deviation, and the coefficients of skewness and kurtosis for various values of c . It may be noted from this table that for $c = 3.6$ (approx.) the coefficient of skewness $\sqrt{\beta_1}$ is zero. In fact, for values of c in the neighborhood of 3.6, the Weibull distribution is similar in shape to a normal distribution. Dubey (1967a) made a detailed study of the closeness of agreement between the two distributions. It is of interest to note from the table that the coefficient of kurtosis β_2 has a minimum value of about 2.71 when $c = 3.35$ (approx.).

Cohen (1973) and Rousu (1973) both examined skewness and kurtosis as a function of the shape parameter c . With $c_0 = 3.6023494257197$, β_1 is observed to be a decreasing function of c in the interval $c < c_0$ and an increasing function in the interval $c > c_0$ ($\beta_1 = 0$ for $c = c_0$). With $c_1 = 3.35$, β_2 is also observed to be a decreasing function of c in the interval $c < c_1$ and an increasing function in the interval $c > c_1$. As mentioned above,

Table 21.1 Moments of Weibull Distributions

c	Mean	Standard Deviation	$\sqrt{\beta_1}$	β_2
1.2	0.9407	0.7872	1.52	6.24
1.4	0.9114	0.6596	1.20	4.84
1.6	0.8966	0.5737	0.96	4.04
1.8	0.8893	0.5112	0.78	3.56
2.0	0.8862	0.4633	0.63	3.25
2.2	0.8856	0.4249	0.51	3.04
2.4	0.8865	0.3935	0.40	2.91
2.6	0.8882	0.3670	0.32	2.82
2.8	0.8905	0.3443	0.24	2.76
3.0	0.8930	0.3245	0.17	2.73
3.2	0.8957	0.3072	0.11	2.71
3.4	0.8984	0.2918	0.05	2.71
3.6	0.9011	0.2780	0.00	2.72
3.8	0.9038	0.2656	-0.04	2.73
4.0	0.9064	0.2543	-0.09	2.75

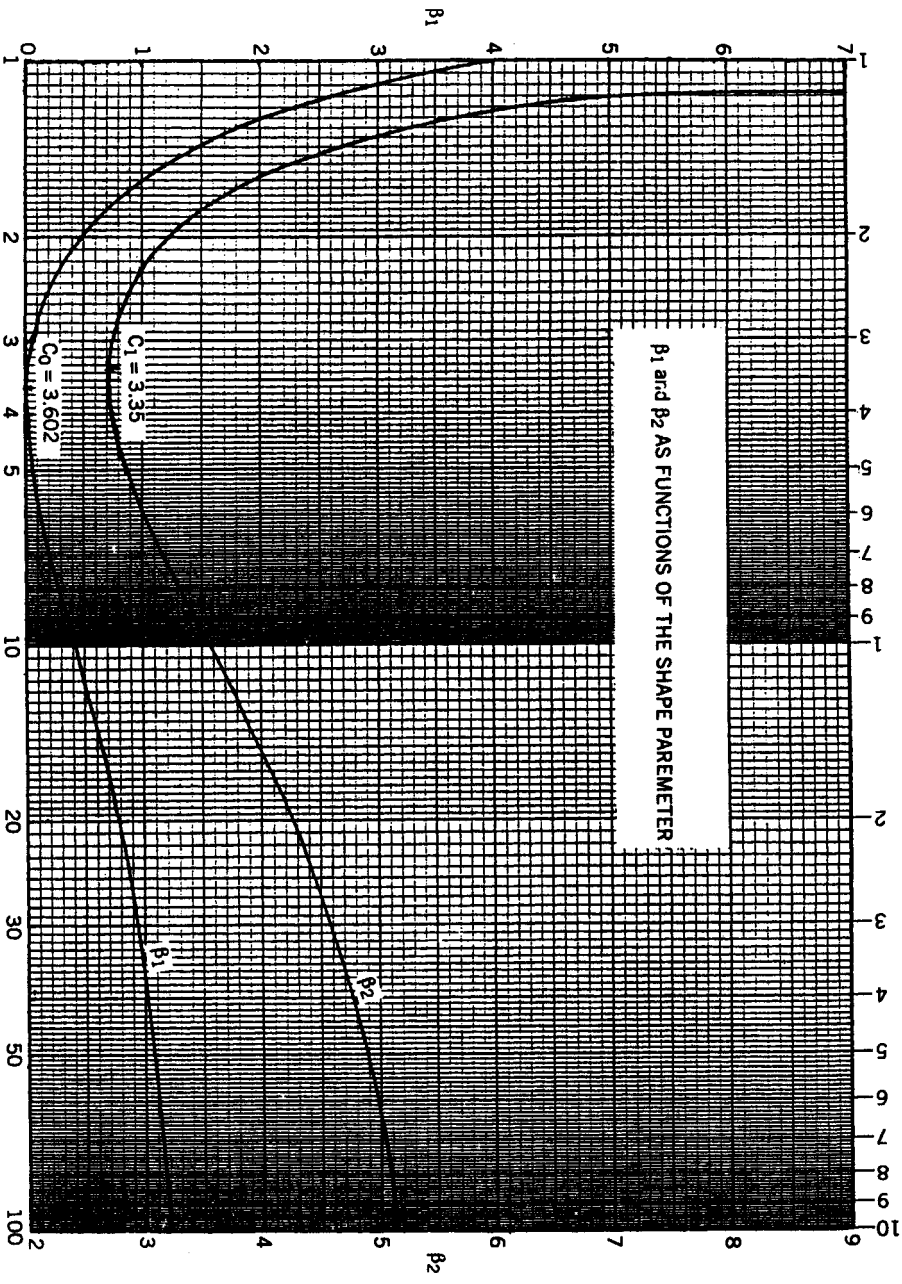


Figure 21.2 β_1 and β_2 as Functions of the Shape Parameter

Dubey (1967a) has studied the behavior of the Weibull distribution in considerable detail for values of c in the vicinity of c_0 and c_1 . Graphs of both β_1 and β_2 as functions of c are presented in Figure 21.2.

When β_2 is plotted as a function of β_1 , two distinct lines or branches are observed intersecting at $(\beta_1 = 0, \beta_2 = 2.72)$. The point of intersection corresponds to $c = c_0$, while the two separate branches correspond to the intervals $c < c_0$ and $c > c_0$. These two (β_1, β_2) lines for the Weibull distribution along with the corresponding lines for the log-normal distribution and for the **Pearson Type III (gamma)** and Type V distributions (see Chapter 12) have been plotted in Figure 21.3. As shown in Figure 21.3, the (β_1, β_2) line for the Weibull distribution with $c < c_0$ lies in the Type I region (region below Type III) and extends approximately parallel to the Type III line until the two lines intersect off the graph at $(\beta_1 = 4.0, \beta_2 = 9.0)$. The Weibull line for $c > c_0$ originates in the Type I region and extends approximately parallel to the Type V line. It crosses the Type III line into the Type VI region (region between Types III and V) at a point where $\beta_1 \approx 0.5$ and then moves in close to the log-normal line. Hence the Weibull distribution with $c > c_0$ will closely resemble the **Pearson Type VI** distribution when $\beta_1 \geq 0.5$, and for values $\beta_1 \approx 1$ or greater it will also closely resemble the lognormal distribution. The skewness factor of the Weibull family has been studied at great length by Groeneveld (1986).

From (21.12) we obtain the moment generating function of $\log X$ to be

$$E[e^{t \log X}] = E[X^t] = \Gamma\left(\frac{t}{c} + 1\right). \tag{21.15}$$

Hence the r th cumulant of $\log X$ is $\psi^{(r)}(1)/c^r$, where $\psi^{(r)}(\cdot)$ are the "polygamma functions" (derivatives of logarithm of gamma function); see Chapter 1, Section A2. In particular, we have

$$\begin{aligned} E[\log X] &= -\frac{\gamma}{c} \\ \text{Var}(\log X) &= \frac{\pi^2}{6c^2} \end{aligned} \tag{21.16}$$

The variable $\log X$ has an extreme value distribution which is discussed in detail in Chapter 22.

The information generating function for the standard distribution in (21.10) is

$$T(u) = E[(p_X(X))^u] = c^u \int_0^\infty x^{u(c-1)} e^{-ux^c} dx. \tag{21.17}$$

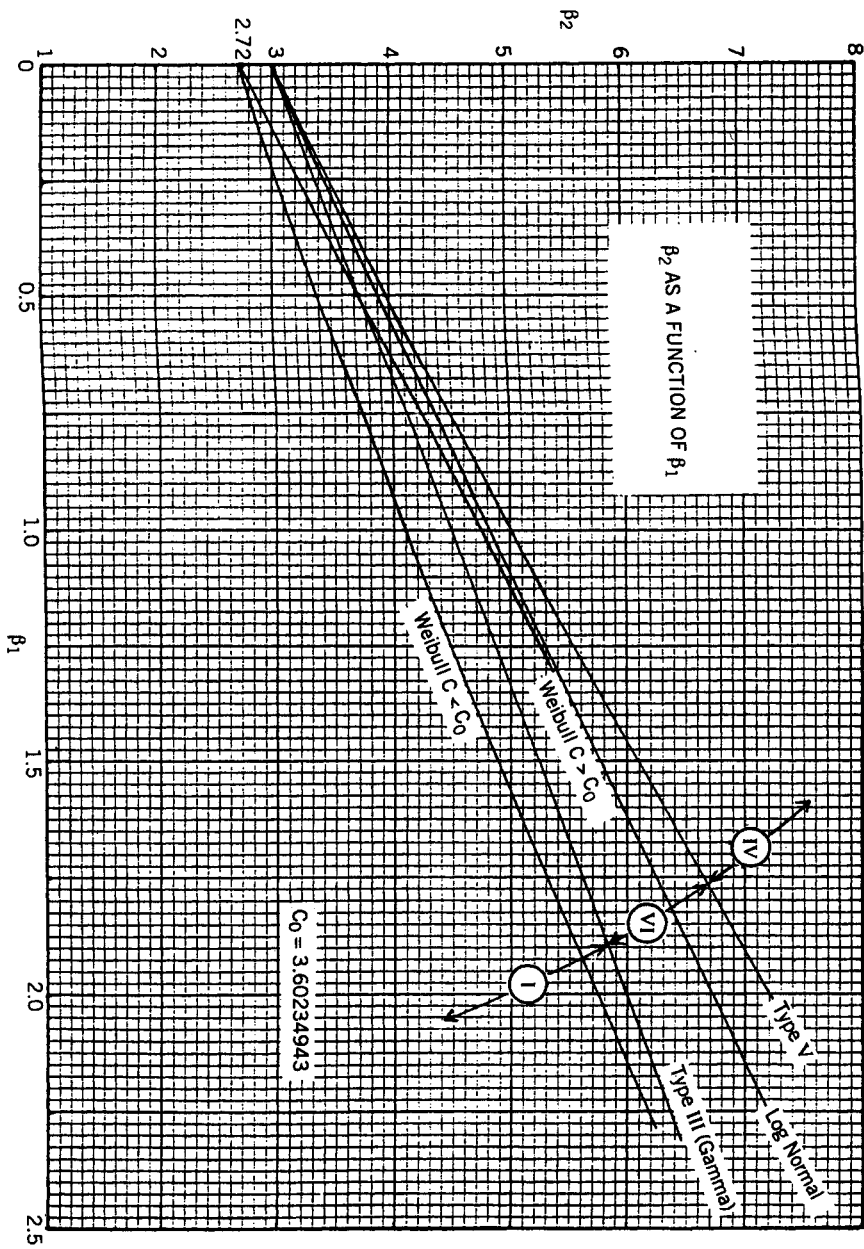


Figure 21.3 β_2 as a Function of β_1

Setting $ux^c = v$ (taking $u > 0$ and noting that $c > 0$), we obtain

$$T(u) = \frac{c^{u-1} \Gamma\{[1 + u(c-1)]/c\}}{u^{(1+u(c-1))/c}}, \quad (21.18)$$

from which the entropy of the distribution is

$$-T'(1) = \frac{(c-1)\gamma}{c} - \log c + 1. \quad (21.19)$$

A detailed account of these and other properties of the Weibull distribution has been presented by **Lehman (1963)**.

3 ORDER STATISTICS

Let X_1, X_2, \dots, X_n be independent and identically distributed Weibull random variables with density function in (21.3) and cumulative distribution function (21.4); further, let $X'_1 \leq X'_2 \leq \dots \leq X'_n$ denote the order statistics obtained from these n variables. The density function of the smallest order statistic X'_1 is

$$\begin{aligned} p_{X'_1}(x) &= n\{1 - F_X(x)\}^{n-1} p_X(x) \\ &= \frac{nc}{\alpha} \left(\frac{x - \xi_0}{\alpha} \right)^{c-1} e^{-n((x-\xi_0)/\alpha)^c}, \quad x > \xi_0. \end{aligned} \quad (21.20)$$

It is readily observed from (21.20) that X'_1 is also distributed as a Weibull random variable, except that α is replaced by $\alpha n^{-1/c}$. In other words, the Weibull distribution is "closed under minima."

From the density function and joint density function of order statistics, exact explicit expressions for the single and the product moments of order statistics can be derived. For this purpose it is convenient to work with order statistics for a random sample from the standard Weibull distribution (21.10), since the corresponding results for the three-parameter distribution (21.3) can be obtained by using the linear transformation $\xi_0 + \alpha X'_r$.

The density function of X'_r ($1 \leq r \leq n$) is

$$p_{X'_r}(x) = \frac{n!}{(r-1)!(n-r)!} (1 - e^{-x^c})^{r-1} e^{-x^c(n-r+1)} c x^{c-1}, \quad x > 0. \quad (21.21)$$

From (21.21), we obtain the k th raw moment of X'_r to be

$$\begin{aligned}
 E[(X'_r)^k] &= \frac{n!}{(r-1)!(n-r)!} \int_0^\infty x^k \{1 - e^{-x^c}\}^{r-1} e^{-x^c(n-r+1)} c x^{c-1} dx \\
 &= \frac{n!}{(r-1)!(n-r)!} \sum_{i=0}^{r-1} (-1)^i \binom{r-1}{i} \int_0^\infty e^{-x^c(n-r+i+1)} c x^{c-1} dx \\
 &= \frac{n!}{(r-1)!(n-r)!} \Gamma\left(1 + \frac{k}{c}\right) \sum_{i=0}^{r-1} \frac{(-1)^i \binom{r-1}{i}}{(n-r+i+1)^{1+(k/c)}}.
 \end{aligned} \tag{21.22}$$

Using (21.22), which is due to Lieblein (1955), Weibull (1967b) tabulated means and variances of order statistics for $n = 5(5)20$ and $c^{-1} = 0.1(0.1)1.0$. Govindarajulu and Joshi (1968) similarly tabulated means and variances of all order statistics for n up to 10 and $c = 1, 2, 2.5, 3(1)10$. Harter (1970) presented a more extensive table of means of order statistics for samples of sizes up to 40 and $c = 0.5(0.5)4(1)8$. Recently Balakrishnan and Chan (1993a) have tabulated means and variances of all order statistics for n up to 20 and $c = \frac{1}{3}, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, 1.5(0.5)3, 4(2)10$.

An alternate simple recursive method of computing the single moments has been proposed by Balakrishnan and Joshi (1981). David and Shu (1978) showed that for an arbitrary distribution with distribution function $F_X(x)$,

$$F_{X'_{r:n}}(x) = F_{X'_{r-1:n}}(x) - \binom{n}{r-1} \{F_X(x)\}^{r-1} \{1 - F_X(x)\}^{n-r+1}, \tag{21.23}$$

with $F_{X'_{0:n}} \equiv 1$ for all x so that (21.23) is true for $r = 1$ as well. Further, for any arbitrary distribution we have the relation [David (1981, pp. 46-47); Arnold, Balakrishnan, and Nagaraja (1992, pp. 111-112)]

$$(r-1)F_{X'_{r:n}}(x) + (n-r+1)F_{X'_{r-1:n}}(x) = nF_{X'_{r-1:n-1}}(x) \tag{21.24}$$

which, together with (21.23), readily yields

$$F_{X'_{r:n}}(x) = F_{X'_{r-1:n-1}}(x) - \binom{n-1}{r-1} \{F_X(x)\}^{r-1} \{1 - F_X(x)\}^{n-r+1}. \tag{21.25}$$

Then, using [Parzen (1960, p. 212)]

$$E[(X'_{r:n})^k] = k \int_0^\infty x^{k-1} \{1 - F_{X'_{r:n}}(x)\} dx$$

and substituting for $F_{X'_{r,n}}(x)$ from (21.25), we get

$$E[(X'_{r,n})^k] = E[(X'_{r-1:n-1})^k] + k \binom{n-1}{r-1} J_k(n-r+1, r-1), \quad (21.26)$$

where

$$J_k(n-r+1, r-1) = \int_0^m x^{k-1} e^{-x^c(n-r+1)} \{1 - e^{-x^c}\}^{r-1} dx. \quad (21.27)$$

These quantities can be computed recursively using

$$J_k(p, 0) = \frac{\Gamma(k/c)}{cp^{k/c}},$$

$$J_k(p, m) = J_k(p, m-1) - J_k(p+1, m-1), \quad m \geq 1, \quad (21.28)$$

and then the single moments may be computed recursively from (21.26).

The joint density function of X'_r and X'_s ($1 \leq r < s \leq n$) is

$$p_{X'_r, X'_s}(x, y) = \frac{n!}{(r-1)!(s-r-1)!(n-s)!} \{1 - e^{-x^c}\}^{r-1} \\ \times \{e^{-x^c} - e^{-y^c}\}^{s-r-1} e^{-x^c} c x^{c-1} e^{-y^c(n-s+1)} c y^{c-1},$$

$$0 < x < y < \infty. \quad (21.29)$$

From (21.29) we obtain the product moment of X'_r and X'_s as

$$E[X'_r X'_s] = \int_0^\infty \int_0^y xy p_{X'_r, X'_s}(x, y) dx dy$$

$$= \frac{n!c^2}{(r-1)!(s-r-1)!(n-s)!} \sum_{i=0}^{r-1} \sum_{j=0}^{s-r-1} (-1)^{s-r-1-j+i}$$

$$\times \binom{r-1}{i} \binom{s-r-1}{j}$$

$$\times \int_0^\infty \int_0^y e^{-(i+j+1)x^c} e^{-(n-r-j)y^c} x^c y^c dx dy$$

$$= \frac{n!}{(r-1)!(s-r-1)!(n-s)!} \sum_{i=0}^{r-1} \sum_{j=0}^{s-r-1} (-1)^{s-r-1-j+i}$$

$$\times \binom{r-1}{i} \binom{s-r-1}{j}$$

$$\times \phi_c(i+j+1, n-r-j), \quad (21.30)$$

where $\phi_c(a, b)$ is Lieblein's ϕ -function defined by

$$\phi_c(a, b) = c^2 \int_0^\infty \int_0^y e^{-ax^c - by^c} x^c y^c dx dy. \quad (21.31)$$

Through a differential equation approach, Lieblein (1955) has shown that for $a \geq b$,

$$\phi_c(a, b) = \frac{\{\Gamma[1 + (1/c)]\}^2}{(ab)^{1+(1/c)}} I_{a/(a+b)} \left(1 + \frac{1}{c}, 1 + \frac{1}{c}\right), \quad (21.32)$$

where $I_p(a, b)$ is incomplete beta function ratio defined by (see Chapter 1, Section A5)

$$I_p(a, b) = \frac{1}{B(a, b)} \int_0^p t^{a-1} (1-t)^{b-1} dt, \quad 0 < p < 1. \quad (21.33)$$

When $a < b$, $\phi_c(a, b)$ may be computed from the identity

$$\phi_c(a, b) + \phi_c(b, a) = \frac{\{\Gamma[1 + (1/c)]\}^2}{(ab)^{1+(1/c)}}. \quad (21.34)$$

After computing the ϕ -function from (21.32) and (21.34), the product moments (and hence the covariances) of Weibull order statistics may be computed from the formula in (21.24). Weibull (1967b) presented covariances of all order statistics for $n = 5(5)20$ and $c^{-1} = 0.1(0.1)1.0$. Govindarajulu and Joshi (1968) tabulated covariances of order statistics for sample sizes up to 10 and $c = 1, 2, 2.5, 3(1)10$. Balakrishnan and Chan (1993a) prepared tables of covariances of all order statistics for n up to 20 and $c = \frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \frac{1}{2}, 1.5(0.5)3, 4(2)10$; see also Adatia (1994) for some extended tables of covariances.

The tables of means, variances, and covariances of order statistics are necessary for the determination of best linear unbiased estimators of the parameters ξ_0 and a (when c is assumed to be known), as explained in the following section. We note here that Patel and Read (1975) and Patel (1975) discussed bounds on moments of linear functions of order statistics. Malik and Trudel (1982) derived the density function of quotient of two order statistics. Recurrence relations satisfied by the product moments of order statistics were derived by Khan et al. (1983). By noting from (21.12) that negative moments (of order $r > -c$) do exist for the standard Weibull random variable, Khan, Khan, and Parvez (1984) discussed the negative moments of all Weibull order statistics (of order greater than $-c$). Further relevant discussions on order statistics have been provided by Miller (1976), Harter (1988), and Shor and Levanon (1991).

4 METHODS OF INFERENCE

For the two-parameter Weibull distribution (with $\xi_0 = 0$) with probability density function

$$p_X(x) = \frac{c}{\alpha^c} x^{c-1} e^{-(x/\alpha)^c}, \quad x > 0, \alpha > 0, c > 0, \quad (21.35)$$

numerous papers have appeared over the years dealing with exact or approximate methods of inference for the shape parameter c and the scale parameter a . In this case the transformed variable $Y = \log X$ is easily seen to have the probability density function

$$p_Y(y) = ce^{c(y \log \alpha)} e^{-e^{c(y - \log \alpha)}}, \quad -\infty < y < \infty, \alpha > 0, c > 0, \quad (21.36)$$

which is a Type 1 extreme-value distribution (a member of the location-scale family of distributions) with the location parameter $\eta = \log a$ and the scale parameter $\delta = 1/c$. Due to this fact, given a sample from the two-parameter Weibull distribution (21.35), after using the logarithmic transformation on the data and estimating the parameters η and δ using some method or criterion, one can obtain estimators of the parameters a and c through the relationships $a = e^\eta$ and $c = 1/\delta$. Of course some properties of the estimators of the parameters η and δ will be passed on to the transformed estimators of the parameters a and c (e.g., the maximum likelihood property), while some other properties may not be inherited by the transformed estimators of a and c (e.g., the unbiasedness property). Almost all the papers that deal with inference for the two-parameter Weibull distribution are based on this transformation idea. Since these results, in principle, were derived primarily in developing inference for the location and scale parameters η and δ of the Type 1 extreme-value distribution, they will be discussed in detail in Chapter 22. Other inference-related topics like tolerance limits and intervals and prediction limits and intervals are handled in Sections 5 and 6, respectively. Once again, most of the developments in these topics are also based on the transformation idea. As a result our primary focus in this section will be on methods of inference developed for the three-parameter Weibull distribution, or those results that do not hinge upon the transformation of the Weibull data to the extreme-value form.

4.1 Moment Estimation

By equating the first three moments of X to the first three sample moments and solving, it is possible to determine the moment estimators of ξ_0 , a , and c . The value of the first moment ratio ($\sqrt{\beta_1}$) depends only on c , and once $\sqrt{\beta_1}$ is estimated from the sample coefficient of skewness ($\sqrt{b_1}$), c can be determined numerically. Using this estimated value of c , a is determined

from the standard deviation, and finally ξ_0 is determined from the sample mean. If ξ_0 is known, then c can be estimated from the ratio (standard deviation)/(mean - ξ_0). A nomogram provided by Kotel'nikov (1964) for this purpose is presented in Section 8, Figure 21.6. Dubey (1966f, 1967b) provided tables of asymptotic relative efficiency of moment estimators.

Using the formula for the moments of X , it is possible to construct simple estimators of c^{-1} , applicable when ξ_0 is known. Menon (1963) proposed the estimator

$$\begin{aligned} (\widetilde{c^{-1}}) &= \frac{\sqrt{6}}{\pi} \times \{\text{Sample standard deviation of } \log X_1, \log X_2, \dots, \log X_n\} \\ &= \frac{\sqrt{6}}{\pi} \times \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\log X_i - \overline{\log X})^2}, \end{aligned} \quad (21.37)$$

which is an asymptotically normal and unbiased estimator of c^{-1} . Its variance is $\{1.1 + O(n^{-1})\}(c^{-2}/n)$, and its asymptotic efficiency, relative to the Cramér-Rao lower bound, is 55%. Kagan (1965) constructed a generalization of Menon's estimator with a higher asymptotic efficiency.

Weibull (1967b) proposed that estimation of the parameters can be based on the first and second moments about the smallest sample value

$$R_i = \frac{1}{n} \sum_{j=1}^n (X'_j - X'_1)^i, \quad i = 1, 2. \quad (21.38)$$

As $n \rightarrow \infty$, the expected value of R_2/R_1^2 tends to a function $f(c)$ of the shape parameter c . By solving the equation

$$f(c^*) = \frac{R_2}{R_1^2}, \quad (21.39)$$

an asymptotically unbiased estimator of c can be derived. The table presented below, taken from Weibull (1967b), gives some values of $f(c)$:

c	$f(c)$
0.0	1.0000
0.1	1.0145
0.2	1.0524
0.3	1.1093
0.4	1.1831
0.5	1.2732
0.6	1.3801
0.7	1.5045
0.8	1.6480
0.9	1.8124
1.0	2.0000

For $c \geq 0.5$, this estimator is markedly more accurate than the estimator based on central moments. The asymptotic efficiency (compared with MLEs) decreases from 97.6% when $c = 0.5$ to 60.8% when $c = 1.0$, while that of a central moment estimator (obtained by equating $\sqrt{\beta_1}$ to the sample value $\sqrt{b_1}$) decreases from 17.1% to 7.6% over the same range of values of c . Of course the moment estimator uses the third central moment, while R_2/R_1^2 in (21.39) uses only the first two moments, so one might expect the former to be relatively inaccurate.

The statistic

$$\frac{1}{\gamma} \left\{ \log a - \frac{1}{n} \sum_{j=1}^n \log X_j \right\} \quad (21.40)$$

is an unbiased estimator of c^{-1} , with variance

$$(c^2 n)^{-1} \frac{\pi^2}{6\gamma^2} \doteq 4.93 \frac{c^{-2}}{n}, \quad (21.41)$$

where γ is Euler's constant. **Menon (1963)** pointed out that this estimator, apart from its unbiasedness, does not have very many desirable properties; for example, its efficiency is as low as 12%. On the other hand, the estimator of a derived from (21.40), given by

$$\tilde{\alpha} = \exp \left\{ \frac{1}{n} \sum_{i=1}^n \log X_i + \gamma(\widetilde{c^{-1}}) \right\}, \quad (21.42)$$

is asymptotically unbiased, with variance

$$\text{Var}(\tilde{\alpha}) = 1.2 \frac{c^{-2}}{n} + c^{-2} O(n^{-3/2}). \quad (21.43)$$

This estimator has an asymptotic efficiency of 95%.

Moment estimation of the shape parameter c was also discussed by **Mihram (1977)**. The properties of moment estimators for the **three-parameter** case have been discussed by many authors, including **Newby (1980, 1984)** and **Cran (1988)**. A nomogram for estimating all three parameters has been prepared by **Sen and Prabhaskanker (1980)**. Tables that would facilitate the method of moments estimation of all three parameters have been presented by **Blischke and Scheuer (1986)**. **Bowman and Shenton (1983)** have given series expressions for moments of these moment estimators.

4.2 Best Linear Unbiased Estimation

Let $X'_{r+1}, X'_{r+2}, \dots, X'_{n-s}$ be a doubly Type II censored sample from the three-parameter Weibull distribution in (21.3), where the smallest r and the largest s lifetimes (out of n components based on a life test) were not observed. Let $Z'_{r+1}, Z'_{r+2}, \dots, Z'_{n-s}$ be the corresponding doubly Type II censored sample from the standard Weibull distribution (21.10), where $Z'_i = (X'_i - \xi_0)/\alpha$ for $r + 1 \leq i \leq n - s$. Further, let us denote $E[Z'_i]$ by μ_i , $\text{Var}(Z'_i)$ by $\sigma_{i,i}$, $\text{Cov}(Z'_i, Z'_j)$ by $\sigma_{i,j}$, and write

$$\boldsymbol{\mu}^T = (\mu_{r+1}, \mu_{r+2}, \dots, \mu_{n-s}),$$

$$\mathbf{1}^T = (1, 1, \dots, 1)_{1 \times (n-r-s)},$$

$$\boldsymbol{\Sigma} = ((\sigma_{i,j}; r + 1 \leq i, j \leq n - s)).$$

Explicit expressions for these quantities have already been presented in Section 3, wherein the available tables for these quantities have also been listed. Realize, however, that these depend on the value of the shape parameter c . With the assumption that the shape parameter c is known the BLUEs of the location (or threshold) and scale parameters ξ_0 and α can be derived as shown below.

With $\mathbf{X}^T = (X'_{r+1}, X'_{r+2}, \dots, X'_{n-s})$, upon minimizing the generalized variance

$$(\mathbf{X} - \xi_0 \mathbf{1} - \alpha \boldsymbol{\mu})^T \boldsymbol{\Sigma}^{-1} (\mathbf{X} - \xi_0 \mathbf{1} - \alpha \boldsymbol{\mu}) \quad (21.44)$$

with respect to the unknown parameters ξ_0 and α , we obtain the BLUEs of ξ_0 and α as

$$\begin{aligned} \xi_0^* &= \left\{ \frac{\boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} \mathbf{1}^T \boldsymbol{\Sigma}^{-1} - \boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1} \mathbf{1} \boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1}}{(\mathbf{1}^T \boldsymbol{\Sigma}^{-1} \mathbf{1})(\boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu}) - (\boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1} \mathbf{1})^2} \right\} \mathbf{X} \\ &= \sum_{i=r+1}^{n-s} a_i X'_i, \end{aligned} \quad (21.45)$$

$$\begin{aligned} \alpha^* &= \left\{ \frac{\mathbf{1}^T \boldsymbol{\Sigma}^{-1} \mathbf{1} \boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1} - \mathbf{1}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} \mathbf{1}^T \boldsymbol{\Sigma}^{-1}}{(\mathbf{1}^T \boldsymbol{\Sigma}^{-1} \mathbf{1})(\boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu}) - (\boldsymbol{\mu}^T \boldsymbol{\Sigma}^{-1} \mathbf{1})^2} \right\} \mathbf{X} \\ &= \sum_{i=r+1}^{n-s} b_i X'_i. \end{aligned} \quad (21.46)$$

The variances and covariance of these estimators are given by

$$\text{Var}(\xi_0^*) = \alpha^2 \left\{ \frac{\mu^T \Sigma^{-1} \mu}{(\mathbf{1}^T \Sigma^{-1} \mathbf{1})(\mu^T \Sigma^{-1} \mu) - (\mu^T \Sigma^{-1} \mathbf{1})^2} \right\} = \alpha^2 V_1, \quad (21.47)$$

$$\text{Var}(\alpha^*) = \alpha^2 \left\{ \frac{\mathbf{1}^T \Sigma^{-1} \mathbf{1}}{(\mathbf{1}^T \Sigma^{-1} \mathbf{1})(\mu^T \Sigma^{-1} \mu) - (\mu^T \Sigma^{-1} \mathbf{1})^2} \right\} = \alpha^2 V_2, \quad (21.48)$$

$$\text{Cov}(\xi_0^*, \alpha^*) = -\alpha^2 \left\{ \frac{\mu^T \Sigma^{-1} \mathbf{1}}{(\mathbf{1}^T \Sigma^{-1} \mathbf{1})(\mu^T \Sigma^{-1} \mu) - (\mu^T \Sigma^{-1} \mathbf{1})^2} \right\} = \alpha^2 V_3. \quad (21.49)$$

The coefficients a_i and b_i and the values of V_1, V_2 , and V_3 have been tabulated by various authors for different choices of the sample size n and values of the shape parameter c . For example, Weibull (1967a) presented tables for $n = 5(5)20$ and $c^{-1} = 0.1(0.1)1.0$. Govindarajulu and Joshi (1968) presented tables for sample size n up to 10 and $c = 1, 2, 2.5, 3(1)10$. Balakrishnan and Chan (1993b) prepared tables for n up to 20 and $c = \frac{1}{5}, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, 1.5(0.5)3, 4(2)10$.

Musson (1965) provided early discussion on the determination of the BLUEs of ξ_0 and a . Stump (1968) proposed nearly best unbiased estimators of ξ_0 and a as functions of order statistics. Further discussion and developments on the best linear unbiased estimators of the parameters \mathbf{C}_s and a obtained through least-squares theory have been provided by Friedman (1981), Friedman and Gertsbakh (1981), Engeman and Keefe (1982), and Yildirim (1990).

For the case when ξ_0 can be assumed to be zero, Vogt (1968) has constructed a median-unbiased estimator of c . Since $Y'_j = (X'_j/\alpha)^c$ ($j = 1, 2, \dots, n$) are order statistics corresponding to independent standard exponential variables, it can be shown that

$$P\left[\frac{Y'_n}{Y'_1} \leq w \right] = n \sum_{j=0}^{n-1} (-1)^j \binom{n-1}{j} \{j(w-1) + n\}^{-1}.$$

There is a unique value of w (> 0), say $w_{1/2}$, such that the probability is equal to $\frac{1}{2}$. Then, since the events $Y'_n/Y'_1 \leq w_{1/2}$ and

$$c \leq (\log X'_n - \log X'_1) - {}^{-1}(\log w_{1/2})$$

are identical, it follows that c is the median of the distribution of

$$(\log X'_n - \log X'_1) - {}^{-1}(\log w_{1/2}).$$

Some values of \log , $w_{1/2}$, based on Vogt (1968), are shown in Table 21.2.

Table 21.2 Values of $g_n = \log_{10} w_{1/2}$ such that $g_n(\log_{10} X'_n - \log_{10} X'_1)^{-1}$ is a Median-Unbiased Estimator of c

n	2	3	4	5	6	7	8	9	10
g_n	0.477	0.802	1.009	1.159	1.278	1.375	1.458	1.530	1.594

For large samples, when ξ_0 is known to be zero, Dubey (1967c) suggested using the estimated 16.7% and 97.4% quantiles, y_1, y_2 , respectively, and estimating c by the formula

$$c^* = 2.989 \left[\log \left(\frac{\hat{y}_2}{\hat{y}_1} \right) \right]^{-1}.$$

This estimator is asymptotically unbiased and normal, with approximate variance $0.916c^2/n$.

The construction of best linear unbiased estimators for c^{-1} and $\log a$ using the first k order statistics has been studied by White (1965). For the special case when $k = 2$, the following estimators have been suggested by Leone, Rutenberg, and Topp (1960):

1. If ξ_0 is known to be zero, c is estimated by solving the equation

$$\frac{X'_2}{X'_1} = n \left(\frac{n}{n-1} \right)^{1/c} - n + 1.$$

2. If the value of ξ_1 is not known but that of c is known, then ξ_0 is estimated as

$$X'_1 - n^{-1}(X'_2 - X'_1) \left[\left(\frac{n}{n-1} \right)^{1/c} - 1 \right]^{-1}.$$

3. If the values of both a and c are known, then ξ_1 is estimated as

$$X'_1 - a(n+1)^{-1/c}.$$

This is an unbiased estimator of ξ_0 .

4. If the value of c is known, a is estimated as

$$\frac{1}{n} (X'_2 - X'_1) \frac{(n-1)^{1/c}}{1 - n^{-1/c} (n-1)^{1/c} \Gamma(c^{-1} + 1)}$$

5. Finally, if the values of both ξ_0 , and c are known, \mathbf{a} may be estimated as

$$(X'_{\mu+1} - \xi_0)[\log\{(n + 1)/(n - \mu)\}]^{-1/c}$$

using the single order statistic $X'_{\mu+1}$, where μ is the largest integer not exceeding $n(1 - e^{-1})$.

Note that a linear function of order statistics $\{X'_j\}$ is also a linear function of c^{-1} -th powers $\{Z_j^{1/c}\}$ or order statistics corresponding to n independent exponentially distributed variables. If all the sample were available, then it would be best to use a linear function of the Z'_j 's (i.e., of X'_j 's). While this may not be so when incomplete sets of order statistics are used, it appears quite likely that if c is known, functions of form $\sum \lambda_j X_j^{1/c}$ will be more useful than those of form $\sum \lambda_j X'_j$.

4.3 Asymptotic Best Linear Unbiased Estimation

By making use of the asymptotic approximations (see Chapter 12), we have

$$\mu_{n_i} \doteq F^{-1}(\lambda_i) + O\left(\frac{1}{n}\right) \tag{21.50}$$

and

$$\sigma_{n_i, n_j} \doteq \frac{\lambda_i(1 - \lambda_j)}{np(F^{-1}(\lambda_i))p(F^{-1}(\lambda_j))} + O\left(\frac{1}{n^2}\right), \tag{21.51}$$

where $p(\cdot)$ and $F^{-1}(\cdot)$ are the density function and the inverse cumulative distribution function of the standard Weibull distribution (with $\xi_0 = 0$ and $\mathbf{a} = 1$), and $n_i = [n\lambda_i] + 1$. Then the asymptotic best linear unbiased estimators (ABLUEs) of ξ_0 and α may be derived, based on k optimally selected order statistics (or **quantiles**), by determining the optimal values of $A_1, \lambda_2, \dots, A_k$ subject to $0 < A_1 < \lambda_2 < \dots < A_k < 1$, that minimize some norm of the variance-covariance matrix of the estimates.

Using the approximations in (21.50) and (21.51), we can write the asymptotic approximations for the variances and covariances of the BLUEs ξ_0^* and α^* in (21.47) through (21.49) as

$$\text{Var}(\xi_0^*) = \frac{\alpha^2}{n} \times \frac{V_{22}}{V_{11}V_{22} - V_{12}^2}, \tag{21.52}$$

$$\text{Var}(\alpha^*) = \frac{\alpha^2}{n} \times \frac{V_{11}}{V_{11}V_{22} - V_{12}^2}, \tag{21.53}$$

$$\text{Cov}(\xi_0^*, \alpha^*) = -\frac{\alpha^2}{n} \times \frac{V_{12}}{V_{11}V_{22} - V_{12}^2}. \tag{21.54}$$

In the above formulas

$$V_{11} = \sum_{i=1}^{k+1} \frac{\{p(F^{-1}(\lambda_i)) - p(F^{-1}(\lambda_{i-1}))\}^2}{\lambda_i - \lambda_{i-1}}, \quad (21.55)$$

$$V_{22} = \sum_{i=1}^{k+1} \frac{\{F^{-1}(\lambda_i)p(F^{-1}(\lambda_i)) - F^{-1}(\lambda_{i-1})p(F^{-1}(\lambda_{i-1}))\}^2}{\lambda_i - \lambda_{i-1}}, \quad (21.56)$$

$$V_{12} = \sum_{i=1}^{k+1} \frac{\{p(F^{-1}(\lambda_i)) - p(F^{-1}(\lambda_{i-1}))\}\{F^{-1}(\lambda_i)p(F^{-1}(\lambda_i)) - F^{-1}(\lambda_{i-1})p(F^{-1}(\lambda_{i-1}))\}}{\lambda_i - \lambda_{i-1}}, \quad (21.57)$$

with $A_0 = 0$, $\lambda_{k+1} = 1$, $p(F^{-1}(\lambda_0)) = F^{-1}(\lambda_0)p(F^{-1}(\lambda_0)) = p(F^{-1}(\lambda_{k+1})) = F^{-1}(\lambda_{k+1})p(F^{-1}(\lambda_{k+1})) = 0$. Then the ABLUEs ξ_0^{**} and a^{**} are derived by determining the optimal spacing (A_1, A_2, \dots, A_k) , subject to $0 < A_1 < A_2 < \dots < A_k$, which minimizes the determinant or the trace of the variance-covariance matrix of $(\xi_0^*$ and a^* . For example, if the determinant norm is used for this purpose, then we will need to determine A_1, A_2, \dots, A_k that maximize the quantity $(V_{11}V_{22} - V_{12}^2)$.

Similarly, if the threshold parameter ξ_0 is unknown but the scale parameter a is known, then the ABLUE ξ_0^{**} is derived by determining A_1, A_2, \dots, A_k to maximize V_{11} since in this case the asymptotic approximation for the variance of the BLUE ξ_0^* is given by

$$\text{Var}(\xi_0^*) = \frac{\alpha^2}{nV_{11}}. \quad (21.58)$$

On the other hand, if the threshold parameter ξ_0 is known but the scale parameter a is unknown, then the ABLUE a^{**} is derived by determining A_1, A_2, \dots, A_k that maximize V_{22} , since in this case the asymptotic approximation for the variance of the BLUE a^* is given by

$$\text{Var}(a^*) = \frac{\alpha^2}{nV_{22}}. \quad (21.59)$$

Estimation of the scale parameter a by the use of one optimally selected order statistic has been discussed by Quayle (1963) and Moore and Harter (1965). Clark (1964) has discussed the estimation of a by the use of k optimally selected order statistics. Moore and Harter (1966) have discussed the interval estimation of the parameter a based on one optimally selected order statistic. Murthy and Swartz (1975) discussed the estimation of parameters based on two order statistics. Chan, Cheng, and Mead (1974) discussed the simultaneous estimation of the parameters ξ_0 and a based on k optimally selected order statistics [also see Hassanein (1971)]. Hassanein, Saleh,

and Brown (1984) provided estimators based on k optimally selected order statistics from complete as well as Type II censored samples. Zanakis and Mann (1982) proposed a simple percentile estimator for the shape parameter c when all three parameters are unknown.

For distribution (21.2), the cumulative distribution function is

$$F_X(x) = 1 - \exp\left[-\left(\frac{x - \xi_0}{\alpha}\right)^c\right].$$

This equation can be written

$$x = \xi_0 + \alpha[-\log\{1 - F_X(x)\}]^{1/c}.$$

Suppose that \hat{X}_{p_i} , \hat{X}_{p_j} , \hat{X}_{p_k} are estimators of the values of X corresponding to $F_X(x) = p_i, p_j, p_k$, respectively. (In a large sample \hat{X}_{p_i} would be the $[(n+1)p_i]$ -th order statistic.) Then the three equations

$$\hat{X}_{p_s} = \xi_0^* + \alpha^*[-\log(1 - p_s)]^{1/c^*}, \quad s = i, j, k,$$

could be solved, yielding the estimators ξ^* , α^* , and c^* .

The equation for c^* is

$$\frac{\hat{X}_{p_i} - \hat{X}_{p_j}}{\hat{X}_{p_j} - \hat{X}_{p_k}} = \frac{[-\log(1 - p_i)]^{1/c^*} - [-\log(1 - p_j)]^{1/c^*}}{[-\log(1 - p_j)]^{1/c^*} - [-\log(1 - p_k)]^{1/c^*}}$$

If it can be arranged that

$$-\log(1 - p_j) = \sqrt{\{-\log(1 - p_i)\}\{-\log(1 - p_k)\}},$$

then the above equation for c^* simplifies to

$$c^* = \frac{\frac{1}{2}\{\log[\{-\log(1 - p_k)\}/\{-\log(1 - p_j)\}]\}}{\log\left[\left(\frac{\hat{X}_{p_i} - \hat{X}_{p_j}}{\hat{X}_{p_j} - \hat{X}_{p_k}}\right)\right]}$$

Dubey (1967c) has discussed the optimal choice of p_i , p_j , and p_k .

If the value of ξ_0 is known (e.g., zero), then a variety of methods of estimating c and α is available. The function $Y_j = 1 - \exp[-(X_j/\alpha)^c]$ is the probability integral transform of X_j if X has distribution (21.2) with $\xi_0 = 0$. If $Y'_1 \leq Y'_2 \leq \dots \leq Y'_n$ are the corresponding order statistics, then

$$Y'_j = 1 - \exp\left[-\left(\frac{X'_j}{\alpha}\right)^c\right], \quad j = 1, 2, \dots, n,$$

and the Y'_j 's are distributed as order statistics in a random sample from the standard uniform distribution over the interval 0 to 1 [see (26.1) of Chapter 26 with $a = h = \frac{1}{2}$], and so $E[Y'_j] = j/(n + 1)$.

Estimators a^*, c^* of a, c , obtained by minimizing

$$\begin{aligned} & \sum_{j=1}^n \left[\log\{-\log(1 - Y'_j)\} - \log\{-\log(1 - E[Y'_j])\} \right]^2 \\ &= \sum_{j=1}^n \left[c \log\left(\frac{X'_j}{\alpha}\right) - \log\left\{-\log\left(\frac{n - j + 1}{n + 1}\right)\right\} \right]^2 \end{aligned}$$

with respect to c and α , are

$$c^* = \frac{\sum_{j=1}^n (K_j - \bar{K})(\log X'_j - \overline{\log X})}{\sum_{j=1}^n (\log X'_j - \overline{\log X})^2},$$

where

$$K_j = \log\left[-\log\left(\frac{n - j + 1}{n + 1}\right)\right]$$

$$\bar{K} = n^{-1} \sum_{j=1}^n K_j$$

$$\overline{\log X} = n^{-1} \sum_{j=1}^n \log X'_j$$

$$a^* = \left(\prod_{j=1}^n X'_j \right)^{1/n} \left[\prod_{j=1}^n \left\{ -\log\left(\frac{n - j + 1}{n + 1}\right) \right\} \right]^{-1/(nc^*)}$$

These estimators were proposed by Gumbel (1958).

Estimators of similar form, with K_j replaced by $\log[\sum_{i=1}^j (n - i + 1)^{-1}]$, were proposed by Bain and Antle (1967), and with K_j replaced by

$$\log\left[-\log\frac{n - j + (3/2)}{n - j}\right]$$

by Miller and Freund (1965). [A further estimator was obtained by Bain and Antle (1967), replacing K_j by minus expected value of the $(n - j + 1)$ -th order statistic of random samples of size n from the standard Type 1 extreme value distribution (22.26) of Chapter 22; see also Kimball (1960) and Mann (1968). Bain and Antle (1967) show that for all estimators of this form the distribution of c^*/c does not depend on any parameter (and so confidence

intervals of c can be constructed from an observed value of c^* . They further found, from a Monte Carlo investigation, that all the estimators (with various values of K_j) just described are comparable with (and rather better than) Menon's estimator (21.40).

The c^* 's are biased estimators of c , but the bias could be removed by an appropriate corrective multiplier (equal to $\{E[c^*/c]\}^{-1}$). Bain and Antle give values for this multiplier.

Sometimes it is desired to estimate the "reliability," that is,

$$R(x) = \Pr[X > x] = \exp\left[-\left\{\frac{x - \xi_0}{\alpha}\right\}^c\right]$$

or, if ξ_0 be known to be zero, $\exp[-(x/\alpha)^c]$. Of course, if \hat{a}, \hat{c} are maximum likelihood estimators of a, c , respectively, then $\exp[-(x/\hat{a})^{\hat{c}}]$ is a maximum likelihood estimator of $R(x)$.

4.4 Minimum Quantile Distance Estimation

In the case of the three-parameter Weibull distribution, the method proposed by Carmody, Eubank, and LaRiccia (1984) provides a minimum quantile distance estimator for the parameter $\theta = (\xi_0, a, c)$. Parr and Schucany (1980) presented a useful discussion on minimum distance estimation using the empirical cumulative distribution function, while LaRiccia (1982) gave a lucid account of the quantile domain approach.

Let $Q(\lambda) = -\log(1 - A)$, $0 < A < 1$, denote the quantile function of the standard exponential distribution. Then the quantile function corresponding to the three-parameter Weibull distribution in (21.3) is

$$Q(\lambda; \theta) = \xi_0 + \alpha\{Q(\lambda)\}^{1/c}. \tag{21.60}$$

Define the sample quantile function as

$$\tilde{Q}(\lambda) = X'_i, \quad \frac{i-1}{n} < \lambda \leq \frac{i}{n}, \quad i = 1, 2, \dots, n. \tag{21.61}$$

For a given set of $k < n$ percentile points $\lambda = \{\lambda_1, \lambda_2, \dots, \lambda_k\}$ with $0 < \lambda_1 < \lambda_2 < \dots < \lambda_k < 1$, let

$$\tilde{Q}_\lambda = (\tilde{Q}(\lambda_1), \tilde{Q}(\lambda_2), \dots, \tilde{Q}(\lambda_k))^T$$

and

$$Q_{\lambda}(\theta) = (Q(\lambda_1; \theta), Q(\lambda_2; \theta), \dots, Q(\lambda_k; \theta))^T,$$

where $Q(\lambda; \theta)$ and $\tilde{Q}(\lambda)$ are as defined in (21.60) and (21.61), respectively. Then the minimum quantile distance estimator of θ is the vector that minimizes the quadratic form

$$(\tilde{Q}_{\lambda} - Q_{\lambda}(\theta))^T W(\theta) (\tilde{Q}_{\lambda} - Q_{\lambda}(\theta)) \tag{21.62}$$

as a function of θ , where $W(\theta)$ is a user-defined $k \times k$ matrix of weights that may be chosen to depend on θ . Thus (21.62) provides an entire family of estimators $\hat{\theta}_{\lambda}(W)$, indexed by both A and W . A good choice of W , suggested by Carmody, Eubank, and LaRiccia (1984), is

$$W^*(c) = H_{\lambda}(c) R_{\lambda}^{-1} H_{\lambda}(c), \tag{21.63}$$

where $R_{\lambda}^{-1} = \min(\lambda_i, \lambda_j) - \lambda_i \lambda_j$ and $H_{\lambda}(c)$ is the $k \times k$ diagonal matrix having its i th diagonal element to be $c(1 - \lambda_i)(Q(\lambda_i))^{(c-1)/c}$. Since R_{λ}^{-1} has a tridiagonal inverse whose typical row has nonzero entries

$$-\frac{1}{\lambda_i - \lambda_{i-1}}, \quad \frac{\lambda_{i+1} - \lambda_{i-1}}{(\lambda_{i+1} - \lambda_{i-1})(\lambda_i - \lambda_{i-1})}, \quad -\frac{1}{\lambda_{i+1} - \lambda_i},$$

the elements of $W^*(c)$ in (21.63) can easily be evaluated.

Although the estimator $\hat{\theta}_{\lambda}(W)$ will not have a closed form, the estimator can be computed without much difficulty, using a standard minimization routine. The interesting thing about this method of estimation is that it requires no modifications if the sample is Type II right censored, left censored, or doubly censored. Carmody, Eubank, and LaRiccia (1984) have established some asymptotic properties of the estimator including the uniqueness, consistency, and asymptotic normality. Further they have made some suggestions on the selection of A , since the variance-covariance matrix of the estimator is a function of the specific quantiles selected, even though the estimator $\hat{\theta}_{\lambda}(W^*)$ is optimal for any given A .

4.5 Modified Moment Estimation

For the three-parameter Weibull distribution, Cohen, Whitten, and Ding (1984) suggested the use of the traditional method of moments equations $E[X] = \bar{X}$ and $\text{Var}(X) = S^2$ along with the equation $E[X_1'] = X_1'$ for the simultaneous estimation of the parameters ξ_0 , a , and c , and this is the

method of modified moment estimation. Realizing from (21.13) and (21.22) that

$$\begin{aligned}
 E[X] &= \mathfrak{D} + \alpha\Gamma_1(c) \\
 \text{Var}(X) &= \alpha^2\{\Gamma_2(c) - \Gamma_1^2(c)\} \\
 E[X'_1] &= \xi_0 + \frac{\alpha}{n^{1/c}}\Gamma_1(c),
 \end{aligned}
 \tag{21.64}$$

the estimating equations readily become

$$\begin{aligned}
 \xi_0 + \alpha\Gamma_1(c) &= \bar{X} \\
 \alpha^2\{\Gamma_2(c) - \Gamma_1^2(c)\} &= S^2 \\
 \xi_0 + \frac{\alpha}{n^{1/c}}\Gamma_1(c) &= X'_1,
 \end{aligned}
 \tag{21.65}$$

where $\Gamma_k(c) = \Gamma[1 + (k/c)]$, $\bar{X} = (1/n)\sum_{i=1}^n X_i$ is the observed sample mean, $S^2 = [1/(n - 1)]\sum_{i=1}^n (X_i - \bar{X})^2$ is the observed sample variance, and X'_1 is the observed smallest order statistic. After a few simple algebraic manipulations, the three equations of (21.65) reduce to

$$\frac{S^2}{(\bar{X} - X'_1)^2} = \frac{\hat{\Gamma}_2 - \hat{\Gamma}_1^2}{\{(1 - n^{-1/\hat{c}})\hat{\Gamma}_1\}^2}
 \tag{21.66a}$$

$$\hat{\xi}_0 = \frac{n^{1/\hat{c}}X'_1 - \bar{X}}{n^{1/\hat{c}} - 1}
 \tag{21.66b}$$

$$\hat{\alpha} = \frac{n^{1/\hat{c}}(\bar{X} - X'_1)}{(n^{1/\hat{c}} - 1)\hat{\Gamma}_1},
 \tag{21.66c}$$

where $\hat{\Gamma}_j = \Gamma_j(\hat{c}) = \Gamma[1 + (j/\hat{c})]$. Equivalent expressions for $\hat{\xi}_0$ and $\hat{\alpha}$ that are convenient for use are

$$\hat{\alpha} = SC(\hat{c}) \quad \text{and} \quad \hat{\xi}_0 = \bar{X} - SD(\hat{c}),
 \tag{21.67}$$

where $C(c) = 1/\sqrt{\Gamma_2 - \Gamma_1^2}$ and $D(c) = \Gamma_1/\sqrt{\Gamma_2 - \Gamma_1^2}$.

With \bar{X} , S^2 , and X'_1 available from the sample data, (21.66a) need to be solved for \hat{c} , and subsequently $\hat{\xi}_0$ and $\hat{\alpha}$ can be determined from (21.66b) and (21.66c), respectively. Although this method of estimation is applicable for all values of the shape parameter c , **Cohen, Whitten, and Ding (1984)** pointed out that some computational difficulties may be encountered when $c < 0.5$ (a case not of great practical importance). Graphs of $\{\Gamma_2(c) - \Gamma_1^2(c)\}/$

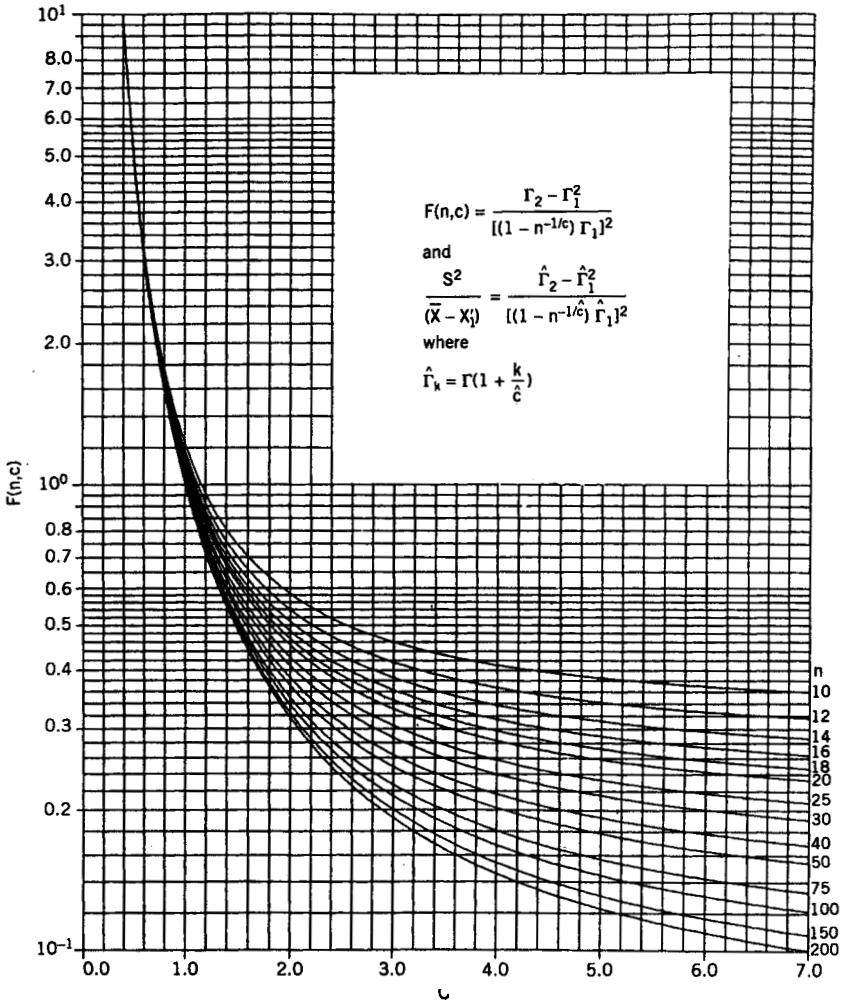


Figure 21.4 Graphs of $(\Gamma_2 - \Gamma_1^2)/[(1 - n^{-1/c})\Gamma_1]^2$

$\{(1 - n^{-1/c})\Gamma_1(c)\}^2$ are presented in Figure 21.4. Similarly graphs of $C(c)$ and $D(c)$ are presented in Figure 21.5.

Even though asymptotic variances and covariances for the maximum likelihood estimates are not strictly applicable for the modified moment estimates presented here, a simulation study carried out by **Cohen and Whitten** (1988) disclosed close agreement between simulated variances and corresponding asymptotic variances. However, when all three parameters ξ_0 , a , and c have to be estimated, the asymptotic variances are valid only if $c > 2$. In fact, in order to avoid possible computational difficulties in practical applications, c needs to be greater than 2.2 approximately (see the next

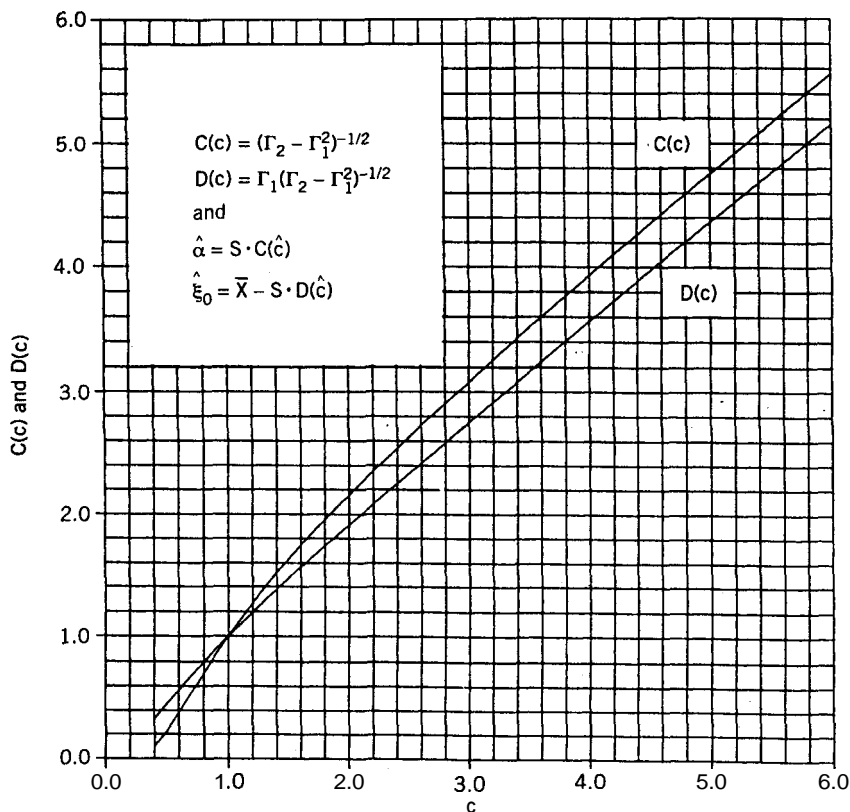


Figure 21.5 Graphs of $C(c)$ and $D(c)$

Section). For more details on this method of estimation, readers are referred to the books by Cohen and Whitten (1988) and Balakrishnan and Cohen (1991).

Instead of the simple modified moment equation $E[X'_1] = X'_1$, Cohen and Whitten (1982) considered some other possible equations:

$$E[F_X(X'_1)] = F_X(X'_1) \tag{21.68}$$

giving $-\log\{n/(n + 1)\} = [(X'_1 - \xi_0)/\alpha]^c$, and

$$\text{median}(X) = \text{Sample median}, x_{\text{Med}} \tag{21.69}$$

giving $\xi_0 + \alpha(\log 2)^{1/c} = x_{\text{Med}}$. Cohen and Whitten (1982) have compared the performance of these estimators with the MLEs (discussed in Section 4.6) and some modified maximum likelihood estimators (discussed in Section 4.7).

4.6 Maximum Likelihood Estimation

The most usual situation is ξ_0 known (e.g., zero, without loss of generality) but c unknown, so both c and a must be estimated. Given sample values from a random sample of size n from the two-parameter Weibull distribution with probability density function

$$p_X(x) = \frac{c}{\alpha} \left(\frac{x}{\alpha}\right)^{c-1} e^{-(x/\alpha)^c}, \quad x > 0, \quad (21.70)$$

the maximum likelihood estimators \hat{c} and \hat{a} of c and a , respectively, satisfy the equations

$$\hat{a} = \left\{ \frac{1}{n} \sum_{i=1}^n X_i^{\hat{c}} \right\}^{1/\hat{c}} \quad (21.71)$$

and

$$\hat{c} = \left[\left\{ \sum_{i=1}^n X_i^{\hat{c}} \log X_i \right\} \left\{ \sum_{i=1}^n X_i^{\hat{c}} \right\}^{-1} - \frac{1}{n} \sum_{i=1}^n \log X_i \right]^{-1}. \quad (21.72)$$

If ξ_0 is not equal to zero, then each X_i is replaced by $X_i - \xi_0$ in the above equations. The value of \hat{c} needs to be obtained from (21.72) and then used in (21.71) to obtain \hat{a} . It should be noted that if c were in fact known to be equal to 2, then \hat{a} in (21.71) would be the maximum likelihood estimator of a .

If the parameter ξ_0 is also unknown, then the maximum likelihood estimates \hat{c} , \hat{a} , and $\hat{\xi}_0$ satisfy the equations

$$\hat{a} = \left\{ \frac{1}{n} \sum_{i=1}^n (X_i - \hat{\xi}_0)^{\hat{c}} \right\}^{1/\hat{c}}, \quad (21.73)$$

$$\hat{c} = \left[\left\{ \sum_{i=1}^n (X_i - \hat{\xi}_0)^{\hat{c}} \log(X_i - \hat{\xi}_0) \right\} \left\{ \sum_{i=1}^n (X_i - \hat{\xi}_0)^{\hat{c}} \right\}^{-1} - \frac{1}{n} \sum_{i=1}^n \log(X_i - \hat{\xi}_0) \right]^{-1}, \quad (21.74)$$

and

$$(\hat{c} - 1) \sum_{i=1}^n (X_i - \hat{\xi}_0)^{-1} = \hat{c} \hat{a}^{-\hat{c}} \sum_{i=1}^n (X_i - \hat{\xi}_0)^{\hat{c}-1}. \quad (21.75)$$

If the value $\hat{\xi}_0$ satisfying (21.73)–(21.75) is larger than X'_1 , then it is the MLE of ξ_0 . Otherwise, the MLE is $\hat{\xi}_0 = X'_1$ in which case (21.73) and (21.74) must be solved for \hat{a} and \hat{c} . It should be noted that the MLEs are "regular" (in the sense of having the usual asymptotic distribution) only for $c > 2$. If c is

known to be in the interval (0, 1), then X'_1 is a "superefficient" estimator for $\hat{\xi}_0$. If the MLEs are regular, then Dubey (1965) has given for large n (when $\hat{\xi}_0$ is known)

$$n \text{Var}(\hat{\alpha}) \doteq \left[1 + \frac{\{\psi(2)\}^2}{\psi'(1)} \right] \left(\frac{\alpha}{c} \right)^2 = 1.109 \left(\frac{\alpha}{c} \right)^2,$$

$$n \text{Var}(\hat{c}) \doteq c^2 [\psi'(1)]^{-1} = \frac{6c^2}{\pi^2} = 0.608c^2,$$

$$\text{Corr}(\hat{\alpha}, \hat{c}) \doteq \frac{\psi(2)}{[\psi'(1) + \{\psi(2)\}^2]^{1/2}} = 0.313,$$

where $\psi(\cdot)$ and $\psi'(\cdot)$ are digamma and trigamma functions (see Chapter 1, Section A2).

Haan and Beer (1967) suggested that (21.74) be solved for 2, for each of a series of trial values of $\hat{\xi}_0$. The value of $\hat{\alpha}$ is then easily obtained from (21.73) and the value of the likelihood can be calculated. An alternative method would be to compare the values of $\hat{\alpha}$ obtained from (21.73) and (21.75). Monte Carlo studies conducted by Aroian (1965) and Miller (1966) established that \hat{c} is a biased estimator of c, the relative bias depending on sample size but not on c. For sample size 170, for example, the bias is about 0.8%.

Based on a Type II censored sample $X'_1 \leq X'_2 \leq \dots \leq X'_k$ with the largest n - k observations censored, Cohen (1965) has given the maximum likelihood equations for estimators of ξ_0 , a, and c. For example, if ξ_0 is known to be 0, then the equations are of form similar to (21.71) and (21.72) but with

$$n^{-1}, \sum_{i=1}^n X_i^{\hat{c}}, \sum_{i=1}^n X_i^{\hat{c}} \log X_i, \sum_{i=1}^n \log X_i$$

replaced by

$$k^{-1}, \sum_{i=1}^k X_i^{\hat{c}} + (n - k) X_k^{\hat{c}},$$

$$\sum_{i=1}^k X_i^{\hat{c}} \log X_i + (n - k) X_k^{\hat{c}} \log X_k,$$

$$\sum_{i=1}^k \log X_i,$$

respectively. For samples of size 10, censored by omission of the five largest values, McCool (1966) presented estimated percentile points of the distribution of \hat{c}/c , based on sampling experiments. The estimates are based on five sets of 1000 samples each, for c = 0.9, 1.1, 1.3, 1.5, 1.7, respectively. It is noteworthy that the estimated value of $E[\hat{c}/c]$ is 1.37, indicating that \hat{c} should be divided by 1.37 to obtain an approximately unbiased estimator of c. McCool also showed that the distribution of $\hat{c} \log(\hat{X}_p/X_p)$, where \hat{X}_p is the

maximum likelihood estimator of

$$X_p = \alpha [-\log(1 - p)]^{1/c}$$

does not depend on any of the parameters.

Since (21.73)–(21.75) do not yield explicit solutions for the estimates, Cohen (1965) suggested eliminating α from the first two equations to give

$$\left[\frac{\sum_{i=1}^n (X_i - \hat{\xi}_0)^{\hat{c}} \log(X_i - \hat{\xi}_0)}{\sum_{i=1}^n (X_i - \hat{\xi}_0)^{\hat{c}}} - \frac{1}{\hat{c}} \right] - \frac{1}{n} \sum_{i=1}^n \log(X_i - \hat{\xi}_0) = 0. \tag{21.76}$$

When ξ_0 is known, (21.76) can be easily solved for \hat{c} . When ξ_0 is unknown, Cohen suggested the following approach: Select a first approximation $\hat{\xi}_0 < X'_1$, and solve (21.76) and (21.73) for \hat{c} and $\hat{\alpha}$; then verify whether the likelihood equation for ξ_0 in (21.75) is satisfied for these values of the estimates, and iterate until a pair of estimates for ξ_0 is attained that is **sufficiently** close.

The asymptotic variance-covariance matrix for the MLEs $\hat{\xi}_0$, $\hat{\alpha}$ and \hat{c} can be shown to be

$$\begin{bmatrix} \frac{\alpha^2}{n} \phi_{11} & \frac{\alpha^2}{n} \phi_{12} & \frac{\alpha}{n} \phi_{13} \\ & \frac{\alpha^2}{n} \phi_{22} & \frac{\alpha}{n} \phi_{23} \\ & & \frac{c^2}{n} \phi_{33} \end{bmatrix}, \tag{21.77}$$

where

$$\begin{aligned} \phi_{11} &= \frac{\psi'(1)}{c^2 M}, \quad \phi_{22} = \frac{KC - J^2}{c^2 M}, \\ \phi_{33} &= \frac{C - \Gamma^2[2 - (1/c)]}{M}, \\ \phi_{12} &= -\frac{J\psi(2) + K\Gamma[2 - (1/c)]}{c^2 M}, \\ \phi_{13} &= \frac{J + \psi(2)\Gamma[2 - (1/c)]}{M}, \\ \phi_{23} &= \frac{C\psi(2) - J\Gamma[2 - (1/c)]}{M}. \end{aligned} \tag{21.78}$$

Here

$$M = KC - 2J\psi(2)\Gamma\left(2 - \frac{1}{c}\right) - C\psi^2(2) - K\Gamma^2\left(2 - \frac{1}{c}\right) - J^2,$$

with

$$C = \left\{ \Gamma\left(1 - \frac{2}{c}\right) + c\Gamma\left(2 - \frac{2}{c}\right) \right\} \frac{(c-1)}{c^2},$$

$$J = \Gamma\left(1 - \frac{1}{c}\right) - A\Gamma\left(2 - \frac{1}{c}\right),$$

$$K = \psi'(1) + \{\psi(2)\}^2,$$

$$A = 1 + \psi\left(2 - \frac{1}{c}\right).$$

The variance-covariance factors in (21.78) have been tabulated by Cohen and Whitten (1988, p. 48) and Balakrishnan and Cohen (1991, p. 125) for various values of the shape parameter $c > 2$.

Harter (1970, pp. 104–106) has presented similar expressions for the case where the available sample is doubly Type II censored. Harter has also given some tables of the variance-covariance factors for selected values of c and different levels of censoring at both ends. Lawless (1982) and Bain and Engelhardt (1991a) have also discussed iterative methods of determining the maximum likelihood estimates of the parameters. Cohen (1975), Lemon (1975), and Wingo (1973) have discussed the maximum likelihood estimation of parameters where the available sample is progressively censored.

Escobar and Meeker (1986a) presented the Fisher information matrix based on complete and censored data. Pertinent discussion on the maximum likelihood estimation for this case may also be seen in the paper by Smith (1985) discussing the problem in general for the class of nonregular cases. Zanakis and Kyparisis (1986) reviewed various maximum likelihood estimation methods available in literature for the three-parameter case. Zanakis (1979) also carried out a simulation study comparing various simplified estimators proposed for the three-parameter case.

By adapting Fisher's conditional approach to inference, Lawless (1978, 1980, 1982) has developed procedures for exact inference concerning the parameters and some functions of them such as quantiles. Although these exact conditional procedures have the advantage of not requiring extensive tables like the unconditional procedures, numerical integration is usually necessary for their application. For this reason DiCiccio (1987) proposed a method of approximate conditional inference based on normal approxima-

tions to the distributions of signed square roots of likelihood ratio statistics. By comparing the results with those of Lawless (1982), DiCiccio has shown that his approximate conditional method provides fairly accurate approximations to the exact method even in case of small samples. DiCiccio, Field, and Fraser (1990) have described two tail probability approximations for this problem in order to avoid high-dimensional integrals.

4.7 Modified Maximum Likelihood Estimation

Cohen and Whitten (1982) proposed modified maximum likelihood estimators (MMLEs) of ξ_0 , α , and c as alternatives for use when the MLEs are likely to be unsatisfactory (when $c < 2$ or perhaps 2.2); these estimators also possess some advantages with respect to ease of computation, bias, and variance for all values of c . The various MMLEs proposed by Cohen and Whitten (1982) are based on replacing the likelihood equation for ξ_0 in (21.75) with alternate functional relationships of the following forms:

$$E[F_X(X'_1)] = \frac{1}{n+1} \quad \text{reducing to} \\ -\log\left(\frac{n}{n+1}\right) = \frac{(X'_1 - \xi_0)^c}{\alpha^c}, \quad (21.79)$$

$$E[X'_1] = X'_1 \quad \text{reducing to} \\ \xi_0 + \left(\frac{\alpha}{n^{1/c}}\right)\Gamma\left(1 + \frac{1}{c}\right) = X'_1, \quad (21.80)$$

$$E[X] = \bar{X} \quad \text{reducing to } \xi_0 + \alpha\Gamma\left(1 + \frac{1}{c}\right) = \bar{X}, \quad (21.81)$$

$$\text{Var}(X) = S^2 \quad \text{reducing to} \\ \alpha^2\left[\Gamma\left(1 + \frac{2}{c}\right) - \Gamma^2\left(1 + \frac{1}{c}\right)\right] = S^2, \quad (21.82)$$

$$E[X_{\text{Med}}] = X_{\text{Med}} \quad \text{reducing to} \\ \xi_0 + \alpha(\log 2)^{1/c} = X_{\text{Med}}. \quad (21.83)$$

Here, X_{Med} denotes the sample median. Then (21.73), (21.74), and one of (21.79)–(21.83) are solved jointly to obtain the MMLEs. Through a simulation study, Cohen and Whitten (1982) have also shown that the entries in the asymptotic variance-covariance matrix of the MLEs in (21.77) and (21.78) provide a reasonable approximation to variances and covariances of the MMLEs (when $c > 2$). Further discussion on the MMLEs may be found in Cohen and Whitten (1988), Balakrishnan and Cohen (1991), and Cohen (1991).

Wyckoff, Bain, and Engelhardt (1980) proposed the following procedure for estimating the parameters ξ_0 , a , and c . X'_1 is used as an initial estimate of ξ_0 . An initial estimate of c is obtained by taking $\hat{5}_1 = X'_1$ and using the estimator of c proposed by Dubey (1967c) given by [see Section 4.2]

$$\hat{c}_1 = \frac{2.989}{\log(X_k - X'_1) - \log(X_h - X'_1)}, \tag{21.84}$$

where X_k and X_h are the 94th and 17th sample percentiles, respectively. $\hat{5}_1$ is reestimated from (21.80), with a replaced by $(\bar{X} - \xi_0)/\Gamma[1 + (1/c)]$ [from (21.81)]; \hat{c}_1 is substituted for c , and the resulting equation is solved for $\hat{5}_1$. The solution is the new estimate for ξ_0 , denoted by $\hat{5}_2$. The parameters a and c are then estimated by assuming $\hat{5}_2 = \hat{5}_1$ and using the estimators given by Engelhardt and Bain (1977). Proceeding somewhat similarly, Kappenman (1985b) proposed the following estimators of ξ_0 , a , and c :

$$\hat{\xi}_0 = \frac{X'_1 - X_m \{ \Gamma[1 + (1/\hat{c}_1)] / n^{1/\hat{c}_1} \}}{[1 - \{ \Gamma[1 + (1/\hat{c}_1)] / n^{1/\hat{c}_1} \}]}, \tag{21.85}$$

$$\hat{c} = \frac{nk_n}{[s/(n - s)] \sum_{i=s+1}^n \log(X'_i - \hat{\xi}_0) - \sum_{i=1}^s \log(X'_i - \hat{\xi}_0)}, \tag{21.86}$$

and

$$\hat{a} = \exp \left\{ \frac{0.5772}{\hat{c}} + \frac{1}{n} \sum_{i=1}^n \log(X'_i - \hat{\xi}_0) \right\}, \tag{21.87}$$

where \hat{c}_1 is given by (21.84), $s = [0.84n]$ with $[\cdot]$ denoting the integer part, X_m is the 63rd sample percentile, and k_n is a constant that depends upon the sample size [Engelhardt and Bain (1977)]. Through a simulation study Kappenman (1985b) has displayed that the mean squared errors for the estimators of $\hat{5}_1$ and c in (21.85) and (21.86) are always considerably smaller than those for the corresponding MMLEs; the same is true for the estimators of a , except for the case where $c = 0.5$.

4.8 Bayesian Estimation and Shrinkage Estimation

Considerable amount of work dealing with Bayes, empirical Bayes, and shrinkage estimation methods for the parameters of the Weibull distribution has been done since 1970. Volumes by Tsokos and Shimi (1977) and Martz and Waller (1982) will provide interested readers with many details and developments in this direction.

Soland (1966, 1967) initiated the Bayesian estimation of the Weibull parameters. Papadopoulos and Tsokos (1975) derived Bayesian confidence bounds for the Weibull model. By considering a two-parameter form under stochastic variation of the shape and scale parameters c and a , Tsokos and

Rao (1976) described the Bayesian analysis. While Kamat (1977) discussed the Bayesian estimation of the system reliability using Monte Carlo simulation, Martz and Lian (1977) considered the Bayes and empirical Bayes point as well as interval estimation of the reliability; see Bennett (1977) for further results on empirical Bayes estimates. Lingappaiah (1977) presented the Bayesian approach to the prediction problem based on complete and censored samples; also see Tziazefas (1987) for further discussion on this issue. By considering the two-parameter Weibull distribution, Erto (1982) derived practical Bayesian estimators for the parameters a and c . Bayesian estimation of the parameters as well as the reliability function for the **three-parameter** case has been discussed by Sinha (1986), Sinha and Guttman (1988), and Sinha and Sloan (1988). Similar discussions have been made by Sinha (1982, 1987) and Sinha and Sloan (1989) for mixtures of Weibull distributions. Singpurwalla (1988) and Singpurwalla and Song (1988) have presented a discussion on how to incorporate expert opinion in the reliability analysis based on Weibull distributions. Smith and Naylor (1987) compared the performance of the Bayesian estimators of the parameters ξ_0 , a , and c with the corresponding maximum likelihood estimators. Canavos (1983) similarly compared the performance of the Bayesian and empirical Bayesian estimators of the parameters. Abdel-Wahid and Winterbottom (1987) proposed approximate Bayesian estimates for the reliability function and the hazard rate based on complete and censored data, while Dey and Kuo (1991) gave a new empirical Bayesian estimator based on censored data.

An experimenter involved in life-testing experiments becomes quite familiar with failure data and hence may often develop knowledge about some parameters of the distribution. In the case of Weibull distribution, for example, knowledge on the shape parameter c can be utilized to develop improved inference for the other parameters. If an **initializing** value θ_0 of a parameter θ is available, say, the shrunken estimator $k\hat{\theta} + (1-k)\theta_0$ ($0 < k < 1$) for θ as proposed by Thompson (1968) is more efficient than the estimator $\hat{\theta}$ only if θ is close to θ_0 and is less efficient otherwise. This shrinkage estimation of the Weibull parameters has been discussed by a number of authors, including Singh and Bhatkulikar (1978), Pandey (1983, 1988), Pandey, Malik, and Srivastava (1989), Pandey and Singh (1984), Pandey and Upadhyay (1985, 1986), and Pandey and Singh (1993). For example, Singh and Bhatkulikar (1978) suggested performing a significance test of the validity of the prior value of c (which they took as 1). Pandey (1983) also suggested a similar preliminary test shrunken estimator for c . In a recent paper Pandey and Singh (1993) derived a test based on **Type II** censored data for the hypothesis $H_0: c = c_0$ versus $H_1: c \neq c_0$ (by minimizing the sum of the probabilities of the two types of error) and used it to propose another preliminary test shrunken estimator for c . The authors have shown that this estimator has higher efficiency and also **Pitman's** closeness than other shrunken estimators even in case of small sample sizes.

Then it is easily verified from (21.89) that

$$L = \hat{\xi}_0 - t_\gamma \hat{\alpha} \quad (21.93)$$

forms a lower γ tolerance limit for proportion β .

Similarly from (21.88) we may define the tolerance limit U to be an *upper γ tolerance limit for proportion β* (setting $L = \xi_0$) if

$$\Pr[F_X(U) \geq \beta] = \gamma. \quad (21.94)$$

It can be constructed based on the pivotal quantity

$$\begin{aligned} T^* &= -\frac{\hat{\xi}_0 - \xi_0}{\hat{\alpha}} + \frac{\alpha}{\hat{\alpha}} F^{-1}(\beta) \\ &= -\frac{\hat{\xi}_0 - \xi_0}{\hat{\alpha}} + \frac{\alpha}{\hat{\alpha}} \{-\log(1 - \beta)\}^{1/c}. \end{aligned} \quad (21.95)$$

Suppose that t_γ^* denotes the lower γ percentage point of the distribution of the pivotal quantity T^* in (21.95); that is,

$$\Pr[T^* \leq t_\gamma^*] = \gamma.$$

Then it is easily verified from (21.94) that

$$U = \hat{\xi}_0 + t_\gamma^* \hat{\alpha} \quad (21.96)$$

forms an upper γ tolerance limit for proportion β .

Tables of lower tolerance limits can also be used to determine lower confidence limits for the reliability function as originally observed by Lloyd and Lipow (1962, p. 204) in the case of normal distributions. Let $R_X(t) = \Pr[X \geq t] = 1 - F_X(t)$ denote the reliability at a specified time t . Then a lower confidence limit for the reliability function $R_X(t)$ can be obtained by setting $t = L$ and then determining for a specified γ the value of β that would make the statement in (21.92) to be true. The value of β thus determined would then be the lower confidence limit for the reliability function $R_X(t)$. To see this, let \hat{R}_1 denote the observed value of the chosen estimate $\hat{R}_X(t)$ for the given sample. Then, by setting

$$L = \hat{\xi}_0 - t_\gamma \hat{\alpha} = t,$$

we obtain

$$t_\gamma = -\frac{t - \hat{\xi}_0}{\hat{\alpha}} = -F^{-1}(1 - \hat{R}_1) = -(-\log \hat{R}_1)^{1/c}. \quad (21.97)$$

Now, we need to choose β so as to satisfy

$$\Pr \left[\frac{\hat{\xi}_0 - \xi_0}{\hat{\alpha}} - \frac{\alpha}{\hat{\alpha}} (-\log \beta)^{1/c} \leq -(-\log \hat{R}_1)^{1/c} \right] = \gamma \quad (21.98)$$

[see (21.91) and (21.92)]. If the reliability function $R_X(t) = \beta$, then $F^{-1}(1 - \beta) = (-\log \beta)^{1/c} = (t - \xi_0)/\alpha$ so that (21.98) becomes

$$\Pr \left[\frac{\hat{\xi}_0 - \xi_0}{\hat{\alpha}} - \frac{t - \xi_0}{\alpha} \frac{\alpha}{\hat{\alpha}} \leq -(-\log \hat{R}_1)^{1/c} \right] = \gamma \quad (21.99)$$

iff
$$\Pr \left[\frac{t - \hat{\xi}_0}{\hat{\alpha}} \geq (-\log \hat{R}_1)^{1/c} \right] = \gamma,$$

or iff
$$\Pr \left[F \left(\frac{t - \hat{\xi}_0}{\hat{\alpha}} \right) \geq 1 - \hat{R}_1 \right] = \gamma,$$

or iff
$$\Pr \left[1 - F \left(\frac{t - \hat{\xi}_0}{\hat{\alpha}} \right) = 1 - \hat{F}_X(t) = \hat{R}_X(t) \leq \hat{R}_1 \right] = \gamma.$$

Thus we have $R_X(t) = \beta$ to be the value of the reliability function which makes (21.99) to be true, and hence β is the lower confidence limit for $R_X(t)$. Such a value exists and is independent of the unknown parameters ξ_0 and α (for the case when the shape parameter c is known), since **Dumonceaux** (1969) has shown that the distribution of $\hat{R}_X(t)$ depends only on the unknown parameter $R_X(t)$.

Thoman, Bain, and Antle (1970) discussed the determination of tolerance limits and the estimation of the reliability $R_X(t)$ and also confidence intervals for the reliability function using the maximum likelihood method. This discussion is for the two-parameter Weibull distribution (with $\xi_0 = 0$ or assumed to be known). Tables are also provided for the lower confidence limits of the reliability and hence the lower tolerance limits. **Mann and Fertig (1973)** presented similar tables based on the best linear invariant estimates of α and c (when $\xi_0 = 0$ or assumed to be known). The results of **Thoman, Bain, and Antle (1970)** were extended to the case of Type II censored samples by **Billman, Antle, and Bain (1972)**, who also presented some

necessary tables for the lower confidence limits of the reliability $R_X(t)$ when the censoring on the right is either 25% or 50%. For the two-parameter Weibull distribution, Lawless (1975) discussed the same issues using the conditional approach which does not require the construction of any tables and is applicable for complete as well as Type II censored samples. Mann and Fertig (1977) discussed the construction of tolerance limits and lower confidence limits on the reliability using the asymptotic linear estimators based on k optimally selected order statistics for the parameters a and c (when $\xi_0 = 0$). Mann (1977) also examined the adequacy of an **F-approximation** for a statistic involved in the derivation of lower confidence bounds on the percentiles of the distribution discussed earlier by Mann, Schafer, and Singpurwalla (1974), for Type II censored data. Mann (1978a, b) has made further investigation on calculating simple approximate small-sample lower tolerance bounds or confidence bounds for percentiles of the distribution based on a two-parameter Weibull accelerated life-testing model. Bain and Engelhardt (1981) provided some simple approximations for the distributions of pivotal quantiles (based on the **MLEs**) for the two-parameter Weibull model that are useful for construction of approximate confidence limits for the parameters a and c , and also in determining approximate tolerance limits and confidence limits on reliability. These involve the chi-square, t , and noncentral t distribution (see Chapters 18, 28, 31) approximations for the pivotal quantities. Based on the least-squares method and median plotting positions, Erto and Guida (1985) determined lower confidence limits for reliability (also useful for finding lower confidence limits for population quantiles), and presented the necessary tables for various sample sizes and different choices of Type II right censoring.

All of these developments are based on the two-parameter Weibull distribution (taking $\xi_0 = 0$) and hence, not surprisingly (as explained in the beginning of Section 4), use the logarithmic transformation of the Weibull data into the extreme-value form and then proceed with the location parameter $\eta = \log(\alpha)$ and the scale parameter $\delta = 1/c$. As mentioned earlier in Section 4, the Weibull distribution with unknown scale and shape parameters is rewritten in the familiar and convenient "location-scale form" of the extreme-value distribution that made all the above-mentioned derivations possible [with η and δ appearing in (21.90)–(21.99) in place of ξ_0 and a].

Johnson and Haskell (1984) considered the three-parameter Weibull distribution in (21.3) and discussed a large-sample approach for deriving lower tolerance bounds. This is based on a large-sample approximation for the distribution of the maximum likelihood estimates established by Johnson and Haskell (1983). By means of a simulation study, they observed that $n = 70$ is even too small for obtaining a good approximate normal distribution for the proposed approximate tolerance limits. The approximation is observed to be particularly weak when β is large (e.g., 0.95), with great improvement taking place when β is around 0.75.

6 PREDICTION LIMITS AND INTERVALS

For the two-parameter Weibull distribution (with $\xi_0 = 0$), Mann and Saunders (1969) used three specially selected order statistics to predict the minimum of a single future sample. Suppose that X'_r , X'_p , and X'_q are the three selected order statistics from the available sample of size n . Further suppose that Y'_1 is the smallest in a future sample of size N . Mann (1970) has presented tables for the factor ν in the probability statement

$$\Pr[Y'_1 > X'_r + \nu(X'_p - X'_q)] = \gamma \tag{21.100}$$

for $\gamma = 0.95$ and selected values of n , N , r , p , and q . If $Y'_{1(i)}$ denotes the minimum in the i th future sample, Hewett and Moeschberger (1976) showed that

$$\Pr\left[\bigcap_{i=1}^k \{Y'_{1(i)} > X'_r + \nu(X'_p - X'_q)\}\right] \geq \gamma^k, \tag{21.101}$$

where the sizes N_1, N_2, \dots, N_k of the future samples all equal N .

In a repairable system suppose that n breakdowns have occurred and that the times of occurrence follow a Weibull process (see Section 12 for details). Engelhardt and Bain (1978) discussed the prediction of the time of the next breakdown, say, T_{n+1} , and in general the time T_{n+k} of the k th future breakdown. In the case of the prediction of T_{n+1} , they derived an exact closed-form prediction limit; for the general case of T_{n+k} , they discussed the exact limit and also an approximate prediction limit. The γ level lower confidence limit for T_{n+k} is a statistic $T_L = T_L(n, k, \gamma)$ such that

$$\Pr[T_L(n, k, \gamma) < T_{n+k}] = \gamma. \tag{21.102}$$

The form of $T_L(n, k, \gamma)$ is

$$T_L(n, k, \gamma) = t_n \cdot \exp\left[\frac{y_{1-\gamma}}{(n-1)\hat{c}}\right], \tag{21.103}$$

where

$$\hat{c} = \frac{n}{\sum_{i=1}^{n-1} \log(t_n/t_i)}$$

and $y_{1-\gamma}$ satisfies the equation in y :

$$1 - \gamma = \sum_{j=1}^k m_j \left\{ 1 - \left[1 + (n + j - 1) \frac{y}{n(n-1)} \right]^{-(n-1)} \right\},$$

with

$$m_j = \frac{(-1)^{j-1} (n + k - 1)!}{(n-1)! (k-j)! (j-1)! (n+j-1)!}.$$

For the case $k = 1$, (21.103) can be written as

$$T_L(n, 1, \gamma) = t_n \exp \left[\frac{\gamma^{-1/(n-1)} - 1}{\hat{c}} \right] \quad (21.104)$$

Assuming that a Type II right-censored sample is available from the **two-parameter** Weibull distribution (with $\xi_0 = 0$), Engelhardt and Bain (1979) used the logarithmic transformation to change to the Type 1 extreme-value distribution form (as explained in the first paragraph of Section 4) and then discussed the construction of prediction limits for the minimum and, in general, the j th smallest in a future sample of size N . These intervals are based on some closed-form estimates of the extreme-value parameters η ($= \log a$) and δ ($= 1/c$) and **F-approximations** to the resulting pivotal quantities. Engelhardt and Bain (1982) subsequently presented a simplified approximation for the lower prediction limit for the smallest in a future sample of size N ; this simplified limit is an explicit form in terms of the estimates of the extreme-value parameters η and δ and the variances and covariance of these estimates. Sherif and Tan (1978) have discussed this prediction problem when the available sample is Type II progressively censored. Fertig, Meyer, and Mann (1980), along the lines of Engelhardt and Bain (1979), discussed the prediction of a single future observation through pivotal quantities based on the best linear invariant estimators of the extreme-value parameters η and δ and presented the necessary tables of percentage points for different sample sizes and levels of censoring.

Wright and Singh (1981) considered the problem of predicting the s th-order statistic X'_s , having observed the first r order statistics in a sample of size n from a two-parameter Weibull distribution (with $\xi_0 = 0$) when (1) n is fixed and (2) n is randomly distributed as a binomial variable. The strong assumption that the shape parameter c is known is made in this analysis. With the assumption that c is known, the prediction problem considered here becomes equivalent to that in the case of the scaled exponential distribution (see Chapter 19).

Adata and Chan (1982) used the maximin estimator and the adaptive estimator of a , both of which are robust as explained briefly in Section 4, to

construct prediction intervals for an order statistic X'_s , having observed the first r order statistics X'_1, \dots, X'_r from a sample of size n from the two-parameter Weibull distribution (with $\xi_0 = 0$). These authors assume that the shape parameter c is known to lie in the interval $[c_-, c_R]$ and then use the maximin or the adaptive estimator to propose "robust" predictors of X'_s . These predictors are taken to be linear functions of the observed order statistics X'_1, X'_2, \dots, X'_r with weights determined from the guaranteed efficiency required. Necessary tables have also been provided by Adataia and Chan (1982). Under the same setup Balasooriya and Chan (1983) carried out a robustness study of four types of predictors of X'_s , given X'_1, \dots, X'_r , assuming that it is only known that the shape parameter c lies in an interval. For this comparative study they considered the following four predictors:

1. Best linear unbiased predictor

$$\hat{X}'_s(c) = \omega(c)^T V(c)^{-1} X + \hat{\alpha}(c) \left[E[Z'_s|c] - \omega(c)^T V(c)^{-1} E \left[\frac{X}{\alpha} | c \right] \right], \tag{21.105}$$

where $\hat{\alpha}(c)$ is the BLUE of α (see Section 4), Z'_i is the i th standardized order statistic ($= X'_i/\alpha$), X denotes the column vector consisting of the given r order statistics, $V(c)$ is the variance-covariance matrix of (Z'_1, \dots, Z'_r) , and $\omega(c)$ is the $r \times 1$ covariance matrix of (Z'_1, \dots, Z'_r) and Z'_s ($1 \leq r < s \leq n$).

2. Best linear invariant predictor

$$\begin{aligned} \tilde{X}'_s(c) &= \hat{X}'_s(c) + \hat{\alpha}(c) \left[E[Z'_s|c] - \omega(c)^T V(c)^{-1} E \left[\frac{X}{\alpha} | c \right] \right] \\ &\times \frac{\text{Var}(\hat{\alpha}(c)/\alpha)}{1 + \text{Var}(\hat{\alpha}(c)/\alpha)}. \end{aligned} \tag{21.106}$$

3. Final linear unbiased predictor

$$X'^*_s(c) = X'_r + \hat{\alpha}(c) \{ E[Z'_s|c] - E[Z'_r|c] \}. \tag{21.107}$$

4. Cross-validatory predictive function

$$X'^{\text{cross}}_s(c; a) = X'_r + a \{ E[Z'_s|c] - E[Z'_r|c] \}, \tag{21.108}$$

where a depends on the sample and is given by

$$a = \frac{\sum_{i=s-r+1}^r \{X'_i - X'_{i-(s-r)}\} \{E[Z'_i|c] - E[Z'_{i-(s-r)}|c]\}}{\sum_{i=s-r+1}^r \{E[Z'_i|c] - E[Z'_{i-(s-r)}|c]\}^2}. \quad (21.109)$$

Balasoorya and Chan (1983) showed that the cross-validatory predictive function is the best in the sense of guaranteed efficiency; in addition this method does not require the knowledge of the covariances of Weibull order statistics or the inverse of an $r \times r$ matrix.

Pandey and Upadhyay (1986) considered the prediction of the smallest or the i th order statistic from a future sample of size N having observed a Type II right-censored sample X'_1, \dots, X'_r from a sample of size n from the two-parameter Weibull distribution (with $\xi_0 = 0$). They assume that the scale parameter a is known and then develop prediction limits by using the preliminary test estimator of the unknown shape parameter c proposed by Pandey (1983) (also see Section 4).

As mentioned in Section 4.8, Tziafetas (1987) considered the Bayesian prediction of a single future observation, having observed a Type II right-censored sample from the two-parameter Weibull distribution (with $\xi_0 = 0$). Bayesian predictive intervals are derived after assigning Weibull and uniform (c_1, c_2) prior distributions for the scale parameter a and the shape parameter c , respectively. Nigm (1990) derived similar Bayesian prediction bounds for order statistics from the same sample and also for order statistics from a future sample, having observed a Type I censored sample up to time t . Based on a Type II censored sample X'_1, \dots, X'_r from a sample of size n , Nigm (1989) had earlier discussed the derivation of Bayesian prediction bounds for the order statistic X'_s ($r < s \leq n$) from the same sample, and also for the order statistic Y'_i in a future sample of size N . For this development Nigm (1989) used an informative prior family for the parameters a^* and c of the bivariate form

$$\Pi(\alpha^*, c) = c^{2a} (\alpha^*)^{a+h/\phi(c)} e^{-cg} e^{-b\alpha^* \psi(c)}, \quad a > -1, g, h, b > 0, c, \alpha^* > 0,$$

where $\phi(\cdot)$ and $\psi(\cdot)$ are increasing functions of c . Here the parameter a^* is given by $\alpha^{-1/c}$ and the reparametrized Weibull density is $c\alpha^* x^{c-1} e^{-\alpha^* x^c}$. The same Bayesian prediction problem had earlier been discussed by Evans and Nigm (1980a, b) but using the noninformative prior for the parameters a^* and c given by

$$\Pi(\alpha^*, c) \propto \frac{1}{\alpha^* c^2}, \quad c > 0, \alpha^* > 0.$$

Dellaportas and Wright (1991) have described a numerical approach to this Bayesian prediction problem and the method of evaluating the posterior expectations. These authors, in addition to constructing prediction bounds for future lifetimes, also discuss the construction of the posterior distribution of the median lifetime.

This section deals only with the two-parameter Weibull distribution (with $\xi_0 = 0$ or known). The prediction problems for the three-parameter Weibull model in (21.3) seem to be unresolved and is certainly worth looking into.

7 RECORD VALUES

Let X_1, X_2, \dots be an i.i.d. sequence of standard Weibull random variables with density function in (21.10), and let $X_{U(1)}, X_{U(2)}, \dots$ be the upper record values arising from this sequence (see Chapter 13, Section 5, for definitions). Then the density function of the n th upper record value $X_{U(n)}$ is

$$\begin{aligned}
 p_{X_{U(n)}}(x) &= \frac{1}{\Gamma(n)} \{-\log[1 - F_X(x)]\}^{n-1} p_X(x) \\
 &= \frac{1}{\Gamma(n)} (x^c)^{n-1} e^{-x^c} c x^{c-1}, \quad x > 0, \quad n = 1, 2, \dots \quad (21.110)
 \end{aligned}$$

Similarly the joint density function of $X_{U(m)}$ and $X_{U(n)}$ is

$$\begin{aligned}
 &p_{X_{U(m)}, X_{U(n)}}(x, y) \\
 &= \frac{1}{\Gamma(m)\Gamma(n-m)} \{-\log[1 - F_X(x)]\}^{m-1} \frac{p_X(x)}{1 - F_X(x)} \\
 &\quad \times \{-\log[1 - F_X(y)] + \log[1 - F_X(x)]\}^{n-m-1} p_X(y) \\
 &= \frac{1}{\Gamma(m)\Gamma(n-m)} (x^c)^{m-1} c x^{c-1} (y^c - x^c)^{n-m-1} e^{-y^c} c y^{c-1}, \\
 &\quad 0 < x < y, \quad m = 1, 2, \dots, n - 1. \quad (21.111)
 \end{aligned}$$

From (21.110), the k th raw moment of $X_{U(n)}$ is obtained to be

$$E[X_{U(n)}^k] = \Gamma\left(n + \frac{k}{c}\right) / \Gamma(n), \quad k \geq 1, \quad n = 1, 2, \dots \quad (21.112)$$

In particular, we have

$$E[X_{U(n)}] = \frac{\Gamma[n + (1/c)]}{\Gamma(n)},$$

$$\text{Var}(X_{U(n)}) = \frac{\Gamma[n + (2/c)]}{\Gamma(n)} - \left\{ \frac{\Gamma[n + (1/c)]}{\Gamma(n)} \right\}^2. \quad (21.113)$$

Observe also from (21.110) that $X_{U(n)}^c$ is distributed as standard gamma with shape parameter n . Dallas (1982) has discussed some further distributional results on upper record values from the Weibull population.

Next, from the joint density function of $X_{U(m)}$ and $X_{U(n)}$ in (21.111), we obtain the product moment to be

$$E[X_{U(m)}X_{U(n)}] = \int_0^\infty \int_0^y xy f_{m,n}(x, y) dx dy$$

$$= \frac{\Gamma[m + (1/c)]}{\Gamma(m)} \times \frac{\Gamma[n + (2/c)]}{\Gamma[n + (1/c)]}, \quad 1 \leq m \leq n - 1. \quad (21.114)$$

From (21.113) and (21.114) we immediately obtain

$$\text{Cov}(X_{U(m)}, X_{U(n)}) = \frac{\Gamma[m + (1/c)]}{\Gamma(m)} \left\{ \frac{\Gamma[n + (2/c)]}{\Gamma[n + (1/c)]} - \frac{\Gamma[n + (1/c)]}{\Gamma(n)} \right\}. \quad (21.115)$$

It is of interest to note here that the variance-covariance matrix $((\sigma_{i,j}))$ is of the form $\sigma_{i,j} = a_i b_j$, $i \leq j$; this will make the inversion of the matrix possible explicitly (see Section 4.4) which will enable us to derive the best linear unbiased estimators of the parameters ξ_0 and α (when c is known) in an explicit form.

In addition to deriving the above results, Balakrishnan and Chan (1993c) also established the following simple recurrence relations satisfied by the

single and the product moments of Weibull upper record values:

$$E[X_{U(n+1)}^k] = \left(1 + \frac{k}{nc}\right) E[X_{U(n)}^k], \quad n \geq 1, \quad k = 1, 2, \dots, \quad (21.116)$$

$$E[X_{U(m)}^k X_{U(m+1)}^l] = \frac{mc}{mc+k} E[X_{U(m+1)}^{k+l}], \quad m \geq 1, \quad k, l = 1, 2, \dots, \quad (21.117)$$

$$E[X_{U(m)}^k X_{U(n)}^l] = \frac{mc}{mc+k} E[X_{U(m+1)}^k X_{U(n)}^l],$$

$$1 \leq m \leq n - 2, \quad k, l = 1, 2, \dots, \quad (21.118)$$

$$E[X_{U(m)}^k X_{U(m+2)}^l] = \left(1 + \frac{l}{c}\right) E[X_{U(m)}^k X_{U(m+1)}^l]$$

$$- m \left\{ E[X_{U(m+1)}^k X_{U(m+2)}^l] - E[X_{U(m+1)}^{k+l}] \right\},$$

$$m \geq 1, \quad k, l = 1, 2, \dots, \quad (21.119)$$

$$E[X_{U(m)}^k X_{U(n+1)}^l] = \left(1 + \frac{l}{c(n-m)}\right) E[X_{U(m)}^k X_{U(n)}^l]$$

$$- \frac{m}{n-m} \left\{ E[X_{U(m+1)}^k X_{U(n+1)}^l] - E[X_{U(m+1)}^{k+l}] \right\},$$

$$1 \leq m \leq n - 2, \quad k, l = 1, 2, \dots \quad (21.120)$$

Suppose that the original sequence of variables arise from the **three**-parameter Weibull population with density function in (21.3). Then the likelihood function based on the first n upper records is

$$L = \frac{p_X(x_1)}{1 - F_X(x_1)} \frac{p_X(x_2)}{1 - F_X(x_2)} \dots \frac{p_X(x_{n-1})}{1 - F_X(x_{n-1})} p_X(x_n)$$

$$= \left(\frac{c}{\alpha}\right)^n \left\{ \prod_{i=1}^n \left(\frac{x_i - \xi_0}{\alpha}\right)^{c-1} \right\} e^{-\{(x_n - \xi_0)/\alpha\}^c},$$

$$\xi_0 < x_1 < x_2 < \dots < x_n. \quad (21.121)$$

Suppose the threshold parameter ξ_0 is known. If the shape parameter c is

also known, then the MLE of a is easily observed to be

$$\hat{\alpha} = \frac{X_{U(n)} - \mathfrak{D}}{n^{1/c}}, \quad (21.122)$$

with the variance [from (21.113)]

$$\text{Var}(\hat{\alpha}) = \frac{\alpha^2}{n^{2/c}} \times \left[\frac{\Gamma[n + (2/c)]}{\Gamma(n)} - \left\{ \frac{\Gamma[n + (1/c)]}{\Gamma(n)} \right\}^2 \right]. \quad (21.123)$$

Suppose that the shape parameter c is unknown. Then the **MLE's** of a and c may be determined numerically from the likelihood function in (21.121), or from the likelihood function based on the first n record values from the extreme value distribution (for details, see Chapter 22). If the threshold parameter ξ_0 is also unknown, then the MLE's of ξ_0 , α and c have to be determined numerically by solving simultaneously the three likelihood equations obtained from (21.121).

For the case when the shape parameter c is known, Balakrishnan and Chan (1993c) derived the **BLUE's** explicitly by making use of the explicit expressions of the means, variances, and covariances of record values presented earlier in (21.113) and (21.115). Because of the form of the variance-covariance matrix elements $\sigma_{i,j} = a_i b_j$, $i \leq j$ (as mentioned earlier), where

$$a_i = \frac{\Gamma[i + (1/c)]}{\Gamma(i)},$$

$$b_j = \frac{\Gamma[j + (2/c)]}{\Gamma[j + (1/c)]} - \frac{\Gamma[j + (1/c)]}{\Gamma(j)}, \quad (21.124)$$

the inverse of $((\sigma_{i,j}))$ can be explicitly written as [Graybill (1983, p. 198)]

$$\sigma^{1,1} = \frac{(c+1)^2}{\Gamma[1 + (2/c)]},$$

$$\sigma^{i,i} = \frac{\Gamma(i)}{\Gamma[i + (2/c)]} \{c^2(2i^2 - 2i + 1) + c(4i - 2) + 1\},$$

$$i = 2, 3, \dots, n-1,$$

$$\sigma^{n,n} = \frac{\Gamma(n)}{\Gamma[n + (2/c)]} \frac{b_{n-1}}{b_n} (nc - c + 1)(nc - c + 2),$$

$$\sigma^{i,i+1} = -\frac{\Gamma(i)}{\Gamma[i + (2/c)]} ic(ic + 1), \quad i = 1, 2, \dots, n-1,$$

$$\sigma^{i,j} = 0, \quad |j - i| > 2. \quad (21.125)$$

For the case when ξ_0 , and c are known, the BLUE of a becomes

$$\alpha^* = \frac{\Gamma(n)}{\Gamma[n + (1/c)]} (X_{U(n)} - \xi_0). \tag{21.126}$$

Its variance is

$$\text{Var}(\alpha^*) = \alpha^2 \left\{ \frac{\Gamma(n)\Gamma[n + (2/c)]}{\Gamma^2[n + (1/c)]} - 1 \right\}. \tag{21.127}$$

For large n , these are easily seen to be equivalent to the MLE in (21.122) and its variance in (21.123). Proceeding similarly for the case where both ξ_0 and a are unknown but the shape parameter c is known, Balakrishnan and Chan (1993c) derived the BLUE's of ξ_0 and a in explicit form, and also presented the variances and covariance of these estimators.

8 TABLES AND GRAPHS

Several tables and graphs relating to different methods of inference for the Weibull parameters have already been listed in Section 4. These will not be repeated here. Although the Weibull cumulative distribution function is available in an exact explicit form [(21.4)] that is easily computable, it is often convenient to have tables, or graphs, from which values can be obtained quickly without direct calculations.

For the standard Weibull case [$\xi_0 = 0$ and $a = 1$ in (21.3)], Plait (1962) presented tables giving values of the probability density function ($cx^{c-1}e^{-x^c}$) to eight decimal places for $c = 0.1(0.1)3(1)10$ and also of the cumulative distribution function ($1 - e^{-x^c}$) to seven decimal places for $c = 0.1(0.1)4.0$. Dourgnon and Reyrolle (1966) also tabulated the cumulative distribution function (less extensively). Harter and Dubey (1967) presented values of the mean, variance, and first six standardized cumulant ratios $\kappa_r/\kappa_2^{r/2}$, $r = 3, \dots, 8$, to eight decimal places for $c = 1.1(0.1)10.0$.

For the case where the threshold parameter ξ_0 is zero, by noting that $E[X] = \mu'_1 = \alpha\Gamma[1 + (1/c)]$, the cumulative distribution function of X in (21.4) can be rewritten as

$$F_X(x) = 1 - \exp \left\{ - \left[\frac{x\Gamma[1 + (1/c)]}{\mu'_1} \right]^c \right\}, \quad x \geq 0. \tag{21.128}$$

As it was indicated in Section 4, Kotel'nikov (1964) used (21.128) in constructing a nomogram for finding $F_X(x)$, given the mean μ'_1 and the standard deviation a . This nomogram is presented in Figure 21.6. One part of the

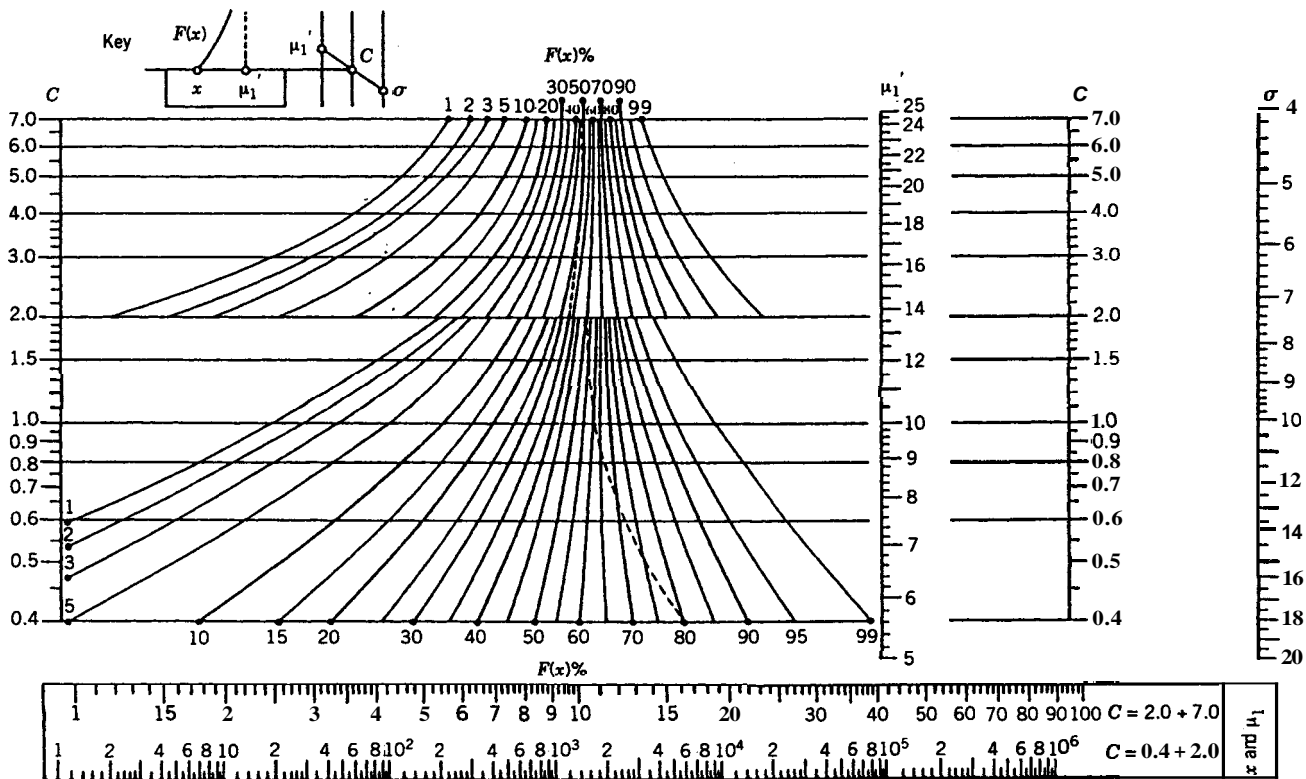


Figure 21.6 Kotel'nikov's Nomogram for the Weibull Distribution

nomogram determines the shape parameter c from given values of μ'_1 and a . This is done by finding the intersection of the straight line joining the appropriate points on the μ'_1 and a scales with the c scale. Then it is necessary to place the scale at the foot of the figure along the appropriate line μ'_1 and move it till the dotted line on the nomogram passes through the appropriate σ value on the scale. (Note that the edge of the scale to be used depends on c .) Then for any given value of x , the value of the cumulative distribution function $F_X(x)$ is the " $F_X(x)$ curve" passing through the value x on the appropriate edge of the scale. It is convenient in practice for the movable scale to be transparent.

Weibull probability paper can be constructed in several different ways [e.g., see Kao (1959); Nelson (1967); Plait (1962)]. Starting with the form of the cumulative distribution function in (21.4), we observe that

$$\log \log\{1 - F_X(x)\} = -c \log\left(\frac{x - \xi_0}{\alpha}\right), \quad x > \xi_0,$$

or

$$\log \log\left\{\frac{1}{1 - F_X(x)}\right\} = c \log(x - \xi_0) - c \log \alpha, \quad x > \xi_0,$$

Setting $\log \log\{1/[1 - F_X(x)]\}$ as w and $\log(x - \xi_0)$ as v , we obtain the linear relationship

$$w = cv - c \log \alpha, \quad c > 0.$$

Therefore, if $1 - F_X(x)$ or $1/[1 - F_X(x)]$ is plotted against $x - \xi_0$ on a *log log* versus *log* paper, a straight line is observed. The slope of the line is $-c$ or c , and the intercept with the y -axis is $c \log a$ or $-c \log a$. This Weibull probability paper, as presented by Nelson (1967), is given in Figure 21.7.

Nelson and Thompson (1971) have provided a detailed discussion on the many different probability papers available for the Weibull analysis. Nelson (1972) also discussed the theory and application of hazard plotting based on censored data. The volume by D'Agostino and Stephens (1986) provides an authoritative account of graphical analysis of Weibull data and also of many formal goodness-of-fit methods such as EDF tests. Fowlkes (1987) has also presented theoretical quantile-quantile plots that provide some insight for users working with real-life data regarding the usage of the Weibull model for the data at hand.

Harter and Dubey (1967) used Monte Carlo simulations to construct extensive tables of the distribution of sample variances, $s^2 = \sum_{i=1}^n (x_i - \bar{x})^2 / (n - 1)$, calculated from random samples from Weibull popu-

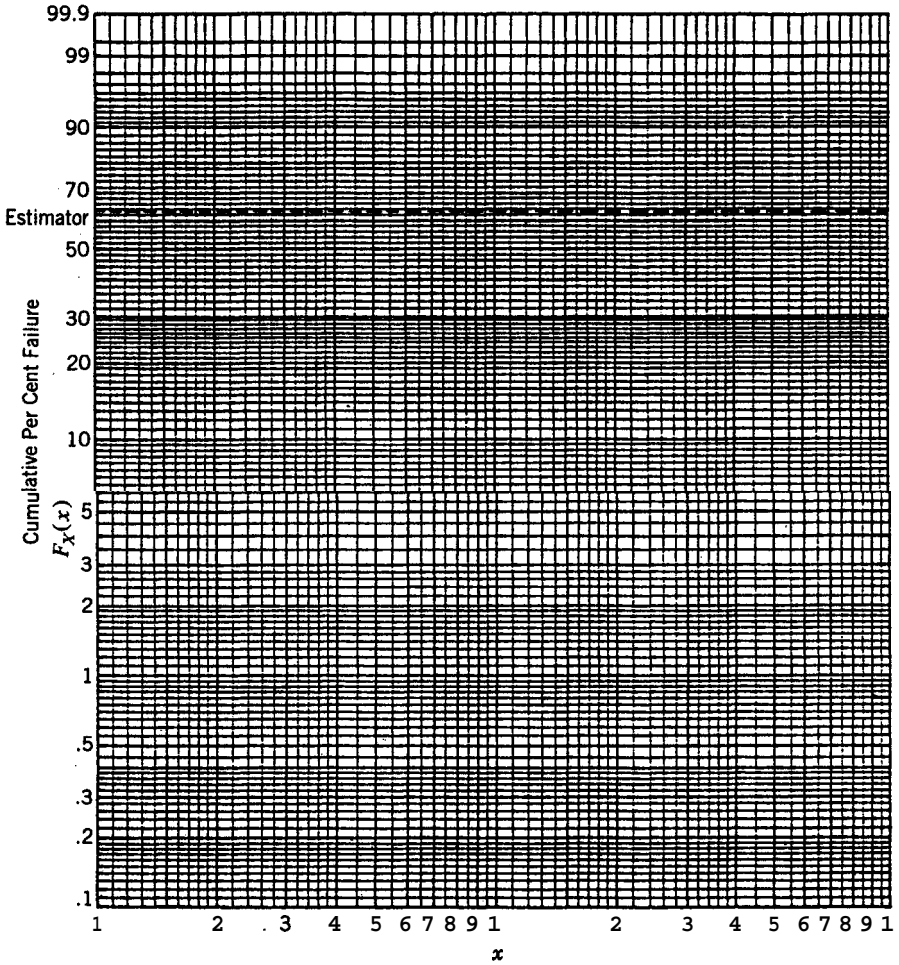


Figure 21.7 Weibull Probability Paper

lations, and also of the "Weibull-t" defined by

$$\frac{\sqrt{n}(\bar{x} - \mu'_1)}{s}$$

constructed from i.i.d. samples from the Weibull distribution. They also constructed tables of the distribution of the sample mean \bar{x} using a Cornish-Fisher expansion (see Chapter 12).

Details of tables relating to order statistics from Weibull populations have been presented in Section 3. As mentioned earlier, tables and graphs have been prepared by several authors in order to simplify the different methods of inference proposed in the literature; for the benefit of readers and users, a description of such tables and graphs may be seen in Section 4. Tables prepared for the determination of Weibull tolerance limits have been de-

scribed in Section 5. Finally, tables relating to the prediction problems concerning the Weibull distribution are detailed in Section 6.

9 CHARACTERIZATIONS

It was already shown in Section 3 that when X_1, X_2, \dots, X_n are independent and identically distributed Weibull random variables, then the smallest order statistic X'_1 is also distributed as Weibull. Dubey (1966a) established this to be a characterizing property of a Weibull distribution by showing that if X'_1 is distributed as Weibull, then the common distribution of the X_i has to be a Weibull distribution. The proof is straightforward if one looks at the survival function of X'_1 (see Chapter 12, Section 6).

By assuming that X and Y are independent nonnegative random variables, Arnold and Isaacson (1976) have shown that, for some pair (a, b) such that $0 < a, b < 1$,

$$\min(X, Y) \stackrel{d}{=} aX \stackrel{d}{=} bY$$

if and only if X and Y have Weibull distributions. More generally, Arnold and Isaacson have proved the following characterization result:

Let X_1, X_2, \dots, X_m be independent non-degenerate non-negative random variables. Suppose that

$$\min(X_1, X_2, \dots, X_m) \stackrel{d}{=} a_1X_1 \stackrel{d}{=} a_2X_2 \stackrel{d}{=} \dots \stackrel{d}{=} a_mX_m,$$

where $0 < a_i < 1, i = 1, 2, \dots, m$. If, for that α for which $\sum_{i=1}^m a_i^\alpha = 1, \lim_{x \rightarrow 0^+} F(x)/x^\alpha = c$, then the X_i 's have Weibull distributions.

By generalizing the Cauchy functional equation $\Phi(x + y) = \Phi(x) + \Phi(y)$ to the form

$$\Phi((x^c + y^c)^{1/c}) = \Phi(x) + \Phi(y), \quad c \neq 0,$$

assuming Φ to be left- or right-continuous, Wang (1976) established a characterization of the Weibull distribution as follows:

Let $c \neq 0$ and X be a non-degenerate non-negative random variable. Then, X has a two-parameter Weibull distribution if and only if X satisfies

$$\Pr(X > (x^c + y^c)^{1/c} | X > y) = \Pr(X > x) \quad \text{for all } x, y > 0 \quad (21.129)$$

with $c > 0$. If $c < 0$, there is no random variable possessing property (21.129).

Note that this characterization is in the spirit of the memoryless property of the exponential distribution [see Chapter 19 for details and also Janardan (1978)].

Let X_1, X_2, \dots, X_n be n positive real random variables. For $a, \geq 0$ and $c > 0$, let

$$Z_j(a_j) = \begin{cases} X_j - a_j, & x_j > a_j, \\ 0, & x_j \leq a_j, \end{cases}$$

and suppose that for some r between 1 and $n - 1$, (Z_1, \dots, Z_r) and (Z_{r+1}, \dots, Z_n) are independent. Then Cook (1978) proved a characterization result that for all $a, \geq 0$, $E[\prod_{j=1}^n Z_j(a_j)]$ depends on the parameters only through a function of $\sum_{j=1}^n a_j$ if and only if all X_j are mutually independent two-parameter Weibull random variables.

Let $X_{1:n}, X_{2:n}, \dots, X_{n:n}$ be the order statistics obtained from n i.i.d. random variables with absolutely continuous strictly increasing distribution function $F(x)$. Janardan and Taneja (1979a) characterized the two-parameter Weibull distribution based on the following statements:

1. For any fixed r and two distinct numbers S_1 and S_2 and with $1 < r < S_1 < S_2 \leq n$, the distributions of

$$V_i = (X_{S_i:n}^c - X_{r:n}^c)^{1/c} \quad \text{and} \quad W_i = X_{S_i-r:n-r}$$

are identical for $i = 1$ and 2 .

2. The statistics $D_1 = X_{1:n}$ and $D_2 = (X_{2:n}^c - X_{1:n}^c)^{1/c}$ are independent.
3. The statistics $U_j = (X_{j+1:n}^c - X_{j:n}^c)^{1/c}$, $1 \leq j \leq n - 1$, and $X_{i:n}$ ($1 \leq i \leq j$) are independent [also see Janardan and Schaeffer (1978)].
4. X, X_1, \dots, X_k are random variables satisfying $\Pr[X - \sum_{i=1}^k X_i > 0]$ is positive, and

$$\Pr \left[X - \sum_{i=1}^k X_i > \left(a^c + \sum_{i=1}^k b_i^c \right)^{1/c} \mid X - \sum_{i=1}^k X_i > \left(\sum_{i=1}^k b_i^c \right)^{1/c} \right] = \Pr[X > a], \quad c > 0.$$

Notice the similarity of condition 4 to (21.129).

Janardan and Taneja (1979b) have provided some further characterization results. One of these is based on the conditional expectation as follows: Let X be a nonnegative random variable with distribution function $F(x)$. Suppose that $E[X] < \infty$ and that y is a positive number. Then $F(x)$ is a two-parameter Weibull distribution if and only if

$$E[X^c | X > y] = y^c + E[X] \quad \text{for all } y, c > 0.$$

Another condition based on which they characterize the Weibull distribution is

$$E \left[(X - (s^c + t^c)^{1/c})^+ \right] = \alpha E[(X - s)^+] E[(X - t)^+]$$

for all s, t belonging to a dense subset of $(0, \infty)$, where $(X - u)^+$ denotes

$\max\{X - u, 0\}$. Roy (1984) established some characterization results for the generalized gamma distribution based on the Fisher-information-minimization and entropy-maximization principles which gives as a special case results for the Weibull distribution. Further, denoting the cumulative hazard function $-\log[1 - F(x)]$ by $H(x)$ and the hazard function by $h(x) = H'(x) = p(x)/[1 - F(x)]$, Roy and Mukherjee (1986) presented some characterizations for the two-parameter Weibull distribution based on the following statements:

1. $H(xy)H(1) = H(x)H(y)$ for all $x, y > 0$.
2. $H(xy)H(1) = H(x)H(y)$, with $H(1) > 0$, for at least one value of $y > 0$ (and not equal to 1), for all $x > 0$, and $xh(x)/H(x)$ is nondecreasing for $x > 0$.
3. $h(x)$ is strictly increasing with $h(0) = 0$ and $h(X)$ is distributed as two-parameter Weibull (shape parameter $c' > 1$) where $(1/c') + (1/c') = 1$.

Khan and Beg (1987) proved that the simple condition that $\text{Var}(X_{r+1:n}^c | X_{r:n} = x)$ does not depend on x characterizes the two-parameter Weibull distribution. This is, in principle, a direct consequence of a characterization of the exponential distribution based on the condition that $\text{Var}(X_{r+1:n} | X_{r:n} = x)$ is a constant, a result due to Beg and Kirmani (1978) (see also Chapter 19). Along similar lines Khan and Ali (1987) have characterized the Weibull distribution through the condition that

$$E[X_{r+1:n}^c | X_{r:n} = x] = x^c + \text{constant}$$

[see also El-Din, Mahmoud, and Youssef (1991)].

Ouyang (1987), Beg and Ali (1989), Moothathu (1990), and Chaudhuri and Chandra (1990) have provided some other characterizations of the Weibull distribution. For example, the characterization result presented by the first author is based on the conditional expectation of the function $g(X)$, given that $X \geq x$. Kamps (1991) has provided a characterization result for the Weibull distribution based on inequalities for moments of record values, with equality being satisfied if and only if the parent distribution is two-parameter Weibull. The proof follows easily from a simple application of Holder's inequality.

Scholz (1990) established an interesting characterization of the three-parameter Weibull density function in (21.3): Let $C = \{(u, v, w) : 0 < u < v < w < 1, \log(1 - u)\log(1 - w) = (\log(1 - v))^2\}$, and $F^{-1}(\cdot)$ denote the inverse of the distribution function in (21.4). Then it is easily verified from (21.4) that for some fixed t , namely $t = \xi_0$, the quantile relation

$$F^{-1}(u)F^{-1}(w) - (F^{-1}(v))^2 = t(F^{-1}(u) + F^{-1}(w) - 2F^{-1}(v))$$

holds for every $(u, v, w) \in C$. Scholz proves that this in fact is a characterizing relation for the three-parameter Weibull distribution in (21.4). He also has made some suggestions with regard to the usage of this characterization

result in developing a goodness-of-fit procedure for the three-parameter Weibull distribution.

Shimizu and Davies (1981) have established the following two characterization results:

1. Let N be an integer valued random variable (independent of the X 's) such that $N \geq 2$ with probability 1 and the distribution of $\log N$ has a finite mean and is not concentrated on a lattice $p, 2p, \dots$ for any $p > 0$. Then the random variable $Y = N^{1/c} \cdot X_{1:N}$ is distributed as X if and only if X 's are distributed as Weibull.
2. Let $m \geq 2$ be a **fixed** positive number, and let Z_1, \dots, Z_m be a set of positive random variables (independent of the X 's) satisfying

$$\Pr \left[\sum_{i=1}^m Z_i^c = 1 \right] = 1,$$

$$\Pr \left[\frac{\log Z_i}{\log Z_j} \text{ is irrational for some } i \text{ and } j \right] > 0.$$

Then the random variable $Y = \min\{X_1/Z_1, \dots, X_m/Z_m\}$ is distributed as X if and only if the X 's have Weibull distributions.

Roy (1984) presented a characterization of the generalized gamma (or generalized Weibull; see Section 12) for two independent nonnegative random variables X and Y based on the conditional distribution of X , given $Z = X/Y$, being also a generalized gamma distribution.

10 SIMULATION ALGORITHMS

Since the cumulative distribution function F of a three-parameter Weibull variable is of a closed explicit form [see (21.4)], it is easy to generate pseudorandom observations through the probability integral transformation approach. Specifically, letting

$$U = F(X; \xi_0, \alpha, c) = 1 - e^{-[(X - \xi_0)/\alpha]^c} \tag{21.130}$$

and inverting this transformation, we obtain

$$X = \xi_0 + \alpha \{ -\log(1 - U) \}^{1/c}. \tag{21.131}$$

Thus, after generating a pseudo-random observation U from the uniform $(0, 1)$ population, the required Weibull observation X can be generated from (21.131) for the specified values of the parameters, ξ_0, α , and c . This simple simulational process is easily programmable in languages such as Fortran. However, within the context of GPSS, (21.131) cannot be directly implemented because GPSS does not contain any built-in functions, and in particular contains no logarithmic function and no exponentiation operator. Tadikamalla and Schriber (1977) have proposed a simulational algorithm in

GPSS that involves the following process:

1. A piecewise linear approximation to the inverse of the cdf (21.131) is formed.
2. This piecewise linear approximation is expressed in **GPSS** by defining a C-type (“**continuous**”) function consisting of ordered pairs of points corresponding to the piecewise linear approximation.
3. When a random observation is needed, the function is invoked; in response, the **GPSS** processor evaluates the function’s argument (which is a value returned by a 0–1 random number generator), then does a table lookup in the function defining set of ordered pairs, performs a linear interpolation across the interval that brackets the argument, and returns the interpolant value as the value of the function.

To improve the piecewise linear approximation involved, they suggested writing (21.131) equivalently as

$$X = \xi_0 + \alpha \exp \left[\left(\frac{1}{c} \right) \log \{ -\log(1 - U) \} \right] \quad (21.132)$$

and using a **GPSS** C-type function to determine a value for $\log \{ -\log(1 - U) \}$ and another **GPSS** C-type function to determine a value for $\exp(\text{argument})$.

Of course the process described above can be used for any distribution by introducing an appropriate piecewise linear approximation (even when the cdf is not available in an explicit form). In languages wherein the logarithmic function and the exponentiation operator are available, (21.132) can be implemented directly to simulate the required Weibull observation.

Another natural way to simulate a Weibull observation is to make use of any efficient exponential simulational algorithm. By realizing that $[(X - \xi_0)/\alpha]^c$ is distributed as standard exponential, we can simulate the required Weibull observation X by

$$X = \xi_0 + \alpha Z^{1/c}, \quad (21.133)$$

where Z denotes the standard exponential pseudo-random observation already simulated. Note that the transformation in (21.133) is equivalent to the transformation in (21.132), since $-\log(1 - U)$ when $U \sim \text{uniform}(0, 1)$, is distributed as standard exponential Z (see Chapter 19).

Ishioka (1990) has discussed the generation of Weibull random numbers using the ratio of uniform pseudorandom observations. **Ramberg** and **Tadikamalla** (1974) have shown how gamma variates can be generated by using Weibull sampling mechanisms.

11 APPLICATIONS

As mentioned earlier in Sections 1 and 2, the fact that the hazard rate of the Weibull distribution is decreasing, constant, and increasing according as $c < 1$, $c = 1$, and $c > 1$ has made this distribution highly useful as a lifetime model. Naturally numerous articles appeared dealing with this particular type of application and the analysis of data resulting from such life tests.

Despite a warning issued by **Gorski** (1968) on the "Weibull euphoria," many more papers have appeared since 1970 exploring several new and interesting applications of the Weibull distribution. Van der Auwera, de Meyer, and **Malet** (1980), Barros and Estevan (1983), **Dixon** and Swift (1984), Conradsen, Nielsen, and Prahm (1984), and **Tuller** and Brett (1984) have all discussed the Weibull distribution in the analysis of wind speed. **Pavia** and **O'Brien** (1986) used the Weibull distribution to model wind speed over the ocean, while Carlin and Haslett (1982) applied the distribution to model wind power from a dispersed array of wind turbine generators. The Weibull distribution also found applications in analyzing rainfall and flood data. Zhang (1982), Boes (1989), and Nathan and **McMahon** (1990) considered the Weibull distribution in the analysis of flood data, while Wilks (1989) and Selker and Haith (1990) applied the distribution to model the rainfall intensity data.

The Weibull model was utilized in many analyses relating to health sciences. For example, Berry (1975) discussed the design of carcinogenesis experiments using the Weibull distribution. Dyer (1975) applied the distribution to analyze the relationship of systolic blood pressure, serum cholesterol, and smoking to 14-year mortality in the Chicago Peoples Gas Company; coronary and cardiovascular-renal mortality were also compared in two competing risk models in this study. Whittemore and **Altschuler** (1976) used the model in the analysis of lung cancer incidence in cigarette smokers by considering Doll and Hill's data for British physicians. Aitkin, Laird, and Francis (1983) applied the Weibull model in analyzing the Stanford heart transplant data. Christensen and Chen (1985) proposed a general **noninteractive** multiple toxicity model including the Weibull. While carrying out a Bayesian analysis of survival curves for cancer patients following treatment, Chen et al. (1985) utilized the Weibull distribution. Portier and Dinse (1987) made use of the Weibull distribution in their semiparametric analysis of tumor incidence rates in **survival/sacrifice** experiments. Rao, Talwalker, and Kundu (1991) applied the model to study the relative relapse rate of placebo versus 6-Mercaptopurine group of acute leukemia patients. Some further uses of the Weibull distribution in analysis relating to health issues may be found in **Goldman** (1984), Achcar, Brookmeyer, and Hunter (1985), Struthers and Farewell (1989), and Koehler and **McGovern** (1990). Ellingwood and Rosowsky (1991), while studying the duration of load effects in Load and Resistance Factor Design (**LRFD**) for wood construction, used the Weibull

distribution function for short-term modulus of rupture, obtained by loading the beam to failure over a period of approximately 5 to 10 minutes.

In addition to the above-mentioned applications, the Weibull distribution also found important uses in a variety of other problems. For example, Fong, Rehm, and Graminski (1977) applied the distribution as a microscopic degradation model of paper. The uses of the distribution in analyzing hydrometeorological, metrological, and pharmacokinetic data have been illustrated by Wong (1977), Vodá (1978), and Schwenke (1987), respectively. A Weibull shelf life model for pharmaceutical problems was proposed by Ogden (1978). Rink et al. (1979) used the three-parameter Weibull distribution to quantify sweetgum germination data in genetic research. The application of the Weibull distribution to the analysis of the reaction time data has been introduced by Ida (1980). A role for the Weibull distribution in offshore oil/gas lease bidding problems has been demonstrated by Dyer (1981). While Berry (1981) used the distribution as a human performance descriptor, Newby and Winterton (1983) applied it to model the duration of industrial stoppages. Applications of the Weibull distribution in lumber industry have been discussed by Johnson and Haskell (1983). Rawlings and Cure (1985) introduced the Weibull function as a dose-response model to describe ozone effects on crop yields. Kanaroglou, Liaw, and Papageorgiou (1986) used the distribution in the analysis of migratory systems. The application of the Weibull model in the analysis of thunderstorm data has been displayed by Schuette, Salka, and Israelsson (1987). Homan, Pardo, and Trudeau (1987) discussed an application of Weibull modeling and discriminant analysis of alcoholism relapse among veterans. In order to evaluate the effect of temperature on cumulative germination of alfalfa, Bahler, Hill, and Byers (1989) considered both Weibull and logistic functions and compared the performance of the two. Lalla (1990) used the distribution to model the spell duration data. Gates (1985) and Braennaes (1986) have illustrated some further applications of the Weibull distribution. Quite interestingly Papastavridis (1987, 1988) and Chryssaphinou and Papastavridis (1990) established Weibull distribution as the limiting distribution for the reliability of consecutive k-out-of-n, consecutive k-within-m-out-of-n, and consecutive k-out-of-n: F systems, respectively.

It is of interest to mention here the works of Revfeim (1983, 1984) and Leese (1973). By assuming that the number of occurrences of an event in a fixed period of time has a Poisson distribution, with probability of r events in a fixed time T given by

$$p_r = \frac{(\rho T)^r e^{-\rho T}}{r!}$$

where p is the mean rate of occurrence of the event per unit of time in which T is measured, and then using a two-parameter Weibull distribution, Revfeim

(1984) obtained the maximum value distribution (in a stochastic form) as

$$G(x) \approx \exp\left\{-\rho T \exp\left(\frac{-x^c}{\alpha}\right)\right\}.$$

He used this stochastic model to analyze extreme annual rainfall data.

Some other applications of the Weibull distribution have been described earlier in Section 1.

12 RELATED DISTRIBUTIONS

As pointed out earlier, the Weibull distribution in (21.4), when $c = 1$, becomes the two-parameter exponential distribution

$$F_X(x) = 1 - e^{-(x-\xi_0)/\alpha}, \quad x > \xi_0,$$

which has been discussed in Chapter 19. For the case where $c = 2$, the Weibull distribution in (21.4) becomes the two-parameter Rayleigh distribution

$$F_X(x) = 1 - e^{-[(x-\xi_0)/\alpha]^2}, \quad x > \xi_0,$$

which has already been discussed in Chapter 18.

If X has a Weibull distribution in (21.4), then the probability density function of $Y = -c \log[(X - \xi_0)/\alpha]$ is given by

$$p_Y(y) = e^{-e^{-y}} e^{-y}, \quad -\infty < y < \infty,$$

which is one of the extreme value distributions that will be discussed in detail in Chapter 22. As mentioned on several occasions in this chapter, this transformation forms a basis for some methods of estimation of the parameters c and α (when ξ_0 is known).

When $\xi_0 = 0$, the probability density function of the random variable X can be conveniently written in the form

$$p_X(x) = c\theta x^{c-1} e^{-\theta x^c}, \quad x > 0, c > 0, \quad (21.134)$$

where $\theta = \alpha^{-c}$. If c is fixed but α varies so that the parameter θ has a gamma probability density function

$$p_\theta(t) = \frac{\delta^p}{\Gamma(p)} t^{p-1} e^{-\delta t}, \quad \theta > 0; p, \delta > 0,$$

then the probability density function of the random variable X can be written as

$$\begin{aligned}
 p_X(x) &= \frac{\delta^p}{\Gamma(p)} cx^{c-1} \int_0^\infty t^p e^{-t(x^c + \delta)} dt \\
 &= \frac{p\delta^p cx^{c-1}}{(x^c + \delta)^{p+1}}, \quad x > 0.
 \end{aligned}
 \tag{21.135}$$

Note that the transformation X^c (of this *compound* Weibull random variable) has a Pareto distribution (see Chapter 20). This was observed by Dubey (1968). It is also of interest to note that the density in (21.135) is Burr's Type **III** distribution with a scale parameter S (see Chapter 12, Section 4). Proceeding on similar lines, Harris and Singpurwalla (1968) derived compound Weibull distributions by assigning for the parameter $\theta = \alpha'$ (1) uniform, (2) two-point, and (3) two-parameter gamma distributions. Harris and Singpurwalla (1969) discussed the estimation of parameters in such Weibull distributions with random scale parameters.

Rodriguez (1977) made an interesting connection between Burr's Type **XII** distribution (see Chapter 12) and the Weibull family. Specifically, he observed that the Weibull curve is the lower bound for Burr's Type **XII** distribution in the Pearson $(\sqrt{\beta_1}, \beta_2)$ plane, and he explained it as follows: For a Burr **Type XII** random variable X , we have

$$\begin{aligned}
 \Pr\left[X \leq \left(\frac{1}{k}\right)^{1/c} x\right] &= 1 - \left(1 + \frac{x^c}{k}\right)^{-k} \\
 &= 1 - \exp\left\{-k \log\left(1 + \frac{x^c}{k}\right)\right\} \\
 &= 1 - \exp\left[-k\left\{\frac{x^c}{k} - \frac{1}{2}\left(\frac{x^c}{k}\right)^2 + \dots\right\}\right] \\
 &\rightarrow 1 - e^{-x^c} \quad \text{as } k \rightarrow \infty.
 \end{aligned}$$

He also noted that Burr's Type **XII** distribution can be obtained as a smooth mixture of Weibull distributions.

On reflecting the Weibull distribution with density (21.3) about the vertical axis $x = \xi_0$, the density function and the distribution function of the reflected distribution become [Cohen (1973)]

$$\begin{aligned}
 p_{X_R}(x) &= \frac{c}{\alpha} \left(\frac{\xi_0 - x}{\alpha}\right)^{c-1} e^{-[(\xi_0 - x)/\alpha]^c}, \quad x < \xi_0, \alpha > 0, c > 0, \\
 F_{X_R}(x) &= e^{-[(\xi_0 - x)/\alpha]^c}, \quad x < \xi_0, \alpha > 0, c > 0,
 \end{aligned}$$

respectively. When any skewed distribution is reflected about a vertical axis, the sign of the skewness is reversed. Accordingly, the "reflected Weibull distribution" will be positively skewed for $c > c_0$ and negatively skewed for $c < c_0$ (see Section 2). With the Weibull distribution in (21.3) being the third asymptotic distribution of smallest values as discussed by **Gumbel (1958)**, the reflected Weibull distribution given above is actually the third asymptotic distribution of largest values or the Fisher-Tippett Type III distribution of largest values.

By reflecting the Weibull density function in (21.3) onto the left of ξ_0 (a mirror image of the function on the right), Balakrishnan and Kocherlakota (1985) defined the *double Weibull distribution* with probability density function

$$p_X(x) = \frac{c}{2\alpha} \left| \frac{x - \xi_0}{\alpha} \right|^{c-1} e^{-|(x-\xi_0)/\alpha|^c}, \quad -\infty < x < \infty. \quad (21.136)$$

The density function in (21.136) is symmetric about ξ_0 . [For the case $c = 1$ it becomes the **Laplace** or double exponential density, which will be studied in Chapter 24.] For this distribution Balakrishnan and Kocherlakota (1985) discussed the properties of order statistics and derived, in particular, explicit expressions for means, variances, and covariances of order statistics. Using these quantities, they derived the **BLUEs** of the parameters ξ_0 and α , assuming the shape parameter c to be known, based on complete samples and presented the necessary tables for sample sizes up to 10. These results were extended by Dattatreya Rao and Narasimham (1989) to the case of Type II censored sample. Vasudeva Rao, Dattatreya Rao, and Narasimham (1991) have also derived optimal linear estimators for ξ_0 based on absolute values of order statistics (when ξ_0 is known).

Zacks (1984) introduced a three-parameter *Weibull-exponential* distribution having a distribution function

$$F_X(x; \lambda, c, \tau) = 1 - e^{-\lambda x - [\lambda(x-\tau)^+]^c}, \quad x \geq 0,$$

where $Y^+ = \max(0, Y)$, $\lambda > 0$ (scale parameter), $c \geq 1$ (shape parameter), and $\tau \geq 0$ (change-point parameter). This family possesses a nondecreasing hazard rate function given by

$$h_X(x; \lambda, c, \tau) = \begin{cases} \lambda & \text{if } 0 \leq x < \tau, \\ \lambda + \lambda^c c (x - \tau)^{c-1} & \text{if } x \geq \tau, \end{cases}$$

which is simply a superposition (for $x \geq \tau$) of a Weibull hazard rate on the constant hazard rate of an exponential distribution. It is clear that as the change-point parameter $\tau \rightarrow \infty$, the distribution approaches the exponential distribution with parameter λ . As Zacks (1984) aptly pointed out, this family

is suitable for modeling systems that, after a certain length of time, enter a wear-out phase in which components of the system have an increasing hazard rate. Adaptive Bayesian inference has also been developed by Zacks for the parameter τ .

Mention should be made here of the piecewise Weibull model discussed by Nelson (1982).

Stacy and Mihram's (1965) generalized gamma distribution with the probability density function

$$p_X(x) = \frac{c}{\Gamma(\beta)\alpha^c\beta} (x - \xi_0)^{c\beta-1} e^{-[(x-\xi_0)/\alpha]^c}, \quad x \geq \xi_0 \geq 0,$$

and cumulative distribution function

$$F_X(x) = \frac{1}{\Gamma(\beta)} \Gamma\left(\beta; \left(\frac{x - \xi_0}{\alpha}\right)^c\right),$$

where $\Gamma(\beta; y) = \int_0^y e^{-t} t^{\beta-1} dt$ is the incomplete gamma function, is a generalization of the three-parameter Weibull distribution in (21.3); the three-parameter Weibull pdf in (21.3) is a special case of this distribution when the second shape parameter $\beta = 1$. A discussion of this distribution is presented in Chapter 17 (as it is a generalization of the three-parameter gamma distribution as well). Cohen (1969) discussed this distribution as the four-parameter generalized Weibull distribution, while Arora (1974) studied in detail various characteristics of this generalized Weibull family.

Suppose that X_i ($i = 1, 2, \dots, k$) are independently distributed as three-parameter Weibull (ξ_0, α_i, c_i) with probability density function (21.3); then a random variable X that is distributed as X_i with probability π_i (such that $\pi_1 + \pi_2 + \dots + \pi_k = 1$) is said to have a finite-mixture Weibull distribution. The density function of X is given by

$$p_X(x) = \sum_{i=1}^k \pi_i \frac{c_i}{\alpha_i} \left(\frac{x - \xi_0}{\alpha_i}\right)^{c_i-1} e^{-[(x-\xi_0)/\alpha_i]^{c_i}},$$

$$x > \xi_0; \alpha_i, c_i > 0, \quad (21.137)$$

and the cumulative distribution function is given by

$$F_X(x) = \sum_{i=1}^k \pi_i \{1 - e^{-[(x-\xi_0)/\alpha_i]^{c_i}}\}, \quad x > \xi_0; \alpha_i, c_i > 0, \quad \sum_{i=1}^k \pi_i = 1.$$

$$(21.138)$$

The case when $k = 2$ is commonly referred to as a two-component mixture Weibull distribution and has received considerable attention over the years from numerous researchers. For example, Kao (1959) suggested the use of this model in life-testing experiment involving electron tubes and proposed a graphical method of estimation of the parameters involved in this model. Rider (1961) discussed the method of moments estimation of the parameters of this mixed-Weibull model. Kaylan and Harris (1981) developed efficient numerical algorithms to derive the maximum likelihood estimates of the parameters involved in the finite-mixture Weibull model. Cheng and Fu (1982) have discussed further on estimation of mixed Weibull parameters. Bayesian inference has been developed for a variety of problems involving the two-component mixture Weibull distribution by many researchers including **Ashour** and **Rashwan** (1981), **Ashour**, Shoukry, and Mohamed (1983), **Ashour** (1987a), **Sinha** (1987), and **Sinha** and Sloan (1989). Of these, the first and the last articles dealt with the prediction problem, while **Sinha** (1987) dealt with the Bayesian estimation of the parameters and the associated reliability function of the model; see also **Sinha** (1982). Dykacz and Hennessey (1989) have explained how a two-component Weibull model can arise due to some natural features of a process. The usage of mixtures of Weibull distributions in order to estimate mixing proportions has been elaborated by **Woodward** and **Gunst** (1987). The special case of mixed Weibull-exponential model (a two-component mixture Weibull distribution in which one of the components has an exponential distribution, i.e., $c_1 = 1$) has also been studied in detail by **Ashour** (1985, 1987b). This author has discussed estimation of parameters from censored samples secured from this model and also the Bayesian estimation of the parameters involved. Mixtures of exponential distributions also could be considered as a special case of mixture Weibull distribution in (21.137) [**Jewell** (1982)], but more details on this specific case may be seen in Chapter 19. An interesting discussion of general mixture models and their role in survival analysis has been made by **Farewell** (1986).

In a similar effort **Al-Hussaini** and **Abd-El-Hakim** (1989) proposed the Inverse Gaussian-Weibull mixture distribution with density function

$$p_X(x; \theta) = \pi p_1(x) + (1 - \pi) p_2(x), \quad 0 \leq \pi \leq 1, \quad (21.139)$$

where $p_1(x)$ is the **IG**(μ, A) density (see Chapter 15) given by

$$p_1(x) = \left(\frac{\lambda}{2\pi x^3} \right)^{1/2} \exp\left(-\frac{\lambda(x - \mu)^2}{\mu^2 x} \right), \quad x > 0; \mu, \lambda > 0,$$

and $p_2(x)$ is the two-parameter Weibull density given by

$$p_2(x) = \frac{c}{\alpha} \left(\frac{x}{\alpha} \right)^{c-1} e^{-(x/\alpha)^c}, \quad x > 0; \alpha, c > 0.$$

The parameter θ in (21.139) is the vector of all five parameters involved in the mixture model. The density in (21.139) can be either unimodal or bimodal. Since the hazard rate of the IG distribution is either upside-down bathtub or increasing and the hazard rate of the Weibull distribution is decreasing, constant, or increasing, the mixture model yields six different combinations of hazard rates; see Al-Hussaini and Abd-El-Hakim (1989). Thus the mixture model in (21.139) provides a very flexible model for reliability studies. Estimation of parameters for this model has been considered by Al-Hussaini and Abd-El-Hakim (1990).

The Weibull distribution in (21.3) can be restricted to lie in the interval (L, U) ; that is, the distribution is truncated below L and above U . In this case the distribution is referred to as the doubly truncated Weibull distribution, and its density function is given by

$$p_X(x) = \frac{1}{\alpha} \left(\frac{x - \xi_0}{\alpha} \right)^{c-1} e^{-[(x - \xi_0)/\alpha]^c},$$

$$\xi_0 \leq L < x < U; c, \alpha > 0. \quad (21.140)$$

The special case of $L = \xi_0$ is referred as the right-truncated Weibull distribution, and its pdf is

$$p_X(x) = \frac{c}{\alpha \{1 - e^{-[(U - \xi_0)/\alpha]^c}\}} \left(\frac{x - \xi_0}{\alpha} \right)^{c-1} e^{-[(x - \xi_0)/\alpha]^c},$$

$$\xi_0 < x < U; c, \alpha > 0. \quad (21.141)$$

Similarly the special case of $U \rightarrow \infty$ is referred as the left-truncated Weibull distribution, and its pdf is

$$p_X(x) = \frac{c}{\alpha} \left(\frac{x - \xi_0}{\alpha} \right)^{c-1} e^{-[(x - \xi_0)/\alpha]^c + [(L - \xi_0)/\alpha]^c},$$

$$\xi_0 < L < x < \infty; c, \alpha > 0. \quad (21.142)$$

These truncated Weibull distributions have also been suggested for use in life-test analysis. Sugiura and Gomi (1985) presented the **Pearson** diagram of $(\sqrt{\beta_1}, \beta_2)$ for truncated Weibull distributions, while **McEwen** and **Parresol** (1991) presented expressions for the moments and summary statistics. **Wingo** (1988) described methods for fitting the right-truncated Weibull distribution in (21.141) to life-test and survival data; see also Martinez and Quintana (1991). **Wingo** (1989) discussed the role and properties of the left-truncated Weibull distribution in (21.142). A mention should be made of Mittal and Dahiya (1989) who have discussed the problem of estimation of parameters of a truncated Weibull distribution.

Nakagawa and Osaki (1975) defined a discrete Weibull distribution as a distribution $\{P_k\}_{k=0}^{\infty}$ such that

$$\sum_{j=k}^{\infty} P_j(q, c) = q^{kc}, \quad k = 0, 1, 2, \dots, \quad c > 0, 0 < q < 1. \quad (21.143)$$

In this case the probability mass function and the hazard rate are given by

$$P_k(q, c) = q^{kc} - q^{(k+1)c} \quad (21.144)$$

and

$$h_k(q, c) = \frac{P_k(q, c)}{\sum_{j=k}^{\infty} P_j(q, c)} = 1 - q^{(k+1)c - kc}, \quad k = 0, 1, \dots \quad (21.145)$$

It is clear from (21.145) that this distribution has decreasing hazard rate if $0 < c < 1$, constant hazard rate if $c = 1$ (in fact it becomes the geometric distribution in this case), and increasing hazard rate if $c > 1$. Thus this distribution mimics the property of the continuous Weibull distribution and hence becomes a natural analogue of it. It is also easy to verify that if X has the discrete Weibull distribution in (21.143), then X^c has a geometric distribution (a property similar to the continuous Weibull distribution). Nakagawa and Osaki (1975) appropriately pointed out that this discrete Weibull distribution will be useful in modeling failures of some devices that often depend more on the total number of cycles than on the total time that they have been used (switching devices, rail tracks, tires, etc.). Stein and Dattero (1984) introduced another discrete Weibull distribution as the distribution whose hazard rate is given by

$$h_k(q, c) = \begin{cases} qk^{c-1}, & k = 1, 2, \dots, m, \\ 0, & k = 0 \text{ or } k > m, \end{cases} \quad (21.146)$$

where m is given by

$$m = \begin{cases} [q^{-1/(c-1)}] & \text{if } c > 1, \\ +\infty & \text{if } c \leq 1. \end{cases}$$

This discrete Weibull distribution has the following appealing properties: (1) the hazard rate behaves similarly to that of the continuous Weibull distribution, (2) it provides the exact lifetime distribution of a specific system, and (3) the lifetime converges in limit to that given by the continuous Weibull distribution. Ali Khan, Khalique, and Abouammoh (1989) have recently proposed a simple method of estimation of the parameters of these two discrete Weibull distributions and compared its efficiency with the method of moments estimates.

When X has a Weibull distribution with density function as in (21.3), the distribution of $1/X$ is referred as the inverse Weibull distribution. Its density function or distribution function can be written down easily from (21.3) and (21.4). Erto (1989) has discussed the properties of this distribution and its potential use as a lifetime model. The maximum likelihood estimation and the least-squares estimation of the parameters of the inverse Weibull distribution are discussed by Calabria and Pulcini (1990).

Starting with the Weibull density with unit median given by

$$p_W(x) = c(\log 2)x^{c-1}e^{-\log 2 \cdot x^c}, \tag{21.147}$$

Ekstrom (1973) used the usual Rice procedure [e.g., see Whalen (1971, pp. 103–105)] to derive the density function of the Weibull-Rician distribution as

$$p_{WR}(y) = \int_{\theta}^{2\pi} \left(cy \frac{\log 2}{2\pi} \right) \left\{ \frac{\exp[(-\log 2)(y^2 - 2Ay \cos \phi + A^2)^{c/2}]}{[y^2 - 2Ay \cos \phi + A^2]^{(2-c)/2}} \right\} d\phi. \tag{21.148}$$

Here y is the envelope, A is the peak signal-to-median clutter ratio, and c is the parameter of the unit median Weibull density in (21.147). The integration on the RHS of (21.148) is not difficult to do numerically. Nilsson and Glisson (1980) derive this density function and the corresponding cumulative distribution function using conditional probability arguments, and in this method the cumulative distribution function is also expressed as a single integral.

A Weibull process is a useful model for phenomena that are changing over time. As noted by **Ascher (1979)**, it is important to distinguish between a Weibull process, which models a repairable system, and the Weibull distribution (discussed so far), which models a nonrepairable system. Crow (1974) proposed a stochastic model in which the number of system failures is assumed to occur according to a nonhomogeneous Poisson process, $\{N(t): t \geq 0\}$, with mean value function of the form $m(t) = E[N(t)] = At^c$ and intensity function of the form $v(t) = dm(t)/dt = \lambda ct^{c-1}$. This is consistent with the empirical finding of Duane (1964) that the number of system failures and operating time are approximately linearly related (in the logarithmic scale), since $\log m(t) = \log \lambda + c \log t$ is a linear function of $\log t$. Another commonly used parametrization is $m(t) = (t/\theta)^c$, with $c < 1$ corresponding to improvement of the system and $c > 1$ corresponding to its deterioration. The Weibull process inherits its name due to the fact that in the sequence of successive failure times T_1, T_2, \dots , the time to first failure T_1 has the Weibull distribution with hazard rate function $v(t) = c(t/\theta)^{c-1}/\theta$. Furthermore the conditional failure time T_n , given $T_1 = t_1, \dots, T_{n-1} = t_{n-1}$, also has a Weibull distribution truncated below at t_{n-1} . More details on various results regarding Weibull processes can be obtained from a review article by

Engelhardt (1988). Moeller (1976) has presented a similar discussion on the Rasch-Weibull process.

Based on the Griffith theory of brittle fracture and the statistical theory of extreme values, Black et al. (1989) proposed the brittle fracture distribution, which is a three-parameter distribution that includes the Weibull and the exponential distributions as special cases. The cumulative distribution function of this distribution is

$$F_X(x; \alpha, \beta, r) = 1 - e^{-\alpha x^{2r} e^{-\beta/x^2}}, \quad x > 0, \alpha > 0, \beta \geq 0, r > 0. \quad (21.149)$$

Here, X represents the breaking stress or strength. The corresponding probability density function is

$$p_X(x; \alpha, \beta, r) = 2\alpha x^{2r-1} \left(\frac{\beta}{x^2} + r \right) e^{-(\beta/x^2) - \alpha x^{2r} e^{-\beta/x^2}}, \quad x > 0. \quad (21.150)$$

Black, Durham, and Padgett (1990) observed that the value of β affects the scale and that α and r both increase the variance as they increase.

For the case when $\beta = 0$ and $\delta = 2r$, (21.149) reduces to the Weibull distribution with shape parameter δ and scale parameter α . If $\beta = 0$ and $r = 1/2$, then (21.149) becomes an exponential distribution with mean $1/\alpha$. Since a closed-form expression does not exist for the moment generating function or the characteristic function of the brittle fracture distribution in (21.149), Gulati, Durham, and Padgett (1993) derived bounds for the k th moment ($k \geq 1$). While the lower bound turns out to be sharp, the upper bound does not. Black, Durham, and Padgett (1990) discussed estimation of the three parameters by a simple least-squares procedure and also by the maximum likelihood method. These authors have noted that the least-squares estimates could be used as good initial values for an iterative procedure for obtaining the maximum likelihood estimates; they also examined the behavior of these estimators by means of simulations.

Kopaev (1990, 1993) has considered a *modified* Weibull distribution with cumulative distribution function

$$F(x) = 1 - e^{-[(x/c)\exp(\pm(x/c))^p/A]^B}, \quad (21.151)$$

where $+(x/c)$ is taken for $p > 0$ and $-(x/c)$ for $p < 0$. Kopaev has discussed many properties of this distribution and also some methods of estimation of the parameters in (21.151).

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Abbreviations

ABLUE	asymptotically best linear unbiased estimator
ARE	asymptotic relative efficiency
BAEE	best affine equivariant estimator
BAN	best asymptotically normal
BLIE	best linear invariant estimator
BLUE	best linear unbiased estimator
cdf	cumulative distribution function
GGC	generalized gamma convolution
GIG	generalized inverse Gaussian distribution
GPD	generalized Pareto distribution
IG	inverse Gaussian distribution
LBIG	length biased inverse Gaussian distribution
MLE	maximum likelihood estimator
MME	(method of) moments estimator
MMME	modified (method of) moments estimator
MPE	maximum probability estimator
MPS	maximum product-of-spacings
MSE	mean square error
MWE	minimum variance unbiased estimator
$N(\mu, \sigma^2)$	normal distribution with mean μ and variance σ^2
$P(X)(\cdot)$	<i>Pareto distribution of X-th kind (X = I, II, or III)</i>
pdf	probability density function
$\Pr\{E\}$	probability of event E
PWM	probability-weighted moment
UMVUE	uniform(ly) minimum variance unbiased estimator

Author Index

The purpose of this Index is to provide readers with quick and easy access to the contributions (pertinent to this volume) of any individual author, and not to highlight any particular author's contribution.

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