Taxonomy (biology)

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For other uses, see Taxonomy (disambiguation).

Taxonomy (from Ancient Greek: τάξις *taxis*, "arrangement," and -νομία *-nomia*, "method"[1]) is the science of defining groups of biological organisms on the basis of shared characteristics and giving names to those groups. Organisms are grouped together into taxa (singular: taxon) and given a taxonomic rank; groups of a given rank can be aggregated to form a super group of higher rank and thus create a taxonomic hierarchy.[2][3] The Swedish botanist Carolus Linnaeus is regarded as the father of taxonomy, as he developed a system known as Linnaean classification for categorization of organisms and binomial nomenclature for naming organisms.

With the advent of such fields of study as phylogenetics, cladistics, and systematics, the Linnaean system has progressed to a system of modern biological classification based on the evolutionary relationships between organisms, both living and extinct. An example of a modern classification is the one published in 2009 by the Angiosperm Phylogeny Group for all living flowering plant families (the APG III system).[4]

Definition

The exact definition of taxonomy varies from source to source, but the core of the discipline remains: the conception, naming, and classification of groups of organisms. Two other terms are related to taxonomy, namely "systematics" and "classification"; their exact relationship to taxonomy also varies from source to source because the usage of the three terms in biology originated independently.[5] As points of reference, recent definitions of taxonomy are presented below:

1. Theory and practice of grouping individuals into species, arranging species into larger groups, and giving those groups names, thus producing a classification[2]
2. A field of science (and major component of systematics) that encompasses description, identification, nomenclature, and classification[3]
3. The science of classification, in biology the arrangement of organisms into a classification[6]
4. "The science of classification as applied to living organisms, including study of means of formation of species, etc."[7]
5. "The analysis of an organism's characteristics for the purpose of classification"[8]
6. "[Systematics] studies phylogeny to provide a pattern that can be translated into the classification and names of the more inclusive field of taxonomy" (listed as a desirable but unusual definition)[9]

The varied definitions either place taxonomy as a sub-area of systematics (definition 2), invert that relationship (definition 6), or appear to consider the two terms synonymous. There is some disagreement as to whether biological nomenclature is considered a part of taxonomy (definitions 1 and 2), or a part of systematics outside taxonomy. For example, definition 6 is paired with the following definition of systematics that places nomenclature outside taxonomy:[8]

- *Systematics*: "The study of the identification, taxonomy and nomenclature of organisms, including the classification of living things with regard to their natural relationships and the study of variation and the evolution of taxa".

The broadest meaning of "taxonomy" is used here. The word *taxonomy* was introduced in 1813 by Candolle, in his *Théorie élémentaire de la botanique*.[10]

Alpha and beta taxonomy

Not to be confused with Alpha diversity.

The term "**alpha taxonomy**" is primarily used today to refer to the discipline of finding, describing, and naming taxa, particularly species. In earlier literature, the term had a different meaning, referring to morphological taxonomy, and the products of research through the end of the nineteenth century.

William Bertram Turrill introduced the term "alpha taxonomy" in a series of papers published in 1935 and 1937 in which he discussed the philosophy and possible future directions of the discipline of taxonomy.[11]

… there is an increasing desire amongst taxonomists to consider their problems from wider view-points, to investigate the possibilities of closer co-operation with their cytological, ecological and genetical colleagues and to acknowledge that some revision or expansion, perhaps of a drastic nature, of their aims and methods may be desirable … Turrill (1935) has suggested that while accepting the older invaluable taxonomy, based on structure, and conveniently designated "alpha", it is possible to glimpse a far-distant taxonomy built up on as wide a basis of morphological and physiological facts as possible, and one in which "place is found for all observational and experimental data relating, even if indirectly, to the constitution, subdivision, origin and behaviour of species and other taxonomic groups". Ideals can, it may be said, never be completely realized. They have, however, a great value of acting as permanent stimulants, and if we have some, even vague, ideal of an "omega" taxonomy we may progress a little way down the Greek alphabet. Some of us please ourselves by thinking we are now groping in a "beta" taxonomy.[11]

Turrill thus explicitly excludes from alpha taxonomy various areas of study that he includes within taxonomy as a whole, such as ecology, physiology, genetics, and cytology. He further excludes phylogenetic reconstruction from alpha taxonomy (pages 365–366).

Later authors have used the term in a different sense, to mean the delimitation of species (not subspecies or taxa of other ranks), using whatever investigative techniques are available, and including sophisticated computational or laboratory techniques.[12] Thus, Ernst Mayr in 1968 defined **beta taxonomy** as the classification of ranks higher than species.[13]

An understanding of the biological meaning of variation and of the evolutionary origin of groups of related speceis is even more important for the second stage of taxonomic activity, the sorting of species into groups of relatives ("taxa") and their arrangement in a hierarchy of higher categories. This activity is what the term classification denotes; it is also referred to as **beta taxonomy**.

Microtaxonomy and macrotaxonomy

How species should be defined in a particular group of organisms causes practical and theoretical problems that are referred to as the species problem. The scientific work of deciding how to define species has been called microtaxonomy.[14] By extension, macrotaxonomy is the study of groups at higher taxonomic ranks than species.

History of taxonomy

While some descriptions of taxonomic history attempt to date it to ancient civilisations, a truly scientific attempt to classify organisms did not occur till the eighteenth century. Earlier works were primarily descriptive, and focussed on plants that were useful from an agricultural or medicinal perspective. There are a number of stages in this scientific thinking. Up to 1830 taxonomy was based on arbitrary criteria, the so called "artificial systems", including Linnaeus's system of sexual classification. Later came systems based on a more complete consideration of the characteristics of taxa, referred to as "natural systems", such as those of de Jussieu (1789), de Candolle (1813) and that of Bentham and Hooker (1862–1863). These were pre-evolutionary in thinking. The publication of Charles Darwin's Origin of Species (1859) led to new ways of thinking about classification based on evolutionary relationships. This was the concept of "phyletic systems, from 1883 onwards. This approach was typified by those of Eichler (1883) and Engler (1886–1892). The advent of molecular genetics and statistical methodology allowed the creation of the modern era of "phylogenetic systems" based on cladistics, rather than morphology alone.[15][16][17]

Pre-Linnaean taxonomy

Early taxonomists

Taxonomy has been called "the world's oldest profession",[18] and naming and classifying our surroundings has likely been taking place as long as mankind has been able to communicate. It would always have been important to know the names of poisonous and edible plants and animals in order to communicate this information to other members of the family or group.

Medicinal plant illustrations show up in Egyptian wall paintings from c. 1500 BC.[19] The paintings clearly show that these societies valued and communicated the uses of different species, and therefore had a basic taxonomy in place.

Aristotle to Pliny the Elder

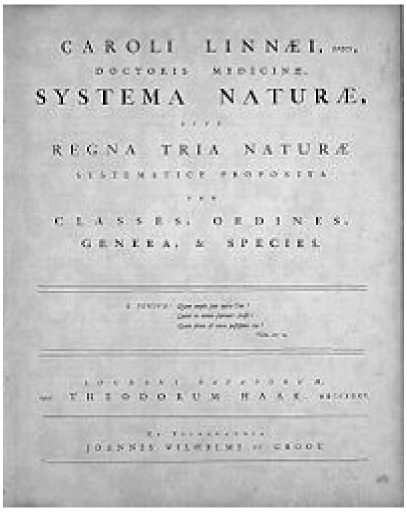
Historical records show that informally classifying organisms took place at least back to the days of Aristotle (Greece, 384–322 BC),[20] who was the first to begin to classify all living things. Some of the terms he gave to animals, such as "invertebrates" and "vertebrates" are still commonly used today. His student Theophrastus (Greece, 370–285 BC) carried on this tradition, and wrote a classification of some 500 plants called *Historia Plantarum*. Again, several plant groups currently still recognized can be traced back to Theophrastus, such as *Cornus*, *Crocus*, and *Narcissus*. The next major turn-of-the-millennia era taxonomist came in the form of Pliny the Elder (Rome, 23–79 AD). His elaborate 160-volume work *Naturalis Historia* described many plants.

Other pre-Linnaean taxonomists

It was not until c. 1500 years later that taxonomic works became ambitious enough to replace the ancient texts. This is often credited to the development of sophisticated optic lenses, which allowed for the morphology of organisms to be studied in much greater detail. One of the earliest authors to take advantage of this leap in technology was Andrea Cesalpino (Italy, 1519–1603), who is often referred to as "the first taxonomist". His magnum opus De Plantis came out in 1583, and described over 1500 plant species. Two large plant families that he first recognized are still in use today: the Asteraceae and Brassicaceae. Then in the seventeenth century John Ray (England, 1627–1705) wrote many important taxonomic works. Arguably his greatest accomplishment was Methodus Plantarum Nova (1682), where he published over 18,000 plant species. At the time his classifications were perhaps the most complex yet produced by any taxonomist, as he based his taxa on many combined characters. The next major taxonomic works were produced by Joseph Pitton de Tournefort (France, 1656–1708). His work from 1700, Institutiones Rei Herbariae, included over 9000 species in 698 genera, and directly influenced Linnaeus as it was the text he used as a young student.[19]

The Linnaean era

Main article: Linnaean taxonomy

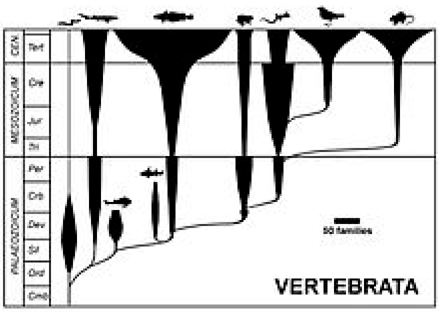

CAROLI LINNÆI,
DOCTORIS MEDICINÆ,
SYSTEMA NATURÆ,
REGNA TRIA NATURÆ
CLASSES, ORDINES,
GENERA, & SPECIES.

Title page of *Systema Naturae*, Leiden, 1735

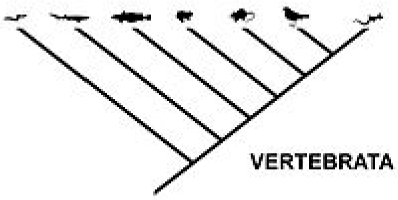
The Swedish botanist Carl Linnaeus (1707–1778) ushered in a new era of taxonomy. With his major works *Systema Naturae* 1st Edition in 1735,[21] *Species Plantarum* in 1753,[22] and *Systema Naturae* 10th Edition,[23] he revolutionized modern taxonomy. His works implemented a standardized binomial naming system for animal and plant species, which proved to be an elegant solution to a chaotic and disorganized taxonomic literature. As a result, the Linnaean system was born, and is still used in essentially the same way today as it was in the eighteenth century. Currently, plant and animal taxonomists regard Linnaeus' work as the "starting point" for valid names (at 1753 and 1758 respectively).[24] Names published before these dates are referred to as "pre-Linnaean", and not considered valid (with the exception of spiders published in *Svenska Spindlar*). Even taxonomic names published by Linnaeus himself before these dates are considered pre-Linnaean.[19]

Modern system of classification

Main articles: Evolutionary taxonomy and Phylogenetic nomenclature



Evolution of the vertebrates at class level, width of spindles indicating number of families. Spindle diagrams are typical for Evolutionary taxonomy



The same relationship, expressed as a cladogram typical for cladistics

Whereas Linnaeus classified for ease of identification, the idea of the Linnaean taxonomy as translating into a sort of dendrogram of the Animal- and Plant Kingdoms was formulated toward the end of the 18th century, well before *On the Origin of Species* was published. Among early works exploring the idea of a transmutation of species was Erasmus Darwin's 1796 *Zoönomia* and Jean-Baptiste Lamarck's *Philosophie Zoologique* of 1809. The idea was popularised in the Anglophone world by the speculative, but widely read *Vestiges of the Natural History of Creation*, published anonymously by Robert Chambers in 1844.[25]

With Darwin's theory, a general acceptance that classification should reflect the Darwinian principle of common descent quickly appeared. Tree of Life representations became popular in scientific works, with known fossil groups incorporated. One of the first modern groups tied to fossil ancestors were birds. Using the then newly discovered fossils of *Archaeopteryx* and *Hesperornis*, Thomas Henry Huxley pronounced that they had evolved from dinosaurs, a group formally named by Richard Owen in 1842.[26] The resulting description, that of dinosaurs "giving rise to" or being "the ancestors of" birds, is the essential hallmark of evolutionary taxonomic thinking. As more and more fossil groups were found and recognized in the late 19th and early 20th century, palaeontologists worked to understand the history of animals through the ages by linking together known groups[27] With the modern evolutionary synthesis of the early 1940s, an essentially modern understanding of evolution of the major groups was in place. The evolutionary taxonomy being based on Linnaean taxonomic ranks, the two terms are largely interchangeable in modern use.

Since the 1960s a trend called phylogenetic nomenclature (or cladism) has emerged, inspired by the cladistic method. The salient feature is arranging taxa in a hierarchical evolutionary tree, ignoring ranks. If a taxon includes all the descendants of some ancestral form, it is called monophyletic. Groups that have descendant groups removed from them (e.g., dinosaurs, with birds as offspring group) are termed paraphyletic, while groups representing more than one branch from the tree of life are called polyphyletic. A formal code of nomenclature, the *International Code of Phylogenetic Nomenclature*, or *PhyloCode* for short, is currently under development, intended to deal with names of clades. Linnaean ranks will be optional under the *PhyloCode*, which is intended to coexist with the current, rank-based codes.

Kingdoms and domains

Main article: Kingdom (biology)

Well before Linnaeus, plants and animals were considered separate Kingdoms. Linnaeus used this as the top rank, dividing the physical world into the plant, animal and mineral kingdoms. As advances in microscopy made classification of microorganisms possible, the number of kingdoms increased, five and six-kingdom systems being the most common.

Domains are a relatively new grouping. The three-domain system was first proposed in 1990, but not generally accepted until later. One main characteristic of the three-domain method is the separation of Archaea and Bacteria, previously grouped into the single kingdom Bacteria (a kingdom also sometimes called Monera). Consequently, the three domains of life are conceptualized as Archaea, Bacteria, and Eukaryota (comprising the nuclei-bearing eukaryotes).[28] A small minority of scientists add Archaea as a sixth kingdom, but do not accept the domain method.

Thomas Cavalier-Smith, who has published extensively on the classification of protists, has recently proposed that the Neomura, the clade that groups together the Archaea and Eukarya, would have evolved from Bacteria, more precisely from Actinobacteria. His classification of 2004 treats the archaebacteria as part of a subkingdom of the Kingdom Bacteria, i.e., he rejects the three-domain system entirely.[29] Stefan Luketa in 2012 proposed a five "dominion" system, adding Prionobiota (acellular and without nucleic acid) and Virusobiota (acellular but with nucleic acid) to the traditional three domains.[30]

<table>
<tr><th>Linnaeus
1735[31]</th><th>Haeckel
1866[32]</th><th>Chatton
1925[33]</th><th>Copeland
1938[34]</th><th>Whittaker
1969[35]</th><th>Woese et al.
1990[36]</th><th>Cavalier-Smith
1998[29]</th></tr>
<tr><td>2 kingdoms</td><td>3 kingdoms</td><td>2 empires</td><td>4 kingdoms</td><td>5 kingdoms</td><td>3 domains</td><td>6 kingdoms</td></tr>
<tr><td rowspan="4">(not treated)</td><td rowspan="4">Protista</td><td rowspan="2">Prokaryota</td><td rowspan="2">Monera</td><td rowspan="2">Monera</td><td>Bacteria</td><td rowspan="2">Bacteria</td></tr>
<tr><td>Archaea</td></tr>
<tr><td rowspan="5">Eukaryota</td><td rowspan="2">Protoctista</td><td rowspan="2">Protista</td><td rowspan="5">Eucarya</td><td>Protozoa</td></tr>
<tr><td>Chromista</td></tr>
<tr><td rowspan="2">Vegetabilia</td><td rowspan="2">Plantae</td><td rowspan="2">Plantae</td><td>Plantae</td><td>Plantae</td></tr>
<tr><td>Fungi</td><td>Fungi</td></tr>
<tr><td>Animalia</td><td>Animalia</td><td>Animalia</td><td>Animalia</td><td>Animalia</td></tr>
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Main article: Kingdom (biology) § Summary

Application

Biological taxonomy is a sub-discipline of biology, and is generally practiced by biologists known as "taxonomists", though enthusiastic naturalists are also frequently involved in the publication of new taxa. The work carried out by taxonomists is crucial for the understanding of biology in general. Two fields of applied biology in which taxonomic work is of fundamental importance are the study of biodiversity and conservation.[37] Without a working classification of the organisms in any given area, estimating the amount of diversity present is unrealistic, making informed conservation decisions impossible. As conservation becomes ever more politically important, taxonomic work impacts not only the scientific community, but society as a whole.[18]

Classifying organisms

Biological classification is a critical component of the taxonomic process. As a result, it informs the user as to what the relatives of the taxon are hypothesized to be. Biological classification uses taxonomic ranks, including, among others (in order from most inclusive to least inclusive): Domain, Kingdom, Phylum, Class, Order, Family, Genus, and Species.[Note 1]

Taxonomic descriptions

See also: Species description

Type specimen for *Nepenthes smilesii*, a tropical pitcher plant.

The 'definition' of a taxon is encapsulated by its description and/or its diagnosis. There are no set rules governing the definition of taxa, but the naming and publication of new taxa is governed by sets of rules. In zoology, the nomenclature for the more commonly used ranks (superfamily to subspecies), is regulated by the *International Code of Zoological Nomenclature* (*ICZN Code*). In the fields of botany, phycology, and mycology, the naming of taxa is governed by the *International Code of Nomenclature for algae, fungi, and plants* (*ICN*).

The initial description of a taxon involves five main requirements:[38]

1. The taxon must be given a name based on the 26 letters in the Latin alphabet (a binomial for new species, or uninomial for other ranks).
2. The name must be unique (i.e. not a homonym).
3. The description must be based on at least one name-bearing type specimen.
4. It should include statements about appropriate attributes to either describe (define) the taxon, and/or differentiate it from other taxa (the diagnosis, *ICZN Code*, Article 13.1.1, *ICN*, Article 38). Both codes deliberately separate defining the content of a taxon (its circumscription) from defining its name.

5. These first four requirements must be published in a work that is obtainable in numerous identical copies, as a permanent scientific record.

However, often much more information is included, like the geographic range of the taxon, ecological notes, chemistry, behavior, etc. How researchers arrive at their taxa varies; depending on the available data, and resources, methods vary from simple quantitative or qualitative comparisons of striking features, to elaborate computer analyses of large amounts of DNA sequence data.

Authorities (author citation)

Main articles: Author citation (botany) and Author citation (zoology)

An "authority" may be placed after a scientific name. The authority is the name of the scientist who first validly published the name. For example, in 1758 Linnaeus gave the Asian elephant the scientific name *Elephas maximus*, so the name is sometimes written as "*Elephas maximus* Linnaeus, 1758". The names of authors are frequently abbreviated: the abbreviation *L.* is universally accepted for Linnaeus, and in botany there is a regulated list of standard abbreviations (see list of botanists by author abbreviation). The system for assigning authorities differs slightly between botany and zoology. However, it is standard that if a species' name or placement has been changed since the original description, the original authority's name is placed in parentheses.

Phenetics

Main article: Phenetics

In phenetics, also known as taximetrics, organisms are classified based on overall similarity, regardless of their phylogeny or evolutionary relationships. It results in a measure of evolutionary "distance" between taxa. Phenetic methods have become relatively rare in modern times, largely superseded by cladistic analyses, as phenetic methods do not distinguish plesiomorphic from apomorphic traits. However, certain phenetic methods, such as neighbor joining, have found their way into cladistics, as a reasonable approximation of phylogeny when more advanced methods (such as Bayesian inference) are too computationally expensive.

Databases

Modern taxonomy uses database technologies to search and catalog classifications and their documentation. While there is no commonly used database, there are comprehensive databases such as the *Catalogue of Life*, which attempts to list every documented species. The catalogue listed 1.4 million species for all kingdoms as of May 2012, claiming coverage of more than 74% of the estimated 1.9 million species known to modern science.[39]