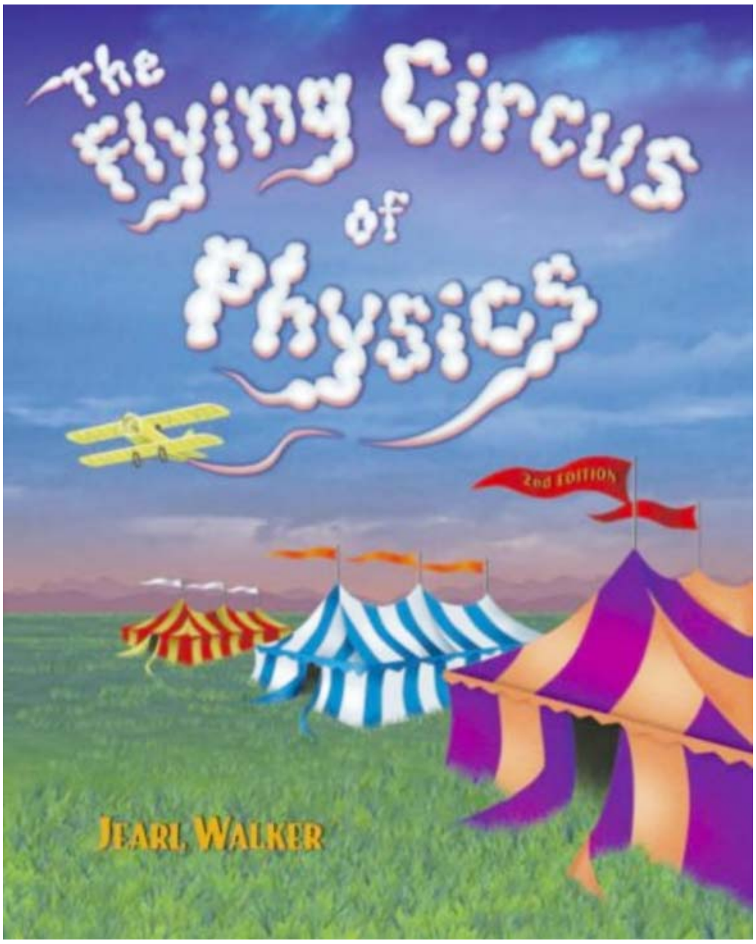
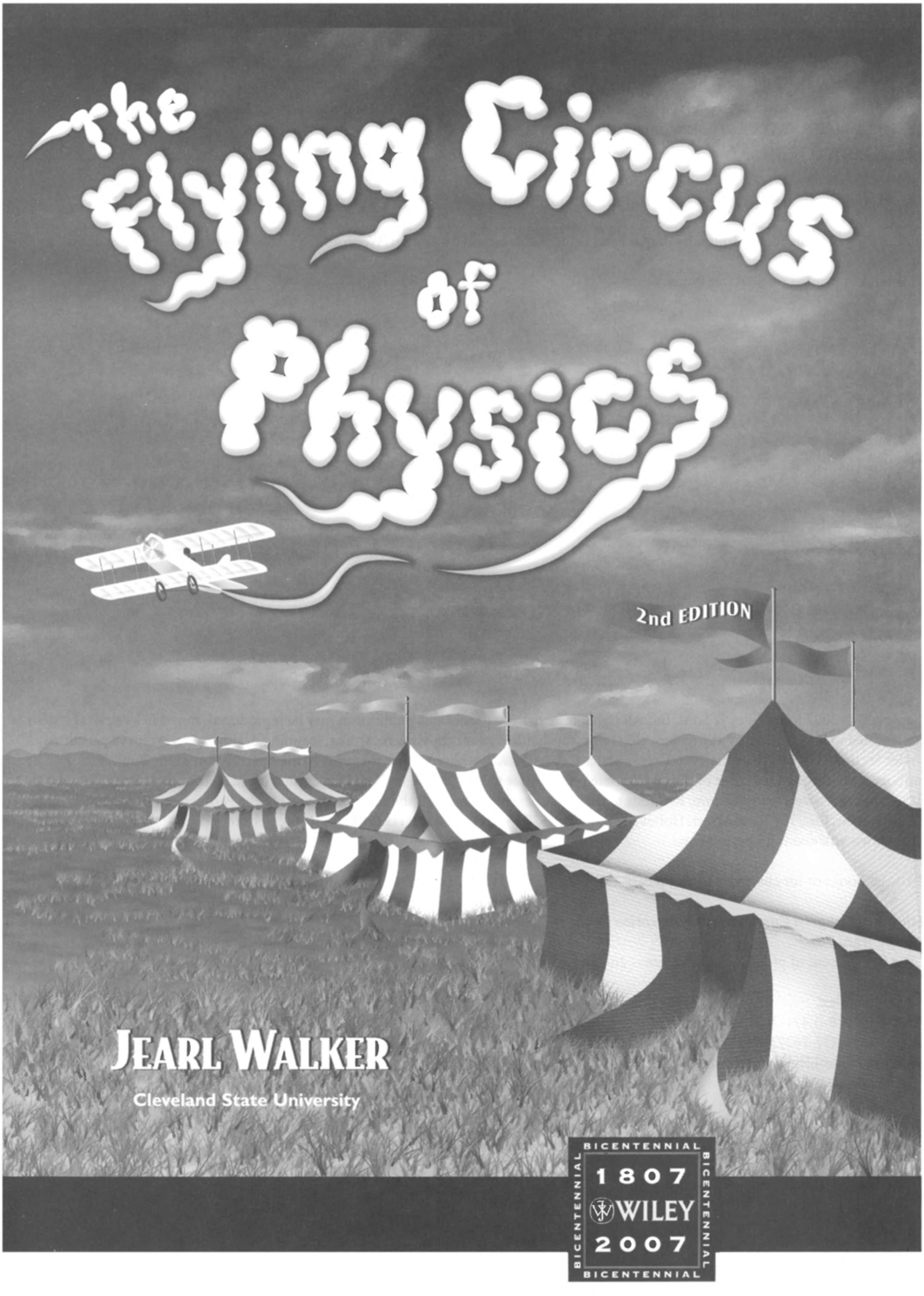

The Flying Circus of Physics
2nd EDITION
JEARL WALKER


The Flying Circus of Physics
2nd EDITION
JEARL WALKER
Cleveland State University
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This book is dedicated to my wife

Mary Golrick

who sat with me for the 13 years I wrote "The Amateur Scientist" for *Scientific American*, the 16 years (and still counting) I spent writing *Fundamentals of Physics*, and the 200 years (seemingly) I spent on developing and writing this edition of *The Flying Circus of Physics.* Without her encouragement, support, love, and tolerance, I would have ended up staring at the wall instead of a word-processing screen.

P • R • E • F • A • C • E

The Flying Circus of Physics began one dark and dreary night in 1968 while I was a graduate student at the University of Maryland. Well, actually, to most graduate students nearly all nights are dark and dreary, but I mean that particular night was really dark and dreary. I was a full-time teaching assistant, and earlier in the day I had given a quiz to Sharon, one of my students. She did badly and at the end turned to me with the challenge, "What has anything of this to do with my life?"

I jumped to respond, "Sharon, this is physics! This has everything to do with your life!"

As she turned more to face me, with eyes and voice both tightened, she said in measured pace, "Give me some examples."

I thought and thought but could not come up with a single one. I had spent at least six years studying physics and I could not come up with even a single example.

That night I realized that the trouble with Sharon was actually the trouble with me: This thing called physics was something people did in a physics building, not something that was connected with the real world of Sharon (or me). So, I decided to collect some real-world examples and, to catch her attention, I called the collection *The Flying Circus of Physics.* Gradually I added to the collection.

Soon other people wanted copies of the *Flying Circus* material, first students in Sharon's class, then my fellow graduate students, and then some of the faculty members. After the material was printed as a "technical report" by the Physics Department at Maryland, I landed a book contract with John Wiley & Sons.

The book was published in 1975, a few years after I became a physics professor at Cleveland State University; it was revised in 1977. Since then it has been translated into 11 languages for publication around the world. This is the second edition of the book, which is completely rewritten and redesigned.

When I began writing *Flying Circus* material, I searched through only a few dozen research journals, page by page, and discovered few relevant papers. Indeed, my metaphor for the project was that I was digging for gold in an almost barren mountainside—the gold nuggets were few and hard to find.

The world has changed: Now, many hundreds of research papers with potential *Flying Circus* material are published every year and, in terms of my metaphor, I find huge gold veins. And now I don't dig through just a few dozen journals; I look through about 400 journals directly and use search engines to sort through hundreds more. On many days my fingers just fly over my computer keyboard. I wish Sharon could look over my shoulder at all the really curious things I find. With this book you get that chance: Come look over my shoulder and you'll see that physics "has everything to do with your life."

Web site for The Flying Circus of Physics

The web site associated with this book can be found at **www.flyingcircusofphysics.com** and contains:

- Over 10 000 citations to journals and books of science, engineering, math, medicine, and law. The citations are grouped according to the items in the book and marked as to difficulty.
- Bonus items.
- Corrections, updates, and additional comments.
- An extended index.

Origin of the Flying Circus name

I named my original collection of problems after the very early airshows in which daredevil pilots performed hair-raising stunts. I thought such an airshow was generically known as a "flying circus" and hoped that the image of daredevil pilots would entice someone to read my words.

I've since learned that a flying circus was originally a circus that moved about on a train and then later the name given to German aircraft that were moved in that way. The term came to be associated with the famous German pilot Red Baron, who in World War I painted his airplane blood-red to scare the pilots he fought in the air.

The comedy troupe known as Monty Python's Flying Circus first appeared in England about a year after I had begun using the *Flying Circus* name. The name must have just been in the air on both sides of the Atlantic Ocean that year. (The "dead parrot routine" is, however, entirely Monty Python's.)

Bibliography

All citations are listed in the *Flying Circus of Physics* web site, grouped according to the items here in the book, and marked as to mathematical difficulty. The site contains over 10 000 citations.

Sending stuff to me

I would very much enjoy receiving corrections, comments, new ideas, and citations. If the latter, I would appreciate if you would send the full citation without abbreviations and with the full page numbers, but if that is not possible, even a scrap will interest me. If you can send me a photocopy of a paper or a web site address, that would be great.

I generally do not list web sites in the citations because I cannot frequently check whether the web sites remain active.

I teach full time, work on this book full time, and work on the textbook *Fundamentals of Physics* twice full time. That is a lot of full times, and yet I am only finite. So, please understand why I cannot answer every letter or note.

Cleveland State University

If you want to attend a solid, middle-size university, come to Cleveland State University (www.csuohio.edu) in Cleveland, Ohio. I have been teaching here for over 30 years and have no intention of stopping (although I hear that Nature will eventually slow me down). I'm the fellow in the small office, surrounded by research papers, with my fingers flying over a keyboard desperately trying to meet yet another publication deadline.

Textbooks

The material in this book assumes that you took elementary physics or physical science in grade school. If you want a good textbook to go with this book, here are some suggestions:

- *How Things Work: The Physics of Everyday Life*, Louis A. Bloomfield (John Wiley & Sons), non-mathematical introduction to physics
- *Physics*, John D. Cutnell and Kenneth W. Johnson (John Wiley & Sons), algebra-based introduction to physics
- *Fundamentals of Physics*, David Halliday, Robert Resnick, and Jearl Walker (John Wiley & Sons), calculus-based introduction to physics

Acknowledgments

I have many people to thank because they encouraged me at times when I thought, "All hope is lost!" Well, ok, that is part of the reason. The rest is that many people tolerated me when I became completely obsessed and thought, "I need to work as if there is no tomorrow!"

Jearl and Martha Walker (my parents, who, when I was a teenager, surely spent many sleepless nights worrying whether I would end up successful or incarcerated), Bob Phillips (my high school math and physics teacher who opened new worlds for me), Phil DiLavore (who got me started in teaching), Joe Reddish (who was instrumental in getting the original notes of *The Flying Circus of Physics* published as a technical report by the University of Maryland Physics Department), Phil Morrison (who was the first to encourage me to publish the technical report as a book and who then wrote a nice review about the book in *Scientific American*, which probably got me the 13-year job of writing the magazine's "Amateur Scientist" section), Dennis Flanagan (the editor at *Scientific American*, who hired me and then guided me for years), Donald Deneck (the physics editor at John Wiley & Sons in the early 1970s, who offered me the first book contract for *The Flying Circus of Physics*), Karl Casper and Bernard Hammermesh (who thought enough of the book work to hire me as an Assistant Professor at Cleveland State University), David Halliday and Robert Resnick (who allowed me to take over their textbook *Fundamentals of Physics* in 1990), Ed Millman (who tutored me on how to write textbooks), Mary Jane Saunders (the Dean of the College of Science at CSU, who set up such a positive atmosphere that this edition of *The Flying Circus of Physics* was possible and who critically reviewed many of the manuscript pages), Stuart Johnson (the physics editor at John Wiley & Sons who guided me through this book and multiple editions of *Fundamentals of Physics*), Carol Seitzer (who read through the manuscripts for this book, making many solid changes), Madelyn Lesure (the designer of this book), Elizabeth Swain (the production editor at John Wiley & Sons who managed the production of this book), Chris Walker, Heather Walker, and Claire Walker (my grown children who tolerated my obsession with writing and teaching their entire lives), Patrick Walker (my growing child—not only did he tolerate the many years I spent working in the basement, but he also taught me how to climb the overhang at the rock-climbing gym), and (most of all) Mary Golrick (my wife, who contributed many ideas to this edition and who kept me going whenever I exclaimed, "All hope is lost!").

Physics for...

- **a first date:** 1.57, 1.75, 1.122, 1.124, 2.51, 2.90, 4.78, 5.17, 5.19, 6.98, 6.122, 7.15, 7.16, 7.50
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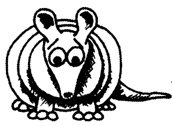
- **an airplane trip:** 1.17, 1.18, 4.53, 4.69, 5.34, 5.35, 6.10, 6.34, 6.35, 6.37, 6.44, 6.63, 6.91, 6.100, 6.105, 6.129
- **a bathroom and toilet:** 1.93, 1.193, 2.21, 2.23, 2.41, 2.60, 2.150, 3.67, 4.65, 4.66, 6.88, 6.99, 6.110
- **a garden:** 1.132, 2.11, 2.80, 2.93, 2.94, 2.99, 3.25, 4.29, 4.57, 4.84, 5.32, 6.84, 6.92, 6.115, 6.118, 6.120, 6.121, 6.126, 7.38

I invite you to create other groupings of problems for certain occasions and locations.



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C • O • N • T • E • N • T • S

Brief Contents

Contents

C • H • A • P • T • E • R 1

Slipping Between Falling Drops

1.1 • Run or walk in the rain?

Should you run or walk when crossing a street in the rain without an umbrella? Running certainly means that you spend less time in the rain, but it also means that you may be intercepting more of the raindrops. Does the answer change if a wind blows the drops either toward or away from you?

If you drive a car through rain, what speed should you choose to minimize the amount of water hitting the front windshield so that you might maintain visibility?

Answer If the rain falls straight down or if the wind blows it toward you, you should run as fast as possible. Although you run into raindrops, the decreased time in the rain leaves you less wet than if you move slower. To decrease the number of drops you run into, you should minimize your vertical cross-sectional area by leaning forward as you run. To move rapidly while also bending over, you might, as one researcher suggested, ride a skateboard through the rain, but that is certain to attract attention and, besides, a skateboard is more trouble to tote than an umbrella.

If the wind is at your back, the best strategy is to run at a speed that matches the horizontal speed of the falling drops. In that way, you still get wet on the top of your head and shoulders, but you do not run into drops along your front surface, nor do they run into you along your back surface. However, this strategy does not work for an object being moved through the rain if the object has a much larger horizontal cross-sectional area than you do. Such an object will collect an appreciable amount of water on its top surface even if its speed matches the horizontal speed of the raindrops. To minimize the wetting, such an object should be moved as quickly as possible.

If you drive through rain, you are concerned with maintaining visibility rather than minimizing wetness. If the drops fall straight down or if they are being blown toward you, you should drive slowly. If the rain is being blown in the direction you are driving, you ideally should match the car's speed to the horizontal speed of the drops, but that may not be practical.

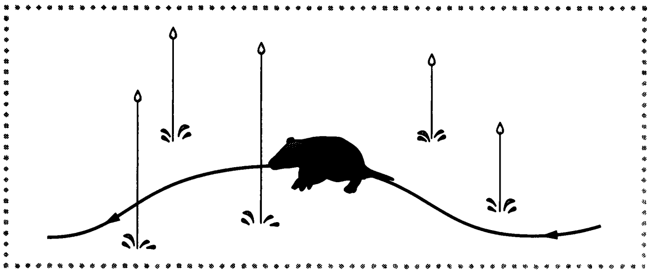


Figure 1-1 / Item 1.1

1.2 • Traffic platoons and gridlock

If heavy traffic is to flow smoothly along a street without stopping, how should the light sequence at the intersections be timed? Should the timing be varied when rush hour begins? Why does the scheme sometimes fail, such as in a snow storm, in which case *gridlock* sets in and the traffic effectively freezes in place?

Answer The cars move in groups called *platoons.* Suppose that a platoon has been stopped at a red light at intersection 1. When the light turns green, the platoon leaders first accelerate and then travel at a certain cruising speed. Before they reach intersection 2, the light there should turn green so that they are not cowed into slowing. If you know the distance between the intersections, the typical acceleration of the leaders, and the time spent at cruising speed, you can calculate when the light at intersection 2 should turn green.

The motion of the cars farther back in the platoon is delayed from the onset of the green because a *start-up wave* must travel to them (the drivers do not begin to move simultaneously). Several tens of seconds may be required. If the tail of the platoon is delayed too much, it is stopped by the next red light at intersection 2. Suppose that the next platoon traveling down the street is as long or longer than the previous one. Then the number of cars stopped by the next red light at intersection 2 increases.

The situation worsens if the platoons continue to be long. The line of cars stopped at intersection 2 might lengthen until it extends back into intersection 1 and blocks the cross traffic there. Gridlock then begins. To relieve the problem, the light sequence of intersections 1 and 2 must be reversed: The light at intersection 2 must now turn green *before* the light at intersection 1 does, so that the cars stopped at intersection 2 can clear out before the next platoon arrives. The change in sequence could be made manually or by a computer that monitors the number of cars stopped at intersection 2.

Platoons can also be found in tunnel traffic (especially where lane changing is forbidden) and on two-lane rural roads. In each case, a platoon begins when faster cars encounter a slower vehicle, such as a truck. In the rural situation, the platoon dissipates if drivers manage to pass the slow vehicle.

1.3 • Shock waves on the freeway

When the traffic density increases on a freeway or highway, why do "waves," in which the drivers slow or speed up, propagate through the traffic? Sometimes they are created when an accident or a stalled car blocks a lane, and sometimes they are caused by *phantom accidents* in which traffic slows because of a relatively minor reason, such as a car changing lanes. Do the waves move in the direction the cars move or in the opposite direction? Why might a wave persist long after the accident or stalled car has been removed?

Answer When the density of vehicles is quite low, the actions of one driver have little effect on other drivers, especially if passing is possible. When the density is somewhat greater, the drivers begin to interact in the sense that they slow, partially because of safety concerns but also because the possibility of passing is diminished. Suppose that you are driving in such traffic. If the driver ahead of you slows or speeds up, you will do the same after a response time of about a second. The driver behind you follows suit after another response time of a second. And so on. This action of speeding up travels back through the lane of cars as a wave. Such a wave is probably invisible to anyone alongside the road because the adjustments to speed are usually slight.

Now suppose that the driver in front of you abruptly brakes hard. You and the drivers behind you will also brake hard, with each requiring about a second for response. The sudden braking also travels back through the lane of cars as a wave, but now the action is apparent to a roadside observer. Such a wave is a shock wave. Depending on the concentration of the cars before and after the wave has passed, the wave can travel in the direction of traffic (downstream) or in the opposite direction (upstream), or it can even be stationary.

Suppose that a shock wave is created when a car stalls in moderately heavy traffic and that 15 minutes are required by the driver to push the car off the road. As cars then begin to accelerate back to the normal cruising speed, a *release wave* travels back through the long line of waiting cars. It may be much later before the release wave catches up with the shock wave that still travels back through the traffic. Only then is the full traffic flow restored to normal.

1.4 • Minimum trailing distance for a car

If one car trails another, what is the minimum separation that will allow the trailing car to stop before colliding with the leading car should the leading driver suddenly brake to a stop? Conventional advice is that there should be at least one car length of separation for each 10 miles per hour (about 16 kilometers per hour) of speed for the cars. Is the advice sound?

Answer The advice is not sound because it is based on two shaky assumptions. One is that the drivers have identical response times to an emergency. If the trailing driver is slower to respond than the leading driver, more separation is required. The other, more subtle, assumption is that the cars slow at the same rate. If they are not put into a full slide, the assumption is likely to be off. The dangerous situation is, of course, when the leading car slows more rapidly than the trailing car.

Suppose that there is only a small difference in the slowing rates. Is there a simple rule for calculating the minimum separation that avoids an accident? Surprisingly there is not, because the minimum separation depends on the square of the speed and thus it is not easily calculated mentally for a given situation. So, if you travel fast behind another car, you had best allow much more separation than suggested by the conventional advice.

1.5 • Running a yellow light

Suppose that the light at an intersection turns yellow shortly before you reach the intersection. Should you brake to a stop before entering the intersection, continue to travel at your current speed, or accelerate? You might make a decision based on experience by judging your speed, the distance to the intersection, the intersection's width, and an assumption about the duration of the yellow light. Is there a possibility that you would violate the law with any of the choices even if you do not exceed the speed limit?

Answer Local law may influence the answer because in some regions you violate the law if you are in the intersection when the light turns red, while in other regions you can be there legally as long as you have entered the intersection before the light is red. In the first situation, you might very well be in a no-win situation because you may not be able to stop in time or accelerate sufficiently (and still not exceed the speed limit) to clear the intersection. In such a situation, there is a range of distances from the intersection in which any strategy fails to avoid violating the law. The problem is worse when the duration of the yellow light happens to be short and the legal speed is low, but the danger of a collision is lessened if the green light for the perpendicular traffic is delayed for one or two seconds after your light has turned red.

1.6 • Spinout during hard braking

When some types of cars without antilock braking systems are braked hard, they begin to spin and may even end up traveling backwards down the road (Fig. 1-2*a*). What produces the spin, and why don't all types of cars spin? If your car begins to spin, what is the best strategy for regaining control of its motion: Should you turn the front wheels in the direction of the skid or in the direction you wish to go?

Answer Reversal is common to cars with front-mounted engines because they have more weight riding on the front wheels than the rear wheels. That means that the rear wheels are likely to *lock up* and begin to skid before the front wheels, and then any chance spin given to the car by, say, some irregular feature in the road quickly leads to reversal.

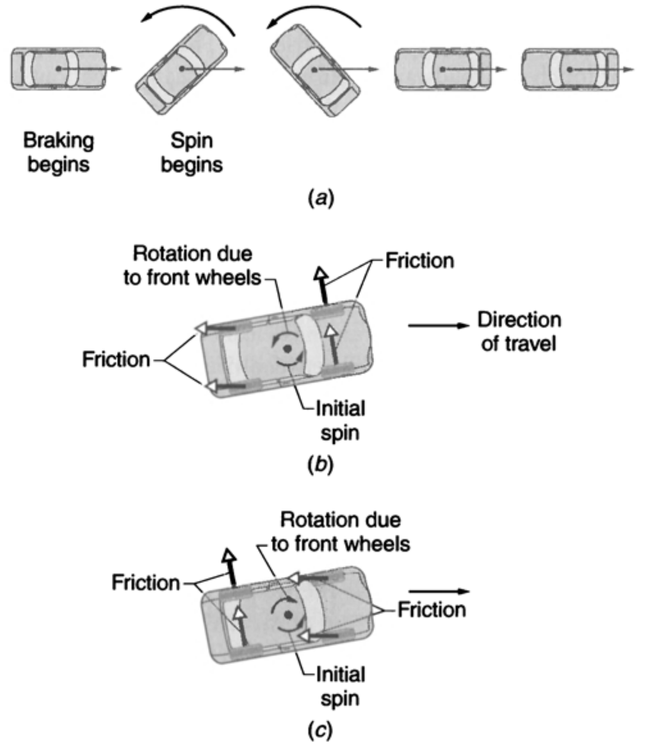


Figure 1-2 / Item 1.6 (*a*) Reversal of car due to hard braking. Frictional forces on tires for (*b*) front-mounted and (*c*) rear-mounted engines.

To picture the reversal, consider the friction on the tires when a car begins to spin to the left of its intended direction of travel (Fig. 1-2*b*). The rear tires, which are sliding, have frictional forces on them directly toward the rear. The front tires, which are still rolling, have frictional forces on them that are parallel to the front axle and point partially toward the left rear. All the forces create torques that attempt to rotate the car horizontally around its center of mass. The torques from the friction on the front wheels dominate because they attempt rotation in the same direction, which is in the direction that the car has begun to spin. So, spin is enhanced and the car is reversed.

If the engine is in the rear of the car, the roles of the frictional forces on the front and rear wheels are interchanged, and the torques from the rear wheels dominate—they counter the initial spin (Fig. 1-2*c*).

According to conventional advice, if your car begins to spin, you should turn the front wheels toward the intended direction of travel. In doing so, you create a torque on the front wheels that counters the spin, but unless you are skilled, you may overshoot and spin out of control in the opposite direction.

1.7 • To slide or not to slide

Suppose that you are driving down the road when a large moose jumps into your path some distance in front of you. And also suppose that your car lacks an antilock braking system. Should you lock the wheels by braking as hard as you can, or should you apply the brakes as much as possible without locking the wheels? If your car goes into a full slide, why is the end of the slide so abrupt?

Answer Textbooks have traditionally argued for the second choice, correctly pointing out that it is the friction on the tires that stops the car. When the wheels are rolling, the friction can be increased to some maximum value by an appropriate amount of braking. If you brake even harder, the wheels lock and the tires skid. The friction is then smaller and, with less friction, the stopping distance must be longer.

The best choice is to brake just hard enough to put the wheels on the verge of sliding, and then you stop in the least distance, right? Well, actually, maybe not, because that choice might give a stopping distance that is 25% longer than if you lock the wheels and fully slide.

The textbook argument may be unwise in an emergency situation for two reasons. One is that you scarcely have time to experiment with the braking. The other has to do with the torques put on the car by the frictional forces on the wheels: Those torques tend to pitch the car forward by attempting to rotate the car around a horizontal axis through its center of mass (Fig. 1-3). The attempt at rotation decreases the load on the rear wheels and increases the load on the front wheels.

Suppose that you brake just hard enough to put the car on the verge of sliding. Because all the wheels are still turning and because the load on the rear wheels is decreased, the rear wheels are the ones on the verge of sliding (not the front wheels with the extra load) and the friction on the rear wheels is small. If the front and rear brakes are identical, the friction on the front wheels is the same small amount, and so the total friction on the car is small, and the stopping distance for the car is large.

Now suppose that you brake hard enough to lock all the wheels and fully slide. With the wheels sliding, the friction on them depends on the load on them. Since the load on the front wheels is increased, the friction on them is large. Even though the friction on the rear wheels is small, this increased friction on the front wheels means that the total friction on the car is greater than in the previous situation, and thus the stopping distance for the car is shorter. However, locking up the wheels is still not desirable because the sliding eliminates your control of the car; you may easily begin to spin (see the

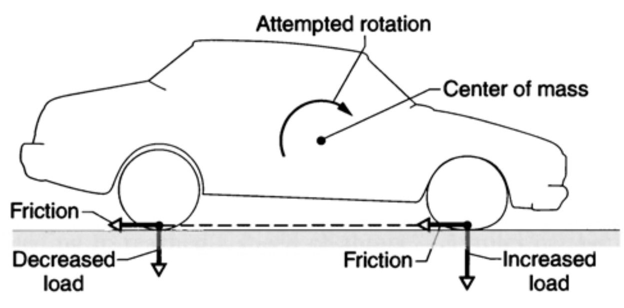


Figure 1-3 / Item 1.7 A car pitches forward during braking.

preceding item), colliding with adjacent cars or cars in the opposing lane of travel.

The abrupt end to a full slide is due to a sudden increase in the friction on the tires. During the slide the region of contact between the tires and the road is lubricated with melted tar and rubber (see the next item). But as the car slows, less material is melted and the lubrication decreases, which suddenly increases the friction.

1.8 • Skidding to a stop

If a car's wheels are locked during emergency braking, the tires will slide along the pavement and leave skid marks. Suppose that a car slides to a stop from a certain speed. Does the car's weight influence the length of the skid marks? How about the tread design and width of the tire? What if the tire is smooth?

Why is stopping a car more difficult when the road is only somewhat wet than when it is covered with flowing water?

Answer In emergency braking the friction on the tires from the road first increases to some maximum value and then it drops when the wheels lock and the tires begin to slip. The slippage rips off bits of the tire and heats the tires and road. The tire may melt and if the road consists of bituminous material, it too may melt. If either one melts, it produces a fluid that lubricates the slide, which further decreases the friction.

The melted material soon re-solidifies, but the trail—the skid mark—persists, perhaps for months. The trail often has striations that run along its length; they are due to the ribs on a tire or to loose gravel that is ground into the road. On concrete surfaces skid marks are rarer and almost invisible, consisting primarily of the bits of tire that have been melted or torn free.

When a car slides to a stop without colliding with anything, the length of its skid marks allows an investigator to estimate the speed of the car when the sliding began. However, so many variables are involved that the calculation can be only an estimate. One of the variables is the mass (or weight) of the car—a heavy car requires a slightly longer distance to stop than a lighter car, due primarily to the increased lubrication that the greater weight produces. (In traffic court and many physics books, this effect is generally neglected.)

The length of a skid mark also depends on the conditions of the roadway—the marks are usually shorter when the road surface is pebbled and longer when it has been polished by extensive use. The stopping distance does not depend on the width of a tire, because generally the frictional force on a tire depends on only the weight bearing down on the tire and the texture and bonding properties of the tire and road surface, not the tire width.

The tread on a tire has little effect on the stopping distance when the road is dry, but it may be crucial when the road is wet. If the water is substantial, as during a heavy downpour, the tires may tend to glide (or *hydroplane*) over a thin layer of water that offers almost no friction. That is, the tire does not touch the roadway because the water cannot get out of the way or out from under the tire. Hydroplaning becomes even worse when the road is dirty and rain has just begun to fall, because the water and dirt mix to form a very viscous lubricant, much like a clay slurry. Thus the friction between tire and road drops significantly, which can take many drivers by surprise in an emergency stop because they think that as rain begins, the road is not yet wet enough to cause hydroplaning. After the rain has cleaned the road and the road has dried, the friction between tire and road is higher than before the rain because the contamination has been removed. Tires that are designed to minimize hydroplaning have tread that channels or throws water from beneath the tire off to one side.

If the water is not enough to make the car hydroplane, it can still significantly reduce friction on the tires. A tire grips a dry road surface because the weight bearing down on it momentarily seals the bottom of the tire against the surface. That sealing allows the tire to mesh with the irregular surface, molding down into the slight valleys and snagging against the slight upward projections. That tight fit of the tire into the irregular road surface can produce much of the friction the tire requires during emergency stopping. However, when the road surface is wet, those valleys are full of water. Then when the tire is momentarily sealed against the road, it traps the water in those valleys, making the road surface relatively smooth and effectively eliminating the upward projectiles. So, the tire can no longer be snagged against those projectiles.

If the car begins to spin during an emergency stop, the marks left on the road will be curved. Such spin can be initiated if the rear wheels lock up before the front ones, or it can be due to a slant of the road. (Often the crown is higher than the sides to drain rainwater.)

If a wheel is still rolling during a spin, it scrapes sideways on the road and leaves a *scuff mark* that lacks the striations which characterize a skid mark. Either type of mark may be intermittent if the road is uneven enough to make the car bounce or if the braking is nonuniform. Short gaps in the marks are usually due to bouncing, while longer gaps might indicate that the driver pumped the brakes.

SHORT STORY

1.9 • Some records for skid marks

The record for skid marks on a public road appears to have been set in 1960 by the driver of a Jaguar on the M1 in England—the marks were 290 meters long. In court the speed was alleged to have been in excess of 160 kilometers per hour (or 100 miles per hour), when the wheels were first locked. If we assume that the coefficient of friction between tires and roadway was 0.7, we can calculate that the car's speed was about 225 kilometers per hour (or 140 miles per hour).

The Jaguar's skid marks were impressive, but they pale next to the ones left by Craig Breedlove in October 1964 at the Bonneville Salt Flats in Utah. Attempting to topple the land speed record and break through the 500-mile-per-hour "barrier" (805 kilometers per hour), Breedlove drove his rocket-powered *Spirit of America* through a measured mile, first in one direction and then in the opposite direction, so that the effects of wind could be averaged out. When he made his second pass through the mile, he was traveling about 540 miles per hour.

To slow, he released a parachute, but its cord snapped under the strain; the secondary chute also failed. Next he applied his brakes, pressing the pedal to the floor, but they did little more than leave skid marks that were almost six miles long before burning out. The vehicle was then traveling at about 500 miles per hour as it narrowly passed through two lines of telephone poles without crashing. It finally stopped when it rode up and over an embankment and then plummeted, nose down and at 160 miles per hour, into a pool of brine that was 5 meters deep. Since Breedlove was firmly strapped into his seat, he nearly drowned in the submerged compartment. Still, Breedlove's runs through the mile set a speed record and broke the 500-mile-per-hour barrier with an average speed of 526 miles per hour.

1.10 • Woodpeckers, bighorn sheep, and concussion

A woodpecker hammers its beak into the limb of a tree to search for insects to eat, to create storage space, or to audibly advertise for a mate. During the impact, the rate at which the head slows is about 1000 *g*s (1000 times gravitational acceleration). Such a deceleration rate would be fatal to a human or at best severely damage the brain and leave the person with a concussion. Why then doesn't a woodpecker fall from a tree either dead or unconscious every time it slams its beak into a tree?

To determine dominance during the mating season, male bighorn sheep charge one another to slam their horns and heads together in a violent collision. Yet, they don't drop to the ground unconscious (it is hard to be a female's choice if sprawled unconscious on the ground). Some types of horned dinosaurs (such as the *Triceratops*) may have had similar collisions. Why don't the collisions hurt the sheep?

Answer The ability of a woodpecker to withstand the huge deceleration when it hammers at a tree limb is not well understood, but there are two main arguments. (1) The woodpecker's motion is almost along a straight line. Some researchers believe that concussion can occur in humans and animals when the head is rapidly rotated around the neck (and brain stem), but that it is less likely in straight-line motion. (2) The woodpecker's brain is attached so well to the skull that there is little residual movement or oscillation of the brain just after the impact and no chance for the tissue connecting the skull and brain to tear.

Head-banging sheep are usually protected by three features. (1) Their horns bend so as to prolong the duration of the collision and thereby reduce the force in the collision. (2) The skull bones (cranial bones) also shift or rotate about their junctions (sutures) in a spring-like or hinge manner in order to cushion the blow to the head. (3) Most of the energy of a collision ends up in the strong neck muscles of the animals. Although the collisions look terribly violent, the muscles and horns of the animals have evolved to the point where breaking a horn or hurting the brain is unlikely. The *Triceratops* probably also benefited from an extensive sinus system that overlaid the brain case and that could have acted as a shock absorber.

SHORT STORY

1.11 • The game of *g*s

In July 1977, at El Mirage Dry Lake, California, Kitty O'Neil set two records for a dragster on a 440 yard run. From a standstill, she reached the greatest *terminal speed* (speed at the end of the run) ever recorded and also broke the record of the lowest elapsed time with her mark of 3.72 seconds. Her speed was an astounding 392.54 miles per hour (about 632.1 kilometers per hour). Her average acceleration during the run was 47.1 meters per second-squared, which is 4.81 times the acceleration of gravity, or 4.81 *g*s for short.

In December 1954, at Holloman Air Force Base, New Mexico, Dr. John Stapp, an Air Force colonel, was strapped in the seat of a rocket sled with nine rockets behind it. When they were fired, Stapp and the sled were propelled along a track for 5 seconds, reaching a speed of 632 miles per hour, about 1018 kilometers per hour. His acceleration during the propulsion stage was approximately 56.4 meters per second-squared, or 5.76 *g*s. The numbers are certainly impressive, but the real test of Colonel Stapp was the stop by the water brakes, which took only 1.4 second—he slowed (decelerated) at the rate of 20.6 *g*s.

In May 1958, in a similar sled at Holloman, Eli L. Beeding Jr. reached a speed of about 72.5 miles per hour, or 117 kilometers per hour. The speed hardly seems noteworthy because it is common on some highways, but it commands respect when the time for the acceleration is noted. The time was 0.04 second, less than the blink of an eye. Beeding's acceleration of 82.6 *g*s remains the record in a controlled situation.

In July 1977, in Northamptonshire, England, David Purley's race car crashed and his speed dropped from 108 miles per hour to zero while he moved through a distance of only 26 inches. (The speed was 174 kilometers per hour; the distance was $\frac{2}{3}$ meter.) His deceleration was a seemingly lethal 179.8 *g*s but, although he had 29 fractures, three dislocations, and underwent six heart stoppages, Purley survived.

1.12 • Head-on car collision

Suddenly you realize that a car is headed toward your car the wrong way in a one-way tunnel. To minimize your danger from the impending accident, should you match your speed to that of the other car, go even faster, or slow to a stop?

A head-on collision is the most dangerous type of car collision. Surprisingly, the data collected about head-on collisions suggest that the risk (or probability) of fatality to a driver is less if that driver has a passenger in the car. Why is that?

Answer The best advice is to stop and, if possible, put your car in reverse. You can get a measure of the severity of the collision by considering the total kinetic energy or the total momentum of the cars before the collision. If you do not decrease your speed toward the other car, both quantities are large, and so the collision will be severe.

The situation is unlike football, where one player may choose to speed up when running head-on into another player. The difference is that a player may want the collision to be violent, and by properly orienting his body he can shift the collision to his opponent's vulnerable area or cause his opponent to become unbalanced and slam into the field.

Data collected about head-on car collisions indicate that adding a passenger to your car reduces your risk of fatality. That risk depends on the change in your velocity during the collision: A large change means that you undergo a severe acceleration due to a severe force. For example, if your car has a small mass and the other car has a large mass, your velocity may be changed so much that you end up going backward. Additional mass in your car, from a passenger or even a sandbag in the trunk, can decrease your change in velocity and thus also your risk. Here is one numerical result: Suppose your car and the other car are identical and that your mass and the other driver's mass are identical. Your fatality risk is reduced by about 9% if you have an 80 kilogram passenger in your car.

SHORT STORY

1.13 • Playing with locomotives

Waco, Texas, September 15, 1896: William Crush of the Missouri, Kansas, and Texas Railroads dreamed up a surefire idea for a show. He arranged for two obsolete locomotives to face each other at opposite ends of a 4 mile track. One was painted red, the other green. The idea was to crash the locomotives into each other at full speed.

Well, nothing sells quite like violence, and 50 000 spectators paid to see the crash. After the engines were fueled and their throttles fixed open, the locomotives accelerated toward each other. When they met, they were going about 90 miles per hour, which is 145 kilometers per hour.

Several of the spectators were killed by the scattered debris and hundreds were hurt. The rest of the crowd probably got their money's worth. Being near the collision, with its transformation of kinetic energy of the trains into kinetic energy of flying debris, was like being near a moderate explosion.

1.14 • Rear-end collision and whiplash injury

In a rear-end collision, a car is hit from behind by a second car. For decades, engineers and medical researchers sought to explain why the neck of an occupant of the front car is injured in such a collision. By the 1970s, they concluded that the injury was due to the occupant's head being whipped back over the top of the seat as the car was slammed forward, hence the common name "whiplash injury." The neck was apparently extended too far by the head's motion. As a result of this finding, head restraints were built into cars, yet neck injuries in rear-end collisions continued to occur. What actually causes these injuries?

Answer The primary cause of a whiplash injury is the fact that the onset of the forward acceleration of the victim's head is delayed from that of the torso. Thus, when the head finally begins to move forward, the torso already has a significant forward speed. This difference in forward motions puts a huge strain on the neck, injuring it. The backward whipping of the head happens later in the collision and could, especially if there is no head restraint, increase the injury.

1.15 • Race-car turns

High-speed motor races are often won by the performance of car and driver on the turns, which is where the speed is lowest. Consider a 90° turn on flat track, as in Formula One racing. Obviously, the best way to take the turn depends on the handling characteristics of the car, the skill and experience of the driver, and the conditions of the track. However, in general, should the driver follow a circular path around the turn? That choice usually guarantees the least time spent in the turn, but why might it not be the best choice?

Why do drivers who are experienced on the flat tracks of Formula One courses have a difficult time if they switch to Indy car racing, which usually has banked turns? In particular, why is such a driver prone to spin out as the car enters the turn?

Answer A novice driver takes a turn along a circular path. A skilled driver brakes while turning a little, then turns sharply, and then follows a less sharply turned path while accelerating. The procedure takes more time in the turn but allows the driver to enter the straightaway at greater speed than the novice driver. That greater speed on the straightaway more than makes up for the time lost in the turn.

The procedure has another advantage. If the turn is taken too fast, the limit of the frictional forces on the tires will be exceeded and the car will slide out of control. To maintain the friction, the skilled driver first brakes and only then takes a sharp turn. Because the rest of the turn is gradual, the driver can accelerate without overwhelming the friction.

A skilled Formula One driver has an intuitive feel for the sensations of force and motion during a flat turn. The sensations on a banked turn are quite different, and a Formula One driver will probably be too late in making the sharp-turn part of the turn procedure.

1.16 • Sprint tracks

Why is a race on a straight track generally faster than one of the same distance on a curved track? When the track is flat and oval, why does a runner in the outside lane generally have an advantage over one in the inside lane, even though the distances in the two lanes are the same? Why does the speed of a race on such a track depend on the shape of the oval?

Answer Entering a curve, a runner slows; leaving the curve, the runner accelerates back to the straightaway speed. In any turn, a centripetal force toward the center of the turn is required. Here, the centripetal force is provided by the friction force on the runner's shoes. During that inward force on the shoes, the runner's body tends to lean outward in the turn, as if it is being thrown outward. So, to maintain balance, the runner slows to decrease the forces and leans inward to offset the outward leaning tendency. The sharper the turn is, the more the runner must slow and lean. Thus, someone running in an outside lane (which has less curvature) will generally have an advantage over someone running in the inside lane (which has more curvature).

When the track is flat and oval, the amount of the race along the curved portions partially determines the speed of the race. In general, a wide oval provides a faster race than a narrow oval because the curvature of the curved portions of a wide oval is smaller than that of the sharp turns of a narrow oval. The best geometry (other than a straight track, of course) is a circle; its curvature is least.

1.17 • Takeoff illusion

A jet plane taking off from an aircraft carrier is propelled by its powerful engines while being thrown forward by a catapult mechanism installed in the carrier deck. The resulting high acceleration allows the plane to reach takeoff speed in a short distance on the deck. However, that high acceleration also compels the pilot to angle the plane sharply nose-down as it leaves the deck. Pilots are trained to ignore this compulsion, but occasionally a plane is flown straight into the ocean. What is responsible for the compulsion?

Answer Your sense of vertical depends on visual clues and on the vestibular system located in your inner ear. That system contains tiny hair cells in a fluid. When you hold your head upright, the hairs are vertically in line with the gravitational force on you, and the system signals your brain that your head is upright. When you tilt your head backward, the hairs are bent and the system signals your brain about the tilt. The hairs are also bent when you are accelerated forward by an applied horizontal force. The signal sent to your brain then indicates, erroneously, that your head is tilted back. However, the erroneous signal is ignored when visual clues clearly indicate no tilt, such as when you are accelerated in a car.

A pilot being hurled along the deck of an aircraft carrier at night has almost no visual clues. The illusion of tilt is strong and very convincing, with the result that the pilot feels as though the plane leaves the deck headed sharply upward. Without proper training, a pilot will attempt to level the plane by bringing its nose sharply down, sending the plane into the ocean.

SHORT STORY

1.18 • Air Canada Flight 143

On July 23, 1983, Air Canada Flight 143 was being readied for its long trip from Montreal to Edmonton when the flight crew asked the ground crew to determine how much fuel was already on board. The flight crew knew they needed to begin the trip with 11 300 kilograms of fuel. They knew that amount in kilograms because Canada had recently switched to the metric system; previously fuel had been measured in pounds. The ground crew could measure the onboard fuel only in liters, which they reported as 7682 liters. Thus, to determine how much fuel was on board and how much additional fuel was needed, the flight crew asked the ground crew for the conversion factor from liters to kilograms of fuel. The response was 1.77, which the flight crew used (1.77 kilograms corresponds to 1 liter) to calculate that 13 597 kilograms of fuel was on board and that 4917 liters was to be added.

Unfortunately, the response from the ground crew was based on pre-metric habits—1.77 was the conversion factor not from liters to kilograms but rather from liters to *pounds* of fuel (1.77 pounds corresponds to 1 liter). In fact, only 6172 kilograms of fuel were on board and 20 075 liters should have been added. This meant that when Flight 143 left Montreal, it had only 45% of the fuel required for the flight.

On route to Edmonton, at an altitude of 7.9 kilometers, the airplane ran out of fuel and began to fall. Although the airplane had no power, the pilot managed to put it into a downward glide. Because the nearest working airport was too far to reach by gliding, the pilot angled the glide toward an old, nonworking airport.

Unfortunately, the runway at that airport had been converted to a track for race cars, and a steel barrier had been constructed across it. Fortunately, as the airplane hit the runway, the front landing gear collapsed, dropping the nose of the airplane onto the runway. The skidding slowed the airplane so that it stopped just short of the steel barrier, with the stunned race drivers and fans looking on. All on board the airplane emerged safely. The point here is this: Quantities without proper units are meaningless numbers.

1.19 • Fear and trembling at the amusement park

What accounts for the thrill of a ride on a roller coaster? Surely, the heights, speeds, and illusions of falling are factors, but all those sensations can be had in a fast, exterior elevator that is glass encased. No one queues up and pays for elevator rides.

And how about the rides that sling you about? Why do you clutch, and maybe even scream, during the rides?

Roller coasters are designed to give the illusion of danger (that is part of their fun), but in fact engineers go to extreme lengths to make them exceedingly safe for riders. In spite of this attention to passenger safety, an unlucky few of the millions of people who ride roller coasters each year end up with a medical condition called *roller-coaster headache.* Symptoms, which might not appear for several days, include vertigo and headache, both severe enough to require medical treatment. What causes roller-coaster headache?

Answer Some rides are exciting because of heights, high speeds, or large accelerations (up to 4 *g*s on a roller coaster), or because rapid rotation creates an amusing sensation of centrifugal (outward-directed) force, but the most frightening rides are usually those that produce rapidly changing and unexpected forces on you. When you feel a constant force and undergo a constant acceleration, things seem under control, but when the force suddenly changes size or direction and you accelerate unexpectedly, you subconsciously sense danger. The element of surprise on a subconscious level generates an existential flirt with death.

Standard roller coaster: The heights and the high speeds are enthralling, as is the clatter on an old wooden coaster. When you travel quickly through a curved low section, an apparent centrifugal force on you seemingly presses you into the seat; when you travel over a short but highly curved hill, the force seems to throw you out of the seat. When you go over the edge of the first and largest hill, you have a distinct feeling of falling. The illusion is best when you sit in the front car so that little of the coaster is in front of you. However, I think that sitting in the rear car is even more frightening. As you approach the edge and more of the coaster begins to descend, the force on your back builds, gradually at first and then ever more rapidly (the rate is exponential), and just as you reach the edge, the force disappears. The experience is as if some diabolical agent shoves you toward the edge in a frenzy and then hurls you into free fall.

Mouse roller coasters: The cars are sent separately along the track. The compartment in which you sit pivots above a wheeled framework that follows the track, with the pivot located near the back of the car. When you reach a sharp turn, the framework faithfully follows the curved track but the compartment continues to travel forward for a moment before it too turns. In that moment you have the illusion that the compartment is flying off the track.

Modern roller coasters: Vertical loops and corkscrews produce sensations of centrifugal forces that rapidly change size and direction, and you are also turned upside down. Both factors produce fear. As you ascend a vertical loop, the apparent centrifugal force should decrease as you slow, but the curvature of the track sharply increases so as to maintain that apparent force. On some coasters you might move along the track while facing backwards so that you cannot foresee any of the changes in force, speed, or acceleration that you are about to undergo. Riding a coaster in darkness also eliminates anticipation and enhances fear.

Rotor: When you stand next to the interior wall of the large spinning cylinder, you feel pinned by a powerful centrifugal force (Fig. 1-4*a*). The force may alter your perception of the downward direction and create the illusion that you are tilted backward. If the force is large enough, the floor can be dropped away while you are held in place by a frictional force between you and the wall. Although the idea of an outward force may then be quite convincing, the force that actually pins you is an inward force—the wall pushes on you toward the center of the cylinder in order to keep you going

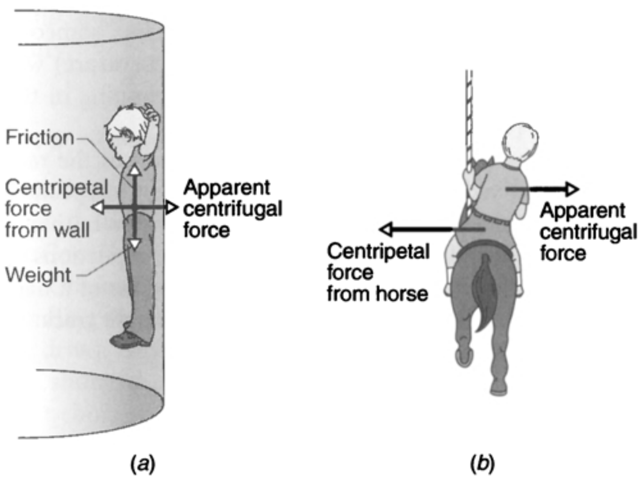


Figure 1-4 / *Item 1.19* Forces involved in (*a*) a rotor and (*b*) a merry-go-round.

in a circle. Since you do not slide down the wall, the frictional force on you must be upward and equal to your weight.

Ferris wheel, merry-go-round, and rotating swings: These rides offer milder sensations of a centrifugal force. When your cage on a Ferris wheel rotates through the top of the circle, you feel as though you are being lifted by the force. At the bottom of the circle, you feel as though you are being shoved downward into the seat. On a merry-go-round, the centrifugal force seems to throw you outward (Fig. 1-4*b*), especially if you ride an outside horse, which moves faster around the circle than horses closer to the center. When you ride in a swing that is rotated around a central hub, the chains move off vertical as if a centrifugal force is pushing you outward. In each of these three rides, there really is no centrifugal force. Rather there is a centripetal force (from the seat in the Ferris wheel, the horse in the merry-go-round, and the chains in the swing), and that force is what keeps you circling.

Rides with rotating arms: You sit in a compartment that is at the outer end of an arm which pivots around the outer end of another, more central arm. If the arms rotate around their pivots in the same direction, you feel the greatest centrifugal force and have the greatest speed when you pass through a point that is farthest from the center of the apparatus. When the directions of rotation are opposite, your speed is least at the far point (due to the opposing rotations), but the force on you varies most rapidly there because you are being whipped through a highly curved path.

Vertical falls: You sit in a compartment that is some 40 meters high when it is suddenly released and allowed to drop in almost free fall. You have a sense of weightlessness because you and the seat below you fall at almost the same rate, and so you no longer feel any support from the seat. Some riders think that the sensation is fun.

Roller-coaster headache can result from any amusement park ride in which the acceleration is large and rapidly changing in direction. The large acceleration puts a strain on the brain and any abrupt change in direction can then cause the brain to move relative to the skull, tearing the veins that bridge the brain and skull.

SHORT STORY

1.20 • Circus loop-the-loop acts

The modern amusement parks may be packed with thrills, but they pale compared to some of the circus stunts involving bicycles that were performed between 1900 and 1912. As one circus attempted to outshine another, daring acts were devised and performed, some more than once if the performers escaped injury. One of the early stunts was demonstrated in 1901 by Adam Forepaugh & Sells Bros. Circus. A man known as "Starr" rode a bicycle down from a height of 18 meters along a 52° ramp. That may not sound too challenging, but the ramp consisted of three sections of extension ladders, which meant that the ride was quite rough, especially near the bottom portion.

The next year at New York's Madison Square Garden, Forepaugh & Sells introduced Diavolo and a bicycle–loop act. With an ambulance standing by, Diavolo began his ride down a ramp from just beneath the ceiling's incandescent lamps and then passed along (inside) a vertical loop with a diameter of 11 meters and into nets to stop the motion. In 1904 the same circus presented the "Prodigious Porthos" in another bicycle act. The ramp was similar but the top of the loop was excluded, requiring Porthos to fly 15 meters through the air, while inverted, to reach the second portion of the loop.

Perhaps the most daring bicycle stunt took place in 1905 when Barnum & Bailey Circus played Madison Square Garden. The act began with Ugo Ancillotti on a bicycle high on one ramp and his brother Ferdinand similarly mounted even higher on a second, facing ramp (Fig. 1-5). On signal, the brothers began their descents. Upon reaching the sharply curved lower end of his ramp, Ugo was projected 14 meters to land on another ramp, and then he repeated the performance across a second gap of 9 meters. Meanwhile, Ferdinand was sent into a curved path by the bottom portion of his ramp so that he soared upside down to reach another curved ramp. The most gripping aspect of the performance was when Ferdinand soared upside down and only few feet below Ugo, who was crossing his first gap. The danger in the performance was quite real—when the act was attempted again in the evening show, Ferdinand took a bad fall during the "loop the gap," and the act was apparently canceled.

Circuses began to substitute "autos," partially because of the novelty of automobiles at the time. One or two occupants would ride an auto down a ramp and flip once or twice in the air before reaching a second ramp. However, these types of circus stunts waned after 1912, probably because audiences grew accustomed to the danger involved. The associated physics did not receive another injection of theatrics until more modern times when Evel Knievel, his son Robbie Knievel, and other stunt people began to ride a motorcycle up or down a ramp and soar over cars and trucks.

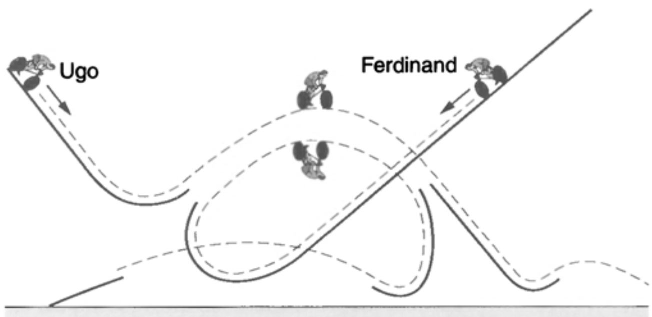


Figure 1-5 / Item 1.20 The bicycle act of Ugo and Ferdinand Ancillotti.

1.21 • Catching a fly ball

When a high fly ball is hit to the outfield, how does the player in the area know where to be to catch it? The outfielder may run to the proper point and wait for the ball. Or the outfielder may run at a measured rate and arrive at the proper point just as the ball arrives. Either way, playing experience surely helps, but are there clues hidden in the ball's motion that can guide the outfielder?

As an example of an outfielder's skill, Robert Weinstock of Oberlin College relates how Babe Ruth once caught a high fly from Jimmy Foxx of the Philadelphia Athletics. Ruth was waiting deep in left field, expecting a long fly ball from Foxx, but Foxx hit the ball askew and it went high and short. As soon as the sound of the hit reached Ruth, he ran to the precise spot on the field, waited, and then snared the ball with his glove.

Answer Although an outfielder uses many clues to catch a fly ball, two angles appear to be important. One is the vertical angle α through which the ball moves in the player's view as the ball travels toward the outfield (Fig. 1-6*a*). If the player is already at the proper point to catch the ball, this angle increases but at a decreasing rate (at first, it increases rapidly and then it increases less rapidly). If the player is too close (and must retreat), the vertical angle increases at an increasing rate; if the player is too far (and must advance), the vertical angle first increases and then begins to decrease. The player knows from experience to move until, in the later part of the ball's flight, the vertical angle increases at the proper decreasing rate.

The other important angle comes into play when the ball is hit off to the left or right of the player. As the ball travels toward the outfield, it moves horizontally through angle θ in the player's view (Fig. 1-6*b*). The player runs so that this angle increases at a constant rate. This allows the player to run to the proper catching point at a fairly steady rate instead of making a dash at the last second. Doing all this well takes practice but it must also come naturally because dogs, such as those who catch a thrown Frisbee with their mouth, use the same procedure (as revealed by video cameras attached to them).

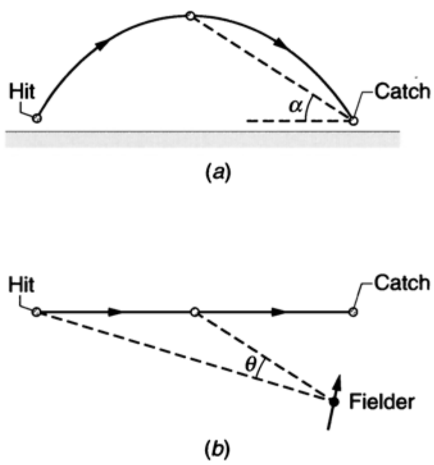


***Figure 1-6** / Item 1.21* (*a*) Side view of fly ball's path. (*b*) Overhead view of the path.

SHORT STORY

1.22 • High ball

In August 1938, Frankie Pytlak and Hank Helf, two catchers from the Cleveland Indians, set out to capture the world's record for catching the longest dropped baseball. While they waited at street level beside Terminal Tower in Cleveland, Ken Keltner, the third baseman, prepared to toss the balls from the top of the building, about 700 feet (or 213 meters) high. The previous record of 555 feet had been set in 1908 by two catchers from another team who caught baseballs tossed off the Washington Monument in Washington, D.C.

Keltner had no way of seeing his fellow players on the street and so he tossed the balls out blindly. Pytlak and Helf wore steel helmets to guard against injury by the balls, which reached estimated speeds of almost 140 miles per hour (or 225 kilometers per hour). Helf made the first catch, claiming with a grin that there was nothing to it, but the next five balls for Pytlak went astray. One bounded up to the 13th floor and was fielded by a police sergeant after its third bounce. On the sixth try, Pytlak made his catch and the shared record.

The next year Joe Sprinz of the San Francisco Baseball Club attempted to catch a baseball dropped 800 feet from a blimp. (Some reports claim the fall was much higher.) On his fifth attempt he got a ball in his glove, but the impact drove hand, glove, and ball into his face, fracturing his upper jaw in 12 places, breaking five teeth, and knocking him unconscious—and he dropped the ball.

Even more ludicrous was an attempt in 1916 to catch a baseball tossed from a small airplane. Wilbert Robinson, the manager of the Brooklyn Dodgers and a former catcher, arranged for the Dodger trainer Frank Kelly to toss the ball from the airplane while at a height of 400 feet. But unknown to Robinson, Kelly substituted a red grapefruit for the ball. When the fruit exploded on impact, its red contents drenched Robinson, who cried, "It broke me open! I'm covered with blood!"

1.23 • Hitting a baseball

If you are right-handed, why do you hold a baseball bat with your right hand higher than the left one and turn your left side to the pitcher? How long does a baseball take to reach home plate? How much time do you have to execute a swing? How much error can you have in your swing and still hit the ball?

Some home-run sluggers prefer heavy bats, claiming that the extra weight in the collision results in a longer hit. Other players choose a light- or moderate-weight bat with a similar claim. (Occasionally, when a wood bat is used, a player will illegally install a cork core to lessen the weight.) Who is correct in the argument about weight? Should a player warm up with a standard bat with a lead doughnut slipped over the outer end or a bat that is much lighter or much heavier than the bat that will be used in the game?

Where should the ball hit the bat to give it the greatest speed? Why does the bat sometimes sting your hands and attempt to jerk out of your grip during its collision with the ball?

Pitchers so feared the power of the legendary hitter Babe Ruth that they sometimes threw him a slow ball instead of a faster one. They figured that if the ball hit the bat with a slow speed, it would rebound with a slow speed and not go as far. Was their reasoning sound?

Answer If you are right-handed, you generally use the right hand in tasks that demand control, such as writing. Swinging a bat is such a task because to hit the ball you must swing the bat almost without error. When you swing, you push on the bat with your right hand and arm while pulling on it with your left hand and arm. The left side does most of the work; the right side does most of the guiding. You can guide the bat better if the right hand is high, and you can pull it better if the left hand is low. In the conventional stance with your left side toward the pitcher, you can turn into the pitch with your controlling hand behind the bat, where it can more easily guide the bat's motion.

Even a slow ball takes less than a second to reach home plate, while a fast ball might take as little as 0.4 second. (A record speed for a fast ball, 100.9 miles per hour, was set on August 20, 1974, by Nolan Ryan, then playing for the California Angels.) You actually have less than 0.4 second to swing, because you must first size up the pitch and mentally extrapolate the ball's flight across home plate. Professional players can swing in about 0.28 second, but some of the highly skilled batters manage to swing in as little as 0.23 second. The faster swing gives a player the advantage of studying the ball's flight a bit longer before beginning the swing.

To hit the ball out of the park, your guidance of the bat must be accurate within a few millimeters. If the bat is slightly low, the ball pops up. If it is slightly high, the ball hits the ground before it goes very far. In addition, your timing of the swing must be accurate within a few milliseconds. And, to make the task even more demanding, you must do all this without seeing the ball as it nears the bat, because your visual system cannot track it during the latter part of its flight. It is a wonder that some players are so consistently successful at hitting the ball.

Experiments have shown that the speed of a batted ball improves with an increase in the weight of the bat until the weight exceeds about 35 or 40 ounces. A bat of moderate weight (about 32 ounces) is better than a heavier bat for at least three reasons. Two are obvious to most players: The moderate weight bat is easier to swing and to control than a heavy bat. Both factors are due to the smaller *rotational inertia* of the bat—that is, the distribution of mass with respect to the center (or centers) about which the bat is rotated during a swing. The third reason has to do with the energy transfer during the bat–ball collision. In general, the transfer of energy in a collision of two objects improves the closer those objects are matched in mass (or weight). Thus, in the bat–ball collision, more energy is transferred from the bat to the ball with a moderate-weight bat than a heavy bat.

So, why do some batters still prefer a heavy bat? The choice might be based on the associated length of the bat. A light bat is short, requiring that the player stand near the plate. If the ball travels through the near part of the *strike zone*, the player might have to hit it with the section of the bat near the hands. As explained below, such a collision greatly diminishes the chance of a good hit. To avoid the problem, players might choose a heavier bat because of its additional length. They then can stand farther from the plate, and the collisions occur in a better region on the bat.

Experiments reveal that a player will swing a bat with *less* speed if the player first warms up with a heavier or lighter bat or the same bat weighted with a lead doughnut on the outer end. The reason appears to be that when warming up with a bat, the player sets up a certain mental program (the procedure of using the muscles) to swing that bat. If the warm-up bat is significantly different than the one actually used in play, then the mental program will not be exactly appropriate and the bat used in play will not be swung well.

The forces you feel during the collision with the ball depend on where it hits the side of the bat. The collision usually shoves and rotates the handle, but not if the ball happens to hit the *sweet spot* that is known as the *center of percussion* (COP). If the collision is between the center of mass and the COP, the handle is shoved in the direction of the pitch. If it is outside the COP, the handle is jerked toward the pitcher.

Another sweet spot involves the oscillations a collision can set up in the bat, which can sting your hands. For most cases, two types of oscillations appear on the bat. The simplest type, called the *fundamental*, is one in which the far end of the bat oscillates the maximum amount. You probably won't notice this oscillation because of its low frequency.

The other oscillation, called the first overtone, is quite perceptible and can even hurt your hands a little. In it the free end of the bat oscillates vigorously, but there is a point, called a *node*, somewhat closer to you that does not move at all. The node also carries the nickname of sweet spot, because if the ball hits there, the first overtone is not produced and so there is no perceptible oscillation on the hands.

You can find the node on a bat by dangling it from your fingers and tapping on its side. When you strike the node, you will notice little or no oscillations. But when you strike at other points, especially nearer the center of the bat, the oscillations can be both felt and heard.

To give the ball the greatest speed, you generally should hit it at a point between the sweet spots and the center of mass, but the exact location depends on the ball's initial speed and on the ratio of the bat's mass to the ball's mass. The faster the ball or the lighter the bat, the nearer to you the ball should hit the bat.

I can imagine that when Ruth saw a slow ball coming his way, he began to grin. Hitting the ball out of the park depends primarily on the control of the bat during the swing and an accurate assessment of where the ball will travel across the plate. A slow ball gave Ruth ample study and the chance to position and time his swing.

1.24 • Legal passes in rugby

In rugby, one player can legally pass the ball to a teammate if it is not forward. If the player with the ball is running toward the opponents' goal, what direction of throw is allowed? Can a toss be toward his rear and still be illegally forward?

Answer The problem has to do with the velocity of the player. When he throws the ball toward the rear, the ball's velocity might actually be forward relative to the playing field. For example, in Fig. 1-7*a* the velocity of the ball relative to the player is toward the rear, but once it is added to his running velocity, it is angled forward (Fig. 1-7*b*).

If the umpire is running while watching the pass, he will see the velocity of the ball angled in yet another direction, because of his own velocity. Only the stationary spectators will properly see whether the ball's flight is illegally forward or not.

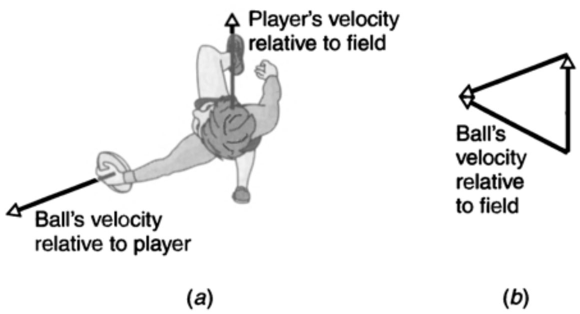


Figure 1-7 / Item 1.24 A rugby pass back to the left may seem legal relative to the player (*a*) but actually be forward to the field (*b*).

1.25 Juggling

The world's record for juggling rings is currently 11; records for other objects involve fewer numbers. Obviously juggling requires good eye–hand coordination and practiced tossing and catching, but is there any other factor that limits the number of objects that can be juggled?

Answer Gravity, of course, imposes a limit. If you want to add to the number of objects being juggled, you must toss the objects higher so that you have some extra time for the additional objects. However, the gain in time is always small. If you throw an object twice as high as previously, you gain only about 40% more time for its flight. Plus, you would have to throw it with 40% more speed, which means that the toss is more likely to be erratic.

1.26 • Pole vaulting

Fiberglass poles revolutionized pole vaulting in the early 1960s. Earlier in the sport, poles were bamboo. Steel and aluminum poles became popular in the 1950s. But nothing could beat out fiberglass poles, and once they were introduced, the record jump quickly rose from 4.8 meters to over 5.8 meters. Some say that eventually the record should be well above 6.0 meters. Why was the fiberglass pole so instrumental in raising the record?

Answer The fiberglass pole was much more flexible than the previous poles of bamboo, steel, or aluminum. This flexibility gives two advantages to a pole vaulter. The athlete can better convert the kinetic energy of the run toward the jump into elastic potential energy of the pole as it is bent. (That stored energy comes from the run, not a muscular effort by the athlete in bending the pole.)

Perhaps that much is obvious. More subtle is that the flexibility of the pole delays the conversion of the elastic potential energy back into the kinetic energy of the then rising athlete. This delay allows the athlete to reposition the body so that the gain of energy from the then straightening pole results in upward motion rather than forward motion.

To make a good jump, an athlete must not only run fast toward the jump to ensure that there is plentiful kinetic energy to be used but must also measure the stride so as to place the far end of the pole properly in the *box* on the ground. As the pole catches in the box, the athlete must jump forward so as to maintain the forward motion and bend the pole properly. As the pole bends, it stores some of the athlete's initial kinetic energy. During this bending and the eventual unbending, the athlete tucks the legs and leans backward so as to rotate the legs and body into a vertical orientation. To help unbend the pole so as to gain back more energy, and to help the reorientation of the body, the athlete pushes forward with the upper hand while pulling backward with the lower hand. If all is timed correctly, the unbending pole feeds back its stored energy to send the athlete upward.

1.27 • Launch of an atlatl and a toad tongue

Several ancient cultures, such as the Aztecs and tribes in the far north of North America, developed a launching mechanism in which a spear (or dart) is propelled by means of a wood stick that is rapidly brought forward until the spear flies free of the stick (Fig. 1-8). Why does the launching device, now called an *atlatl*, give a greater spear speed than if the spear is simply thrown forward? The speed was large enough that the spear could fly through about 100 meters and then rip through, say, the armor on a Spanish conquistador confronting the Aztecs. Why was a stone often attached to the launching device?

How can a toad propel its tongue outward at a surprising speed and for a surprising distance to catch a fly?

Answer In a conventional launch of a spear, you provide the spear's kinetic energy through the work your hand does in moving the spear forward through a certain distance. The launching device that ancient cultures discovered adds to the length through which the spear is propelled and so also to the energy that is given it. The advantage of attaching a stone to the launching device is not understood. Indeed, experiments indicate that the added mass results in a slightly slower launching speed of the spear.

A toad appears to snare its prey with its tongue by a mechanism similar to that of an atlatl. When it spots the prey, the toad rapidly propels its tongue toward the prey, but the soft outer portion of the tongue remains folded back on the (now stiffening) rest of the tongue. As the tongue nears the prey, the outer portion is suddenly rotated forward to plop down on the prey. By thus rotating the outer portion forward while the rest of the tongue is still moving forward, the toad adds to the kinetic energy of the outer portion. This extra energy increases the chance that the prey will stick to the outer portion even if the prey lies on a surface (such as a leaf) that yields when the prey is hit. Once the prey is stuck, the toad rapidly pulls the tongue and prey back into its mouth.

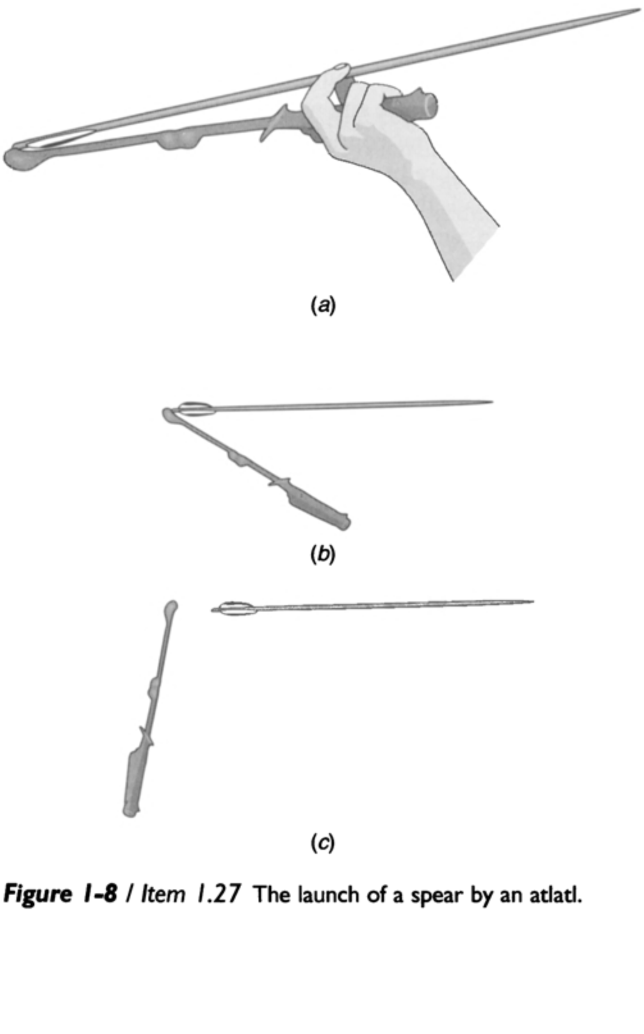


***Figure 1-8** / Item 1.27* The launch of a spear by an atlatl.

1.28 • Slings

Someone moderately skilled with a sling can hurl a stone of 25 grams at a speed of 100 kilometers per hour (about 60 miles per hour) to hit a target 200 meters or more away. How is the stone given such a large speed, or more to the point, such a large momentum? In some battles of the past the weapon proved more valuable than an arrow, for even if an enemy soldier wore leather armor, the stone's collision could inflict lethal internal damage whereas an arrow might just be deflected. When the soldier lacked any armor, the stone could easily penetrate the body. A sling was also more accurate than an arrow and could often travel farther. For this reason, slingers were often grouped behind the archers, who needed to be closer to the enemy to be effective.

The most famous battle involving a sling was, of course, the brief one between David and Goliath. For 40 days the giant Philistine had challenged the Israelis, but none had dared take up the fight until David. He chose five smooth stones from a brook and then walked into range of Goliath. David kept the situation safe because Goliath's sword was useless at such a large separation. David retrieved the first stone from his carrying pouch and slung it at the giant. The stone hit with such momentum that it burrowed into the giant's forehead.

Answer The stone, which may be a real stone or one that is made from clay or metal, is placed in a flexible pocket to which two straps are attached. The opposite ends of the straps are held in the hand—the right hand if the person is right-handed. One of the straps is fastened around several fingers, while the other one has a knot that rests against the thumb and forefinger.

The straps are made taut by the left hand as all is lifted above the person's head. There the left hand lets go and the right hand does work on the stone by pulling the pocket toward the rear, then down and toward the front. This motion is accomplished largely with the wrist rather than the whole arm. The stone is then pulled around in a vertical circle three or four times to build up its kinetic energy. Just as the stone reaches the bottom of the last circle, the knotted strap is released, loosening the stone, which then flies toward the target.

The advantage in the weapon is that work can be done on the stone for a longer distance and time than if the stone is merely thrown forward like a baseball. The radius of the circle also plays a role, because the larger it is, the greater the launch speed of the stone is, and so also the range. In times past some soldiers carried several slings with different strap lengths in order to sling stones at different ranges.

1.29 • Tomahawks

Someone skilled at burying the sharp edge of a tomahawk in a target may just be experienced, but is there any scientific basis to the skill? Knowing that basis, would you be able to hit a target on the first try?

Answer To launch a tomahawk, you hold its handle perpendicular to your forearm, pull your arm back past your head, and then rotate the forearm and tomahawk forward around the elbow, releasing the tomahawk so that its velocity is horizontal and forward. The weapon then spins about its center of mass (located in the heavy head) as it flies through the air.

Unless you are well practiced with throwing one, a tomahawk will probably have a different launch speed and spin rate every time you throw it. That seemingly means that hitting a target at a certain distance will take luck. However, a curious feature of the launch is that the ratio of the launch speed to the spin rate is independent of how rapidly you bring your forearm forward. That independence means that, regardless of your launch, the tomahawk will turn and be in a striking orientation at certain distances from you. So, to hit a target, all you must do is stand at one of those certain distances (which you would determine by observation or by calculation) and throw the tomahawk. You probably could accomplish this on the first try.

Of course, when tomahawks were really used as weapons in the early days of the United States, a warrior could not afford to adjust his distance from a target before he threw his tomahawk. Instead, he would quickly adjust the distance between his hand and the head of the weapon. That hand–head distance determines the values of the target distances at which the weapon will be in striking orientation. To make this adjustment for any target distance in a fighting situation, the handle of the tomahawk must be long; indeed, early tomahawks were made with long handles.

1.30 • Bolas

A bola consists of three heavy balls connected to a common point by identical lengths of sturdy string (Fig. 1-9*a*). To launch this native South American weapon, you hold one of the balls overhead and then rotate that hand about its wrist so as to rotate the other two balls in a horizontal path about the hand. Once you manage sufficient rotation, you cast the weapon at a target. During the weapon's flight, its rotation rate increases, and when it reaches the target, the string rapidly wraps around the target until the balls crash into the target. Why does the rotation rate of the balls increase during the flight?

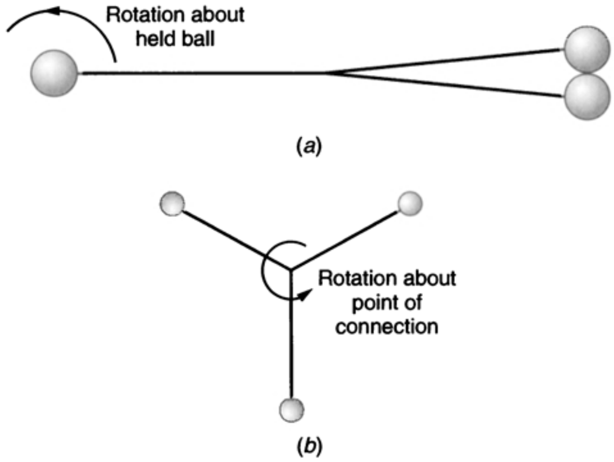


Figure 1-9 / Item 1.30 A bola as (*a*) it is thrown and (*b*) it flies through the air.

Answer Let L be the length of the string from any one of the balls to the common point to which the balls are attached. As you spin up the bola with your hand holding one of the balls, the other two balls begin to orbit (together) about the held ball at a distance of $2L$. But once you cast the bola and it flies freely through the air, this configuration of two balls orbiting the third ball is unstable, and the bola soon begins to orbit about the common connection of the three strings, at a distance of L and with the three balls symmetrically placed about that connection (Fig. 1-9*b*). This change in configuration reduces the bola's mass distribution. Because the bola is flying freely, its angular momentum cannot change. So, with the mass distribution decreasing, the rotation rate must increase. The situation is similar to an ice skater spinning on point while bringing in the arms to reduce the mass distribution and thus increase the rotation rate.

1.31 • Siege machine

Suppose that you are in a medieval siege of a heavily fortified castle. You don't want to get too close to the castle because of the archers on the fortress walls. From a distance, how could you attack the walls?

Answer Two main types of siege machines were used to attack fortified walls: the catapult and the trebuchet. The catapult was effectively a bow that fired an arrow or a stone (perhaps 25 kilograms). The machine was much bigger than an archer's bow, the arrow could have been 2 meters long, and the string was ratcheted back so that far more energy could be stored and then transferred to the arrow during launch. Still, the arrows could do little damage against a stone wall because both the energy and momentum of the arrow were not large.

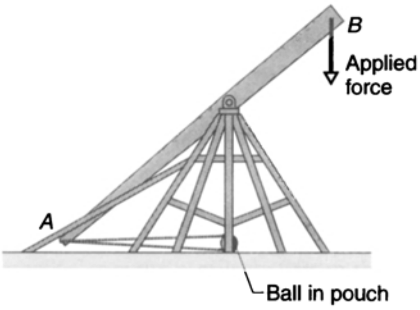


***Figure 1-10** / Item 1.31* Trebuchet.

The trebuchet was far more destructive, and some models could hurl 1300 kilogram stones. They could also hurl dead horses or even bundles of human corpses. The latter was used when an attacking army was ravished by the Black Death and they wished to send the disease into the fortress to infect the defenders. In more humorous situations, modern trebuchets have been used to hurl pianos and even small cars.

Figure 1-10 gives the essential trebuchet design. A projectile lies in a pouch that is attached to end *A* of a long wood beam. A large downward force is suddenly applied to end *B* so that the beam is rotated around an axle and the pouch is rapidly brought up and then over the machine. As the pouch and projectile pass over the machine, the pouch's tie on the beam slips off a hook and then they fly through the air. The energy given to the projectile thus comes from the work done by the force applied at end *B*.

That force could simply be the coordinated downward pull by several men. However, the trebuchets that could hurl large objects significant distances used a heavy counterweight at *B*; then the applied force was the gravitational force acting on the counterweight. The counterweight was first gradually lifted by men using a ratchet. Then the counterweight was allowed to fall so that some of the gravitational potential energy stored in it by the men could be transferred to the kinetic energy of the projectile. The kinetic energy and momentum of the projectile were very large and if the projectile was stone, it could knock a hole into a fortress wall. Once trebuchet use became widespread, castle walls were redesigned so that they could better withstand the impacts. For example, some walls were slanted instead of vertical so that the projectile might move somewhat along the wall instead of directly into it.

1.32 • Human cannonball

The circus stunt in which a person is propelled into the air from a cannon or some other contraption began in the early 1870s when a human cannonball was sent up only a short distance and was caught by an assistant on a trapeze bar. When the Zacchini family revived the stunt in 1922, they decided to make more daring flights by having the performer fly through the air and land in a net. Their first cannons depended on springs to propel the performer, but by 1927 compressed air was put to work.

Striving to increase the excitement of the stunt, the family began to send the performer over Ferris wheels. They started with one Ferris wheel, but by 1939 or 1940 they reached the limit of even unreasonable safety when Emanuel Zacchini soared over three Ferris wheels and through a horizontal distance of 70 meters.

The human cannonball act is probably one of the most impressive acts of projectile motion, for it obviously involves the chance that the performer might miss the net. Are more subtle dangers involved?

Answer To get ready for a shot, the performer would slip his or her legs down inside "metal trousers" on the piston inside the barrel of the cannon. The trousers were fitted closely to the shape of the legs and were needed to supply support when the piston was suddenly shoved upward. The subtle danger involved that shove, because the acceleration required for a long flight was so severe that the performer would momentarily black out. Part of a performer's training was to regain awareness during the flight so that a controlled roll could be made on the net. If the landing were uncontrolled, then the collision and rebound on the net could easily break the limbs or neck of the performer. The family claimed that the muzzle speed of a performer was as much as 600 kilometers per hour, but a speed of less than 160 kilometers per hour seems more credible.

Another subtle danger lay in the air drag encountered by a performer. The size of the air drag depended on the orientation of the body as it flew through the air: It was smaller if the body was oriented along the direction of travel, and larger if the body was oriented perpendicular to that direction (which might happen during the descent). A smaller air drag increased the range of the shot; a larger air drag reduced the range. Because the performer's orientation varied from shot to shot, someone had to calculate (or guess) approximately how far the performer would go and then make the net wide enough to account for the possible variations due to the air drag.

1.33 • Basketball shots

Basketball is, of course, a game of both skill and chance. Is there some best way in which to throw the ball to increase the probability of making a basket? For example, is it better to toss the ball in a high arc or to throw it along a flatter trajectory? When might spin be beneficial, and when is it undesirable?

In a *free throw* (where a player gets an uncontested shot at the basket from about 4.3 meters), a player might employ the *overhand push shot*, in which the ball is pushed away from about shoulder height and then released. Instead, the player might use an *underhand loop shot*, in which the ball is brought upward from about the belt-line level and released. The first technique is the overwhelming choice among professional players, but the legendary Rick Barry set the record for free-throw shooting with the underhand technique. Does one technique actually provide a better chance at making a shot?

Answer From any position on the court, there is a wide range of angles at which you can launch the ball to send it through the basket, provided that you give the ball the proper speed. However, the fact that the ball is smaller in diameter than the basket allows a certain margin of error in the launch speed. If you choose a low angle, the margin for error is small and you must be quite accurate. You also must give the ball a large speed, which requires more force from you and which works against accuracy. If, instead, you choose an intermediate angle, the margin for error in the speed is larger, and the speed and force are smaller. So, you have a better chance at making the shot. For even larger angles, the margin for error is approximately the same, but the required speed and necessary force are larger, which makes larger angles less desirable.

Novice players usually shoot the ball along too flat a trajectory, but seasoned players learn through practice to arc the ball into the basket. The higher the shot is released, the slower the required launch must be, which gives an advantage to a tall player. The height advantage is so strong that some players elect to release the ball during a jump even when unchallenged by an opponent. If you put backspin on the ball and happen to hit the backboard instead of the basket, the spin creates friction that may cause the ball to rebound into the basket. When the shot is taken from one side, sidespin on the ball may also help.

The underhand free throw has a greater chance of success than the overhand throw, but the reasons are still debated. The success might be because the underhand throw is easier to execute, but a greater advantage seems to lie in the fact that the throw allows a player to put more backspin on the ball, which can make up for an errant toss onto the backboard.

SHORT STORY

1.34 • Records in free throws

In 1977, Ted St. Martin set the world's record for consecutive baskets while standing at the free-throw line—he made the shot 2036 times. The next year Fred L. Newman made a stranger record. While blindfolded, he made 88 consecutive baskets from the line. During a 24 hour period several years later, and with his eyes open, Newman managed to score 12 874 baskets out of 13 116 attempts.

1.35 • Hang time in basketball and ballet

Some skilled basketball players seem to hang in midair during a jump at the basket, allowing them more time to shift the ball from hand to hand and then into the basket. Similarly, some skilled ballet performers seem to float across the stage during the leap known as a *grand jeté*. Obviously no one can turn off gravitation during a jump or a leap, so what accounts for these two examples of apparent hanging in midair?

Answer The hang-in-midair of both basketball player and ballet performer is an illusion. In basketball the illusion is primarily due to a player's agility to perform so many maneuvers during the jump. In ballet's grand jeté, the illusion comes from a shift of the performer's arms and legs during the leap: She raises her arms and stretches her legs out horizontally as soon as her feet leave the stage. These actions shift her center of mass upward through her body (Fig. 1-11). Although the center of mass faithfully follows a

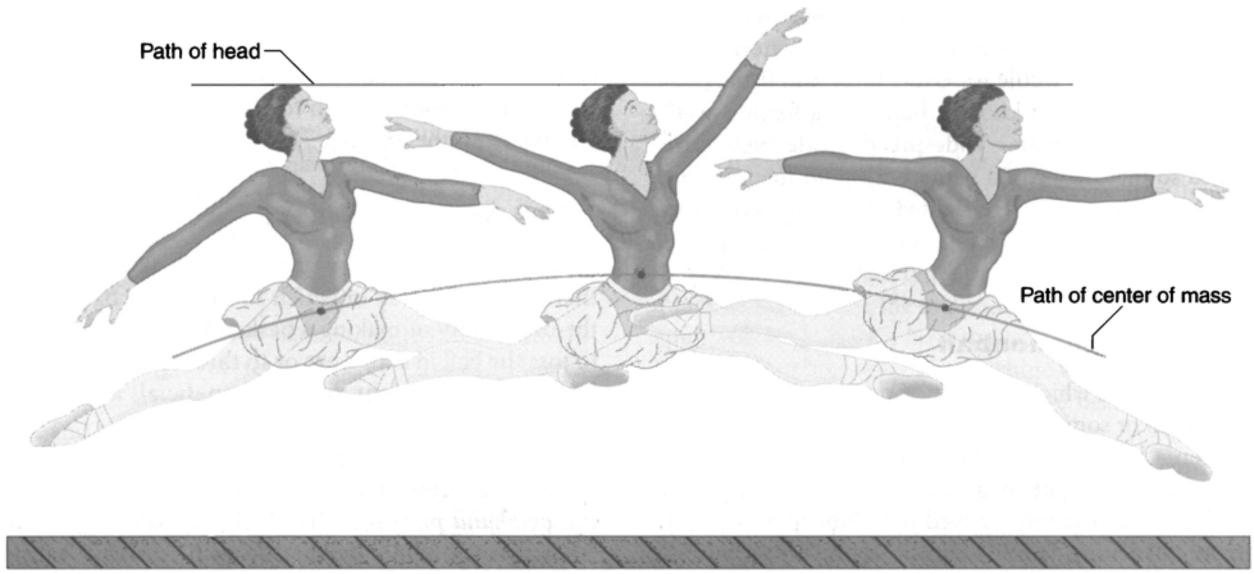


Figure 1-11 / *Item 1.35* Path of the center of mass during a grand jeté.

(curved) parabolic path across the stage as required by gravitation, its movement relative to the body decreases the height that would have been reached by the head and torso in a normal leap. The result is that the head and torso follow a nearly horizontal path during the middle of the leap. This path seems strange to the audience who, out of normal experience, expect a parabolic path even if they do not even know the term.

A basketball player can similarly flatten the path taken by the head during a jump across the floor if the player pulls up the legs and raises up the arms and ball. However, I don't think that this technique is commonly planned by players. Although a player raises the arms and ball toward a basket during a jump near the basket, a player rarely lifts the legs, and the resulting slight flattening of the path taken by the head hardly seems to fool a defensive player who jumps alongside the shooting player.

1.36 • Golfing

How should you swing a golf club to best hit a golf ball during a drive? For example, should you swing down as hard as you can, somewhat like striking an assailant with a club in a fight? If, instead, you should increase or decrease your effort sometime during the swing, will the flexibility of the shaft of the golf club affect when you make that change?

Why is hitting a 1 meter putt considerably harder than a half meter putt? Is a 3.5 meter putt considerably harder to hit than a 3.0 meter putt? Why can the ball be rolling directly toward the cup and yet still not go in?

Answer When you swing the golf club down during a drive, you begin the swing with your wrists cocked so that the club is at an angle of about 90° with your arms. If you swing the club as in a fight, you will automatically allow the wrists to uncock during the swing. The club head will actually have a greater speed when it hits the ball if you resist that uncocking by reducing the torque you apply to the club somewhere during the swing. Just when this uncocking should be done is learned through experience. Once the wrists are uncocked, the club swings around the wrists as they swing around the shoulders, resulting in the increased speed of the club head.

Many players believe that the flexibility of the club shaft affects the flight of the ball because it determines the angle at which the club's head meets the ball. The argument has been that a more flexible shaft first bends backward during the swing and then springs forward more just before impact with the ball than does a stiffer shaft and thus delivers more energy to the ball. However, studies show that the club's flexibility has little effect on the ball's flight—indeed, greater flexibility might result in a decrease in the energy transferred to the ball because the impact sets the club oscillating. Thus, a stiff club is more desirable because it gives greater control in hitting the ball squarely.

One measure of the difficulty of a putt is the angle occupied by the cup in the ball's point of view. If you move the ball away from the cup, the angle initially decreases rapidly, which means that the difficulty of making the shot increases rapidly. However, beyond a distance of about a meter, the angle begins to decrease rather slowly, which means that the associated difficulty begins to increase rather slowly. Of course, this simple analysis overlooks other difficulties with a long putt, such as the increased number of variations in the grass texture and in the slope of the ground along the path to the cup.

If a ball is rolling directly toward the cup, it will not score if its speed is above some critical value when it leaves the near side of the cup's rim. Such a ball travels across the mouth of the cup, falling during its passage, but the fall is insufficient to keep the ball from rolling out of the cup once it hits the wall on the far side.

SHORT STORY

1.37 • Curtain of death of a meteor strike

Whenever a metallic asteroid reaches the ground (instead of burning up in the atmosphere), it digs a crater by throwing rock into the air. However, the *ejecta material*, as it is called, does not come out haphazardly. Rather, the faster moving rocks tend to be ejected at steeper angles to the ground. If you were to witness this ejecta fly toward you, you would see that at any instant it forms a thin, curved curtain (Fig. 1-12): Particles higher in the curtain are ejected at greater speeds and angles than the particles lower in the curtain. The slower rocks hit the ground earlier than the higher rocks; thus you see and hear a steady pounding of the ground as the curtain moves toward you.

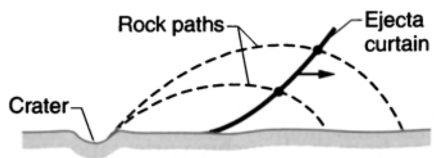


Figure 1-12 / *Item 1.37* Rocks ejected from a meteor strike.

1.38 • The high jump and the long jump

A novice in the sport of high jumping might be tempted to hurdle over the bar by throwing one leg up over it and then dragging the other leg over, while bent forward at the waist. A more successful jump is made with the *straddle*, in which the person essentially rolls over the bar face down and with the length of the body parallel to the bar.

When Dick Fosbury won the high-jump contest in the 1968 Olympics in Mexico City, he introduced what appeared to be a bizarre way to jump. The technique is now known as the *Fosbury flop* and is used almost universally by high jumpers. To flop, a competitor runs with a measured pace up to the bar and then twists at the last moment, going over the bar backwards and face up. What advantage does such a style have? Why is the approach to the bar at a measured pace? Surely a faster pace would give the athlete more energy to jump higher.

One of the most stunning events in the history of track and field sports also occurred at the Mexico City Olympics. In mid-afternoon on October 18, Bob Beamon prepared for the first of three allowed attempts at the long jump by measuring off his steps along the approach path. Then he turned, ran back along the path, hit the takeoff board, and soared through the air. The jump was so long that the optical sighting equipment for measuring the jumps could not handle it, and a measuring tape had to be brought out. One judge said to Beamon, who then sat dazed off to one side, "Fantastic, fantastic." The jump was an astounding 8.90 meters, easily beating the previous record of 8.10 meters (a difference of nearly two feet!).

Beamon was certainly aided somewhat by the wind at his back, because it was just at its allowed upper limit of 2.0 meters per second. Did he also benefit from the high altitude and low latitude of Mexico City; that is, did matters of air density and the strength of gravity account for his astonishing jump?

The length of a long jump is measured to where the jumper's heels dig out sand upon landing, unless the jumper's buttocks then land on and erase the heel marks. If those marks are erased, the length of the jump is only to the near edge of the hole left in the sand by the buttocks. Thus, landing in the proper orientation is important in the long jump.

When a long jumper takes off, with the final footfall on a takeoff board, the torso is approximately vertical, the launching leg is behind the torso, and the other leg is extended forward. When the long jumper lands, the legs should be together and extended forward at an angle so that the heels will mark the sand at the greatest distance but still disallow the buttocks from erasing that mark. How does the jumper manage to go from the launching orientation to the landing orientation during the flight?

In the standing long jump in the ancient Olympiad, why would some of the athletes jump with handheld objects called *halteres* that were several kilograms in mass?

Answer The height that is recorded in high jumping is, of course, the height of the bar, not the maximum height of the head or some other part of the jumper. Suppose that during a jump, the athlete can raise the center of mass (com) to a height L. If the athlete hurdles over the bar, the bar must be considerably lower than L if the body is not to touch it, and so the height of the jump is not very much (Fig. 1-13a). In a straddle jump, the body is laid out horizontally and can pass over the bar with the bar much closer to the center of mass, and so the bar can be higher (Fig. 1-13b). In a flop, the curvature of the body around the bar lowers the center of mass to a point below the body, and the athlete can pass over an even higher bar than with a straddle jump (Fig. 1-13c). The last-moment twist and backward leap in a flop also gives a stronger launch.

The approach to the jump is slow compared to, say, a sprint, because the key to winning is a flawless execution, and so timing is essential. At the end of the approach, the athlete plants the launching foot well ahead of the body's center of mass, and then, as the launching leg flexes, the body is twisted around that foot. This procedure allows some of the kinetic energy of the run to be stored in the flexing leg. As the leg then pushes against the ground, it propels the athlete upward, transferring some of the stored energy, and also additional energy gained from muscular effort, into the flight of the athlete.

Beamon's long jump was aided only slightly by the wind and the location. Mexico City is at an altitude of 2300 meters, which is considerably higher than the altitudes of many other locations for the Olympics. The high altitude meant that the air density was low, and so the air drag retarding the jump was smaller than if the jump at been at a lower altitude. The high altitude also meant that the gravitational acceleration was smaller, and so the gravitational pull that opposed Beamon's launch and that eventually pulled him back to the ground was smaller. The acceleration and pull were further reduced because of the *effective* centrifugal force on Beamon due to Earth's rotation. That effective force is larger at lower latitudes, because such places travel faster during the rotation.

However, all of these factors played only a small role in the jump. So, why then did Beamon travel so far? The primary reason is that he hit the launch board while running rapidly. Most long jumpers approach more slowly so as to avoid placing their last step just past the board, which would disqualify the jump. They also want to avoid taking off before the board and losing the solid support it gives during the launch while also losing distance in the jump since the jump is measured from the board. Because the board is only 20 centimeters long, the final step must be planned.

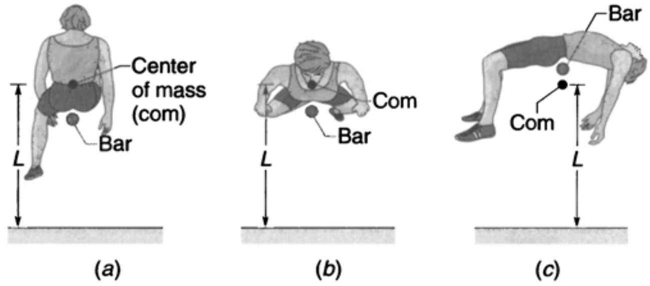


Figure 1-13 / Item 1.38 The (*a*) hurdle, (*b*) straddle, and (*c*) flop styles of high jumping.

Beamon, who was known for disqualified jumps, apparently decided to gamble on his first try and sprinted to the board. His last step barely avoided extending beyond the board. Had he gone beyond the board, he presumably would have made his next two jumps with more concern about the board and less speed.

No one jumped as far as Beamon, including Beamon himself, for the next 23 years. Then, finally, at the 1991 World Track and Field Championship, Mike Powell jumped 8.95 meters—2.0 inches farther than Beamon. He did it in Tokyo and thus without any benefit of higher altitude, and he did it with only a mild wind of 0.3 meter per second at his back. Powell stunningly demonstrated that the effects of altitude and wind are secondary to athletic ability.

To consider the reorientation of a long jumper during flight, suppose that the jump is to the right in your perspective. During the launch from the board, the force on the launching foot from the board produces a clockwise rotation of the body, which tends to bring the trunk of the body forward and the forward leg rearward. This tendency of clockwise rotation is increased as the trailing leg is brought forward to ready for the landing. The reason is that the jumper is then free of the ground, and so the angular momentum of the body must remain constant. So, when the trailing leg is rotated counterclockwise to be forward, the rest of the body tends to rotate clockwise.

To decrease the clockwise rotation, so that the jumper is in the proper orientation for landing, the arms are rapidly swung clockwise about the shoulders. In addition, the legs might continue to move as in running, with a leg outstretched when rotated clockwise to the rear and pulled in when rotated counterclockwise to the front. (None of this motion alters how far the jumper goes; it only alters the orientation of the body.) Novice jumpers often fail to swing the arms sufficiently or, worse, they swing one or both arms in the wrong direction. The trunk and legs are then not in the best orientation, and the jump is short because the heel marks are short or the buttocks erase the heel marks.

The halteres used by jumpers in the ancient Olympiads could increase the length of the jump. An athlete would swing the handheld objects forward and backward in preparation for a jump, then swing them forward during the first part of the jump, and finally swing them backward in preparation for the landing. Properly used, this technique could add 10 or 20 centimeters to the length of the jump for two reasons. (1) As the center of mass of the athlete–halteres system moved through the air, the last backward swing shifted the halteres backward relative to the center of mass and thus shifted the athlete forward relative to the center of mass. (2) During the launch, the forward swing of the halteres increased the downward force on the launch point, thereby giving a greater launch force on the athlete. (In effect, the athlete was using shoulder and arm muscles in addition to the leg muscles during the launch.) A jump could have been increased a bit more if the athlete would have hurled the halteres backwards during the last part of the flight, effectively rocketing the body forward. The center of mass of the athlete–halteres system still lands at the same point, but the athlete is now a bit forward of that point.

1.39 • Jumping beans

If a young girl who is sitting on a blanket gathers up the blanket's four corners and then pulls up very hard on them, can she lift herself? Well, of course not, although I know of one girl who tried with all her might. How, then, do jumping beans manage to jump up into the air?

Answer A bean contains a small worm that first pushes off from the bottom of the bean and then collides with the top, propelling the bean upward. The external force (the force outside the worm–bean system) that is responsible for the motion is the upward force on the worm as it initiates the jump.

1.40 • Somersault of a click beetle, attack of a mantis shrimp

If you poke a click beetle when it is lying on its back, it throws itself up into the air as high as 25 centimeters, with a noticeable click. During the leap it may turn over so that it lands right-side up. The launch involves an acceleration that is as large as 400 *g*s (that is, 400 times the acceleration of gravity) and requires a power that may be 100 times the possible power of any one muscle in the beetle. How does the beetle produce such enormous power, which, of course, cannot be due to its legs because it begins on its back? One clue is the click and another is the fact that the beetle cannot immediately repeat the performance.

The peacock mantis shrimp (*Odontodactylus scyllarus*) attacks its prey by quickly rotating a feeding appendage toward it. The appendage does not strike the prey but instead produces air bubbles that produce a destructive sound wave when they suddenly collapse. The acceleration at the outer tip of the appendage can be as much as 10 000 *g*s. How can a shrimp achieve such high acceleration?

Answer The beetle's leap is somewhat like a mousetrap that is triggered—both jackknife upward. In the beetle a muscle in the front of the body slowly contracts and moves a peg-like section over the *mesosternum* until a notch in the peg (the peghold) catches on the *lip* of the mesosternum, arching the beetle (Fig. 1-14*a*). After tension builds in the muscle, the peg suddenly slips over the lip and slides

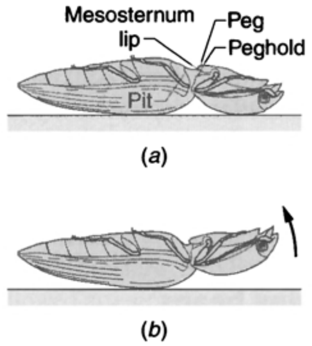


Figure 1-14 / Item 1.40 **(*a*) Click beetle on its back, with peghold caught and muscles under tension. (*b*) Peg has slipped over the catch and beetle jackknifes upward.**

down into a pit. The abrupt slip forces the front end of the beetle to jackknife upward and causes the hind end to push down on the ground (Fig. 1-14*b*). The push hurls the beetle upward, and the rotation initiated by the slip of the peg allows the beetle to spin around its center of mass while in the air. It may spin around enough so that it lands on its feet. The click emitted by the beetle is produced either by the slip of the peghold over the lip or the abrupt stop of the peg after it enters the pit.

The initial slow contraction of the muscle allows the beetle to store energy. The sudden release of that energy is responsible for the high power of the jump. Before the jump can be repeated, energy must again be stored, which takes some time. This type of energy storage and sudden release is used by many animals for abrupt motion, either to catch lunch or to avoid becoming lunch.

A similar process is used by mantis shrimp. The appendage used in an attack is held tightly against the body while a saddle-shaped element is slowly put under tension like a spring can be compressed. The appendage is held in place by a latch. Once the saddle-shaped element is under maximum tension, the latch is released and the element drives the rapid rotation of the appendage.

SHORT STORY

1.41 • Some record lifts

In the sport of weight lifting, records are frequently broken, but the record for the greatest lift of any kind was firmly set in 1957 by Paul Anderson. He employed a *back lift* in which he stooped beneath a reinforced wood platform that was supported by sturdy trestles. In front of him was a short stool against which he could both steady himself and push downward. On the platform were auto parts and a safe filled with lead. With an astonishing effort of both arms and legs, he lifted the platform—the composite weight was 6270 pounds (27 900 newtons)!

Perhaps equally impressive was a reported lift by Mrs. Maxwell Rogers of Tampa, Florida, in April 1960. Discovering that a car had fallen off a bumper jack and onto her son who was working underneath the car, she lifted one end of the car so that her son could be rescued by a neighbor. The car weighed 3600 pounds (16 000 newtons), of which she presumably lifted at least 25%. She suffered several cracked vertebrae. (Accounts of this sort appear occasionally in newspapers. In a panic, an untrained person can manage to lift something that has a weight greatly exceeding the person's body weight and that could not possibly be lifted under calmer circumstances.)

1.42 • Chain collisions

If one ball runs into a stationary ball, under what conditions does the second ball receive the most energy? Are the same conditions needed if the second ball is to receive the greatest speed? What are the answers if a ball runs into a chain of initially stationary balls?

Suppose that initially there is a large ball that is moving and a smaller ball that is stationary. Can you increase the energy that is given to the smaller ball by inserting additional balls between the two? If so, what should the masses of the intermediate balls be?

A golf ball is flying toward your head. If you wish to decrease the energy that will be transferred to your head, should you guard your head with a hand so that the hand is knocked into your head?

A popular toy consists of a row of adjacent balls that can each swing as a pendulum (Fig. 1-15*a*). The balls are elastic; that is, only a little energy is wasted when they collide with other objects. You draw back an end ball and then release it

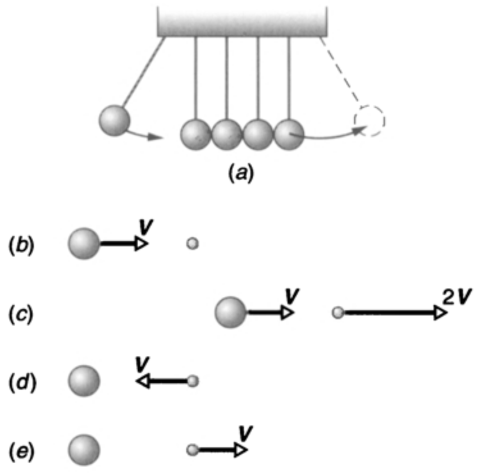


Figure 1-15 / Item 1.42 **(*a*) The first ball is released; the last ball is knocked aside. (*b*) Before and (*c*) after a collision of a very large ball with a very small ball. (*d*) Before and (*e*) after the collision from the perspective of the large ball.**

so that it crashes into the next ball. Why does only the ball at the opposite end of the row move?

Rehang the balls so that there is a small space between them, and then send the first ball into the second at a slight angle to the row. Although the initial collisions are skewed, the misalignment gradually disappears as the collisions proceed. However, if you increase the space between the balls enough and repeat the demonstration, the misalignment increases with each collision. The collisions may even stop if one ball is knocked to the side so much that it fails to hit the next ball. Why does the alignment–misalignment behavior depend on the spacing between the balls?

Answer The second ball receives the greatest energy when its mass matches that of the first ball. If the balls are highly elastic, almost the full energy is transferred, in which case the final speed of the second ball almost equals the initial speed of the first ball, and the first ball stops.

The second ball receives the greatest speed when its mass is much less than the mass of the first ball. Let V represent the speed of the first ball (Fig. 1-15*b*). If the mass ratio is very large and the collision is very elastic, the second ball may receive a speed that is $2V$ (Fig. 1-15*c*). That may seem incorrect, but for a moment take the perspective of the first ball, as if you were that ball. The second ball seemingly approaches you with a speed of V (Fig. 1-15*d*), bounces elastically, and then heads away from you with a speed of V (Fig. 1-15*e*). Now go back to your original perspective. The second ball moves away from the first ball with a relative speed of V. What is the first ball doing? Since the second ball has such little mass, the collision does not appreciably alter the speed of the first ball and it is (approximately) still V. So, the speed of the second ball must be $V + V$, or $2V$. If there is a chain of such collisions, then the speed imparted by each collision is (approximately) double that imparted by the preceding collision.

When the end balls are already chosen and you want to improve the transfer of energy to the smaller ball, insert intermediate balls such that each one has a mass that is the geometric mean of the masses on the opposite sides of it. (The geometric mean of the masses is the square root of the product of the two masses.) Other choices of intermediate mass also improve the transfer of energy but not as much.

This conclusion figures into the question about the golf ball. If you guard your head with a hand, you may actually increase the transfer of energy to your head, because your hand has a mass that is intermediate to the masses of the ball and your head. Still, inserting a hand is wise because it is broad and will spread the force you will receive on your head.

The toy with a series of pendulum-like balls is usually explained in terms of the momentum and kinetic energy of the initially moving ball. The only way for those quantities to go unchanged as they are relayed through the series is for the final ball to end up with all of the momentum and kinetic energy. So, in the end, it alone moves. However, the explanation is misleadingly simple, because the actual behavior of the intermediate balls can be quite complex if they are initially touching.

In the demonstration where the first ball hits the second one at a skewed angle, the ratio of the separation D between the balls to their radius R is important. If D/R is smaller than 4, the misalignment decreases during the collisions because the collisions gradually shift inward and become more direct. If the ratio is greater than 4, the misalignment increases because the collisions shift gradually outward on the curved surfaces of the balls.

1.43 • Dropping a stack of balls

Hold a baseball just above a basketball with a slight separation and then drop the balls from about waist height (Fig. 1-16*a*). Although neither ball bounces particularly well on its own, the combination of the two gives a surprising result: The basketball goes almost dead on the floor and the

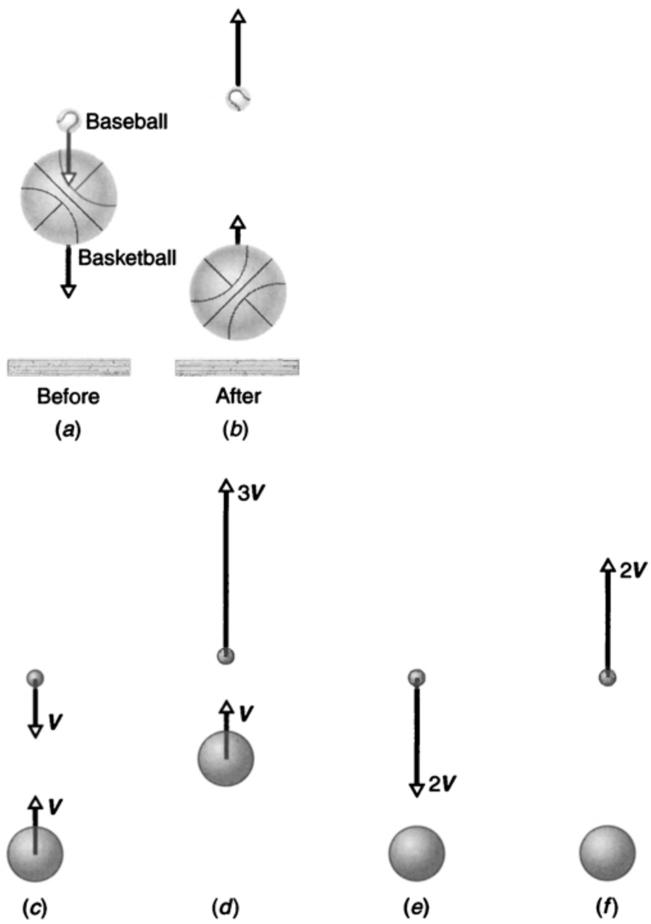


Figure 1-16 / *Item 1.43* (*a*) Before and (*b*) after a baseball and basketball are dropped together on a hard floor. (*c*) Before and (*d*) after a collision of a very large ball with a very small ball. (*e*) Before and (*f*) after the collision from the perspective of the large ball.

baseball may bounce to the ceiling (Fig. 1-16*b*). The height reached by the baseball is greater than the sum of the heights that the balls would bounce individually. (Be careful. If the alignment is off, the baseball shoots out sideways with such speed that it can injure you or someone nearby.) If you repeat the demonstration but add a small elastic ball to the top of the stack, the third ball takes off like a rocket and can go even higher than the baseball did, although it receives less energy.

In theory and if the balls are chosen appropriately, the top ball in a dropped stack of two balls can reach a height that is nine times the height from which the stack is dropped. With three balls, again appropriately chosen and under ideal conditions, the top ball can reach a height that is 49 times the drop height.

You might like to experiment with a variety of different balls, such as a Ping-Pong ball, a "Super Ball" (a highly elastic ball, under trademark by Wham-O Inc.), or a tennis ball. How should the balls in a stack be chosen to launch the top ball to a great height, and why does it go so far?

Answer When a stack of two balls is dropped, the bottom ball rebounds from the floor and then collides with the still falling second ball. The collision transfers energy to the top ball and gives it an upward velocity. Suppose that you want to maximize the transfer of energy so that the bottom ball goes dead. If the balls are elastic, then the best transfer of energy occurs when the bottom ball is about three or four times as massive as the top ball, as is the case with a basketball and a baseball.

If, instead, you want the top ball to go as high as possible, you should choose one that is much lighter than the bottom ball. The height reached by the top ball depends on the square of the velocity it receives from the collision. If the mass of the top ball is much smaller than the mass of the bottom ball, the top ball gets a large velocity-squared and can reach a height that is nine times the drop height.

To see the result, first examine the speeds of the balls just before their collision. The top ball falls with a speed V while the bottom ball heads upward with the same speed V (Fig. 1-16*c*). If the collision is very elastic, the second ball may receive a speed that is $3V$ (Fig. 1-16*d*). That may seem wrong, but for a moment take the perspective of the first ball, as if you were that ball. The second ball seemingly approaches you with a speed of $2V$ (Fig. 1-16*e*), bounces elastically, and then heads away from you with a speed of $2V$ (Fig. 1-16*f*). Now go back to your original perspective. The second ball moves away from the first ball with a relative speed of $2V$. What is the first ball doing? Since the second ball has such little mass, the collision does not appreciably alter the speed of the first ball and it is (approximately) still V. So, the speed of the second ball must be $V + 2V$, or $3V$.

If you play with a larger stack of balls, you need to arrange for the masses of the balls to decrease upward in the stack. When the bottom ball rebounds, it hits the second ball and transfers some of its energy. Once the second ball is redirected upward, it runs into the descending third ball, and transfers some of its energy. The third ball then reverses direction and runs into the fourth ball, and so on. If the stack were large enough, you could, theoretically, launch the top ball into orbit.

SHORT STORY

1.44 • A crashing demonstration

When he was a student in the 1970s, John McBryde of Houston and two other students experimented with the physics of dropped balls by releasing a softball and basketball from a third story walkway that linked two dorms. Repeatedly, the basketball went dead on the ground and the softball was hurled up well over their heads, at least 10 meters above the ground. The stunt was great fun until on the last drop the alignment of the balls was skewed, and the softball shot through the window of the resident assistant, hurling glass everywhere within the room. The cost of the repair was $250, but the penalty may have been considerably higher had the resident assistant been in his room at the time.

1.45 • Karate

Consider a forward punch in which the closed fist begins palm up near the belt and is then thrust forward and turned palm down. Why is this procedure taught with two precautions: Go out to a full arm's length but no farther (you don't lean forward), and make contact with your opponent when the fist has traveled about 90% of the way out (so you aim the punch about 10% of the way into the opponent's body)? Why are the hips and torso swiveled during the early stage of the punch?

Why are a punch, chop, kick, and other maneuvers usually made with a small area of contact? How fast can an expert move fist or foot, and how much force and energy can be delivered? When a karate expert breaks the bone in an opponent, why isn't bone in the expert also broken? When a stack of objects such as wood slabs is broken, why are the objects set up with separators such as pencils?

I never broke boards in karate class, but when I began teaching I thought board breaking would make a vivid demonstration of the forces involved in a collision. So, one day as I raced off for lecture, I hastily grabbed two pine boards that I found in the lab. In class I chose a burly student to hold the boards vertically so that I might punch into them, striking with the first two knuckles on my right fist. Unfortunately, the student flinched when I struck the boards, and they did not break. I struck again and again but with no better luck. After partially covering the front board with blood and swelling my first two knuckles by several millimeters, I quit and shuffled from the classroom. These days I use a "patio brick" that rests on rigid supports at each end, and I strike the block with the bottom of my clenched fist. Why is the new strategy more successful than the previous one?

Answer You should not lean forward into the punch for at least two reasons. You want to be stable so that you can immediately deliver another strike, and you want proper stance so that the force you experience does not break one of your bones. Karate experts can throw a barrage of strikes that are so fast that you cannot see them clearly. Ron McNair, one of the astronauts killed in the explosion of the *Challenger* space shuttle, was such an expert. He could deliver a multitude of strikes with hands, feet, knees, and elbows so rapidly that he appeared to be a fluid flowing around his opponent.

When you fight in karate, you want to make contact with your opponent when your fist is traveling its fastest, because it then has the greatest momentum and you will deliver the greatest force and energy. That optimum point is when the fist is about 90% of its way out, and so you mentally space the punch as if the fist will come to a full arm's extension about 10% into the opponent's body. If you make contact too early or late, the force and energy of the collision are less.

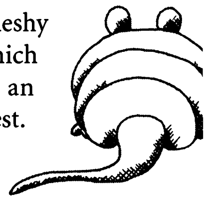
You should strike with a small part of your body so that the force per unit area on your opponent is largest and you transfer energy to only a small section of the opponent's body. The strike might then bend and break bone in the opponent. The technique also serves to protect you. When you strike properly, such as with the first two knuckles, the side of an open and rigid hand, or the edge of a foot, and also orient yourself correctly, the force in the collision does not break any of your bones.

The fact that bending is important in breaking an object is demonstrated when a karate expert strikes a board or concrete block that spans two supports. Each support is positioned at one end of the object so that when the strike is delivered to the center of the span, the force creates a large torque around each support point. The torques rotate the left and right halves of the object around the support points, and the object bends downward. If it bends enough, a crack begins at the lower surface and races upward, and the object fully breaks.

When a stack of separated objects is broken, the karate expert breaks the first object, and its pieces then break the second object, and so on. The breaking travels through the stack faster than does the expert. Dry white pine boards and concrete patio blocks are typical props for such demonstrations. The pine is cut and mounted with the grain running across the short width; such a board is weaker to a strike than if the grain runs lengthwise. The patio blocks are usually dried in an oven beforehand so that internal water is eliminated, because the water can add to the block's strength.

Collisions with board or block typically last for 0.005 second. The speed of a fist in a forward punch can be up to 10 meters per second. Kicks and downward strikes can be even faster. A strike with the fist can deliver a force up to 4000 newtons when a typical board breaks. The force is larger when the board does not break because the hand then does not penetrate through the board with some residual momentum. Instead the hand must stop or even ricochet, either of which requires that the force in the collision be greater than with the board breaking.

When my student flinched, he allowed the boards to move toward him. The action increased the duration of the collision, and because my force in the collision depended inversely on that duration, he decreased my force and it was then insufficient to break the boards. The demonstration with a brick is more dramatic but is also more trustworthy because the brick is rigidly mounted and the duration of the collision is short. It is also safer because the fleshy bottom of the fist hits instead of the knuckles, which are rather vulnerable, as anyone who has hit an opponent in the chin with bare knuckles can attest.



1.46 • Boxing

Why, exactly, do boxing gloves make boxing safer? In spite of the measure, why does the sport still lead to long-term brain damage and an occasional death?

Answer In earlier days when men fought with bare knuckles, injuries and deaths were more likely. A glove serves to spread the force out over a larger area, making injury to both fighters less probable. The glove also softens the blow because its material must be compressed during the impact. That action increases the duration of the collision and thus decreases the force in the collision. Still, especially in heavyweight boxing, the force delivered by a powerful fighter can be severe, even lethal.

A skilled fighter knows how to *roll with a punch* directed to his head; that is, he moves his head backwards. Were he to keep his head stationary or, worse, move into the punch, the force in the collision would be greater. The most dangerous time in a fight comes during the later rounds when both men are tired and unable to anticipate a punch and to respond to it by moving backward.

The most dangerous punch is one delivered to the chin or forehead, especially when the punch is skewed, because it rotates the head backward, compressing the brain stem and shearing the brain (attempting to make part of the brain slide past another part). Even if a fighter is not knocked out by a punch, the brain inevitably undergoes damage from a punch because the skull crashes into it to initiate the backward motion. The collision disrupts the blood flow in the area of the collision and abrades the surface of the brain. Shearing from the backward rotation damages the interior of the brain. Additional damage occurs on the side of the brain opposite the punch, because when the skull begins to move backward, pulling away from the brain, the fluid pressure in the space separating the skull and brain decreases, causing capillaries to rupture.

With repeated damage, the fighter's ability to think, remember, and speak diminishes and he is then irreversibly *punch-drunk*. The sport may be an adult's game, but the game reduces the capabilities of a participant to those of an infant.

1.47 • Skywalk collapse

July 17, 1981, Kansas City: The newly opened Hyatt Regency was packed with people listening and dancing to a band playing favorites from the 1940s. Many of the people were crowded onto the walkways that hung like bridges across the wide atrium. Suddenly two of the walkways collapsed, falling onto the merrymakers on the main floor, killing 114 people and injuring almost 200 others.

What caused the collapse? Certainly the weight of the throng on the walkways was a factor, but was there a structural fault in the design of the walkways? After several days of investigation, a Kansas City newspaper pointed out that a detail in the original design had been altered during construction. In the original the end of three walkways was to be suspended from a single rod hanging from the ceiling. A washer and nut threaded onto the rod just below a skywalk would bear the skywalk's weight (Fig. 1-17*a*).

Apparently someone responsible for the actual construction realized that such a suspension system would be nearly impossible to build, and so where a single rod was to run through a skywalk, two rods extending from the skywalk were used instead (Fig. 1-17*b*). How would such a simple and reasonable change lead to the tragic death and injury during the celebrations that Friday evening?

Answer Consider the way in which weight was supported at the end of the highest walkway. In the original design, the weight of the walkway and the people on it would have been supported by the nut that was to be threaded onto the rod there. How about in the altered design in which two nuts were used? On the top walkway, the nut on the rod that extended downward had to support the weight of both lower walkways and people on them. More dangerous, the nut on the rod that extended upward had to support the weight of all three walkways and all the people on them. Apparently when the walkways became crowded, the combined weight ripped or broke some of these nuts and caused the structure to collapse. A simple change—a tragic difference.

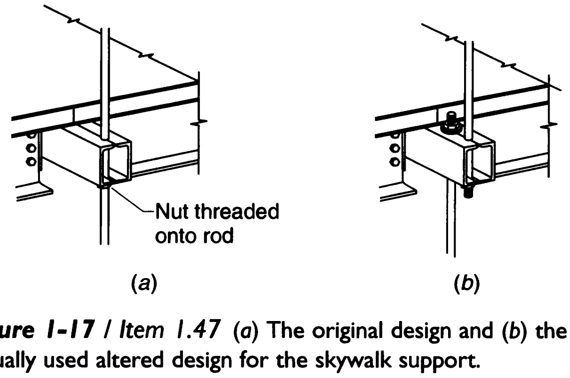


Figure 1-17 / Item 1.47 (*a*) The original design and (*b*) the actually used altered design for the skywalk support.

1.48 • World Trade Center collapse

Why, physically, did the WTC Twin Towers eventually collapse after being struck by airplanes on September 11, 2001?

Answer There have been two major explanations of the collapses of the Twin Towers.

(1) The collision and the ignition of an airplane's fuel led to a fire with a temperature exceeding 800° Celsius. Because the collision removed the thermal insulation on the vertical steel columns, the high temperature caused the columns to soften and then buckle under the weight of all the floors higher in the building. Then, suddenly, many of those vertical columns failed and the higher part of the building collapsed onto a lower floor. Even if the columns of the lower floor were not heated, this sudden and huge impact caused its supporting columns to buckle. Therefore, floors *pancaked* downward.

(2) The collision and the ignition of the fuel led to a fire, but the temperature was less than the amount needed to soften the vertical supporting columns. (As some researchers have reasoned, the airplane-damaged floors did not have enough ventilation for a large fire and the smoke escaping through the hole created by an airplane did not indicate a large fire.) Instead, the fire caused one or more floors and their supporting horizontal beams (trusses) to expand. Because these floors and horizontal beams were constrained, they could expand only by bowing, which then pulled the vertical supporting columns inward. This inward pull could have been enhanced if the columns and horizontal beams were softened by the fire. Once the vertical columns were pulled inward, they could no longer support the higher part of the building, which then collapsed.

1.49 • Falls from record heights

February 1955: A paratrooper fell 370 meters (1200 feet) from a C-119 airplane without managing to deploy his parachute. He landed on his back in snow, creating a crater that was a meter deep. Air-evacuated to a hospital, he was found to have only several minor bone fractures and a few bruises.

March 1944: Flight Sergeant Nicholas Alkemade, an RAF rear gunner on board a Lancaster bomber on a bombing raid over Germany, discovered that his plane was on fire and that he was unable to reach his parachute. After jumping from 5.5 kilometers, he hit a tree and then snow, and yet he suffered only scratches and bruises.

World War II: I. M. Chissov, a lieutenant in the Soviet air force, decided to bail out of his airplane when attacked by a dozen Messerschmitts. Since he did not want to be a "sitting duck" for the German pilots, he decided to delay the deployment of his parachute until he was well below them.

Unfortunately, he lost consciousness during the 7 kilometer fall. Fortunately, he happened to hit a snowy ravine. Although hurt by the impact, he was back in military service in less than four months.

Perhaps even more bizarre is the stunt that was long performed by Henri LaMothe. He would dive from 12 meters to belly-flop into a pool of water that was only 30 centimeters deep, hitting with a force that was about 70 times his body weight. (The stunt is quite dangerous and should not be repeated. I heard of one foolish young man who attempted it and ended up being paralyzed from the neck down.)

The news media commonly report stories of other survivors of long falls (and plenty of stories of nonsurvivors). Why do the survivors survive?

Answer The lethal factor in a fall is, of course, the force the victim experiences during the collision with the ground (or some other solid surface). The force depends directly on the momentum of the victim just before the collision and inversely on the duration of the collision. The momentum depends on the victim's speed and mass. When the fall is from a great height, the victim reaches a *terminal speed* sometime during the fall. Although gravity certainly continues to pull downward, the victim's acceleration is eliminated by air drag that then matches the pull of gravity. The size of the terminal speed depends on the victim's orientation: Being spread-eagled creates more air drag than a feet-down or head-down orientation and so has a smaller terminal speed. However, landing spread-eagle after falling a great distance is hardly an advantage.

The time the collision takes is a more crucial factor. If the collision is "hard," it may last for 0.001 to 0.01 second, and the force stopping the victim is certain to be lethal. But if the collision is "softer" (the victim takes longer to stop), then the force is smaller and the victim might survive. A fall into deep snow may prolong the collision enough to reduce the force to a survivable level. Apparently the 30 centimeters of water was sufficient for La Mothe to survive his dives.

A victim that falls head-down is far more likely to be killed than with any other orientation, because of the great vulnerability of the spine, brain stem, and brain.

1.50 • A daring parachuting rescue

In April 1987, during a jump, parachutist Gregory Robertson noticed that fellow parachutist Debbie Williams had been knocked unconscious in a collision with a third sky diver and was unable to open her parachute. Robertson, who was well above Williams at the time and who had not yet opened his parachute for the 4 kilometer plunge, managed to catch up with Williams and, after matching her speed, grab her. He opened her parachute and then, after releasing her, his own, with a scant 10 seconds before impact. Williams received extensive internal injuries due to her lack of control on landing but survived. How did Robertson manage to catch Williams?

Answer Robertson was able to saved Williams by manipulating the (upward) air drag he experienced as he fell. As a sky diver begins to fall and the downward speed increases, that force, which opposes the gravitational force pulling the diver downward, builds in strength until the air drag matches the gravitational force. Once this match is made, the diver falls with a constant speed, said to be the *terminal speed.* The size of the terminal speed depends on the cross-sectional area the diver has with the passing air. A diver has less cross-sectional area and a greater terminal speed when either head-down or feet-down than when horizontally spread-eagle.

When Robertson first noticed the danger to Williams, he reoriented his body head-down so as to minimize the air drag on him and thus maximize his downward speed. Williams, falling uncontrollably with much more air drag on her, had reached a terminal speed of about 190 kilometers per hour. Robertson, with his streamlined orientation, reached an estimated speed of 300 kilometers per hour, caught up with Williams and, as he neared her, went into a horizontal spread eagle to increase the air drag on him and slow him to Williams's speed.

1.51 • Cats in long falls

Humans rarely survive long falls, but cats apparently have much better luck. A study published in 1987 considered 132 cats who had accidentally fallen from heights of two to 32 floors (6 to 98 meters), most of them landing on concrete. About 90% survived, and about 60% even escaped injury. Strangely, the extent of injury (such as the number of fractured bones or the certainty of death) decreased with height if the fall was more than seven or eight floors. (The cat that fell 32 floors had only slight damage to its thorax and one tooth and was released after 48 hours of observation.) Why might a cat have a better chance of survival in a longer fall? (The survival is by no means guaranteed, so if you live in a high-rise apartment, be sure to keep your cat away from any open window.)

Answer If a drowsy cat accidentally topples from a window sill, it quickly and instinctively reorients its body until its legs are underneath. The cat then uses the flexibility of its legs to absorb the shock of the landing: The flexibility lengthens the time of the landing and thereby reduces the force on the cat.

As a cat falls, the force of air drag that pushes upward on the cat increases. If the fall is from the sill onto the floor, the air drag is never very much. But if the fall is longer, then the air drag may become large enough to reduce the cat's downward acceleration. In fact, if the fall is more than about six floors, the air drag can become large enough to match the gravitational force pulling downward on the cat. The cat then falls without acceleration and with a constant speed called *terminal speed.*

Unless terminal speed is reached, the cat is frightened by its acceleration and keeps its legs beneath its body, ready for the landing. (Your body is also sensitive to accelerations rather than speeds.) But if terminal speed is reached, the acceleration disappears, and the cat relaxes somewhat, instinctively spreading its legs outward (in order to increase the air drag on it) until it must finally get ready for the landing.

Once the cat spreads out, the air drag automatically increases, which reduces the speed of the cat. The longer the fall, the more the speed is reduced, until a new and reduced terminal speed of about 100 kilometers per hour is reached. Thus, a cat falling from, say, 10 floors will land with a speed that is less than that of a cat falling from five floors and will have a better chance of escaping serious injury.

1.52 • Land diving and bungee jumping

On Pentecost Island in New Hebrides, one native test of manhood is to dive from a high platform and toward the ground, trusting that a length of liana vines tied around the ankles and secured to the top of the platform will halt the fall before the ground is reached. In May 1982, a young man made such a leap from more than 81 feet. Just before he was stopped by the vines, his speed was reported to be about 55 kilometers per hour. The acceleration that he then underwent while being stopped was estimated to be 110 *g*s (110 times the free-fall acceleration). There are no reports on how well he could walk thereafter.

A tamer version of vine jumping, but one that still occasionally leads to injury and death, is bungee jumping, in which a person leaps from a high platform with an elastic band attached to the legs and to the platform. This practice began on April Fool's Day (of course!) in 1979 when members of the Dangerous Sports Club leaped from a bridge in Bristol, England. Suppose that you bungee-jump from a bridge (and, of course, stop short of whatever lies below you, which does not always happen). Where do you experience the greatest force and acceleration? If you are frightened of the experience and decide to use only half the length of the bungee cord, will the greatest force and acceleration be half as much?

Answer You feel the greatest force and undergo the greatest acceleration, both upward, when you reach your lowest point, where the bungee cord is reversing your motion and you are momentarily stopped. If we can treat the cord as being exactly like an idealized spring as used in textbooks, then the values of the greatest force and acceleration are independent of the length of the cord and thus also the distance that you fall. Although a shorter fall gives you less downward speed for the bungee cord to arrest, the correspondingly shorter cord that you would use will be stiffer (like a shorter and thus stiffer spring) and will reduce your smaller speed to zero with the same acceleration as a less stiff cord would reduce a larger speed to zero.

The upward acceleration stopping the jumper is sometimes great enough to injure the jumper. The eyes are especially vulnerable because, with the head downward during the stopping, the increased blood pressure in the eyes can cause hemorrhage.

1.53 • Trapped in a falling elevator cab

Suddenly it happens—you are in an old elevator with no safety backup system when the cable snaps, and the elevator cab falls. What should you do to optimize your chance of survival, as slim as that might be? For example, should you jump up just before the cab collides with the bottom of the shaft?

Answer The best advice is probably that you should lie down. You might think that the action is impossible since both you and the floor are falling, but there is sure to be some drag on the cab from the guide rails along which it slides and from the air through which it falls. So, you can drop to the floor. There you should spread out, preferably on your back. The idea is to spread the force you are about to experience over as much surface area as possible.

Standing is ill advised, because then the force is spread over a smaller area, such as the cross section of your ankles. If the collision is severe, your ankles will collapse and the trunk of your body will then crash to the floor.

Jumping up at the last moment (surely that is impossible to time from an enclosed cab) may be the worst thing to do. If you jump up sometime during the fall, you will probably only reduce your downward speed. Suppose that the cab ricochets from the bottom of the shaft. You are then traveling downward as the floor of the cab is traveling upward, and shortly later . . . well, no need for the gory details.

SHORT STORY

1.54 • Bomber crashes into Empire State Building

At 9:45 A.M. on Saturday, July 28, 1945, a U.S. Army B-25 bomber crashed into the 78th and 79th floors of the Empire State Building in New York City while flying through dense fog. The airplane's three occupants and ten workers inside the building were killed, and 26 others were injured. Had the day been a regular work day, the toll could have been much higher.

The collision ripped off the airplane's wings and sent the fuselage and the two motors into the interior of the building, where the fuel then burst into flames that were so bright that onlookers from the street could see them in spite of the fog. One motor went completely through the building and out the other side to fall onto the roof of a 12-story building, where it started another fire.

As the airplane crashed through the Empire State Building, it struck one of the girders in the elevator region, damaging it and some of the elevator cables. An elevator operator, who had just opened her door on the 75th floor, was blown out of the elevator by the explosion of the airplane and then set on fire by burning fuel that had been propelled down through the shaft. Her flames were extinguished by two nearby office workers. After giving her first aid, they escorted her to another elevator where a fellow operator agreed to take her to the first floor for further medical help. Just as the door closed, the cables on the elevator were heard to "snap with a crack like a rifle shot," and the elevator cab then fell to the building's subbasement.

Rescuers who reached the subbasement shortly later expected to find both occupants of the cab dead. However, after they cut a hole in the basement wall to reach the cab, the rescuers found both women alive, although badly hurt. The women had fallen more than 75 stories, but the safety devices on the elevator had apparently slowed the descent sufficiently to diminish the crash at the bottom of the shaft. There is no report on what the women did during the fall, but because of fear and the jostling, I doubt that they remained standing.

1.55 • Falls in fighting, landing during parachuting

When someone is thrown down in judo or aikido, how should the person land to minimize the chance of being hurt? How do professional wrestlers manage to go unhurt when they throw themselves or each other down onto the mat of the wrestling ring? In any of the cases, if a person does not land properly, there is a good chance bones will be broken or internal organs hurt.

How should a parachutist land so as to lessen the danger of injury? Although the parachute greatly reduces the downward speed, the speed is still appreciable, being equivalent to a jump from a second-story window.

Answer You should land so as to maximize the region of contact. The technique reduces the force per unit area on the part of the body hitting the floor and lessens the chance that a bone will bend or twist to the point of breaking or an internal organ will be stressed to the point of rupturing. If you are thrown in judo or aikido, you should slap the mat as the trunk of your body hits. The arm adds to the area making contact, and the slap also helps lift the body and reduce the collision force on the rib cage. Professional wrestlers are usually in superb shape and can withstand long falls (such as when they jump from the top of the ropes onto an opponent lying on the mat). They also fight on a floor that is highly flexible. When they land on it, the collision duration is lengthened by its give, and the force in the collision is thereby reduced.

A parachutist is trained to collapse and roll by first making contact with the balls of the feet, then bending the knees and turning so as to come down on the side of the leg and finally the back side of the chest. The procedure has two advantages: It prolongs the collision (and so it reduces the force on the parachutist) and it spreads the force of the collision out over a large area. If the parachutist were to land standing up, the compression on the bones in the ankles would likely rupture the bones.

1.56 • Beds of nails

I introduced the beds-of-nails demonstration to physics education after seeing it as part of a theatrical karate demonstration. My version comes in two parts: In the first part, I am sandwiched shirtless between two beds of nails with one or two persons standing on top of the sandwich. Although the nails hurt a great deal, I am rarely punctured by them. What factor decreases the risk of puncture?

In the second part, I am again sandwiched between the two beds of nails when an assistant places a concrete cinder block on the top bed and then smashes it with a long, heavy sledgehammer. This part is dangerous for many reasons, one of which is the debris that can hit eyes and teeth. (Once when I gave the "Flying Circus Show" with the beds-of-nails demonstration as a finale, my regular assistant was unable to make the trip, and I enlisted the aid of the professor who had invited me. He swung the sledgehammer hard but came in at such an angle that most of the concrete chunks were propelled across my face. One of the chunks cut deeply into my chin, and when I staggered up to deliver my closing remarks, I bled profusely over body, pants, and shoes. I have never again had such a dramatic end to a talk, or such audience response.) Why is a large block somewhat safer to use than a small block?

Answer When people stand on me, their weight is spread over enough nails in the top bed that the force from each nail is usually insufficient to pierce my skin. The force from the nails on my back is larger, because they must also support my weight. By experimenting I discovered how much weight the people standing on me can have before I am pierced. (Don't think that I go without pain, because the demonstration hurts a lot.)

The large block that is smashed not only adds a theatrical flare to the demonstration but it also increases the safety in three subtle ways. (1) If I am to be squeezed hard, then the block and top bed must accelerate rapidly downward; a larger block diminishes the acceleration because of its greater mass. (2) Much of the energy in the sledgehammer goes into rupturing the block rather than into the bed's motion. (3) The fact that the block disintegrates means that the collision time is longer than if the block were not present, and so the force in the collision is smaller than it would be otherwise. When I first gave the beds-of-nails demonstration in class, I used a small brick instead of a large block. The impact of my assistant's sledgehammer left me lying stunned on the floor for several minutes.

1.57 • Hanging spoons

Clean a lightweight spoon and the skin on your nose, breathe lightly onto the interior surface of the spoon's bowl and then hold it so that the surface rests against your nose. Test for adherence by repositioning the spoon and partially releasing it. When you feel it hold, let it go. There, just what you've always wanted: A spoon dangles from your nose. Who can resist you now?

Why does the spoon hang? How does breathing on it first help? Can you hang spoons from other parts of your face, or, if you're into that kind of thing, from other parts of your body?

How long can you hang a spoon from your nose? I have long claimed that my record is 1 hour and 15 minutes, set in a French restaurant in Toronto. However, the truth is that it was actually in a truck stop in Youngstown, Ohio, where a burly member of a motorcycle gang suggested that the spoon would hang better if he reshaped my nose.

Answer If the spoon and your nose are free of oil, there can be enough friction between the spoon and the skin to hold the spoon in place. The spoon is stable provided that the center of its mass distribution lies along a vertical line through the region where it sticks to your nose. Otherwise, gravity rotates the spoon when you release it, and the motion may cause the spoon to slide off. Condensation from your moist breath helps glue the spoon to your nose. Although a water layer acts like a lubricant when it is relatively thick, a very thin layer acts like a glue because of the electrical attraction between water molecules and the nearby surfaces of spoon and skin.

1.58 • Trails of migrating rocks

Stones in the dry lake beds dotting California and Nevada sometimes have long trails extending from them across the hard-baked desert floor. The trails might be tens of meters long, and the mass of the stones can range up to 300 kilograms. What causes the trails? Are the rocks trying to make a break for the gambling casinos in Las Vegas? Is some weirdo pushing them about? Whatever the cause, the trails must be difficult to make because the friction between a rock and the desert ground is certainly large.

Answer Many theories attempt to explain how the stones leave trails. One involves the rare freezing of rainwater. Stones trapped in a thin ice sheet catch in chance wind gusts and scrape trails in the underlying desert floor when the gusts are strong enough to move the stones and ice sheet.

Another theory is that a stone leaves a trail when pushed by wind during one of the rare rainstorms in the region. Once the water lubricates the ground, the wind in the storm can push or roll a stone over the ground so that it leaves a trail. The friction between the stone and ground is least when the water forms a thin layer of mud lying over a still-firm base. A gust of wind might then abruptly shove a stone from its sitting position. Once moving, the stone would require less force to keep moving.

1.59 • Hitches

The clove hitch that is illustrated in Fig. 1-18*a* has one free end and one end under load. If the load increases, can the hitch slip; that is, can the free end be pulled through the knot so that the knot fails? Or is the knot self-tightening?

Answer The friction forces and the tension in a knot can be mathematically analyzed to determine whether the knot will hold or fail under some arbitrarily large load. Here, let's just do a simple analysis, beginning with the free end, which is under no tension (Fig. 1-18*b*). The cord passes beneath another section in a *wrap-over*—the top section presses down on the lower section. If the free end is not to slip through the wrap-over, the friction created by that pressure must not be smaller than the tension attempting to pull the free end through the wrap-over.

Next, in the hitch the cord winds around the rod in two *wrap-arounds.* The end of this coiled section that is nearer the free end is under small tension, while the other end of the section is under larger tension. If the section is to be stationary, the friction between the cord and the rod must be large enough to withstand the difference in tension between the two ends.

Finally, the cord passes through another wrap-over. On the other side, the cord is under whatever tension is created by the load. If the top section in the wrap-over presses on the bottom section hard enough, the wrap-over is stable.

So, there are three requirements of the friction at points along the cord in the clove hitch. If either the wrap-overs or

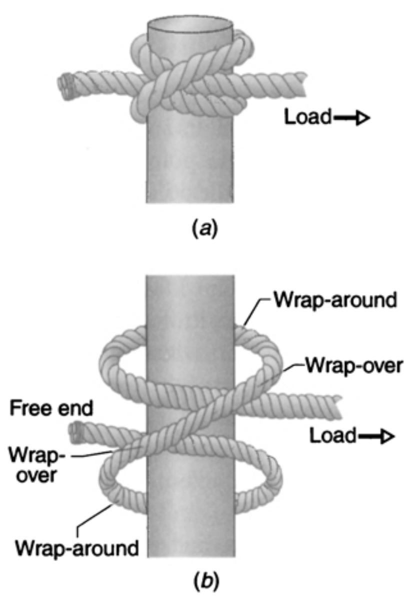


***Figure 1-18** / Item 1.59* (*a*) Clove hitch. (*b*) The elements of a clove hitch.

wrap-arounds are especially strong, the hitch will hold under any load. But if either are weak, then the hitch will fail if the load is made large enough. Other types of knots will fail under a large load even though the wrap-overs and wrap-arounds are both strong, while some knots will automatically tighten to meet any load, and then failure can occur only if the rope between the knot and load breaks.

1.60 • Rock climbing

When climbing a wide crack on a mountainside you might be able to *chimney climb* by pressing your shoulders against one wall and your feet against the opposite wall (Fig. 1-19). You are stable as long as the pressure on the rock is large enough, but the procedure is tiring. Is there a particular vertical distance between feet and shoulders that minimizes the pressure you need to apply?

A narrow, vertical crack where the rock extends out more on one side than the other can be climbed with a *lie-back*. You get on the side opposite where the rock juts out, grip the near side of the crack with your hands, and press your feet on the exposed opposite side. The technique is quite tiring because of the tension in your arms. If you want to minimize the tension, how far down from your hands should you place your feet?

Here are a few more of many possible questions:

(a) If, while climbing a nearly vertical rock face, you find a narrow ledge at foot level, should you press the toe of your climbing shoe or the side of the shoe onto it?

(b) Suppose that you are confronted with a steeply slanted rock slab on which you can stand upright. Are you more stable if you bend over and put your hands on the slab to get some friction on the hands?

(c) If two tilted slabs join at an acute angle, is it safer to climb directly up one of the slabs or along their juncture?

(d) How can you gain purchase with vertical cracks in the rock without having to employ a lie-back?

(e) Why do climbers frequently dip their fingers into a bag on their belt to coat the fingers with chalk?

***Figure 1-19** / Item 1.60* Chimney climb.

(f) As you climb on a rope, the rope runs back down through one or more *runners* (metal loops anchored into the rock) to a climbing partner. Should you use a rope with a lot of stretch or one with almost no stretch?

(g) The advantage of using runners is that a climber can fall only a certain distance below the highest runner. A subtle danger, however, is that the rope may snap as it is stretched during the fall. Many novice rock climbers reason that this danger depends on the climber's height above the last runner just before the fall: the greater this height, the greater the stretch and thus the greater the danger of snapping the rope. Why is that reasoning wrong?

(h) Some types of spiders climb with a safety line of silk, called a drag-line, that would help arrest a fall. Surprisingly, the drag-line has little stretch and should snap even if the spider goes through a moderate fall. Why then does the spider produce a drag-line?

(i) Many skilled rock climbers suffer from chronic pain that runs along their fingers, and some climbers also display a noticeable bulge along the palm side of an injured finger when they draw the finger in toward the palm. What is the connection between the bulge, the pain, and the physics of climbing?

Answer First, a serious caution: None of the rock-climbing examples discussed should be tested without expert instruction, because there are so many variables and assumptions involved that the explanations are only approximate.

In a chimney climb there is a best location of the feet if you wish to minimize the push that is required against the rock at feet and shoulders. In principle you can find it by first putting your feet at some low position and then decreasing your push until the feet are on the verge of slipping. If you then raise your feet while continuing to keep your feet close to slipping, you further diminish the required push. However, the action increases the friction required at the shoulders because the friction at the feet is now less, and the sum of the frictional forces must always equal your weight if you are not to fall. If you continue to shift your feet upward until your shoulders are also about to slip, you are then in the position that requires the least push against the rock.

A lie-back also has a best location for the feet, at which the tension is minimized in the arms. Start with the feet high and then gradually lower them as you decrease the tension. When they are low enough that they are on the verge of slipping, the tension is least.

Answers for the rest of the questions, in order:

(a) The least effort is gained by using the side of the shoe. To stabilize the foot, the leg muscles must counter a torque by the force from the ledge. The torque is larger when the toe is used because the distance between toe and leg bone is larger than the distance between the side of the foot and the leg bone.

(b) As a rule, you are more stable if you stand upright. Leaning over can easily require too much friction at the feet, and so they might slip. Also, you gain little friction from the hands and, if you lean too far forward, the friction on them can actually be down the slope and work against your stability.

(c) Climb the juncture because it is necessarily less tilted than either slab.

(d) Many vertical cracks can offer support if you can jam fingers, hand, arm, foot, or leg into them and then press against the sides.

(e) Chalk is used by climbers to absorb moisture on the fingertips, to give a firmer grip on the rock face. The wide belief is that the moisture decreases the static friction between fingers and rock, and so chalk should bring the friction back up to the dry-skin value. However, one study revealed that chalk actually *decreases* the friction for two reasons: (1) In drying the skin, the chalk decreases the compliance of the fingertips. (2) The chalk particles form a slippery layer between the fingertips and the rock. Still, chalk is an overwhelming favorite among rock climbers; more study is needed here.

(f) Rock climbers (as opposed to spelunkers) use rope that gives considerably under stress, so that if you fall, your stop at the end of the fall is not sudden and the force stopping you is not huge. As the rope begins to stretch, the rope materials rub against one another and become warmer; most of the potential energy and kinetic energy that you lose during the fall ends up as thermal energy within the rope.

(g) Skilled climbers know that the danger of snapping a rope depends on the *fall factor* $2H/L$, where H is the climber's height above the highest runner and L is the length of rope between the climber and where the rope is secured, probably at the *belayer* handling the rope. Depending on the values of H and L, the fall factor may be dangerously high when H is small if L is also small. As a climber ascends and L increases, the same value of H is not as dangerous.

(h) As the spider reaches the end of the drag-line during a fall, the force on it from the drag-line pulls more line from the spider's spinnerets. The force on the spider from the drag-line is not so severe as to snap the drag-line as the spider is brought to a stop.

(i) Many rock climbers have injured their fingers when hanging by them in a *crimp hold*, in which a climber presses down with four fingers to gain purchase on a narrow, overhead ledge. When the full weight of the climber is supported in this way, the fingers can be damaged. Specifically, the fingers are held in place by means of tendons passing through guiding sheaths, called *pulleys*, that are attached to the finger bones. When the full weight is supported by the fingers, the forces required of those tendons can rip the tendons through the pulleys. Thereafter, the climber has not only pain in the fingers but also a noticeable bulge when the fingers are clinched because the tendons are no longer constrained to be next to the bones.

1.61 • Rock climbing by bighorn sheep

Rock climbers wear shoes with special soles to get large frictional forces between the shoes and the rocks on which they climb. If the rocks are wet, the climbing can be treacherous. Indeed, many of us have trouble walking across a wet floor without slipping. Bighorn sheep don't wear shoes with special soles but still manage to scamper up rocky slopes without an obvious care and even when the rocks are wet or covered with moss. How do the sheep cling to the rocks?

Answer A walking person makes first contact on a floor with the heel of the descending foot. If the floor is wet, the heel encounters little frictional force to stop it at the first point of contact and may slip forward, causing the person to fall. A bighorn sheep makes first contact with a rock with the rear section of a cloven hoof, at the point where the two digits of the hoof join. This section is narrow enough that it penetrates moss or anything else coating the rock. As weight then comes down on the hoof, more of the two digits make contact with the rock and slide away from each other to form a V-shaped region of contact with the rock. By sliding in this way, the two digits scrape the rock to remove material that might be slippery and jam themselves into any rough regions on the rock, thereby preventing the hoof from sliding forward as the weight is brought down on the hoof.

1.62 • Pulling statues across Easter Island

The prehistoric people of Easter Island carved hundreds of giant stone statues in their quarries and then moved them to sites all over the island. How could they do this using only primitive means?

Answer The giant stone statues of Easter Island were most likely moved by the prehistoric islanders by cradling each statue in a wooden sled and then pulling the sled over a "runway" consisting of almost identical logs acting as rollers. Although pulling the sled required a tremendous effort by the islanders (a tremendous amount of energy), it was far easier than pulling a statue across the ground, which would require overcoming the friction from the ground. In a modern reenactment of the roller technique, 25 men were able to move a 9000 kilogram Easter Island–type statue 45 meters over level ground in 2 minutes.

1.63 • Erecting Stonehenge

How were the stone blocks for Stonehenge, the megalithic construction on the Salisbury Plain in England, transported to the site and lifted into position? The *sarsens* are the huge upright stone blocks; the *lintels* are the somewhat smaller stone blocks that straddle pairs of sarsens.

Answer The stone blocks were unlikely to have been transported for more than 5 to 10 kilometers in spite of the romantic tales and ingenious schemes that have been attributed to them. The blocks were all available to the ancient builders, perhaps after having been moved from the stone source by ice flow during early ice ages, long before Stonehenge was built. To move a block, the builders may have made a rolling rig out of it by binding logs and smaller blocks around the main block so as to form (roughly) a cylinder. Then, with teams pulling on ropes, the cylinder could be rolled over level ground and even up gentle slopes. Modern-day enthusiasts have moved blocks in this way.

A more likely procedure for the ancient builders was to leverage a block onto a sled constructed from lashed-together logs. The sled then was dragged by teams of people or work animals pulling on ropes, and the progress was eased by grease slopped onto the ground in front of the sled's runners. Modern-day enthusiasts have also moved blocks in this way.

Uprighting a sarsen at the building site was likely done by pulling the sled up onto a mound that ended abruptly at a hole (Fig. 1-20*a*). A counterweight block was probably placed on the top rear of the sarsen as the sarsen was pulled past the mound's edge overlooking the hole. The counterweight served as a control to the motion of the sarsen and also allowed the center point of the sarsen to be pulled past the edge. With the sarsen thus poised, the counterweight was pulled forward until the sarsen rotated and fell into the hole. Ropes around the top of the tilted sarsen were pulled to make it vertical.

One possible way to lift a lintel to the top of a pair of adjacent sarsens was tested in modern times in a small Czech town. A concrete block (5124 kilograms) was pulled along

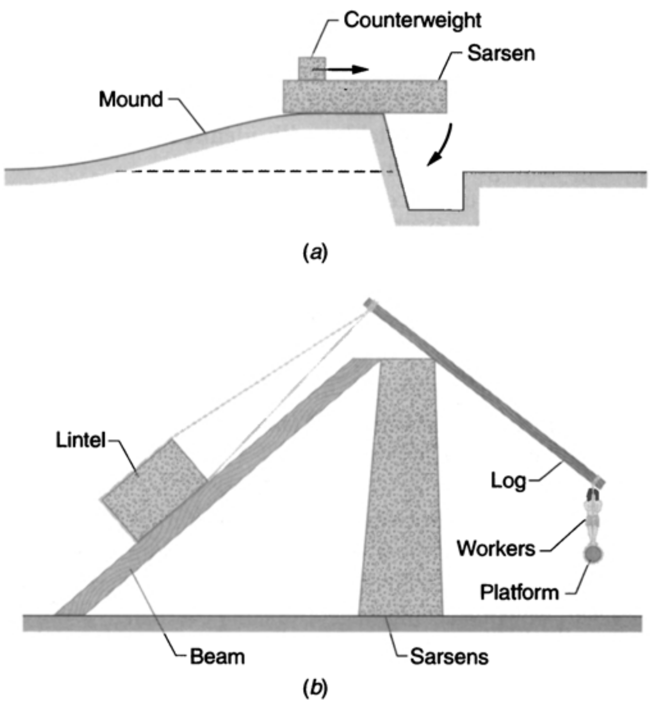


***Figure 1-20** / Item 1.63* (*a*) Righting a sarsen at Stonehenge. (*b*) Raising a lintel.

two oak beams with surfaces that had been debarked and lubricated with fat (Fig. 1-20*b*). Each of these 10 meter beams extended from the ground to the top of one of two upright pillars onto which the block was to be raised. The pull on the block was via ropes wrapped around it and around the top ends of two spruce logs. A platform was strung at the opposite end of each log. When enough workers sat or stood on a platform, the attached spruce log would pivot about the top of its upright pillar and pull one end of the block a short distance up a beam. Once the block was moved, stops were positioned at its lower end to prevent it sliding back down as the platform was repositioned for another pull on the block. By duck-walking the block up the oak beams (moving one side and then the other side), only eight or nine people were needed on the platform.

1.64 • Lifting the blocks for the Egyptian pyramids

At the quarry, the builders of the Egyptian pyramids had to lift the stones (which averaged 2300 kilograms and were as massive as 14 000 kilograms) from the quarry onto sleds, which were then moved out of the quarry. How could the stones be lifted without machines, pulley systems, or any wheeled devices?

The following method may have played a role: A block is wedged upward to allow a number of flexible poles to be positioned underneath it, extending out on opposite sides of the block. Then the exposed ends of one or more of the poles are lifted up slightly (say, half a centimeter) and held in place by sturdy material wedged under the ends. The procedure is next repeated for more of the poles, until all of the poles have been raised the same amount. The block is then higher. How does the technique allow a tremendous weight to be lifted by a few people, and why is the flexibility of the poles important?

At the pyramid site, how were the workers able to pull the blocks up into place on the pyramid? In particular, were earthen ramps used?

Answer Raising a large stone block with flexible poles is considerably easier than with rigid poles. Suppose the rigid poles are in place. To raise the exposed ends of one of them, say one at the end of the block, workers would have to apply upward forces on the ends that almost match the weight of the stone. The reason is that as the stone is lifted by that one pole, it would lose contact with (and thus support from) all but one of the other poles. So, the workers would have to supply that tremendous support.

However, with flexible poles in place, you alone can raise the end of any one pole with a force that is considerably less than the weight of the block. The reason is that as an end is lifted, the block does not lose contact with the other poles, which continue to help support it.

To get the blocks into place on a pyramid, the workers may have used earthen ramps, either directly up a side of the pyramid or spiraling around the pyramid. Presumably teams of men would pull a stone up such a ramp with ropes, using water to decrease the friction between the stone and its path. The gradual climb of a ramp would decrease the required force and thus also the required number of men in a team. However, as appealing as that fact is, the ramps would have been enormous (up to 1.5 kilometers long) and pulling a huge block around the corner of a spiraling ramp would have been slow and daunting.

More likely the blocks were pulled directly up the side of the pyramid on sleds, using the side as a ramp (Fig. 1-21*a*). As each layer of the pyramid was finished, workers mounted blocks on the outside surface and then dressed them (smoothed them). A sled pulled along the dressed stone faces, with water lubricating the runners, would encounter surprisingly little friction. Calculations suggest that a team of 50 men could raise an average block within several minutes, a pace that would allow a pyramid to be built in the time intervals as historically recorded. Even fewer men would be needed if the ropes looped over the construction site to a sled on the opposite side (Fig. 1-21*b*). That sled and the men that could have ridden within it would have acted as a counterweight. Once the men on top of the construction site got the upward-directed sled moving, the downward-directed sled would have helped drag it to the top. This scheme had the advantage of getting empty sleds back down to the ground where they could be reloaded.

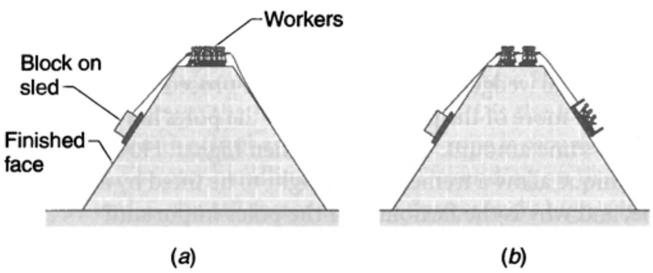


Figure 1-21 / Item 1.64 **Two arrangements to pull a stone block up a pyramid.**

1.65 • A Slinky

A Slinky is the well-known spring toy of Poof-Slinky, Incorporated, that can be made to climb down (somersault down might be a better description) a flight of stairs. You place the spring on the highest step, pull the top of the spring up and then down onto the second step, and then let go. Provided the step dimensions are appropriate, the Slinky then climbs down the steps until it reaches the bottom of the flight. The time the Slinky takes to climb down a flight depends on the number of steps it takes (you might arrange it to take the steps two at a time) but is independent of the height of each step. (A Slinky climbs down a tall step and a short step in the same time.) How does the Slinky accomplish this motion?

Answer When you pull the coils up and then down onto the lower, second step, you send a wave through the length of the coil. As the wave travels, more coils move onto the second step by first moving upward, then along the arc of the spring, and then down onto the second step. When the wave reaches the last coils on the first step, those coils are pulled up with enough speed along the arc that they overshoot the second step and (provided the step dimensions are appropriate) land on the third step. The whole process is then repeated.

A Slinky's success in climbing down stairs (and slowly enough that you can see the climbing) is due to the rectangular cross section of its wire. That design, patented by Richard T. James in 1947, reduces the ratio of the spring's stiffness to its mass compared to wire with a circular cross section. The smaller ratio results in a slower speed for the wave you set up along the length of the spring. A plastic Slinky, with a different ratio and thus a different wave speed, climbs about half as fast as the original steel-wire Slinky.

With either type, the time required for a Slinky to climb down one step is set by the ratio of stiffness to mass, not the height of the step. On a short step, the wave travels slowly; on a tall step, the wave travels faster; and the time required by the wave to travel the length of the Slinky is the same for the two steps.

1.66 • Leaning tower of blocks

Using blocks, books, dominoes, cards, coins, or any other set of identical objects, construct a stack that extends from the edge of a table. For a given number of objects, what arrangement gives the maximum overhang (the horizontal distance from the table's edge to the farthest point on the stack)? Suppose that the objects are dominoes with a length L. How many are needed to give an overhang of L? How about $3L$?

With a full set of 28 dominoes, build an arch that spans the space between two tables with identical heights. What arrangement gives the maximum span?

Lego bricks (under copyright by Wham-O, Inc.) are small, plastic, toy blocks. On one of the broad sides of a block there are four holes and on the opposite side four short projections. One block can be stacked directly over another so that four connections are made, or the top block can be shifted by half a block's length so that two connections are made. Let x be half the length of a block, and n be the number of blocks you have. How many different stable (free-standing) towers can you build with all n blocks?

Consider a tower in which each block except for the lowest one is stacked either directly above or shifted to the right of the block just below it. What is the minimum number of blocks needed to give an overhang of, say, $4x$? Is there a more efficient way of stacking to get the same overhang?

Answer A stack is stable if a vertical line through its center of mass extends through the table. So, of course, to get a large overhang, you want the line to pass through the edge of the table. One popular way to build a large overhang is based

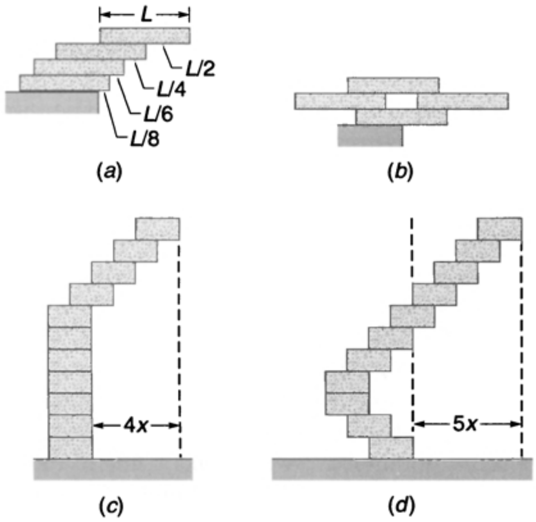


Figure 1-22 / Item 1.66 Stacking schemes for (*a*)–(*b*) blocks and (*c*)–(*d*) Lego blocks.

on the *harmonic series* (Fig. 1-22*a*). Suppose that you use dominoes. To balance one domino, you would put its center over the edge and get an overhang of $L/2$. Then you can replace the edge of the table with the edge of another domino and arrange for the center of mass of the two dominoes to be over the edge of the table. The overhang is now $(L/2)(1 + 1/2)$. Next you replace the edge of the table with the edge of a third domino and arrange for the combined center of mass of the three dominoes to be over the edge of the table. The overhang is now $(L/2)(1 + 1/2 + 1/3)$. With n dominoes played in this fashion you produce an overhang of $(L/2)(1 + 1/2 + 1/3 + \cdots + 1/n)$, where the expression in parentheses is the harmonic series. Here are some results:

Overhang	Number of dominoes required
L	4
$2L$	31
$3L$	227
$4L$	1674

There is no theoretical limit to the scheme, only practical ones.

More economical schemes use dominoes to counterbalance the ones extending outward from the edge. For example, in one stacking scheme four dominoes give an overhang that is slightly larger than L (Fig. 1-22*b*), and another uses only 63 dominoes to get an overhang of $3L$.

Counterbalancing also helps if you want to build an arch with a full set of 28 dominoes. If the left and right sides are self-supporting, the span can be about $3.97L$, but there is at least one design in which the sides are not individually self-supporting that gives a span of about $4.35L$.

All of the overhangs and arches can be improved if you arrange for the diagonals of the dominoes, rather than their long sides, to be perpendicular to the table's edge.

With three Lego blocks, you can build five different towers (mirror-image arrangements excluded) and four of them are quite stable. One tower is marginally stable—the slightest disturbance will topple it because the center of mass is on a line that passes through an edge of the lowest block. The maximum overhang is $2x$ (a block's length) for the marginally stable tower, x for three of the other towers, and zero for the most stable tower (which is built straight up).

The rules under which a leaning tower can be built determine the proper strategy for gaining the maximum overhang. Suppose that you are to avoid any marginally stable tower and must either put one block directly over another or shift it only to the right. Then the most economical plan is to build a tower straight up except for the last blocks, which are fastened to make a stair-like structure to the right. For example, to get an overhang of $4x$, you need a minimum of 11 blocks positioned with the top four forming stairs (Fig. 1-22*c*). To get an overhang of nx, you need a minimum of $0.5n(n + 1) + 1$, with the top n forming stairs. For a marginally stable tower, leave off the lowest block.

Fewer blocks are needed to get a given overhang if you build first to the left and then to the right. For example, 11 blocks can give a stable overhang of $5x$ (Fig. 1-22*d*).

1.67 • Leaning tower of Pisa

The famous tower in Pisa, Italy, began to lean toward the south even during its construction, which spanned two centuries. Indeed, when the bell chamber was finally added at the top, it was made vertical in the hope of arresting the lean of the rest of the tower. (If you see the tower or a photograph of it, you will notice that the bell chamber gives a banana-shape to the tower.)

The tower was closed to tourists for many years after a tower in Pavia collapsed, killing four people. But was the tower in Pisa on the verge of collapse? After all, it was leaning toward the south by only a little more than 5°, and though the leaning had increased yearly, the increase amounted to only a little more than 0.001° per year. If the tower was to collapse, didn't the tower's center of mass have to move out beyond the base of the tower? That would not have happened for quite some time.

Answer Although the lean of the tower was always small and the center of mass was well over the support area of the base of the tower, before modern repair work was done on the tower, the lean had shifted the support of the tower's weight onto the outside wall at the south side. This shift put the lower section of the south wall under tremendous compression, which threatened to buckle the wall outward in an explosive failure. The danger was increased by a staircase spiraling around the outside of the tower, weakening the structural strength of the wall. From the start, the leaning was due to the compressible soil beneath the tower and the situation was worsened with each heavy rainfall. To stabilize the tower and partially reverse the leaning, engineers have put in an underground drainage system to decrease the water content of the soil and have excavated soil beneath the north side of the tower.

1.68 • Falling dominoes

Once the first domino in a long line of upright, regularly spaced dominoes is toppled against the second one, the toppling moves like a wave along the line. After the wave begins, how many dominoes are moving at any given instant and what determines the speed of the wave? Obviously the dominoes should be spaced no farther apart than the length of one domino, but is there also some minimum spacing? Why doesn't a line of children's blocks topple in domino fashion? Can you send a chain reaction through a line of dominoes where the first one is quite small and each of the others is scaled up from the preceding domino by some factor?

Answer An upright domino has two positions of stability, or *equilibrium.* It reaches one when it stands flat on its bottom side (Fig. 1-23*a*) and the other when it is angled so that its center is directly above its supporting edge (Fig. 1-23*b*). In both positions, the gravitational force, which we assume acts at the domino's center of mass, pulls downward through a supporting point. However, the second position is said to be one of *unstable equilibrium* because the slightest disturbance will upset the domino, shifting the downward gravitational force to the left or right of the support edge. If it is to the right as in Fig. 1-23*c*, the domino topples over.

When you topple the first domino in a line of dominos, it rotates through the position of unstable equilibrium and then falls over to crash into the second domino. If you barely nudge the first domino, then the energy in the crash comes from its fall from the position of unstable equilibrium. When the dominos are too close, the fall is too short to provide enough energy to topple the second domino. Toppling is more likely with a larger spacing, provided that it does not exceed a domino's length. The story is similar for dominos farther down the line. (Of course, you could just wallop the first domino and not worry about the spacing, but that is hardly sporting.)

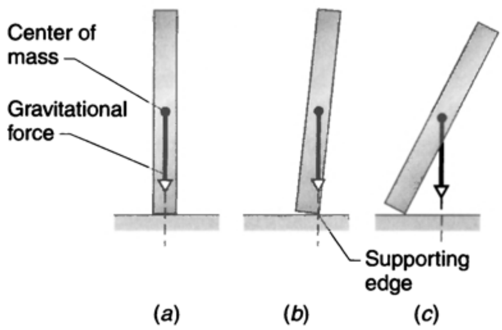


Figure 1-23 / Item 1.68 Domino passing through position of unstable equilibrium.

At any one instant there may be five or six dominoes in motion. The wave picks up speed as it moves along the line, with the speed approaching a certain value that depends on the spacing, the friction between dominoes, and how well the dominoes bounce from one another. When the spacing is smaller, the wave travels faster and the clatter from the collisions has a higher pitch.

Lorne Whitehead of Vancouver once described how a chain reaction sweeps through a line of dominoes that are scaled up by a factor of 1.5 (on all sides) from one domino to the next. When he topples over the first by "nudging it with a long wispy piece of cotton baton," the energy in the chain reaction is amplified by about 2 billion when the 13th and last domino is knocked over. He figures that given the proper set of dominoes, it would take a line of only 32 to knock over a domino as tall as the Empire State Building. (That's more than King Kong could do.)

1.69 • Falling chimneys, pencils, and trees

When a tall chimney falls, it likely will rupture somewhere along its length. What causes the rupture, where is it located, and which way does the chimney bend after the rupture (Fig. 1-24*a*)? You can check your answer by toppling a stack of children's blocks and noting which way the stack curves during the fall. You might also set up a stack of short, hollow cylinders that are held together internally with elastic bands.

If you stand a pencil upright on its point and then let it fall, does the pointed end move in the direction of the fall or in the opposite direction?

When a tree falls, which way does the lower end move and what shape does the tree take during the fall? Can a tree break like a chimney? Why does a tree sometimes seem to float just before it hits the ground? Why does the butt end sometimes strike the stump so hard that it might almost uproot it?

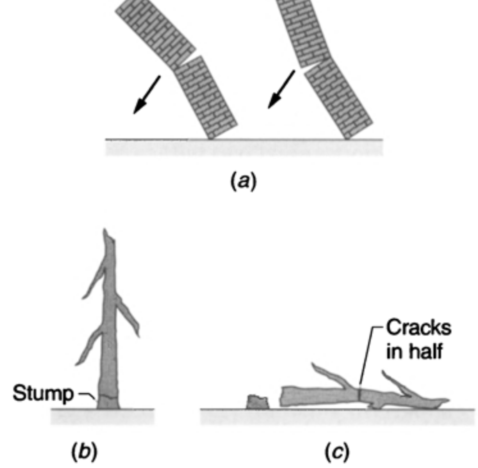


Figure 1-24 / Item 1.69 (*a*) Which way will a chimney break? An old tree (*b*) initially and (*c*) when the top hits the ground and cracks the tree in half.

(There you are, out in the woods, playing at being a lumberjack, and watching your first big tree fall. You're no dummy—you figure out which way the tree will fall and stand on the opposite side. But just after the tree hits the ground, it comes roaring back at you with revenge, hitting you in the chest and breaking three ribs. It's time to put away the axe.)

Answer As the chimney rotates around its base, the lower part attempts to rotate more quickly than the upper part, and the chimney begins to bend backwards. If the chimney is a uniform cylinder, the greatest attempt at bending is at a height of $\frac{1}{3}$ the chimney's height, and so the chimney is most likely to rupture there. If a chimney has some other shape, the rupture point will be elsewhere. The rupture begins to travel across the width of the chimney from the front of the fall, but the compression on the back side drives the crack downward somewhat. A second break point sometimes occurs lower on the chimney as the top part attempts to slide backwards over the bottom part, thus pulling against the fall on the upper surface of the bottom part.

The direction in which the pointed end of a pencil moves when the pencil topples depends on the amount of friction between the tip and the surface it touches. If the friction is small, the pointed end moves opposite the direction of the fall. With larger friction, the pointed end moves in the direction of the fall, even if it might first move opposite that direction.

A felled tree will bend backward like a chimney but will break only if it is dead and rotted. If the break occurs early in the fall, the top part may fall in the opposite direction of the lower part, making the situation dangerous if you are nearby. If you cut a notch in one side of a live tree and then cut a horizontal slice almost through on the opposite side, the tree will fall toward the notched side, snap the hinge and hurl the butt end upward and then pull it in the direction of the fall. If the tree has plentiful branches, they will be compressed when the tree hits the ground, and their recoil might propel the butt back toward the stump. The impression of floating comes from the air resistance that a tree with full foliage meets as it nears the ground.

Some trees end up in pieces on the ground because of the way they hit the ground. If the initial break is due to, say, strong winds and is at the top of a short stump (Fig. 1-24*b*), then the top of the tree can hit the ground first. In that case, the falling section can snap in half (Fig. 1-24*c*). That leaves a shorter section that hits shortly later; it too snaps in half. Before the final piece hits the ground, tree sections may snap in half several times.

1.70 • Breaking pencil points

The point of a wood pencil often breaks when I write with enthusiasm. Where exactly does the break take place? Why is a break more likely if the point is sharp and less likely if it has been dulled from use?

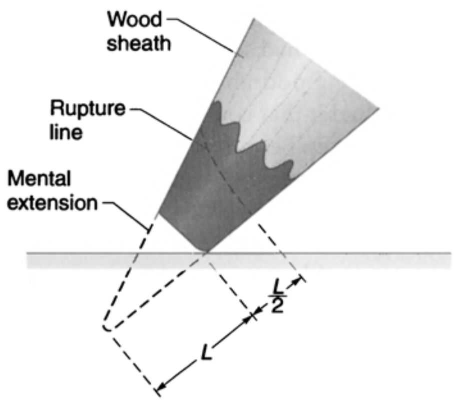


Figure 1-25 / Item 1.70 Rupture line in a pencil point.

Answer When you write, you press down on the pencil point with the pencil held at a tilt. The action creates forces that attempt to bend the exposed length of lead by elongating the lower side (the side facing the paper) and compressing the top side. The lead is weaker to the attempted elongation, and so the fracture begins on the lower side. While the fracture races up across the width of the lead, it is driven back toward the wood sheath as one side of the rupture attempts to slide past the opposite side.

The rupture begins at the spot where the attempt at elongation is greatest. To find that spot, mentally complete the cone of which the pencil point is part (Fig. 1-25). If the missing length is L, then the rupture begins $L/2$ up from the actual writing tip, or $3L/2$ up from the imaginary tip of the completed cone. That fact means that the rupture begins at the spot where the diameter of the lead is $\frac{3}{2}$ times the diameter of the writing tip, a result that can be tested if you wish to sacrifice a number of pencils. (You should do this in private, because repeatedly breaking off pencil points is probably a sign of abnormal behavior—a pencil-breaking syndrome, or something like that.)

When a point is freshly sharpened, the fracture occurs at a narrow section, and so it requires only a small force to initiate it. If the point is blunter, the maximum extent of bending occurs farther up the lead and at a wider section, and the required force is larger. In that case breaking is less likely under normal writing conditions. If the point is so blunt that the spot of maximum bending is within the wood sheath, the analysis here is inappropriate, and the point can break only if you slam the pencil point down on the writing surface (which is certainly a sign of abnormal behavior).

1.71 • Failure of a bridge section

June 28, 1983, Greenwich, Connecticut, USA: At 1:28 A.M., a 30 meter length of the bridge spanning the Mianus River on Route I-95 collapsed. In the dark the occupants of two cars, a tractor-trailer, and another truck failed to spot the missing section in time, drove over the exposed edge, and fell 20 meters into the river. Three people were killed and three others were hurt.

Bridges sometimes collapse because of age or disrepair, but that bridge on I-95 had seemed to be in good condition. Was there something odd about its design or the way in which traffic crossed it that could have led to the tragedy?

Here are some clues. Because of the angular approach the highway takes to the river, the bridge sections are diamond shaped. Each section was supported along two edges. Along the southern edge of the failed section, the support was provided by two *pin and hanger assemblies*, one at each corner (Fig. 1-26*a*). Each assembly consisted of two steel bars through which steel pins passed. At both ends of each pin a large nut had been tightened and welded to secure the pin.

The assemblies allowed some flexibility in the bridge section so that it could respond to vibrations from the traffic load and to any variation in length from a temperature change. Apparently one of the nuts at the corner farther from the center of the section fatigued and its pin worked its way free, causing the section to fall into the river. What sideways force freed the pin? The answer proves to be a worthy study if such catastrophes are to be avoided.

Answer Consider a truck in an outside lane as it crossed a section of the bridge. For the truck to maintain speed, its tires had to push back continuously against the section, creating a torque that attempted to rotate the section around its center (Fig. 1-26*b*). The attempted rotation produced a sideways force on both sets of support pins and nuts on the southern end, but the force was largest at the farther corner because of its greater distance from the center.

After considerable vibration and stress, one of the nuts at that corner failed and its pin slipped out of place, allowing the corner to drop. The diminished support of the section overloaded the rest of the support points and the section fell. Had the section been square instead of diamond, the resistance to rotation would have been shared uniformly by all four corners, and so the failure at one corner would have been less likely.

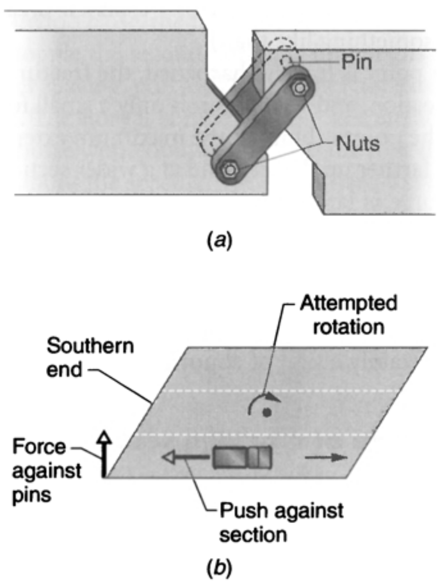


***Figure 1-26** / Item 1.71* (*a*) A pin and hanger assembly holds the span. (*b*) Tendency of rotation due to truck.

1.72 • Jackknifing of a train

When a train engine happens to collide with a massive object and derail, why do the engine and cars usually jackknife instead of all being deflected to one side of the track? Why doesn't the jackknifing extend past the first few cars?

Answer Suppose that the front end of a train engine strikes a massive object that partially straddles the track. Consider the force on the engine in two parts: The force parallel to the track acts to slow the train. The force perpendicular to the track causes the engine to move off to one side of the track. That perpendicular force also tends to rotate the engine around the engine's center of mass. Suppose the front end of the engine is deflected to the right of the track. Then the rotation tends to bring the rear of the engine to the left of the track. Since that rear is attached to the first car, the leftward deflection is not as great as the rightward deflection of the front of the engine.

As the front of the first car is deflected to the left, the car tends to rotate around its center of mass, which brings the rear of the first car to the right of the track. And because of the attachment between the first and second cars, the front of the second car is also deflected to the right. However, this deflection is less than that of the engine or front of the first car. And so it goes.

1.73 • Bowling strikes

In ten-pin bowling (Fig. 1-27) how should you play the ball so as to maximize the chances of a *strike*, in which all the pins are knocked down? Novice bowlers aim for the headpin (the central and foremost one) from the middle of the alley, but seasoned bowlers throw the ball from one side of the alley while putting sidespin on it. The ball seems to *break* or *hook* (that is, changes its course abruptly) at some point down the alley and then head toward the pins along an oblique path. Ideally, the ball should enter the array just to one side of the headpin in what is called the *pocket* (usually the right side if the ball is released on the right side of the alley).

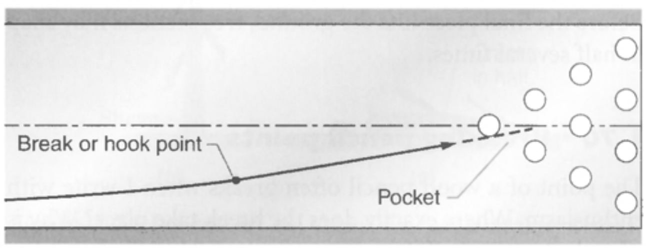


***Figure 1-27** / Item 1.73* Path of a bowling ball.

Is the break real or illusionary? And is the seasoned bowler's strategy of angling the ball into the array actually warranted?

Answer Getting strikes with the novice's scheme is difficult for at least two reasons. The ball may penetrate the array but the pins on the extreme left and right are likely to be left standing. If the ball is somewhat off the mark, its collision with the headpin may knock the ball to the side so severely that it misses the rest of the pins.

If the ball enters the array along a slanted path through the pocket, a wide bounce is much less likely, and so more pins will be downed. If the path is angled several degrees with respect to the central axis of the alley, and if the ball hits the side of the headpin properly, the outside pins along both sides of the triangular array fall in domino fashion and the ball crashes through two of the interior pins, causing one to fall against the other.

The angle of the ball's approach to the pocket depends on the initial ratio of sidespin to forward speed and also on the increase in the friction the ball encounters as it moves down the lane. Normally the first 50% or so of the lane is oiled to decrease the friction. Just after it is thrown, the ball slips over the oiled lane and travels in a curved path toward the pins. When it suddenly begins to roll without slipping, somewhere in the dry (oil-free) region of the lane, its path straightens. The hook is the tightly curved path taken by the ball just before rolling begins. The ability of a bowler to hook a ball depends primarily on the change in the friction along the ball's path, but it also depends somewhat on the fact that the ball is not a uniform sphere because of the finger holes.

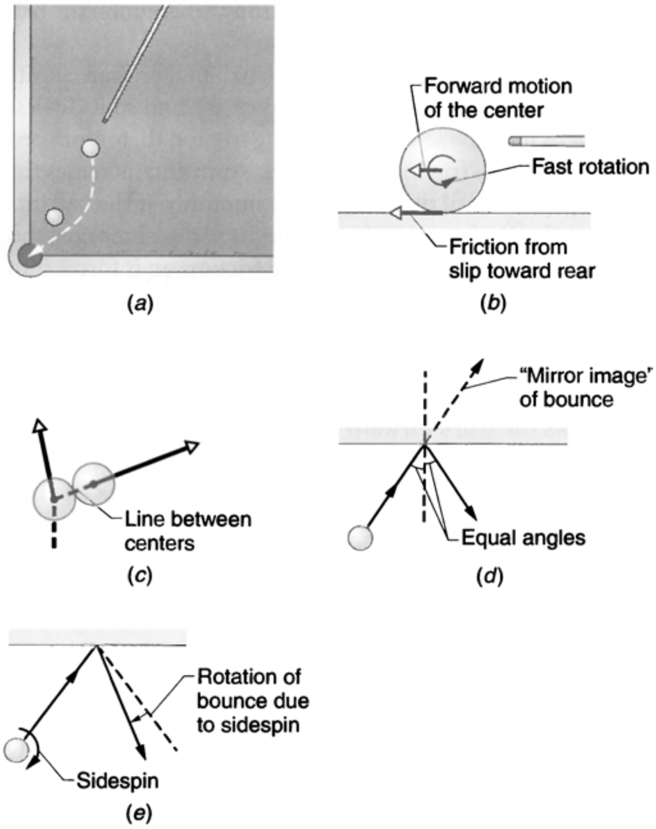


Figure 1-28 / Item 1.74 **(*a*) Masse shot. (*b*) High strike produces a friction force in the forward direction. (*c*) A glancing collision. Bounce from a rail (*d*) without English and (*e*) with left English.**

1.74 • Shots in pool and billiards

Where should the cue stick strike the cue ball for the following results, and why do they occur?

(1) The ball immediately rolls without slipping.

(2) The ball runs into a stationary object ball, and then, shortly afterwards, follows after that ball—a *follow shot.*

(3) The ball similarly runs into an object ball but comes back toward you afterwards—a *draw shot.*

(4) The ball similarly runs into an object ball but then stops after moving only briefly.

When the cue ball is hit by the stick anywhere along a vertical plane through its center and then runs into an object ball, what is the angle between the paths then taken by the balls? If the cue ball collides with the rail (the elevated side of the table) at a certain angle, in what direction does it bounce? If it has been struck by the stick off to either side of the central vertical plane and then runs into the rail, how does the direction of the bounce differ?

A *masse shot* can send the cue ball around an object ball that is an obstacle along the direct path to the target ball (Fig. 1-28*a*). How is the shot executed and what produces the curved path that is taken? (The shot is outlawed in most pool-rooms because it runs the chance of ripping the felt covering on the table.)

Why is the height of the rail always $\frac{7}{5}$ of a ball's radius R?

Answer Situations 1 through 4 involve hitting the cue ball somewhere along the central vertical plane through the ball. For 1 and 4, hit the ball at a height of $\frac{7}{5}R$ (that is, $\frac{2}{5}R$ above the center). For 2, hit it anywhere else above the center, and for 3, anywhere below the center.

The answers involve the way the stick puts spin on the ball. If the ball is struck at a height $\frac{7}{5}R$, the impact produces just enough *topspin* for the ball to roll forward without initially slipping over the table. If the ball then hits an object ball, the energy associated with the forward motion is transferred to the object ball, and the cue ball spins briefly in place until friction from the rubbing drains its rotational energy. (The friction is in the forward direction and may drive the ball a short distance in that direction before the ball stops spinning.)

If the ball is hit anywhere else above its center, its spin is in the proper direction for the ball to roll forward, but the spin rate is either too large or too small, and so the ball initially slips. The slippage generates friction, which brings the spin and forward motion into synchrony, whereupon the ball rolls smoothly forward.

For example, suppose you hit the ball higher than $\frac{7}{5}R$. Its spin is then too large for its forward speed, and so its lowest point slips toward the rear, producing friction that is forward (Fig. 1-28*b*). The friction decreases the spin and increases the forward speed until the ball can roll smoothly. If the ball hits an object ball before then, it transfers its forward motion and briefly spins in place, but the strong friction on it forces it to chase after the object ball.

If the ball is hit below the center, its *backspin* is in the wrong direction for smooth rolling and the friction is large and toward the rear. The friction soon reverses the spin and also slows the ball's forward motion, and then the ball rolls smoothly. If the ball hits an object ball before that stage is reached, the forward motion is transferred, and the cue ball briefly spins in place before the strong friction on it causes it to roll back toward you.

When a cue ball strikes an object ball along a glancing path, the object ball is propelled off to the side along a line that extends through the centers of the balls at the moment of impact (Fig. 1-28*c*). The cue ball bounces to the opposite side. The angle between the final paths is often cited as being 90°, but it has that value only when the collision is on the extreme side of the object ball. (The initial path of the cue ball is actually curved because the cue ball slips on the table just after the collision, but the curved portion is usually too short to perceive.)

If the cue ball rolls smoothly into the rail, its angle of approach matches the angle at which it bounces (it is much like a light ray reflecting from a mirror). One way to visualize the bounce is to imagine that the target (pocket or object ball) lies on the opposite side of the rail, just as distant from the rail as it truly is on the near side (Fig. 1-28*d*). It is then like an image "inside" a mirror. Shoot the cue ball toward that image and the ball will take the appropriate bounce on the rail to hit the target.

However, if the ball has *sidespin* or *English* (it spins around a vertical or tilted axis in addition to spinning around a horizontal axis for rolling), the angle of the bounce is altered. Such sidespin is created when the ball is hit to the left or right of the centerline. From your view, left English (the ball is hit on the left side) rotates the bounce clockwise (Fig. 1-28*e*), and right English rotates it counterclockwise.

A masse shot is made by striking downward on the side of the cue ball. The strike forces the ball to spin as if it has a combination of draw and English. The strike also propels the ball in one direction, but the friction that is produced by the spin curves the path.

The height of the rail is chosen so that a ball's collision with the rail does not cause the ball to slip over the table and lose energy to friction. Instead, the ball rolls smoothly immediately after the collision.

1.75 • Miniature golf

In a game of putt-putt, or miniature golf, a golf ball is hit along a small course enclosed by short walls. The idea is, of course, to get the ball into a cup, or hole, with the fewest strokes. Often the cup lies beyond some barrier or corner of the course, and to reach it economically, a player must bounce the ball off the wall. How should the ball be played to put it in the cup with only one stroke?

Answer When a golf ball bounces from a wall, it reflects much like a ray reflects from a mirror: The angle of its reflection equals the angle of its approach. That fact allows you to picture a tricky shot as if it involves reflecting a beam of light off a mirror. Figure 1-29 shows an example in which a ball is to be hit off a wall and into a cup. Pretend that the wall is a mirror producing an image of the cup. That image, which appears to be behind the wall, has the same distance from the wall as the cup. If you hit the ball toward the image position of the cup, it will reflect from the wall and into the cup.

Players that are skilled at miniature golf (and pool, in which similar bounces occur) can mentally picture a sequence of such bounces. Of course, several practical matters, such as rough and tilted terrain and details of an actual collision with a wall, spoil this simple analysis, and so miniature golf still requires some measure of luck.

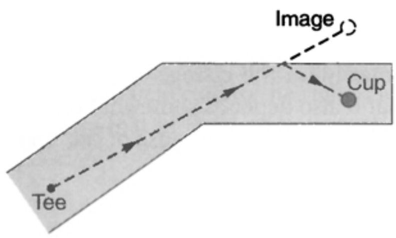


Figure 1-29 / Item 1.75 Overhead view of a miniature golf course hole.

1.76 • Super Ball tricks

If you drop a Super Ball (the highly elastic rubber ball from Wham-O, Inc.), it bounces almost back to your hand. Suppose that you throw it straight down and also put spin on it. Where then does it go?

If you throw the ball down at an angle and with *backspin*, it bounces back and forth between two spots on the floor (Fig. 1-30*a*). If instead you give it *topspin*, it alternates between long and short bounces while moving away from you (Fig. 1-30*b*). (The height of the bounces may seem to alternate between being low and high, but the impression is an illusion.) If you put backspin on the ball while throwing it beneath a flat table, it may refuse to continue beneath the table and fly out toward you (Fig. 1-30*c*). If you throw it onto one wall of two parallel vertical walls that are fairly close together, the ball will probably bounce back to you (Fig. 1-30*e*). What accounts for such strange and headstrong behavior, and why

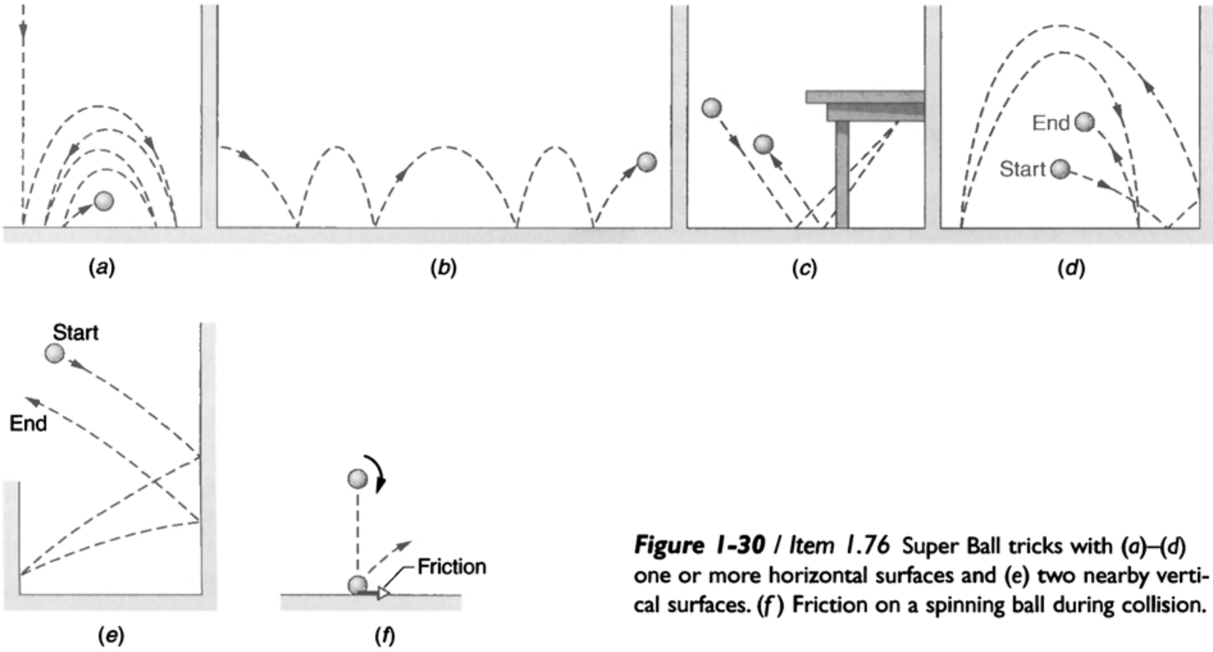


Figure 1-30 / Item 1.76 Super Ball tricks with (*a*)–(*d*) one or more horizontal surfaces and (e) two nearby vertical surfaces. (*f*) Friction on a spinning ball during collision.

does a Super Ball bounce so much better than a normal rubber ball?

Answer When the ball has spin, its rough surface momentarily catches on the floor, and the friction that is generated sends the ball off in a surprising direction. The friction also alters the spin on the ball, and so the next bounce may be quite different.

For example, if the ball is thrown downward with clockwise spin as seen from one side, the friction is toward the right (Fig. 1-30*f*). The ball also experiences an upward force from the floor during the collision. The combination of the two forces directs the ball upward to the right. When the ball is thrown down at an angle and with spin, it may bounce away from you, straight up, or even back toward you depending on the direction and size of the spin, which determines the direction and size of the friction.

The illusion that the bounce height alternates comes from the variation in steepness of the path taken by the ball. As the ball alternates between short and long hops, the angle of the bounce also alternates. (The illusion is so seductive that I twice gave it credence in my writings even though I had just argued how the height cannot vary.)

A Super Ball bounces so well because of the way the collision sets up oscillations within it. When a normal rubber ball hits, the sudden compression on its lower side causes the ball to oscillate. The time for one oscillation depends on the material makeup of the ball. Chances are that the time differs from the time required for the full collision, in which case the ball continues to oscillate after it has left the floor. The oscillations require energy, and so the ball then has less energy for its upward travel and does not go particularly high.

A Super Ball consists of a core that is surrounded by a shell of different material. The construction alters the oscillations so that the time taken by the first one matches the time the ball is on the floor. Just as the bottom of the ball is reversing its compression and shoving off from the floor, the oscillation is outward against the floor, and so it helps launch the ball. As a result, the oscillation's energy is put back into the upward motion of the ball, allowing the ball to go high.

To determine the direction in which a spinning Super Ball bounces, here is a recipe that comes from the need to keep the ball's kinetic energy and angular momentum constant during the bounce. The vertical velocity is merely reversed. The horizontal velocity of the lowest point on the ball is also reversed, but it is harder to picture because it consists of both the ball's spin and the horizontal velocity of its center. If you combine the directions of the vertical and horizontal velocities just after the collision, you then have the direction in which the ball bounces.

1.77 • Racquetball shots

The bounce of a racquetball, which is a reasonably elastic ball, is partially determined by the spin on the ball. You can give it spin by stroking the racquet over the top or bottom of the ball as you hit it. Or you can hit the ball into a wall or ceiling so that the collision produces spin. Once created, the spin might give the ball a bounce that will perplex your opponent. For example, what does the ball do if it hits the front wall horizontally with either topspin or backspin?

One of the finest plays in racquetball is the Z-shot, which was discovered in the 1970s. As shown in Fig. 1-31*a*, the ball is hit from the right side of the court. After it strikes high on

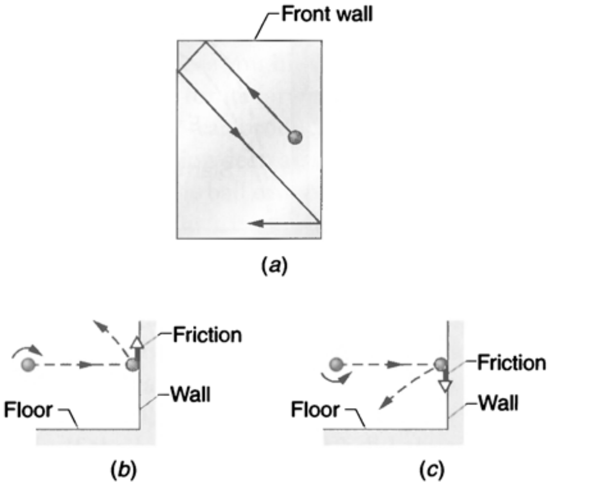


***Figure 1-31** / Item 1.77* **(*a*) Racquetball Z-shot. Bounce from a wall with (*b*) topspin and (*c*) backspin on the ball.**

the left side of the front wall and next on the forward part of the left wall, it bounces low on the rear part of the right wall. It then travels parallel and so close to the rear wall that your opponent has great difficulty in returning the shot. One reason is that the ball travels across the width of the court, an unusual situation in the game. The other reason is that the ball is so near the wall that your opponent cannot get behind it for a forward return. The only hope is to slam the ball into the rear wall hard enough that it rebounds to the front wall.

What accounts for the path taken by the ball in a Z-shot?

Answer The role of spin and friction on a bouncing ball is explained in the preceding item. If you slam the ball horizontally into the front wall with topspin, the ball leaps high and then descends far down the court (Fig. 1-31*b*). If, instead, you give it backspin, it bounces down to a spot near the front wall (Fig. 1-31*c*). (Thus, by using spin you can have your opponent running all over the court.)

In a Z-shot you hit the ball without giving it spin, but it picks up clockwise spin (as seen from overhead) with its first two bounces. When it undergoes the third bounce, the friction generated by the spin arrests the ball's rearward motion, and the collision propels the ball along a path that is perpendicular to the right wall. The player who first discovered this shot stunned his opponents because the ball's final trajectory was so novel that their playing experience could not anticipate it.

SHORT STORY

1.78 • A controversial goal

In the 1975 World Cup final for field hockey, India won a goal with a play in which an umpire ruled that the ball crossed the goal line, struck the upright wood member on the right of the goal (which was scarcely inside the goal line), and then bounced back into the field of play (Fig. 1-32, which is an overhead view and not to scale). Although such a bounce is highly unlikely and certainly uncommon to the sport, it might occur if the ball happens to take a certain angle toward the goal while also having spin. Less spin is required if the shot comes from the near left side of the goal. If the angle to the goal (between the incoming path and the goal line) exceeds 25°, the backward bounce of the ball is impossible. No one remembers the exact details of the shot in the contest, but the umpire's ruling was at least plausible.

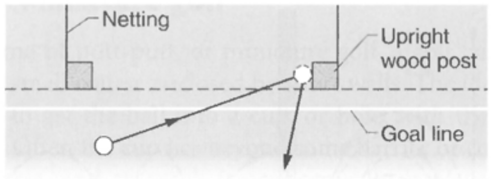


***Figure 1-32** / Item 1.78* **Overhead view of a field hockey ball striking goal post and bouncing back into play.**

1.79 • Tennis

Where on the head of a tennis racket should you hit the ball if you want (a) the greatest speed for the ball, (b) the least force on your hand due to the collision, or the least attempt of the racket handle to rotate out of your grip during the collision, or (c) the least oscillations of the racket due to the collision (and thus the least oscillations of the handle against your hand)?

Does the firmness of your grip affect the rebound speed of the ball? Are there really such things as a fast court and a slow court?

Answer When you hit the ball, you should strive to have the collision along the long axis of the racket; you will not only give the ball more speed, but you will also avoid the racket twisting in your grip. But just where along that axis you should hit the ball depends on the type of racket and exactly which goal of those listed in the question you value most. Each of the regions on the strings meeting any one of those goals is said to be a *sweet spot.* Thus the term is often confusing unless the goal is defined with it.

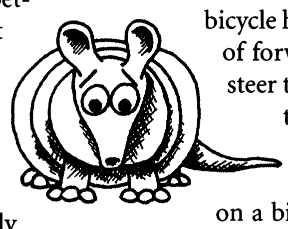
Sweet spot 1 is a region where a collision will give the ball the largest speed. This sweet spot is close to the throat of the racket and not, as you might think, at the center of the head. The position has to do with the energy lost in the collision. During the collision, both the racket and the ball deform and then spring back to their original shape. The energy going into the racket's deformation is not returned to the ball because the ball leaves the strings before the racket springs back. So, to minimize this loss of energy, the ball should hit very near the throat where the frame of the racket is stiffest because of the nearby handle. However, the energy lost in the ball's deformation shifts the sweet spot up from the throat somewhat. This loss is greater very near the throat where the strings are tighter and thus present a more rigid structure to the ball than those nearer the center. So, sweet spot 1 is located near the throat because of the racket's stiffness but somewhat above the throat because of the looser strings there.

Sweet spot 2 is a region where the collision produces no force on the hand at the handle. Although the collision tends to push both racket and hand backward, it also tends to rotate the racket. When the collision is at sweet spot 2, the backward push on the hand is canceled by a forward motion of the handle due to the rotation. If the ball hits farther from the hand than sweet spot 2, the rotation of the racket causes the handle to pull outward from the hand. If it hits nearer the hand than the sweet spot, the rotation causes the handle to move into the hand.

Sweet spot 3 is a region where the collision produces little oscillation of the racket (and thus little oscillation against the hand at the handle). If the racket is hit elsewhere, it briefly and perhaps strongly oscillates, somewhat like a plate on a xylophone oscillates when struck.

There is also an ill-defined sweet spot 4 where a player subjectively judges the collision to be best, for any number of reasons.

Although some tennis instructors advise a player to hold the racket very firmly during the ball–racket collision so as to increase the rebound speed of the ball, research shows that the rebound speed is unaffected by the firmness of the grip. The main advantage of a firmer grip seems to be the better control against the resulting twisting of the racket when the collision is off the long axis of the racket. The main disadvantage of a firmer grip is that the impact force and the resulting oscillations of the racket are transmitted more to the arm, which may contribute to the ailment known as *tennis elbow.* Perhaps to lessen this transfer, a skilled player partially relaxes the grip on the racket just prior to impact with the ball by ceasing to accelerate the racket just then.



The material along a court (clay, wood, grass, carpet, and other coverings) can affect the horizontal speed of a ball that is hit low over the net and then strikes the court, skidding across the court before it rebounds. Just how much of the ball's horizontal speed is retained after the strike determines whether the court is fast or slow: On a fast court, the friction is low and more of the horizontal speed is retained. On a slow court, the friction is high and less of the horizontal speed is retained. When the ball is sent into a high lob, it comes down at a steep enough angle that it rolls (rather than skids) over the court, and the ball always loses about 40% of its horizontal speed for any of the traditional court materials.

1.80 • Bicycles and motorcycles

Why is a moving bicycle or motorcycle fairly stable, even if you ride without using the handlebars? How do you initiate a turn? Can you turn a bicycle without using the handlebars? Why is the modern design of a bicycle considerably more stable than earlier designs? In particular, why does the modern bicycle have a front wheel fork that curves away from the rider? What advantage would a bicycle with a low center of mass have in a race?

Answer The question of why a moving bicycle or motorcycle is stable has long been debated. Some investigators have championed the idea that the wheels act like a gyroscope—they tend to resist any chance tilt because of their angular momentum. However, research has demonstrated that the effect is small, especially for a bicycle. Another argument is that you turn the wheel in the direction of the deflection, and the motion of you and the bicycle in the forward direction rights the bicycle. But that cannot be the whole story, as anyone who has ridden a bicycle without touching the handlebars knows. Both explanations also fail to explain how a rider can keep a bicycle upright even when the bicycle is stationary.

The best explanation appears to be one that involves the *trail* of the front wheel—that is, the distance along the ground between where a vertical line through the front axle touches and where a mental projection of the steering axis touches. If the trail extends forward from the tire (as is the case with most—perhaps all—bicycles), then when you undergo some chance tilt, the front wheel automatically steers into the tilt, reducing it. If you help turn the wheel, you can aid the correction, but you do not have to help. If the bicycle had a trail that extended toward the rear instead of forward, the front wheel would not automatically steer to correct a chance lean, and so you would have to make the correction yourself, which makes such a bicycle difficult to ride.

The question of how you initiate a turn on a bicycle or motorcycle has also been long debated, partly because the correct explanation seems wrong. If you want to turn a bicycle, say, to the right, you must turn the front wheel to the left in what is called *countersteering.* You, the bicycle frame, and the front wheel then automatically lean to the right, that is, into the intended turn. This lean causes a torque that opposes the countersteering, turning you, the bicycle frame, and the front wheel to the right. The bicycle is then brought upright.

In a bicycle race where the rider is upright and pumping rapidly on the pedals, the bicycle is thrown vigorously left and right, pivoting around the contact points on the roadway or ground. The lower the center of mass of the bicycle is, the closer it is to the pivot points, and the easier the left and right oscillations are for the rider.

1.81 • Motorcycle long jumps

The stuntman Evel Knievel made numerous stunning jumps in the 1960s and 1970s in which he rode a motorcycle up a ramp, flew through the air over numerous cars or trucks, and then landed on another ramp on the far side. He often made the jumps successfully but on occasion lost control of the motorcycle during the landing and was seriously injured. In

1978, a young man attempted a similar jump over the wings of a DC 3 aircraft but made the fatal mistake of keeping the motorcycle's throttle wide open during the flight. Why did that mistake lead to his death?

Answer When the rear wheel clears the first ramp, the friction retarding its motion suddenly disappears. If the throttle is still open so that the engine continues to drive the wheel, the wheel then turns faster than when it was in contact with the ramp. Since the motorcycle and rider are airborne and free of any external torques, their angular momentum cannot change. So, when the rear wheel begins to turn faster, the motorcycle and rider must rotate in the opposite direction to maintain the initial angular momentum. The rotation brings the front of the motorcycle upward, perhaps by as much as 90°, which makes landing on the far ramp almost impossible. Closing off the throttle at the instant of launch would prevent the dangerous rotation. Slowing the wheel somehow would be even better because it would pitch the front of the motorcycle downward, readying it for the landing.

1.82 • Skateboards

Why do you have an easier time of balancing on a skateboard when you get it moving than when it is stationary? How can you get a skateboard (and yourself) to jump over an obstacle, a maneuver known in the street as an *ollie*?

Answer Your instability comes from an inevitable tilt to the left or right. One investigator showed that in a simple model of a skateboard, the tilt is automatically corrected by the forward motion of the board provided that your speed exceeds a critical value, about 0.8 meter per second. Any chance tilt then turns the front and rear wheels and sets up a small oscillation to the left and right without spilling you off the board. The frequency of the oscillation increases with speed.

In a more complicated model the investigator discovered that when the speed exceeds a second critical value, the board is again unstable to chance tilts and requires agility by the rider. However, stability seems to be reinstated if the speed exceeds a third critical value, but such a speed is uncommonly high in the sport.

To execute an ollie as you ride the skateboard on a sidewalk toward an obstacle, you go through the following routine. At the appropriate moment, you slide your forward foot toward the rear, lower yourself, and then push downward hard on the skateboard to propel yourself upward. Because your rear foot is on the rear of the skateboard, behind the rear wheels, your downward push slams the rear of the skateboard onto the sidewalk. The collision propels the skateboard upward and also begins to rotate it around its center of mass. As the skateboard rises and rotates, you contract both legs so as not to impede the rise, but you also slide your forward foot toward the front to control the rotation. If you are successful, your forward foot will level the skateboard near the top of the skateboard's rise. You then ready yourself for the landing, allowing your legs to flex upon impact so as to cushion the shock.

1.83 • Pitching horseshoes

In the game of horseshoes you toss a metal shoe (it resembles a horseshoe) at a metal stake 12 meters away. In the toss, you bring your arm down and to the rear, and then you rapidly swing it forward, releasing the shoe once your arm is about horizontal. When the shoe lands on the ground, you want the stake to be within its arms. It might end up there if it skips over the ground, but your chance is better if it hits the stake during its flight and then falls into place.

If you are unschooled in the game, you might be tempted to toss the shoe in what is called a *flip*, holding the midpoint of the shoe as shown in Fig. 1-33*a*. When you release the shoe, its plane is horizontal and its arms point toward the stake. During the release you flip the shoe so that it then rotates end over end during the flight.

A flip was originally the most common tossing technique, but then skilled players adopted other ways of holding, orienting, and spinning the shoe. In one technique the grip is up on an arm, with the plane of the shoe extending away from you and at a tilt to the vertical, and with the arms pointed upward (Fig. 1-33*b*). Depending on the speed of the flip you give the shoe, it turns through $\frac{3}{4}$, $1\frac{3}{4}$, or even $2\frac{3}{4}$ revolutions before it hits the stake. In another technique the grip is also off-center, but the arms point downward and the shoe is rotated through $\frac{1}{4}$, $1\frac{1}{4}$, or $2\frac{1}{4}$ revolutions. Why might these more modern techniques produce more *ringers* (the shoe hits the stake, circles it, and then drops into place) than does a flip?

Answer If the interior of the shoe hits the stake in a traditional flip throw, the shoe will likely rebound toward you and land away from the stake (Fig. 1-33*c*). In the modern tosses, part of the shoe's rotation is around a vertical axis. When the interior of the shoe hits the stake, that part of the rotation continues, causing the shoe to spin around the stake. Quickly the flared section on one arm catches on the stake, trapping the shoe, and the shoe eventually falls into place (Fig. 1-33*d*). The name *ringer* probably comes from the ringing of the shoe around the stake or from the clatter that the rotation makes.

1.84 • Spinning hula hoops and lassos

How does one keep a hula hoop (the ring under trademark by Wham-O, Inc.) up and spinning around the body in an almost horizontal plane? How does a cowboy accomplish a similar motion with a lasso?

Answer Both types of motion are due to the force on the spinning object that is provided at a support point. With the hula hoop, the force is at the hoop's point of contact with

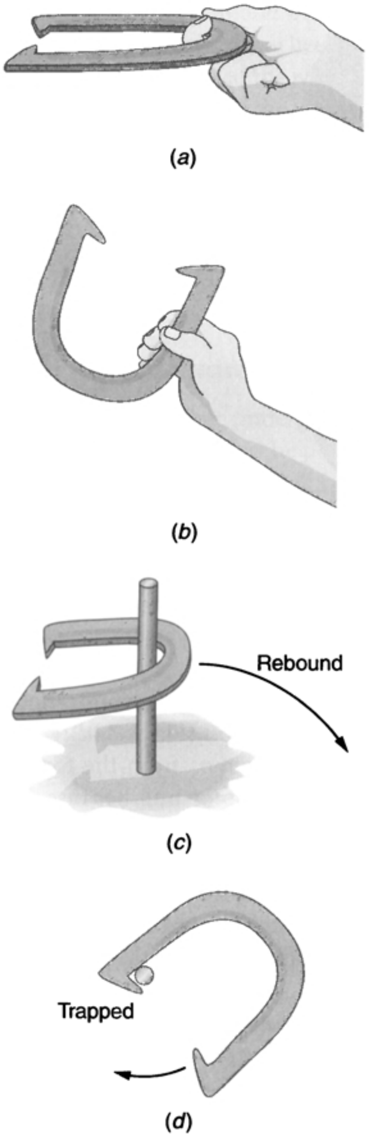


Figure 1-33 / Item 1.83 (*a*) Release for horseshoe flip throw. (*b*) A better release. (*c*) Rebound from the stake. (*d*) A ringer.

the body. With the lasso, the force is due to the hand pulling on the short length of rope between the hand and the loop of rope. In each case the support point moves in a small circle and pushes or pulls outward on the spinning hoop or lasso, and the force tends to bring the plane of the object close to horizontal. To maintain the spin, the circling by the support point must be somewhat ahead of the circling by the object.

1.85 • Yo-yo

When a yo-yo is tossed downward in the normal manner, how does its rotation gain energy? Why does its downward speed first increase and then decrease? Why can some types of yo-yos *sleep*—that is, remain spinning at the end of the string—while others immediately begin to climb the string once they have reached its end? How do you awaken a sleeping yo-yo to initiate a climb? Why does it climb more poorly, or not at all, if you let it sleep too long? When a yo-yo is near the hand, why does its plane turn around the string (a motion that is called precession)? Why is a sleeping yo-yo much less likely to precess?

A number of tricks can be performed with a yo-yo, including *around the world* and *walking the dog*. In the first one, the spinning yo-yo is made to swing around a large vertical circle while at the end of the string. In the second, a sleeping yo-yo is lowered to the floor, where it then rolls. If the string is kept taut and is also made horizontal, which way will the yo-yo move if the string is suddenly jerked?

Yo-yos come in a variety of styles but among the most impressive must have been the one that was constructed at MIT in 1977. The string (actually, nylon cord) was 81 meters long; the yo-yo structure consisted of two 66 centimeter bicycle wheels coupled with a steel shaft; and the yo-yo was released over the side of a 21-story building.

Even more striking was a 116 kilogram yo-yo that in 1979 Thomas Kuhn yo-yoed about 30 meters from a crane to set the record for the heaviest yo-yo. The yo-yo, 1.3 meters tall and almost 0.80 meter wide, was proportional to a standard yo-yo.

Yo-yos in space: On occasion an orbiting astronaut may play with a yo-yo. Why is it difficult to make a yo-yo sleep in such an environment?

Answer Suppose that you drop the yo-yo rather than throw it downward. Normally when you drop an object, its potential energy is transformed into kinetic energy and the object travels progressively faster with descent. A yo-yo is different for two reasons: It rotates and the rotation rate depends on the thickness of the layer of wound-up string on the yo-yos shaft. As the yo-yo descends and unwraps that string layer turn by turn, the yo-yo spins faster and faster. That leaves less energy for the descent itself. As a result, the rate at which the yo-yo descends first increases and then, about halfway down, it decreases. When the yo-yo reaches the end of its descent and the string is completely unwound, the yo-yo bounces.

If the string is attached to the shaft (usually through a hole in the shaft), the yo-yo immediately begins to wrap back up on the shaft, with the direction of the yo-yo's rotation unchanged. If, instead, the string is looped around the shaft and the bounce is not severe, the yo-yo will sleep. You can awaken it by jerking upward on the string. The jerk yanks the yo-yo upward and momentarily relieves the tension in the string. Since the yo-yo is turning, it catches up some of the slack string on the shaft. Provided there is enough friction, the captured section of string holds, and then the yo-yo is forced to wrap up more string, which makes it climb. If you wait too long to awaken a sleeping yo-yo, too much energy is lost to the rubbing between the shaft and the loop around it, and the yo-yo will be unable to climb back to your hand.

In space, gravity is effectively turned off because both the astronaut and the yo-yo are in free fall. To yo-yo, an astronaut must throw the yo-yo—it won't fall away on its own. When it reaches the end of the string, the abrupt stop makes it bounce, and it most likely will catch up on slack string and be forced to return. To make it sleep, the astronaut must pull gently on the string during the bounce so that the tension prevents slack string. The astronaut could instead swing the yo-yo in a circle to maintain the tension.

Chance disturbances tend to make the yo-yo precess, but the precession is normally appreciable only when the yo-yo is near the hand, where it spins slowly. When it is sleeping, the high speed of rotation creates a large angular momentum that stabilizes the yo-yo against the disturbances. The yo-yo is then much like a gyroscope.

I leave the tricks for your analysis, but for walking the dog, you might want to consider some variations in the orientation of the string as suggested by the next item.

1.86 • Unwinding a yo-yo

Suppose that you unwind a short length of the string on a yo-yo, place the yo-yo on a table such that the string unwraps from the bottom of the central axle, and then pull the string horizontally toward you. Will the yo-yo move toward you or away from you, or will it turn in place? What will it do if you pull upward at an angle to the tabletop? How does it behave if you turn it over so that the string unwraps from the top of the central axle? Before you test a yo-yo, guess at the answers. If you do not have a yo-yo, you can substitute many types of spools, such as a spool of thread.

Stand a bicycle against a table, arrange for a pedal to be in its lowest position, and then pull that pedal toward the rear of the bicycle. Does the bicycle move, and if so, in what direction?

Answer The analysis of the yo-yo is easiest if you consider the point of contact between the yo-yo and the table as being the point around which a torque is to be calculated. Since the friction on the yo-yo from the table acts at that point, friction does not create any torque to turn the yo-yo. To determine the direction in which the yo-yo moves, you then need only consider the torque from the string. If the torque is clockwise (see the figures), the center of the yo-yo must move past the contact point in a clockwise direction and so toward you. If the torque is counterclockwise, the motion is the reverse.

Suppose that the string unwraps from the bottom of the axle. When you pull the string horizontally, the torque it creates with respect to the point of contact is clockwise and the yo-yo moves toward you (Fig. 1-34*a*). To see what happens when you pull somewhat upward, extend the force vector from the string backward until the extension reaches the table. If the extension is to the left of the contact point as in Fig. 1-34*b*, the torque is still clockwise and the yo-yo still moves toward you. If the extension passes through the contact point (your pull is at a larger tilt), the torque is eliminated and the yo-yo spins in place (Fig. 1-34*c*). If the extension is to the right of the contact point (your pull is at

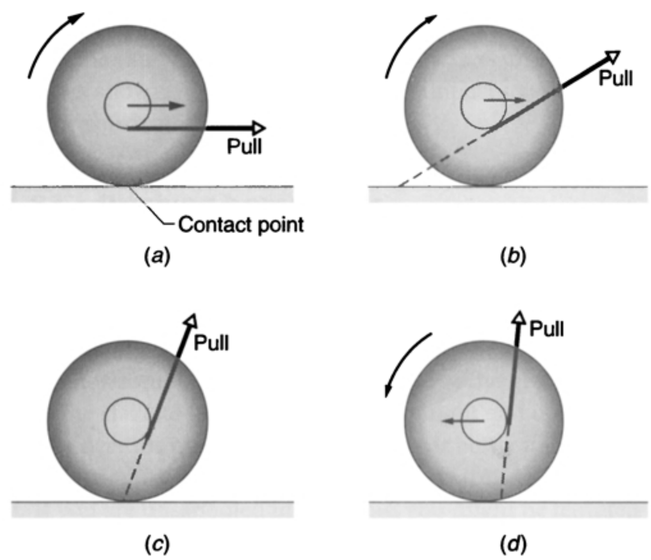


***Figure 1-34** / Item 1.86* (*a*)–(*d*) The direction of pull determines the direction of the yo-yo's roll.

an even larger tilt), the torque is counterclockwise and the yo-yo moves away from you (Fig. 1-34*d*).

When the string unwraps from the top, the yo-yo rolls toward you for any angle of pull because the extension is always to the left of the contact point.

For the bicycle setup, the bicycle rolls to the rear because of your pull. The forward-pointing frictional forces on the tires, though smaller than your pull, act at a large radius and dominate the turning, rotating the pedal forward against your pull.

1.87 • Driving through the sound barrier

The current land-speed record was set in the Black Rock Desert of Nevada in 1997 by the jet-powered car Thrust SSC. The car's speed was 1222 kilometers per hour (or 759 miles per hour) in one direction and 1233 kilometers per hour in the opposite direction. Both speeds exceeded the speed of sound at that location (1207 kilometers per hour), and the car sent shock waves (sonic booms) across the desert floor to the observers. Setting the land-speed record was very dangerous for many obvious reasons, such as the chance that the air pressure under the car's nose could lift the nose and cause the car to flip over backwards (while traveling faster than sound!). A more subtle danger had to do with the car's wheels. Can you find that danger?

Answer With the car traveling faster than the speed of sound there on the desert floor, each wheel rotated in excess of 6800 revolutions per minute, with a huge centripetal acceleration of 35 000 *g*s (35 000 times the gravitational acceleration) on the rim. Although the wheels were cast aluminum, the radial acceleration put the material of the wheel on the edge of what it could withstand without rupturing. The unknown factor was how that material would fare as the wheels rolled over the desert. Had a wheel hit even a small object, the shock would have caused the wheel to explode and the car to crash. Because that part of the desert had once been used for artillery practice, the ground crew had to walk the route to carefully inspect for partially buried artillery shells and similar debris before the car could be run along its course.

SHORT STORY

1.88 • Spin test explosion

Large machine components that undergo prolonged, high-speed rotation are first examined for the possibility of failure in a *spin test system.* In this system, a component is *spun up* (brought to high speed) while inside a cylindrical arrangement of lead bricks and containment liner, all within a steel shell that is closed by a lid clamped into place. If the rotation causes the component to shatter, the soft lead bricks are supposed to catch the pieces for later analysis.

In early 1985, spin testing was being conducted on a solid steel rotor (a disk) of mass 272 kilograms and radius 38 centimeters. When the sample reached an angular speed of 14 000 revolutions per minute, the test engineers heard a dull thump from the test system, which was located one floor down and one room over from them. Investigating, they found that lead bricks had been thrown out in the hallway leading to the test room, a door to the room had been hurled into the adjacent parking lot, one lead brick had shot from the test site through the wall of a neighbor's kitchen, the structural beams of the test building had been damaged, the concrete floor beneath the spin chamber had been shoved downward by about 0.5 centimeter, and the 900 kilogram lid had been blown upward through the ceiling and had then crashed back onto the test equipment. The exploding pieces had not penetrated the room of the test engineers only by luck.

1.89 • Kayak roll

You are riding the rapids in white water when you and your kayak are up-ended. Realizing that it would be unwise to continue the trip upside down, you try to right the kayak without leaving the cockpit so that you are still somewhat protected. How do you do this?

Answer Here is one strategy. As you roll through the inverted orientation, bend over and extend your paddle toward the water surface that lies in the direction of the roll. Then pull down sharply on the paddle so that the upward resistance it meets provides a torque that will continue the roll and bring you up to the surface. Instead, you might tilt the plane of the paddle and pull parallel to the length of the kayak. In that case, the upward force on the paddle comes from the deflected path the water is forced to take by the paddle.

Until your body breaks the surface, it experiences buoyancy that effectively cancels your weight. However, as your body clears the surface, your weight becomes important and can easily stop the rotation. To avoid stopping, keep your body in the water as long as possible by bending over to the side and let the kayak continue to roll to the upright position while you continue to pull down or backward on the paddle. Just as the kayak becomes upright, sit up.

Some kayakers also employ a *hip snap* during the inverted phase. By snapping the hips in the direction opposite the intended roll, the kayak is forced into the roll. This procedure is most helpful when the paddle has been lost and only outstretched arms can be used in its place.

1.90 • Curling

In the sport of curling, a rotating *stone* is sent sliding along an ice rink toward a target region. The stone, a heavy object, is supported by a narrow circular band. The path the stone takes is initially straight but gradually begins to curve to one side, with the curvature increasing as the stone nears the end of the path. For example, if the stone is launched with a clockwise spin as seen from above, the path curves off to the right. Skilled curlers employ the curvature to send their stone around another one that might shield the target. Why does a stone's path curve?

Curling is often played on pebbled ice (ice with small upward protrusions) that is formed when water is sprayed onto the rink, possibly because such a surface gives more deflection. Vigorously sweeping the ice just in front of the stone is thought by many players to add length to the path and also to increase the deflection. What might account for these effects?

Answer The sideways deflection of the stone (curving the stone's path) is due to the friction on the stone's narrow supporting band. The friction is not a *dry friction* between the band and the ice. Rather, it is a *wet friction* between the band and a thin layer of liquid water melted from the ice by the rubbing of the band. The amount of the friction is not uniform around the band because the friction at any point depends on the speed of the point. If the stone were sent sliding with no rotation, every point would have the same speed and would experience the same amount of friction. However, in play, the stone is sent sliding with some rotation. The combination of the forward motion with this rotation means that different points on the band move at different speeds and thus experience different amounts of friction. The result of this uneven distribution of friction on the band is a net force to the side, deflecting the stone. If the stone is rotating clockwise, the net force and the deflection are rightward. The uneven distribution of friction is also responsible for the stone's behavior at the end of its path: For a while after its forward motion ceases, it spins around one side as if pinned at that side.

The matter of pebbled ice is not understood, and the practice of sweeping is sometimes unfairly scoffed at. A pebbled surface may enhance the friction's dependence on speed. Sweeping certainly removes grit and loose ice that would hinder the stone, but it may also lubricate the stone's motion by partially melting the ice.

1.91 • Tightrope walk

How does a long, heavy bar help a tightrope walker maintain balance, especially if the performance is outdoors and in a moderately gusty wind?

Some tightrope performances have seemed incredibly dangerous. In 1981, Steven McPeak walked a wire strung peak to peak at the Zugspitze, which lies on the border between Austria and Germany. During part of the traverse he was a kilometer above the ground. On the same day he walked up the cable that is normally used by the cable cars on the mountain. He somehow managed slopes that exceeded 30°.

In 1974, Philippe Petit walked across a wire that was between the twin towers of the World Trade Center in New York City and 400 meters above street level. He had shot the wire from one tower to the other with a bow and arrow. After at least seven passages, he was arrested by the police for criminal trespassing. Presumably, they could think of no other reason to stop him, because lawmakers had not foreseen the possibility of criminal wire walking.

Answer Balance is maintained if the center of mass is kept, on the average, over the rope. When the performer leans too far in one direction, the body must bend back in the opposite direction to correct the problem. A heavy bar helps: If the performer leans, say, to the left, the bar is shoved to the right so that the combined center of mass of the performer and bar is kept over the rope. The procedure must be executed quickly before the performer leans too far. A light bar is of little help—with little mass, it would have to be shifted too far to be practical.

1.92 • Bull riding

Why is riding a wild bull or a bucking bronco in a rodeo (or a mechanical bull in a bar, as was sometimes popular in the 1970s) so difficult? Is there anything that a seasoned rider does to help stay on the bull other than just hold on to the strap wrapped around the animal's chest?

Answer The rider's perch depends on the location of the bull beneath her, but the bull suddenly twists, pitches, runs, and stops. With each sudden move of the bull, the rider's momentum and angular momentum tends to send or rotate her from her perch. If she just holds on to the strap with both hands, she must use her strength to arrest the motion of the upper portion of her body off her perch.

She can do better if she throws one arm high while holding onto the strap with the hand of the other arm. She can then throw the free arm in a direction that counters any sudden rotation given her by the bull. The free arm must be held high instead of low so that its mass is far from the center about which the rider tends to rotate at any given instant. Only then can the motion of the free arm effectively counter the rotation of the more massive upper body. If the rider holds a large hat with the free hand, the air drag on the hat as it is waved might give an extra measure of resistance to the rotation of the upper body.

A first-time skater, either on blades or wheels, does something similar to partially correct a problem with imbalance. During my first time on roller skates, when the skates tended to roll out in front of me, I automatically rotated my arms in vertical circles back over my shoulders (like a windmill) to keep my center of mass positioned over the skates and thus to maintain my balance and what little was left of my pride.

1.93 • Tearing toilet paper

One of the frequent, albeit minor, frustrations of life is pulling on a roll of perforated toilet paper, only to pull off a single square, which, of course, is useless to your purpose. The problem is characteristic of fresh rolls and rarer with ones that have been almost depleted. Why are fresh rolls so troublesome? Does the angle at which you pull matter? Is the problem worse if the paper is pulled off the top of the roll or, with the roll reversed, off the bottom?

Answer Your force on the loose end of the toilet paper creates a torque that attempts to rotate the roll. Countering your torque is a torque from the friction between the cardboard interior of the roll and the dispenser rod. When your pull is small, the friction is also and just enough to prevent the roll from turning. As you increase your pull, the friction increases until it reaches some upper limit. Any stronger pull forces the roll to turn, and once there is slippage, the friction is suddenly diminished. But if the required pull is too much, the paper rips.

When the roll is fresh, its weight bears down on the rod and makes the upper limit to the friction large, which means the pull that is required to turn the roll is certain to rip the paper. When the roll is almost depleted and weighs less, the upper limit is smaller and then you can overwhelm the friction with a smaller pull, probably without ripping the paper. If your pull is upward, as is usually the case if the loose end is on the bottom of the roll, you help support the roll, and the upper limit to the friction is thereby smaller. You are then less likely to rip the paper. (In this explanation I have ignored the role played by the lever arms of the torques. You might want to re-examine my conclusions by considering how the lever arm of your pull changes as the roll is depleted.)

Alas, there is no escape from physics, not even in the bathroom.

1.94 • Skipping stones and bombs

How can you manage to skip a flat stone over water? Can you increase the number of skips by increasing the speed or spin that you give the stone? How does a stone skip over wet sand, and why is its path marked with widely spaced pairs of closely spaced nicks?

During World War II, the skip of stone, over water inspired one of the weapons of the British Royal Air Force. The RAF was determined to demolish several of the vital dams in Germany, but the dams were so sturdy that they could be broken only if explosives were placed near the bottom. Bombing the top surfaces would have been useless, and torpedoes dropped by airplanes into the water would have just been snared by the nets that had been deployed near the dams. The difficulties of the task were augmented by the facts that the dams were located in narrow, deep valleys that would confine an air attack, and any attack would have to be made on a dark night if the aircraft were to avoid the artillery that protected the valleys.

To solve the problem, the RAF developed a cylindrical bomb with a length of about 1.5 meters and a slightly smaller diameter. As an airplane approached a dam, a motor gave a bomb a large backspin (top moving opposite the airplane's motion), and the bomb was then released 20 meters above the water surface. (The airplane was equipped with two bright lamps whose beams were angled so that they crossed 20 meters below the airplane. By finding the altitude that gave the smallest spot of light on the water, the pilot could put the airplane at the right height.)

What did the bomb do when it reached the water? Was its rotation of any further use at the dam?

Answer To get a good skip you need to skim the stone over the water so that its plane and its approach path are both nearly horizontal. You should also give it as much spin as possible because the spin stabilizes the stone's orientation, much like spin stabilizes a gyroscope. When the stone hits the water properly, a small wave springs up in front of the leading edge, and the stone then ricochets from it in the forward direction. The initial speed of the stone determines the distance between skips. The number of skips is set by the loss of energy at each skip. The stone not only gives up energy to make the wave but it also briefly rubs against the water surface.

Skipping stones is an ancient pastime, but in recent years a manufactured "stone" consisting of sand and plaster has been introduced. Its bottom surface is concave so as to reduce the rub with the water and so also the energy loss. While the world's record with a natural stone is currently about 30 skips, the artificial stones give 30 or 40 skips.

To explain a stone's pockmarked path over sand, suppose that it hits first along its trailing edge. A shallow pit is dug into the sand, and the collision rapidly flips the front edge down to dig out another nearby pit. The second collision then propels the stone through the air and also reorients the stone so that another pair of pits is dug out farther along the beach.

When the RAF bomb hit the water, its backspin forced it to skip because of the rapid motion of the bottom surface against the water. The gradual loss of energy during the skips reduced the length of each hop, but the hops were still large enough to pass over the tops of the torpedo nets. When the bomb hit the dam wall, the backspin forced the cylinder to roll down the wall. A hydrostatic charge, set for a depth of 10 meters, then ignited the bomb. One reviewer commented, "It was a beautifully simple idea for positioning a bomb weighing almost 10,000 pounds to within a few feet."

A similar bomb, but smaller and spherical, was developed to sink ships. Two of the weapons were to be given backspins of 1000 revolutions per minute and then dropped from 8 meters about 1.5 kilometers from the target. The thought was that as they went leaping over the water surface like flying fish, they might possibly avoid the nets and booms that guarded the target. Once they collided with the hull, they would roll down it until at some preselected depth the 600 pound charge would be detonated. The weapons could also be used to penetrate long tunnels: Released into a tunnel's opening, they would skip their way deep in the tunnel before exploding. For various reasons, the smaller bombs were never used for either purpose. (Physics, though always interesting, can sometimes be horrible in its application.)

1.95 • Spinning ice-skater

An ice-skater spinning on point is a standard device to demonstrate the conservation of angular momentum. When he pulls in his arms, the skater spins faster. The increase in spin is due to the fact that there are no external torques on him, and so his action cannot change his angular momentum. Thus, because he moves some of his mass (arms and possibly one leg) toward the axis around which he spins, his spin rate must increase. This argument is certainly correct, but what force makes him spin faster, and why exactly does his kinetic energy increase?

Answer Both questions can be answered in terms of two *fictional forces* experienced by the skater. The forces are said to be fictional because, although quite apparent to the skater from his rotating perspective, the forces do not actually exist from our stationary perspective—they are not real pushes or pulls. Instead, they are his interpretation of what he feels. One of these interpreted forces is radially outward, a *centrifugal force*. When he brings in his arms and a leg, he must work hard against that apparent outward force. His work goes into his increased kinetic energy. The other interpreted force, a *Coriolis force*, seemingly pushes him around the axis about which he spins. As he brings in his arms and legs, he feels as though an invisible agent is pushing on him with that force, making him spin faster.

1.96 • Spinning a book

Fasten a rubber band around a book to keep it closed and then toss it into the air while spinning it around one of the three basic axes that are shown in Fig. 1-35*a*. For two choices of axes, the spin is stable. Why does the book noticeably wobble when spun around the other axis? Similar instabilities can be seen when a hammer, tennis racket, or a variety of other objects are flipped into the air.

Answer The axes through the book are characterized by the rotational inertias associated with them. The rotational inertia has to do with the way the mass is distributed with respect to the axis around which the book rotates. With one axis the mass is distributed far from the axis (the *rotational inertia* is largest), while with another the mass is close to the axis (the rotational inertia is smallest). (See Fig. 1-35*b*.) When you spin the book around either of these axes, the spin is stable.

The troublesome axis is the one for which the mass distribution and the rotational inertia are intermediate. Were you to toss the book perfectly around that axis, it would spin stably. The problem is that you cannot execute such an ideal toss. Inevitably you err, and the error then produces a wobble that quickly grows. In one interpretation, the error in the initial alignment produces an effective centrifugal force (a fictional force that is radially outward) on the book that causes it to rotate around the axis with the largest rotational inertia. The wobble you see is the combination of the spin you intended and the extra spin produced by the centrifugal force.

The problematic axis with an intermediate distribution of mass shows up in all sorts of objects. However, if any two of the axes have equal rotational inertias, rotation around either axis is unstable, and the rotation may amount to a slow roll around an axis rather than an obvious wobble. In addition, if air drag on a spinning object is significant, rotation about the axis with the largest mass distribution and rotational inertia is also unstable. To show this feature, toss a rectangular card into the air while making it spin around that axis; chances are that the card ends up spinning around the axis with the smallest rotational inertia.

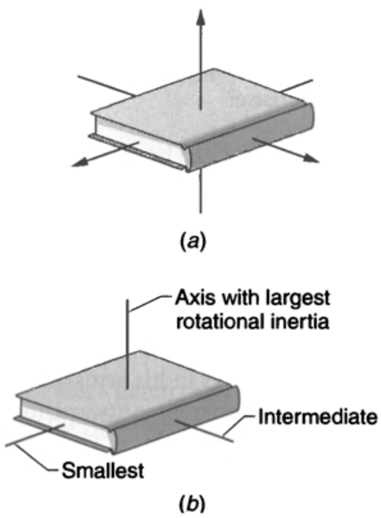


Figure 1-35 / *Item 1.96* (*a*) Three axes through the book. (*b*) The rotational inertias associated with the axes.

1.97 • Falling cat, astronaut antics, and fancy diving

If a cat is released upside down from a height of a meter or more, it quickly rights itself so that it lands on its paws. The action seems to violate a firm rule in physics: When there is no torque acting on an object, the object's angular momentum cannot change. A cat is such an object. It begins the fall with no rotation and so has zero angular momentum, and there is no torque acting on it. Yet its rotation seems to imply that its angular momentum does not remain zero. Does the cat violate the rule?

In an orbiting spacecraft, how can an astronaut undergo *yaw*, turn left or right, without touching anything? How might the astronaut *pitch*, which is to rotate forward or backward around a horizontal axis that runs left and right? Is a *roll*, which is a rotation around a horizontal axis that runs forward and rearward, possible? (Here again is an object that has zero angular momentum and no torque acting on it, and yet it somehow turns.)

A diver jumping from a board or platform is different because the fall usually begins with some angular momentum when the diver pushes off from the diving surface during the jump. In the simplest dive the diver turns over so that the hands are the first to enter the water. Why does the rate of rotation increase when the diver *pikes* or *tucks* before straightening out to enter the water? The rapid rotation is needed if the diver is to turn over several times before reaching the water.

How does a diver manage to add twist to a dive? For example, a diver might include three twists in a forward one-and-a-half somersault. Must the twisting motion come from a certain push from the diving surface, or can the diver leave the surface in a purely somersault motion and then initiate the twist while in midair? Many of the physics techniques employed by divers are also employed by skiers *hot dogging* (performing fancy maneuvers while airborne), gymnasts, skateboarders, and BMX bikers.

Some dives and some jumps from a trampoline are similar to the fall of a cat in that they begin with no angular momentum. But somehow, without benefit of a torque from a push on a surface, the diver or trampoline performer manages to create rotations while in the air.

Answer Explanations for how a cat turns over have been offered for about a century and still there is controversy. I'll give two of the explanations (each supported by photographic evidence), but keep in mind that since cats do not study physics, they may not all use the same technique.

Explanation 1: Think of the cat as consisting of two halves connected by a flexible joint that is midway along the spine. An axis runs through each half, and the two axes initially meet at an angle because the body is convex downward. Once the cat is released, both halves rotate around their individual axes in the *same* direction, while the joint rotates around a horizontal axis in the *opposite* direction. For example, if from an end view the halves both rotate clockwise, then the joint rotates counterclockwise. (Notice that since the two halves rotate together, the body of the cat does not become twisted.) Each rotation involves angular momentum, but the sign of the clockwise angular momentum is negative while the sign of the counterclockwise angular momentum is positive. So, the net angular momentum of the cat during its turning continues to be zero, which is the value with which the cat began its fall.

Explanation 2: Again take an end view. The cat pulls in its front legs, keeps its rear legs extended, and whips its tail around counterclockwise. The action forces a clockwise rotation of both head and body, but with the front legs pulled in, the front half of the cat turns more than the rear half. (Notice that in this explanation, the body of the cat becomes twisted.) As the tail continues to turn, the cat then extends its front legs and draws in its rear legs. The adjustment causes the rear half to turn clockwise more rapidly than the front half, and so the twist of the body diminishes. Eventually the cat is righted and lands, catching the floor with its front paws. (If the cat lacks a tail, one of its rear legs takes on the role of the tail.) As in the first explanation, the net angular momentum remains zero throughout the fall.

If you are the astronaut mentioned in the item, here is one way for you to create yaw. Extend your right leg forward and your left leg rearward. Then bring the legs together again after sweeping the right leg to the right and rear and the left leg to the left and front. As seen from above, the legs move in a clockwise direction. During their motion, your torso must turn in the counterclockwise direction so that your net angular momentum continues to be zero.

To undergo pitch, raise your arms off to the left and right and then move them in circles in the same direction, as if swimming. Your torso rotates in the opposite direction, and again, your net angular momentum remains zero. A roll comes from a combination of pitch and yaw. (Where do you end up if you undergo a sequence of left yaw, forward pitch, and then right yaw? How about a sequence of forward pitch, right yaw, and then backward pitch? Surprisingly, you end up in the same orientation, although you resemble one of the Three Stooges with either sequence.)

If you pike or tuck during a somersault dive, your rate of rotation increases because you pull mass in toward the axis around which you spin. (You are like an ice-skater who pulls in arms and a leg while spinning on point.) The inward pull reduces your distribution of mass. Your angular momentum, which is the product of that distribution and your spin rate, goes unchanged.

If during a somersault you move your right arm upward and your left arm downward, their motion forces your torso to rotate, with your head moving rightward. The action does not alter your angular momentum but it does misalign the axis around which you somersault from the direction of the angular momentum. The result is a twist. So, you need not initiate a twist by some special push from the diving surface but can instead produce it in midair.

1.98 • Quadruple somersault

July 10, 1982, Tucson, Arizona, USA: The aerial acrobat, Miguel Vazquez, released his grip on the bar of his swing during a performance of the Ringling Brothers and Barnum & Bailey Circus, tucked, rotated a full four times, and then was caught in the hands of his brother, Juan, who was inverted on another swing. It was the first time that a *quad* had been performed before a circus audience, although the attempt had been made since 1897 when the first triple somersault was accomplished. What made a quadruple jump so difficult (and thus probably makes a *quad and a half* impossible)?

Answer To set up the jump, the aerialist and his partner each swing on a trapeze. When the aerialist moves upward and toward his partner, he releases from his trapeze, immediately pulls into the tuck position, and then somersaults. As he completes his fourth rotation, he must stretch out so that his partner can catch his arms. Thus the jump has two primary requirements: (1) The aerialist must turn rapidly enough to complete four rotations in the time he takes to fly to his partner. (2) He must pull out of the rotation just as he reaches his partner, or he will be rotating too quickly to be caught.

To meet the first requirement, the aerialist goes into the tuck position to bring his mass closer to his center of mass about which he rotates. This move increases the rotation rate just as the rate is increased when a spinning ice-skater pulls in arms and a leg. However, most aerialists cannot pull themselves in tightly enough to get the required rotation rate for a quadruple jump.

To meet the second requirement, the aerialist must see his surroundings well enough to know how many times he has rotated, so that he comes out of the rotations just in time to be caught. However, the rotation speed for a quad (and thus also a quad and a half) is so large that the surroundings are too blurred for the aerialist to judge the rotation correctly. Thus, the catch is almost never made.

1.99 • Tumbling toast

A piece of toast lies butter side up across the edge of a kitchen table when the table is accidentally bumped, sending the toast tumbling to the floor. Is there any truth to the common thought that the toast always lands butter side down (as an example of Murphy's law, which here might be stated, if a mess *can* happen, it *will* happen)?

Answer If the toast is nudged (rather than hit hard) from the table, the face that lands on the floor can be predicted if we know three quantities: the height of the table, the amount of friction between the toast and the table edge, and the initial overhang of the toast (how far the center of the toast lies beyond the table edge when the tumbling begins). When the table is bumped, the center of the toast is moved out beyond the table edge and the toast begins to rotate around that edge. It also slides along the edge. Both the rotation and the sliding determine the rate at which the toast rotates as it falls through the table's height to the floor. If the rate is enough to turn the toast between 90° and 270° during the fall, then the toast lands butter side down. For typical table height and friction and for common toasted bread, a range of small overhang values and a range of large overhang values yield a butter-side-down landing, while intermediate overhang values yield a butter-side-up landing. Here you can do your own experimentation.

1.100 • Ballet

The grace and beauty of ballet are partly due to a subtle, hidden play of physics. If the performer is skilled, you will never notice the physics. Instead you will see motions that seem oddly wrong, as though they defy some physical law, and yet you may not be able to pinpoint what is odd about them. Here are two examples:

In a *tour jeté* (or turning jump), the performer leaps from the floor with no apparent spin and then somehow turns on the spin while in midair. (The performer does not go through the gyrations of an astronaut as described in a preceding item—they would hardly be regarded as graceful and probably would require too much time.) Just before the performer lands, the spinning is turned off.

A *fouetté turn* is a series of continuous *pirouettes* in which the performer turns on one foot while periodically extending the opposite leg outward and then drawing it inward. One of the most demanding examples of *fouetté* in classical ballet occurs in Act III of *Swan Lake* when the Black Swan must execute 32 turns.

In both of these examples, how is rotation accomplished?

Answer In a tour jeté, the illusion that the spin is turned on and then off in midair is due to how the performer moves her arms and legs inward and then outward during the jump. That shift changes her *rotational inertia*, which has to do with the performer's mass and how it is distributed relative to the axis around which she spins. The performer's *angular momentum* is the product of her rotational inertia and the rate at which she spins. While she is in the jump, she cannot change her angular momentum. She begins the jump with her arms and one leg extended and with a small rate of spin, too small for the audience to perceive. Once she is in the air, she gracefully moves her arms and leg inward to decrease her rotational inertia. Because her angular momentum cannot change, her rate of spin increases and is then perceptible to the audience, so to them it seems to magically turn on after she leaves the stage. As she prepares to land, she re-extends her arms and a leg and regains her initial rotational inertia. Her rate of spin is then again too small for the audience to perceive, and she has seemingly turned off the spin while still in the air.

In a fouetté turn, the performer pushes on the floor to initiate the turn and then comes up *on point* on one foot. She next brings the opposite leg in toward the body axis to increase the spin. As she turns back toward the audience, she extends the free leg so that it gradually takes up the angular momentum of the rest of the body, and for a moment the leg continues to turn around the body axis while the rest of the body does not. The pause allows her to drop momentarily off point and push on the floor with the foot for another revolution.

1.101 • Skiing

There are a variety of ways you can turn while skiing down a slope, but what exactly makes you turn? In the *Austrian turn*, you bring your body down toward the skis and then quickly lift it while also rotating the upper part in the opposite direction of the intended turn.

Another technique requires that you keep the skis flat on the snow while you shift your weight forward or to the rear. Which way you turn depends on how your path is angled down the hillside. The path directly down the slope is the *fall line*. If you travel to the left of it and bring your weight forward, you turn clockwise as seen from above. A backward shift of your weight produces an opposite turn. The results are reversed if you ski to the right of the fall line.

Turns can also be produced if you *edge* your skis—that is, tilt them so that the uphill edge bites into the snow. For example, if you shift your weight forward while edging as you ski to the left of the fall line, you turn counterclockwise. Notice that with edging the shift creates a direction of turn that is opposite to the one created when you keep the skis flat.

Why is the outside edge on a racing ski curved from front to rear? Why do some skiers prefer long skis instead of short ones? When you ski down the fall line, why must you lean forward so that your body is perpendicular to the slope? If you unwisely choose to remain upright, why do you fall?

A novel way of turning while skiing was reported in 1971 by Derek Swinson of the University of New Mexico. Instead of ski poles, Swinson carried a heavy rotating bicycle wheel, holding it by an axle equipped with handles. The plane of the wheel was vertical and the section at the top of the wheel rotated away from him. When he wanted to turn right, he lowered his right hand and raised his left hand. Turning to the left required just the opposite adjustments. What caused the turns?

Answer The Austrian turn is similar to the rotations discussed in the preceding items. When you quickly lift your body, you lessen the contact between the skis and the snow, momentarily reducing or eliminating the friction on the skis. Your angular momentum just then is zero, and since friction no longer acts, it cannot produce a torque on you and the angular momentum cannot change. So, if you rotate the upper part of your body to the left, the lower part of your body and the skis must rotate to the right. When your weight is again felt by the skis and friction returns, the friction allows you to turn the upper part of your body to face the new direction of travel.

To see how the other turning techniques work, consider the case where you ski to the left of the fall line and assume that your normal stance places your weight over the center of the ski. Also assume that the friction on the ski is uniformly distributed along its length. The friction along the front of the ski is partially uphill and creates a torque that attempts to rotate you to the left around your center of mass (Fig. 1-36*a*). The friction at the rear counters with a torque that attempts to rotate you to the right. In each case the torque size depends on how much friction there is and also how it is distributed with respect to your center of mass (*com*). Friction at a point far from your com creates a greater torque than friction at a point nearby. With both amount and distribution evenly matched between front and rear of the ski, you do not rotate.

If you shift your com forward, you upset the balance of torques (Fig. 1-36*b*). There is now more ski behind your com and less in front, and so the total friction behind is larger than the total friction in front. Also, the friction at many of the points along the rear is now far from your com, while most of the friction at the front is now near it. So, the torque from the rear wins out and you turn to the right.

If you edge the ski while shifting forward, the bite into the snow increases the size of the friction at the front and decreases it at the rear (Fig. 1-36*c*). In this case, the torque from the front wins out, and you turn to the left.

The edge of a racing ski is mildly curved so as to allow easier turns. When you push the edge down onto the snow, the ski meets the least resistance by gliding along a path that is a continuation of the curve.

Short skis are so easily vibrated by a rough path that you may lose your balance. Although long skis are more difficult to maneuver, they vibrate less.

To see why you must lean forward while skiing down the fall line, imagine that your weight is represented by a vector at your center of mass. The vector can be broken up into two *components*, or parts. One component points down the slope and is responsible for your motion, and the second component points directly toward the slope. If you are to be stable, the second component must also point toward your feet. If you decided to ski while being vertical, the second component would create a torque around your feet and rotate you rearward to the snow.

In Swinson's demonstration, assume that the friction on the skis can be neglected—he and the wheel are isolated from any outside torques. Next, consider an overhead view. Since the wheel initially rotates around a horizontal axis, there is no rotation of either the wheel or Swinson around your line of sight. That means there is no angular momentum of the wheel and Swinson around the vertical, a condition that cannot change because of the lack of any outside torques. If Swinson lowers the right handle and raises the left one, you would then see the wheel rotate counterclockwise, which means that it now has some vertical angular momentum. To keep the total angular momentum zero as it was initially, Swinson must be turned clockwise in your view. So, his maneuver turns him to his right.

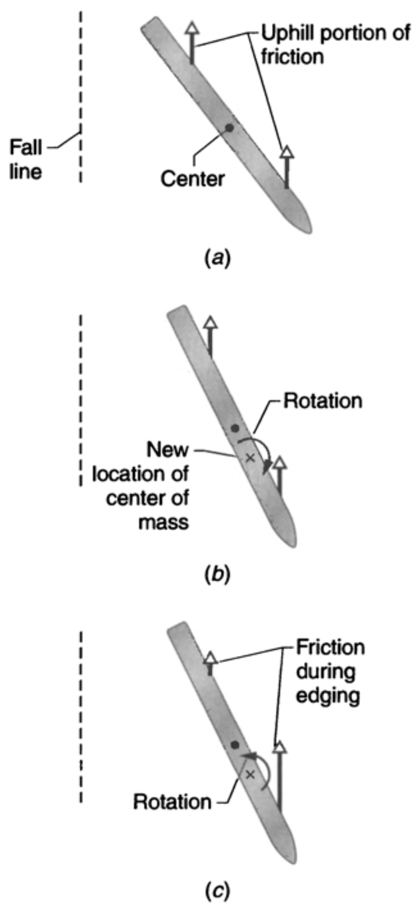


Figure 1-36 */ Item 1.101* Forces on a ski with (*a*) normal stance, (*b*) forward stance, and (*c*) rear stance.

1.102 • Abandoned on the ice

You wake up to find that you are deserted in the middle of a large frozen pond with ice that is so very slippery that you can neither walk nor crawl over it. How can you escape?

Suppose that you happened to be lying face down on the ice. As you consider your escape, you decide that you must turn over onto your back to keep from freezing to death. How can you turn over?

Answer Throw a shoe or any other item in one direction; you will move (albeit, slowly) in the opposite direction. Since there is no force on you from the ice, the total momentum of you and the tossed item must remain zero. When you give momentum to the item, you also give just as much momentum to your body in the opposite direction.

Similar physics occurs if someone attempts to roll a bowling ball while on in-line skates with little friction on the wheel rotation. I attempted this. Although the skates began to move backward, my torso did not and I managed to avoid a face-down fall only by grabbing the closest person.

To roll over while on very slippery ice, raise one arm and then, with it outstretched, strike it smartly against the ice. Although there can be no friction on your hand from the slippery ice, there is a force on your hand vertically upward from the ice. That force allows you to rotate the trunk of your body so that you are then on your back.

SHORT STORY

1.103 • Rotation sequence matters

If you are to walk 3 meters north, 3 meters east, and 3 meters south, you end up at the same point no matter how you choose the sequence of those three short walks. Rotation can be different. Hold your right arm downward, palm toward your thigh. Keeping your wrist rigid, (1) lift the arm until it is horizontal and forward, (2) move it horizontally until it is pointed toward the right, and (3) then bring it down to your side. Your palm faces forward. If you start over, but reverse the motion, which way does your palm end up facing?

1.104 • Personalities of tops

Why does a spinning top stay up, even when it tilts appreciably from the vertical? Why do some tops initially *sleep*—that is, stay vertical—while others undergo *precession* (the top's central axis rotates around the vertical as in Fig. 1-37*a*)? Why does the precession often involve *nutation*, a nodding up and down of the top's central axis? Are there distinct types of nutation? Why do some spinning tops die rapidly while others linger?

Answer Usually when a force pulls on an object, the object moves in the direction of the force. But if the object is spinning, the force can make it move perpendicularly to the direction of the force. Such motion seems all wrong, and that is one reason why tops are so fascinating. Even if a child knows nothing about the laws of physics, he or she still knows that a tilted top should just fall over, not precess around in a circle.

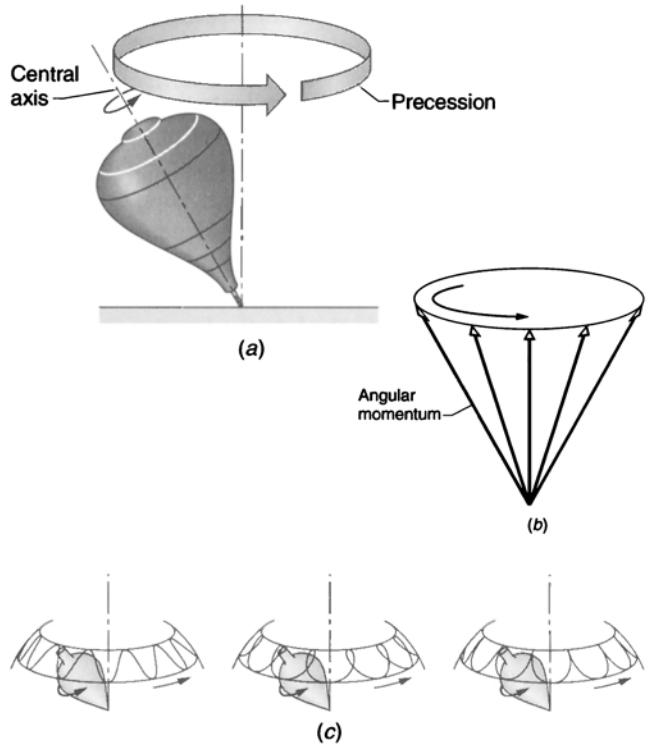


***Figure 1-37** / Item 1.104* **(*a*) Precession of a top around a vertical axis through the contact point. (*b*) The top's angular momentum vector moves around the vertical. (*c*) Nutation during the precession.**

The traditional explanation of the precession involves the top's angular momentum. This quantity involves the rate at which the top spins around the axis along its length. Moreover, it is a vector quantity that points along that axis. Consider a snapshot of a top that is tilted somewhat and that has a fast counterclockwise spin as seen from above. In Fig. 1-37*b*, the top's angular momentum is represented by a vector that points upward along its central axis.

Because the gravitational force pulls downward on the top, it creates a torque on the top, tending to rotate it around its point on the floor and thus causing it to fall. In fact, if the top were not spinning, it would fall. However, because the top is spinning and already has angular momentum, the torque merely changes the orientation of that angular momentum, rotating the vector around its tail so that its head traces out a cone. Because the angular momentum is along the top's central axis, the central axis also traces out a cone.

Once a top is launched, its center of mass falls somewhat, as the top leans over, and two rules must be obeyed: Its angular momentum around the vertical axis and its total energy must each remain constant. Since the fall tilts the top's spin away from the vertical, the precession must be fast enough to keep the total angular momentum around the vertical constant. The kinetic energy for the precession comes from the fall of the top's center of mass and consequent decrease in the potential energy.

The top cannot continue to fall and still obey both rules, and so the center of mass comes to some lowest point. Then it begins to rise again and the precession slows. The up and down oscillations between the extreme points allowed by the rules is the nutation that is superimposed on the precession. The nutation comes in three types that are characterized by what the center of mass does at the highest point. The top might momentarily stop its precession, continue to move in the same direction as it does at the lowest point, or briefly move opposite that direction (Fig. 1-37*c*). Which occurs depends on the initial precession you give the top in the launch—it might be in the same direction as the precession generated by gravity or opposite it, or maybe you give the top no precession.

If you launch a top with enough spin, it will stay vertical without precession and nutation. But as air drag and the friction on the point gradually steal energy, the spin drops below some critical value, and then the top begins to fall, precess, and nutate. With further drain of energy, the top tilts more, precesses faster, and nutates more wildly, until it finally hits the floor.

A *sleeper* is a top with a design that allows it to spin above the critical value long enough for friction on the point to rotate the top vertically so that it stands upright. Typically such a top is wide and has a blunt point, but the floor surface is also a factor. The friction occurs because the point slips as it spins while also moving through a circle on the floor due to the precession.

SHORT STORY

1.105 • A headstrong suitcase

Robert Wood, the noted physicist from Johns Hopkins, was said to have once played a joke on an unsuspecting porter at a hotel. According to the story, Wood spun up a massive flywheel and then closed it up in his suitcase before the porter arrived. When the porter walked the suitcase down a straight hallway, he noticed only the weight. But when he attempted to turn the corner, the suitcase mysteriously refused to turn. The porter was reportedly so frightened that he dropped the "possessed" suitcase and ran from the scene.

1.106 • Tippy tops

A peculiar type of top, called a *tippy top* or a *tippe top*, consists of part of a sphere with a stem substituting for the missing section. You spin the top by twirling the stem between thumb and finger, releasing it with the spherical (and heavier) side down. Provided there is enough friction between the top and the floor, the top rights itself and then spins on the stem. Relative to you the direction of spin goes unchanged, but relative to the top it reverses.

You can see the same sort of standing up if you spin a football, hard-boiled egg, or the type of school ring that has a smooth stone. In each case, why does the object's center of mass move upward against gravitation?

Answer There has been no simple explanation of a tippy top, only mathematically difficult ones. However, the key element is the friction on the part of the top that touches the floor. Somehow the friction creates a torque that leads to the righting but the details of the process remain elusive. Here is a simple possibility: The friction acts to increase the precession (see above), which then causes the center of mass to move upward, as happens with other types of tops.

1.107 • Spinning eggs

You can tell whether an egg is fresh or hard-boiled without cracking it open if you spin it on its side. A fresh egg spins poorly while a hard-boiled egg spins well. If you spin a hard-boiled egg fast enough, it rises up on one end. If you briefly touch the top center of a fresh egg that is spinning on its side, the rotation starts up again after the touch, but with a hard-boiled egg, the touch eliminates any subsequent motion. Can you account for these behaviors?

Answer The difference between the two types of eggs is, of course, that one is filled with a fluid that sloshes while the other is rigid. The sloshing interferes with the spin of a fresh egg and restarts the rotation when you briefly touch and stop the egg. When a hard-boiled egg is spun fast enough, it behaves like a tippy top (see the preceding item) and stands up.

1.108 • Diabolos

A diabolo is an ancient toy that consists of a spool with conical ends that join at a narrow waist (Fig. 1-38). It is spun by means of a string that runs under the waist and is tied to handles. You begin with the toy on the floor and (if you are right-handed) your right hand low and your left hand high. You then tighten the string by bringing your right hand up smartly and letting the string drag the left hand down. The friction between the string and waist rotates the diabolo.

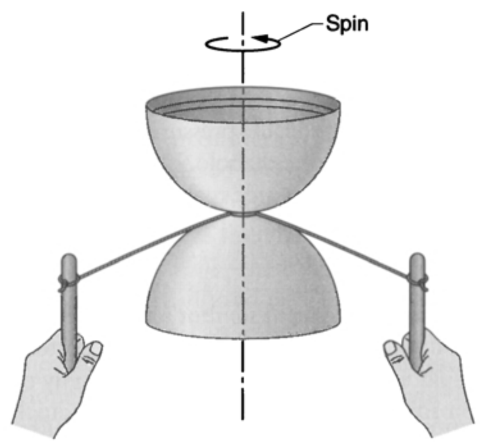


***Figure 1-38** / Item 1.108* Overhead view of a spinning diabolo.

You increase the speed by loosening the string somewhat, allowing the diabolo to descend, repositioning your hands, and then repeating the procedure. If you produce enough speed, the diabolo spins stably on the string. By rapidly raising both hands, you can even toss the diabolo up into the air and then recapture it on the string when it descends.

Why does spin stabilize the diabolo? (Without it the toy merely topples off the string.) If it begins to tilt, how can you stabilize it? For example, if the far end begins to droop, how can you bring it back up? How can you turn the diabolo to your left or right? (Search the Web under "diabolo" for sites that list and demonstrate diabolo tricks.)

Answer If you pick up the diabolo with the string without making the diabolo spin, it is unlikely to be balanced on the string and will fall off. If, instead, you rapidly spin the diabolo, you give it angular momentum, which stabilizes its perch. The angular momentum is a vector that lies along the main axis of the toy. With the launch described in the item, the vector is horizontal and points toward you. A spinning diabolo is stable, because only a torque can change the direction of its angular momentum. If the diabolo is balanced on the string, the diabolo's center is just above the string, and the pull of gravity on the diabolo is down through the string and it does not cause any torque about the string. Thus, the angular momentum cannot change.

If the diabolo is almost balanced, the pull of gravity on the heavier side creates a small torque and gives the diabolo a small, additional angular momentum vector that points to the left or right. As a result the diabolo does not topple over because of gravity but *precesses* left or right; that is, its central axis rotates left or right. (Friction from the string also creates a torque, but if the string is centered or nearly so, this torque will only gradually slow the spin.)

If the far end begins to droop, you can use the string to create a torque to bring the end back up. Pull the string in your right hand toward you and against the right side of the diabolo. The press against the side produces a torque that is downward and that brings the angular momentum vector of the toy back to the horizontal.

To make the diabolo turn to the right, move your hands apart and then pull them toward you. Either the string pulls against the underside of the diabolo or it actually slips toward you, which makes the far end of the diabolo heavier than the closer end. If it does not slip, the pressure on the underside creates a torque that turns the diabolo. If it does slip, the torque from gravity on the heavier side makes the diabolo turn.

1.109 • Rattlebacks

A *rattleback* (also called a *celt stone* or a *wobblestone*) is a curious type of top that has a skewed ellipsoidal bottom surface. The ones sold as a toy insist on spinning in only one direction. If you spin one in the other direction, it quickly stops, rattles up and down, and then spins in the direction it desires. Some stream-polished rocks behave similarly, but you might find a rare type that will reverse its spin several times before its energy dies out. Why does a rattleback reverse direction?

Answer A rattleback is quite difficult to explain in detail but its spin reversal is due to the fact that its bottom surface is an ellipsoid that is misaligned with the general shape of the stone. That is, the long and short axes of the ellipsoid are not aligned with the length and width of the stone. When the stone is spun around the vertical in the "wrong" direction, the misalignment destabilizes the spin and the stone begins to wobble. The friction on the stone from the tabletop transfers energy from the spinning to the wobble. When the transfer is almost complete, the friction reverses the transfer, but this time the stone spins in the opposite direction. With some rattlebacks, the spin in the "correct" direction is also somewhat unstable, in which case wobbling again appears and the spin is again reversed.

1.110 • Wobbling coins and bottles

Flick a coin with your finger to send it spinning on a tabletop, and then both watch and listen to it. As it begins to lie down, the pitch of its clatter first drops and then rises. Is it simply spinning faster? No, if you look down on it, its face is initially blurred by the motion and then later becomes clear enough to recognize.

Balance a bottle on an edge, and then by pulling in opposite directions with a hand on each side, spin it. As it spins, it gradually moves toward the vertical and the clatter increases in pitch. You can also spin a bottle that is almost horizontal, but the launch is more difficult. If you can manage the launch, the bottle will gradually become horizontal during its spin, but unlike the coin, the clatter only decreases in pitch during the descent.

Can you account for these behaviors?

Answer The coin spins around its central axis but the axis is also driven around the vertical, a motion that is called *precession*. The precession comes from a torque that is created by the coin's weight, which can be considered to act at the coin's center. As friction and air drag gradually drain energy from it, the coin begins to lie down and also spin around its central axis slower, which makes the face easier to see. Initially the drain slows the precession but then later the descent of the center of mass actually begins to convert potential energy into addition kinetic energy for the precession. The clatter you hear is made by the precession as it slaps the edge of the coin on the table. The pitch of the clatter increases as the rate of precession increases.

When a bottle is spun in a nearly upright orientation, it too precesses. As its central axis gradually moves toward the vertical, its center of mass descends, and again energy is fed into the precession and the pitch increases. When a bottle is spun in a nearly horizontal orientation, its precession decreases as the bottle falls until the precession reaches some final small value. Then the bottle lies down and rolls on the table.

1.111 • Judo, aikido, and Olympic wrestling

Karate often relies on strength and on collisions with large forces, but judo, aikido, and Olympic wrestling usually employ techniques by which you make your opponent unstable enough to fall. Most familiar is the basic hip throw in judo—you somehow cause your opponent to rotate over your hip from your rear to fall to the mat. You might be surprised to learn that unless you think through the physics, the technique is likely to fail, especially if your opponent is larger and stronger than you. How should you properly execute a hip throw?

Consider also the following example from aikido. An opponent grabs you from the rear, with his arms wrapped around yours and his hands tightly on your wrists. How can you throw him to the mat?

Aikido includes stick fighting, in which the following might occur. An opponent thrusts at you with the end of a long stick. The opponent is too near for you to grab the stick and pull it forward even farther, and besides, that plan would pit strength against strength. Is there a better way to down your opponent?

Answer To perform a hip throw, wait for your opponent to step forward on his right foot, and then step forward with your right foot between his feet, pull down toward the right on his uniform to curve his body forward and move his center of mass out to his navel, and simultaneously turn around toward your left and bring your hips up next to him.

His center of mass is then approximately on your right hip (Fig. 1-39*a*). By pulling on the right shoulder of his uniform, you can easily rotate him around your right hip and to the mat. A key element here is to bend him over in the initial move. If you do not, his center of mass remains buried in his body (Fig. 1-39*b*). If you then twist about and attempt to rotate him over your hip, you must fight against his weight, which creates a torque that counters your torque and so also your attempt at rotation. Your throw then requires strength because you must essentially lift him; if he is heavy, you will probably fail.

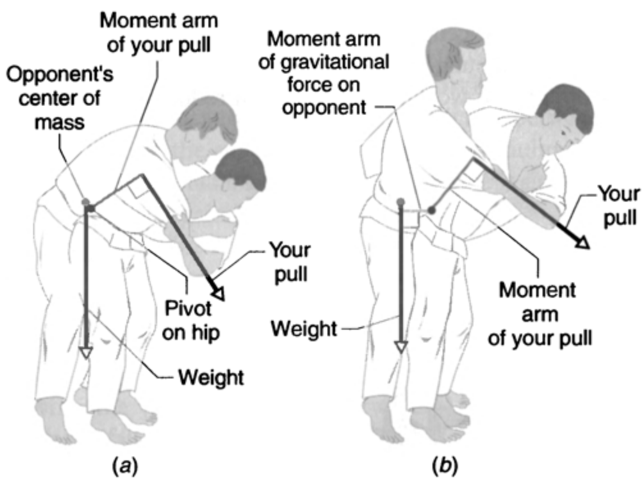


Figure 1-39 / *Item 1.111* A judo hip throw (*a*) correctly executed and (*b*) incorrectly executed.

In the first aikido question, you should bring your hands smartly to your chest (to trap your opponent's arms) while also sliding your right foot forward, dropping downward and rotating your body to the right. In doing so, you bend him and move his center of mass to a point of rotation on your back. He then cannot prevent being thrown over you to the mat.

Stick fighting is difficult to master and my answer here is too brief to explain the art. When your opponent thrusts forward, you should step to the right of the stick, turning so that your left hand can grab its outer portion and your right hand can grab the portion between his hands. Then rapidly bring the stick up and backwards over his head so that he topples backwards. It is important that you begin the technique while the stick is moving forward, because then your opponent is committed to the forward momentum he has created and cannot counter your upward deflection of the stick.

1.112 • Bullet spin and long passes

Why does a rifle come with *rifling* (spiral grooves along the bore's interior) that imparts a spin to a bullet? When the shot is long and arced, what causes the bullet to nose over so that it hits the target front first?

In the American version of football, why must the quarterback put a strong spin on the ball if it is to fly smoothly and then nose down during the latter half of the flight? This procedure not only makes the ball go farther but also makes the receiver's catch easier. A punter kicks the ball with a bit of spin in order to get the same smooth trajectory, but why? Doesn't that just make the ball easier to catch by someone on the opposing team?

Answer If the bullet or the thrown or punted football is given sufficient spin around its long axis, it acts like a gyroscope in that it tends to maintain its orientation instead of tumbling, which would disrupt and thereby shorten its flight. As it travels along a curved path due to the pull of gravity, it encounters air drag on its underside. The drag can be considered to be concentrated at a point somewhat in front of the center of the object. If the spin is large enough, the object is then like a top and tries to align itself with the force it feels—namely, the air drag. So, as it passes through the arc, it gradually noses down.

Some quarterbacks can manage only a wobbly pass because they fail to spin the ball only around the long axis. The additional spin around a short axis through the football produces the wobble, which is an example of precession—the long axis around which the football spins rotates around a circle. The spin and precession are in the same direction (for example, clockwise if the quarterback is right-handed), and the precession is about $\frac{3}{5}$ the rate of the spin.

If a quarterback successfully spins the ball during a pass, not only will it travel farther because of its more streamlined orientation but also the receiver can determine far better just where the ball will come down. When a punter puts spin on a ball, usually the intent is to get the ball to travel farther, but a second intent is to keep the ball aloft longer so that the punter's team can get downfield before the ball comes down. The time aloft is the so-called *hang time.* When the ball is kicked without spin or made to fly in an erratic manner, air drag more quickly removes kinetic energy from the ball and the hang time is decreased.

When bullets are fired directly upward, they sometimes maintain their stability throughout the flight, returning to the ground base-first. Although they probably would then not be lethal, they could still injure someone. If they tumble while falling back down, they will come in much slower than their muzzle speed and the chance of injury is decreased. Still, if someone near you starts shooting in the air, you best hide instead of standing in the open in admiration.

1.113 • Pumping playground swings

How do you *pump* a swing to get it to go higher? And if the swing is initially at rest, how do you start it without shoving off from the ground or having someone push you?

Answer One method is to stand in a swing and pump it by squatting at the high points of the arc and standing up at the lowest point. Standing increases your speed. You can explain the increase by arguments of either energy or angular momentum. By standing you lift your center of mass and do work against the centrifugal force you feel. The work goes into your kinetic energy and increases your speed. By standing you also shift your center of mass toward the point about which you rotate. The action is similar to that of an ice-skater who spins on point while pulling in her arms: The fact that her angular momentum cannot change means that her speed of rotation must increase. On a swing, your rotational speed also increases. With either argument, the increased speed at the low point adds height to the arc. Although the height of your body influences the rate at which you put energy into the swinging, your mass does not.

You can also pump on a swing by pulling on the ropes when you swing forward and pushing on them when you swing back. The distortion you create in the ropes produces forces on your hands that propel you—forward when you pull and rearward when you push.

One way to start a swing is to stand or sit upright with your hands on the ropes and your arms bent, and then fall backward until your arms are fully extended. Your center of mass rotates around the seat of the swing, while the seat rotates around the bar that supports the swing. Your brief fall supplies the kinetic energy for the motion and also its angular momentum.

1.114 • Incense swing

For the last 700 years, ceremonies at the Cathedral of Santiago de Compostela in northwest Spain have been marked by a dramatic swinging of a large censer that hangs some 20 meters from its support. The censer, which weighs about as much as a thin man, is held by rope that wraps around a support and extends down to floor level where it is controlled by a team of volunteers (Fig. 1-40).

After someone begins the pendulum motion with a push, the team pumps the swinging by pulling hard on the rope when the censer passes through its lowest point and then relaxing their pull when it reaches its highest point. The hard pull reduces the length of the pendulum by about three meters, and the reduced pull restores the length. After 17 pulls, which takes less than two minutes, the censer swings up by almost 90°, nearing the ceiling. Its rapid travel through the lowest point fans the coals and incense that burn within it. Why does the team's timed action add energy to the pendulum?

Answer Energy is added to the incense swing by the same mechanics behind the stand-and-squat procedure in the preceding item. When the team reduces the length of the pendulum, the censer is moving rapidly through the low point of its circular arc and they must pull very hard. Thus they do a lot of work on the censer in reducing the pendu-

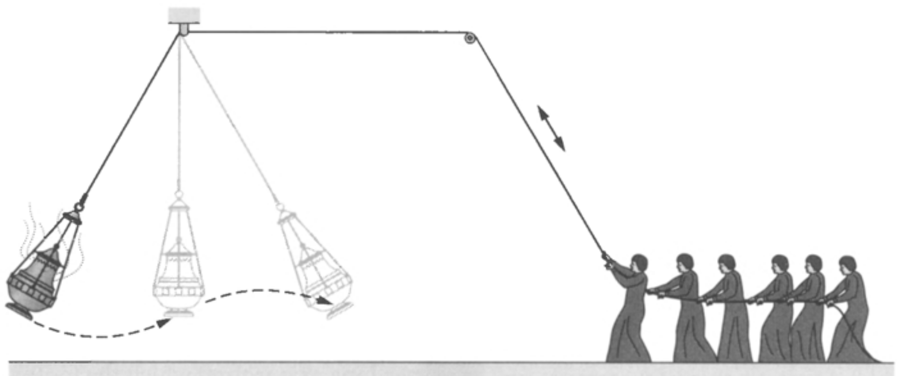


Figure 1-40 / *Item 1.114* Pumping an incense censer.

lum's length, and that energy goes into the kinetic energy of the censer. When the team restores the length at the pendulum's high point, the censer is moving slowly or is momentarily stopped.

1.115 • The pendulum in the pit

In Edgar Allan Poe's masterpiece of terror, "The Pit and the Pendulum," a prisoner finds himself strapped flat on a floor above which a pendulum hangs some 30 to 40 feet. Initially the pendulum seems to be motionless, but later when the prisoner looks up again, he discovers that it is swinging through a distance of a yard and that it appears to have descended. And then to his horror, he realizes that the lower end consists of "a crescent of glittering steel, . . . the under edge as keen as that of a razor . . . ."

As hours go by, the pendulum's motion becomes mesmerizing—the crescent gradually descends and the swing increases in distance, becoming "thirty feet or more." Its intent becomes clear: It is to sweep directly across the prisoner's heart. "Down—steadily down it crept. I took a frenzied pleasure in contrasting its downward with its lateral velocity. To the right, to the left—far and wide—with the shriek of a damned spirit! . . . Down—certainly, relentlessly down!"

Suppose that the crescent is suspended by a rope that is gradually let out. Why would the extent of swinging increase with the crescent's descent?

Answer The extent of the swinging increases because as the crescent descends, its potential energy is gradually converted into kinetic energy. However, calculations reveal that given the initial height and swing as graphically described by Poe, the crescent is unlikely to swing left and right by more than 10 feet when it reaches the prisoner, not the 30 feet or more as reported in the narrative. (The mathematical inconsistency would hardly be of any comfort to the prisoner in Poe's tale.)

1.116 • Inverted pendulums, unicycle riders

If a standard pendulum is inverted, it is, of course, unstable and will easily topple. However, if its support is oscillated vertically and quickly and if there is a bit of friction between the pendulum and the support, why does the pendulum stand upright? It is so stable that were you to nudge it sideways, it would quickly regain its upright stand.

If the pendulum's support is, instead, rapidly oscillated horizontally, the pendulum will swing about the vertical while upside down, as if gravity were reversed in direction. A unicycle rider employs similar physics. When the rider begins to fall—say, forward—stability is momentarily regained by driving the wheel somewhat forward. As the rider then begins to fall backward, the wheel is driven backward.

Can multiple rods, connected in series, be made to stand upright as a series of inverted pendulums if the lower one is oscillated vertically? Can a long wire be made to stand upright like this? And the biggest question of all is, can a rope be made to stand upright like in the classic Indian rope trick where a rope extends upward with no means of support at the upper end?

Answer During vertical oscillations, the pendulum stands approximately upright if the acceleration produced by the oscillations exceeds the acceleration of gravity. In a sense, the pendulum has no chance to fall over, because it is periodically pulled rapidly downward and thereby righted. If the support is horizontally oscillated rapidly enough, the pendulum is also unable to fall. As in the unicyclist's strategy of support, as soon as the pendulum begins to fall one way, the support is brought underneath it in that direction and the fall is arrested.

Several rods connected in series can be made to stand upright if the lower one is oscillated vertically and rapidly enough. A wire that is too long to stand up on its own (it bends over under its own weight) can be made to stand upright if oscillated. However, a rope cannot be made to stand upright because it is too flexible, and thus the Indian rope trick remains just an illusion.

1.117 • Carrying loads on the head

In some cultures, such as in Kenya, people (especially women) can carry enormous loads on their heads. They may have strong neck muscles and an acute sense of balance, but the really surprising feature is how little effort is required of them. For example, a woman might be able to carry a load up to 20% of her body weight without having to breathe heavily (in fact, without any extra effort on her part), whereas a European or American woman of comparable health and strength would find carrying such a load very difficult. What is the secret of the elite load bearers?

Answer During walking, a person's center of mass moves up and down in a periodic fashion. The high point occurs when the body is over one foot while the other foot is moving past that foot, toward the front. The low point occurs when both feet are on the ground and her weight is being shifted from the rear foot to the front foot. This periodic vertical motion of the center of mass, with the support point periodically moving horizontally beneath the center of mass, is similar to the motion of a unicyclist who moves back and forth to maintain balance. In particular, part of the woman's energy is periodically shifted between potential energy (related to the height of her center of mass) and kinetic energy (the speed at which her center of mass moves forward). Normally a person is inefficient in the energy transfer for about 15 milliseconds just after the high point is reached. That is, as the center of mass begins to descend, not all of the potential energy is transferred to kinetic energy, and muscles are used to propel the person forward.

An elite load bearer in, say, Kenya walks in this normal and slightly inefficient way when she is *not* carrying a load.

However, when she carries a load, the interval of inefficiency just after the high point is reached is less. In fact, carrying a moderate load (20% of body weight) may require no more effort than carrying no load at all, presumably because the load causes the woman to shift potential energy to kinetic energy more efficiently than normally. Only if the load exceeds 20% of body weight does a woman have to expend more energy than when unloaded, but even then she expends less energy than, say, a European woman who walks differently.

1.118 • Carrying loads with oscillating poles

In Asia, some people carry light to moderately heavy loads by tying them to opposite ends of a springy pole such as a bamboo pole (Fig. 1-41). As the person walks or runs, the load and pole oscillate vertically. Does this arrangement offer any advantage in carrying the loads?

Answer The vertical oscillations of the person's torso cause the pole and the loads to oscillate vertically. Suppose a rigid pole is used across a shoulder. Then when the torso moves upward, the shoulder must apply a large force to lift the pole and its load. And when the torso moves downward, the shoulder applies little force because the pole and its load fall with the shoulder. So, there can be a considerable variation in the force on the shoulder as the person walks or runs.

The primary purpose of a springy pole is to smooth out the variation in the force on the shoulder. The key is that once oscillations are set up in the pole, the loads oscillate out of step with the pole's center—when the loads move upward, the center moves downward, and vice versa. The center also oscillates out of step with the shoulder—when the shoulder moves upward, the center moves downward. Thus, the shoulder is in step with the loads, which results in a nearly constant force required of the shoulder. When the shoulder moves upward, the spring of the pole is sending the loads upward. When the shoulder moves downward, the upward motion of the center of the pole helps support the downward-moving loads.

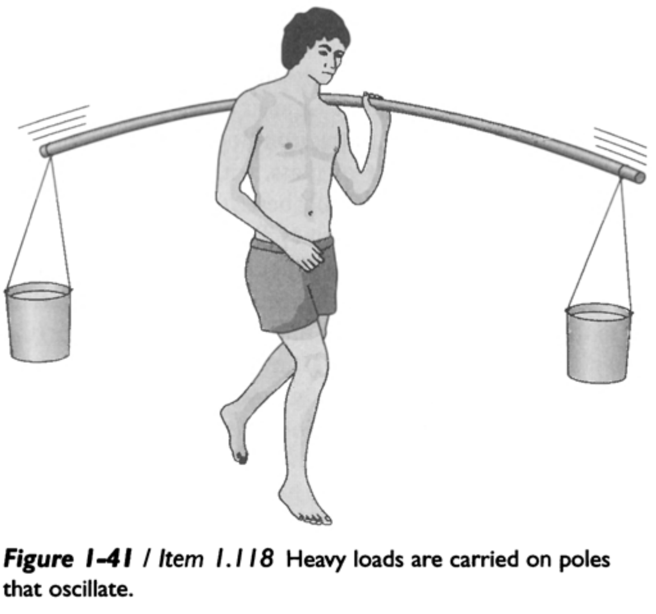


Figure 1-41 / *Item 1.118* Heavy loads are carried on poles that oscillate.

1.119 • Coupled pendulums

Make a system of pendulums by attaching two equal lengths of thread to a support and then wrapping each thread once around a horizontal rod (Fig. 1-42*a*). Add an identical object to the lower end of each thread, and position the rod about a third of the way from the top. Hold one of the objects, move the other one to one side parallel to the rod, and then release both objects. You might think that the displaced pendulum would be the only one to swing, but the motion is gradually transferred to the second pendulum. Once the transfer is complete and the first pendulum is stationary, the transfer is reversed. Thereafter, the motion periodically shifts between the two pendulums.

Similar behavior is shown by the other systems in Fig. 1-42. In Fig. 1-42*b*, a spring connects two pendulums. In the third system (Fig. 1-42*c*), the pendulums are tied to a narrow tube that can rotate around a horizontal string, and the pendulums swing perpendicularly to the tube. In the fourth (Fig. 1-42*d*), they swing perpendicularly to a short string that connects them.

Perhaps surprisingly, the exchange of oscillations can be seen with two identical toy compasses. Place one on a table and then place the other next to it after shaking it to make the needle oscillate. The oscillations are shuttled back and forth between the compasses.

What accounts for the behavior?

Answer Let's consider only the first system described. The transfer of motion comes from a transfer of energy as the pendulums push and pull on each other by means of the rod. If you were to swing the pendulums in either of two special ways, called *normal modes*, there would be no transfer. In one of these modes, the pendulums are made to swing in step (Fig. 1-42*e*), in which the full length of the threads participate in the motion and the swinging has a low frequency. In the other normal mode, the pendulums are made to swing exactly out of step (Fig. 1-42*f*). The opposing motions prevent the thread above the rod from participating, and so the effective length of the pendulums is now smaller than in the first normal mode and the swinging has a higher frequency.

If you start only one pendulum, both modes appear and compete with each other. The pendulums then swing with a frequency that is the average of the frequencies associated with each mode. Their amplitude (the extent of each swing) varies at a rate that is equal to the difference of the frequencies of the modes. As the amplitude for one pendulum decreases, the amplitude for the other pendulum increases, and then the changes are reversed. Similar exchange of

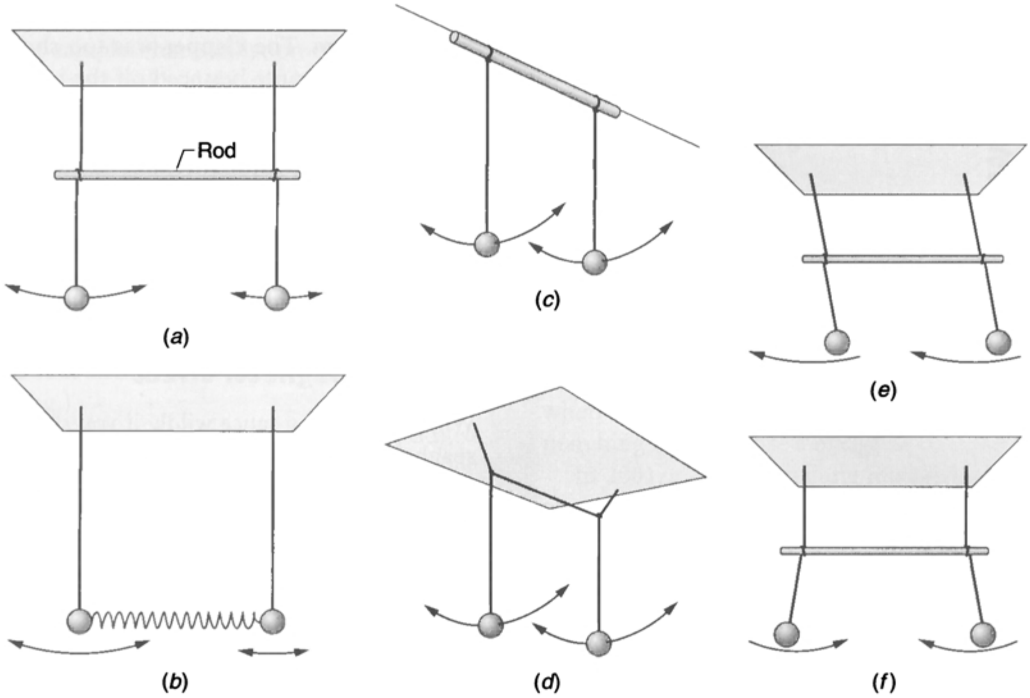


***Figure 1-42** / Item 1.119* (*a*)–(*d*) Coupled pendulums. (*e*)–(*f*) Normal modes.

motion occurs with the compasses because their needles oscillate around the direction of magnetic north just like pendulums oscillate around the direction of gravity.

1.120 • Spring pendulum

Hang a fairly stiff spring by one end and then attach an object at its lower end so that the spring is stretched to about $\frac{4}{3}$ of its initial length. Pull down on the object and then release it. The object initially bobs vertically (Fig. 1-43*a*) but soon the bobbing is replaced with a pendulum motion (Fig. 1-43*b*). Once the bobbing has disappeared, the pendulum motion begins to die out and the bobbing reappears. Thereafter, the motion periodically shifts back and forth between the two types. You can also set up the bimodal behavior if you start the pendulum motion instead of the bobbing.

A similar exchange of motion is displayed by the apparatus shown in Fig. 1-43*c*). The pendulums are connected by a flexible beam that happens to oscillate at twice the frequency of either of the pendulums were they free. In this case energy is periodically exchanged between the pendulum motion and the oscillations of the beam.

An equally complicated example is shown in Fig. 1-43*d*. The horizontal bar can pivot around the support rod. At one end of the bar a vertical bar is fixed in place, while at the other end another vertical bar is free to swing around a pivot. There are two pendulums here: Pendulum *A* is the second vertical bar and pendulum *B* is the combination of the horizontal bar and the fixed vertical bar. If the lengths of the bars are adjusted so that the frequency of swinging of *A* is twice that of *B*, there will be a periodic exchange of motion once the swinging of *A* is begun by hand (as in Fig. 1–42*a*).

In these examples, what accounts for the periodic exchange of motion?

Answer Let's consider just the first arrangement. If you could pull down and then release the object perfectly vertically, the object might just bob, but such perfection is unlikely as you are sure to give the object some slight sideways motion. When you choose the object as described, a purely bobbing motion has a frequency twice that of purely pendulum motion.

Suppose that at one moment the object is primarily bobbing. Energy then begins to transfer from the bobbing to pendulum motion. The transfer is due to the fact that the length of the pendulum changes during the bobbing. The situation is similar to a child standing and squatting twice during each complete oscillation of a playground swing. The child changes the effective length of the swing, and the action feeds energy into the swing's motion so that it goes higher.

Once the transfer is complete, it is reversed because of the pull of the object on the spring each time the object swings to an extreme point. The pull comes twice during each complete pendulum swing, and so its frequency matches the frequency of the purely bobbing motion and the bobbing reappears. When it again dominates, the energy is transferred back to the pendulum motion. And so on.

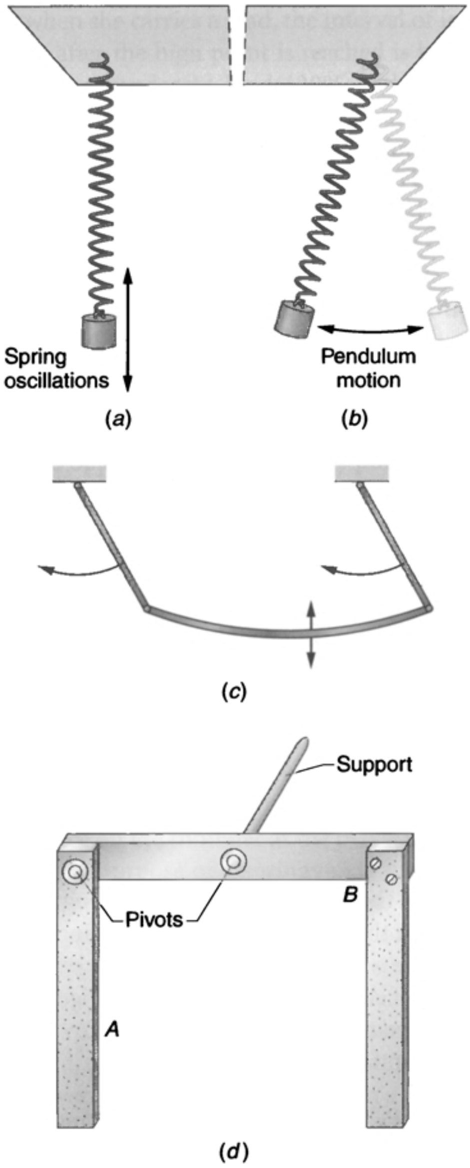


Figure 1-43 / Item 1.120 Oscillations alternate between (*a*) spring oscillations and (*b*) pendulum oscillations. (*c*) Oscillations alternate between pendulum oscillations and vertical oscillations of the interconnecting beam. (*d*) Oscillations alternate between pendulum oscillations of part *A* and part *B*.

1.121 • The bell that would not ring

When a bell was once installed at the Cathedral of Cologne, it would not ring when swung because it and its clapper swung in step and so the clapper never collided with the bell's interior. What can be done about the problem, short of throwing the bell out of the belfry?

Answer When two pendulums are hinged together and one is both shorter and less massive than the other, they can swing in step. At the cathedral the bell was the longer, more massive pendulum and the clapper was the shorter, less massive pendulum. The clapper was too short. After the bell struck it, the clapper bounced off the bell and matched the bell's motion. So, the two swung together, with no additional collisions. To eliminate the synchronous motion, the clapper was lengthened and thus also made more massive. Then when the bell struck it, the clapper was slower to move and did not keep up with the bell. Thus, as the bell swung back and forth, it would run into the clapper.

1.122 • Spaghetti effect

Why do you sling sauce wildly if you slurp a long strand of spaghetti into your mouth? The effect is not only great fun at the dinner table but is also of concern to engineers designing equipment that either pulls in sheets of paper (which can exhibit the *spaghetti effect*) or ejects sheets of paper (which can exhibit the *reverse spaghetti effect*).

Answer Here is one explanation. Suppose that when the strand is free of the dish, it has some sideways motion. As you suck the strand into your mouth at a constant rate and decrease the length that is still free, the kinetic energy associated with the sideways motion becomes concentrated in a smaller amount of mass. If the amount of kinetic energy is not to change, the speed of the sideways motion must increase. As the end of the strand nears your mouth, the speed becomes large enough that sauce on the strand is slung outward.

A compatible explanation involves angular momentum. If the free end of the strand initially rotates around the entrance point of your mouth, it must rotate faster as it nears that point. It is somewhat like an ice-skater who first spins on point with outstretched arms and then brings them inward.

The spaghetti effect can also be seen with a metal tape measure that is automatically drawn into its case when a button is pressed. As the end of the tape nears the case, the end may lash out sideways and injure you. Instructions advise that you draw in the last part slowly to avoid the problem.

1.123 • The spider and the fly

How does a spider that sits at the center of an orb web know where a fly has become entangled or stuck to the web? Why doesn't a web just break when the fly runs into it? After hitting a web, why doesn't a fly simply fly away?

Answer Because of its thrashing, the fly sends waves along the threads, including some of the radial threads on which the spider sits. The waves on the radial threads can be divided into three types according to the direction of the oscillations of the threads. In two types, the oscillations are perpendicular to a thread, either in the plane of the web or perpendicular to the plane. In the third type the oscillations are parallel to the thread. It is the third type that alerts the spider. If the spider samples that oscillation on two or three adjacent threads, it can quickly determine the direction of the fly because the thread that runs out toward the fly carries the strongest oscillations. Even if an ensnared prey does not thrash about long enough to be detected, the spider can still locate it by plucking the radial lines with its legs. Any line weighted down by the prey will oscillate differently than a free line, cluing the spider about the direction and maybe even the distance to the prey. (There is some experimental evidence that a human can also determine the distance to a load attached to a taut string—without looking—by simply oscillating the string.)

Some spiders tune their webs in the sense that they adjust the tension in the threads. When they are very hungry, they increase the tension so that even the thrashing of a small prey sends noticeable waves through the web. When they are less hungry, they decrease the tension so that the thrashing of only a large prey sends noticeable waves.

In 1880, C. V. Boys (well remembered for his popular book on soap films) described how he could attract the attention of a garden spider by touching a vibrating tuning fork (tone A) to the edge of a web or whatever supported the web. Provided the spider was at the center of the web, it could easily find the fork. However, if the spider was not centered, it had to go to the center first before being able to find the fork. When Boys brought the fork near the spider rather than to a portion of the web away from the spider, the spider took the vibrations as a danger and quickly dropped from the web on a safety thread.

A certain type of tropical spiders is said to be kleptoparasitic because it does not weave its own web but steals prey from a host spider who does weave a web. To monitor the web, the kleptoparasitic spider runs threads (20 or 30 centimeters long) from its resting place to the hub and radial lines of the web. Whenever the host spider's web ensnares, say, a fly, oscillations are sent along the monitoring threads. From the pattern of oscillations, the kleptoparasitic spider can even tell whether the fly was wrapped by the host for later eating. If so, then it will soon sneak onto the web to steal the wrapped food.

A web functions as a filter to catch flying prey that are approximately the size of the spider or smaller by absorbing the prey's kinetic energy and momentum. The web is designed to fail (break) if the prey is larger than the spider because then the prey could hurt the spider.

When a prey hits the web, the threads stretch but they act like a viscous liquid in that they retain most of the energy of the collision internally. Thus, the prey cannot simply bounce from the web. In addition, adhesive drops (which look like microscopic beads) are positioned along some of the threads (the *capture threads*) to trap the prey. (The beads are spaced far enough apart that the spider can pick its way along a thread without itself being stuck to the thread.) A prey will struggle but because the thread is so easily stretched, the prey cannot find anything against which it can push to free itself from the drops.

1.124 • Footbridge and dance floor oscillations

In 1831, cavalry troops were traversing a suspension bridge near Manchester, England, while supposedly marching in time to the oscillations they had created on the bridge. The bridge collapsed when one of the bolts that anchored it failed, and most of the men fell into the water below the bridge. Ever since, troops have been ordered to *break step* when marching across any lightweight bridge. How can marching in step cause a bridge to collapse?

In 2001, a sleek, low-slung footbridge across the Thames was opened in London to connect the Tate Modern art gallery with the vicinity of St. Paul's Cathedral and to mark the new millennium. However, as the first surge of pedestrians began to walk over it, the Millennium Bridge, as it is called, began to oscillate so much that some of the pedestrians kept their balance only by hanging on to the handrail. What caused the oscillations?

Why can similar oscillations occur on a dance floor or at a lively rock concert?

Answer The danger is that if the troops march in step to the oscillations they set up in the bridge, the oscillations might grow to the extent that they rupture part of the bridge's support. (I cannot tell if such was actually the case in the Manchester example.) By breaking step, the pounding on the bridge by the troops was no longer coordinated (synchronized) and the oscillations could not grow.

In walking over the Millennium Bridge, each pedestrian produced forces on the bridge that were not only downward but also left or right. Such forces occur because a person normally walks by swinging the body left and right. These left–right forces are small but on the bridge they happened to occur at a frequency (0.5 hertz, or 0.5 times per second) that approximately matched the frequency at which the bridge could sway left and right. Such a match in frequency is said to be a condition of *resonance*, and the oscillations tend to grow much like the swinging of a child in a playground swing grows if you provide a push with a frequency that matches the swinging frequency.

Initially the pedestrians were largely out of step with one another, the forces were largely unsynchronized, and thus the oscillations grew only slowly. Soon, however, the oscillations were large enough that some of the pedestrians kept their balance by walking in step with them. As more pedestrians fell into step, the oscillations grew even more, which made walking even more difficult and caused even more pedestrians to fall into step. Eventually about 40% of the pedestrians on the bridge were walking in step and the left–right oscillations were appreciable and had even led to up–down oscillations. To fix the bridge, engineers installed devices to drain energy from any left–right swaying of the bridge and thus to prevent pedestrians from falling into step.

Similar oscillations, but largely from vertical impacts, can occur in the floors of offices, gymnasiums, and dance halls. It is especially noticeable when spectators jump in unison as in some forms of dancing such as *pogoing*. The oscillations can also occur in the spectator seating area at a concert if the spectators stamp their feet or even vigorously clap their hands in time with the music. Such spectator activity usually has a frequency of 1 to 3 hertz. If that value is close to the lowest resonant frequency of the dance floor or seating area, resonance can be set up, and then the amplitude and acceleration of the spectators can be not only noticeable but even frightening. To avoid resonance and possible damage or collapse to the structure, building codes commonly recommend that the lowest resonant frequency of the structure be no less than 5 hertz.

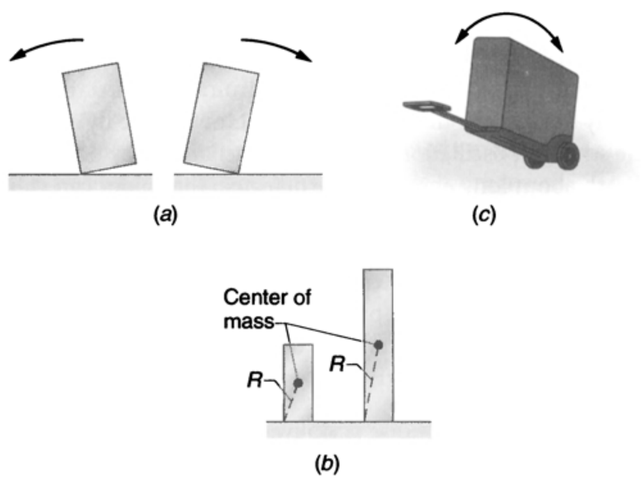


Figure 1-44 */ Item 1.125* **(*a*) Block set rocking by ground shake. (*b*) Danger of toppling depends on distance *R*. (*c*) Two-wheeled suitcase can rock and then topple.**

1.125 • Precariously balanced structures and rocks

During some earthquakes, seemingly stable block-like structures have been toppled over by the ground shake while seemingly unstable column-like structures have been left standing. Even structures such as community water tanks in the shape of a golf ball balanced on a tee have survived earthquakes while cylindrical water tanks have not. What accounts for the stability of the seemingly unstable structures? This question is obviously important in the design of modern structures in regions where there is seismic activity. It is also important in the preservation of ancient structures such as the classic statues and columns in regions such as Greece.

In rock-strewn terrain, where rocks have been exposed by weathering, the rocks can reveal whether appreciable seismic activity has occurred there. For example, the rocks in some regions in California, even as close as 30 kilometers from the notorious San Andreas fault, indicate that there has been no appreciable seismic activity there any time in the last several thousand years. What simple evidence in the rocks can indicate that lack of activity?

Answer Ground shake (a single pulse, a series of pulses, or to-and-fro oscillation) can cause an unanchored structure to rock on its edges (Fig. 1-44*a*). If the center of mass of the structure moves over an edge, the structure will topple. If you attempt to topple the structure with a push at its top (as you might topple an upright domino), then the structure is more unstable the taller it is. However, toppling by ground shake is a very different mechanism because the push is at the bottom of the structure. Now, the stability of a structure depends on the distance R from the structure's center of mass to an edge (Fig. 1-44*b*); greater R generally means greater stability. Although the effect of ground shake depends on a great many variables, a tall column with a large R may be more stable than a short column with a small R when each is set rocking by the shaking.

You may have seen similar rocking if you have ever pulled a two-wheeled suitcase through an airport (Fig. 1-44*c*). If you walk slowly so as to pull steadily on the suitcase handle, the suitcase is stable (remains upright). But if you walk quickly, periodically pulling on the handle, the suitcase can rock left and right on its wheels. If the rocking is large enough, the suitcase will topple over, even if you attempt to arrest the fall by twisting the handle in the opposite direction.

In some rock-strewn regions, weathering of rocks has left some of them balanced on a narrow pedestal of remaining material. Such *precariously balanced rocks* (as they are called) can usually be toppled by hand and would be toppled by even moderate ground-shaking during seismic activity. Thus, the fact that the rocks have been standing for thousands of years means that the region has not seen appreciable seismic activity during that period.

1.126 • Sinking of the nuclear submarine *Kursk*

In August 2000, as Russia's Northern Fleet conducted exercises in the Barents Sea north of Russia, the nuclear submarine *Kursk* mysteriously sank. As word of the loss spread, seismologists from around the Northern Hemisphere realized that on the day the *Kursk* sank, they had recorded unusual seismic waves originating in the Barents Sea. Analysis of the data suggested the reason the submarine sank, and—more surprising—it also revealed the depth. How could the submarine's depth be determined from measurements made very far away?

Answer Seismic waves are waves that travel either through Earth's interior or along the ground. Seismology stations are set up mainly to record seismic waves generated by earthquakes, but they also record seismic waves generated by any large release of energy near Earth's surface, such as an explosion. As the seismic waves travel past a station, they oscillate a recording pen and the pen traces out a graph. The traces attributed to the *Kursk* consisted of a first set of small-amplitude oscillations; 134 seconds later, oscillations with much greater amplitudes began.

From these tracings, analysts concluded that the first seismic waves were generated by an onboard explosion, possibly a torpedo that failed to launch when fired. The explosion presumably breached the hull, started a fire, and sank the submarine. Then later, much stronger seismic waves were generated after the submarine was sunk and were possibly generated when the fire caused several (probably five) of the powerful missiles on board to explode simultaneously. These stronger waves arrived at seismology stations as pulses separated by a time interval of about 0.11 second.

From that time interval, analysts could calculate the depth of the sunken submarine. The stronger explosion occurred when the submarine was sitting on the ocean floor (the seabed). It sent a pulse into the seabed and a pulse upward through the water. The pulse traveling through the water "bounced" several times between the water surface and the seabed. Each time it hit the seabed, it sent another pulse into the ground, and seismology stations detected those ground pulses as they arrived one after another. Thus, the time of 0.11 second between any two successive ground pulses was equal to the round-trip time for the water pulse to travel up to the water surface and back to the seabed. Using that time interval, analysts calculated the submarine was at a depth of approximately 80 meters; in fact, it was later discovered at a depth of about 115 meters, remarkably close to the calculated depth.

Seismologists have recorded other major explosions, such as the truck-bomb blast in Nairobi, Kenya, in 1998 in a terrorist attack on the American embassy. In 1989, they recorded the seismic waves produced by the (acoustic) shock wave generated by the space shuttle *Columbia* as it flew over Los Angeles on its (successful) return to Edwards Air Force Base. And on September 11, 2001, seismologists recorded the collisions of the hijacked airplanes with the towers of the World Trade Center and the subsequent collapse of the towers.

1.127 • Detection by sand scorpion

When a beetle moves along the sand within a few tens of centimeters of a sand scorpion, the scorpion immediately turns toward the beetle and dashes to it (for lunch). The scorpion can do this without seeing (it is nocturnal) or hearing the beetle. How can the scorpion so precisely locate its prey?

Answer A sand scorpion determines the direction and distance of its prey from the waves the prey's motion sends along the sand surface. With one type of wave, transverse waves, the sand on the surface moves vertically and thus perpendicularly to the wave's travel direction. With the other type, longitudinal waves, the sand moves parallel to the wave's travel direction. The longitudinal waves travel three times faster than the transverse waves. The scorpion, with its eight legs spread roughly in a circle about 5 centimeters in diameter, intercepts the faster longitudinal waves first and learns the direction of the beetle; it is in the direction of whichever leg is disturbed earliest by the waves (Fig. 1-45). The scorpion then senses the time interval between the first interception and the interception of the slower transverse waves and uses it to determine the distance to the beetle. For example, a time interval of 0.004 second between the arrivals of the two types of waves means that the waves originated 30 centimeters from the beetle. In this way, the scorpion immediately determines the direction and the distance to its prey.

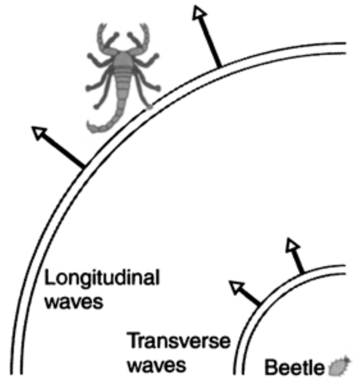


Figure 1-45 / Item 1.127 Waves alert a scorpion as to the beetle's motion.

1.128 • Snow waves

Why, in apparently rare circumstances, can a footstep in a field of snow set off a *snowquake* that travels away from the site, usually with a low-frequency plopping sound?

Answer A snowquake is probably the progressive lowering of the snow surface due to the collapse of a structurally weak layer of hoarfrost below the snow (and thus hidden). The footstep causes the collapse of the hoarfrost just below it, and that collapse tugs and shakes on the surrounding hoarfrost, which then collapses, and so on. As the hoarfrost collapses, the snow slumps down with a plop, making a sound much like snow does when it falls from a tree branch onto a bed of snow.

1.129 • Football-stadium wave

A football-stadium wave is a spectator-created pulse that travels around large, crowded stadiums during sporting events. The effect first gained widespread attention at the 1986 World Cup (soccer to the United States, football to the rest of the world) in Mexico and thus is often called the *Mexican wave* or *La Ola*. As the pulse travels around the stadium, spectators stand with raised arms and then sit back down. How does the wave get started (there is no signal from, say, an announcer) and how fast does it travel?

Answer The wave can begin only if it is noticeable. One or even a few people standing and sitting back down is insufficient because such action would be lost in the normal motion of spectators. Instead, a wave needs a sizable number of participants to stand and sit in unison. Thus, the wave can begin only if one or more initiators can organize the first group of, say, 20 or 30 participants. The initiators could turn to face the group with perhaps a flag to gather attention. The simultaneous motion of the first group would then be noticed by the adjacent group of people, who would then stand and sit, and so on. Studies show that the wave usually travels clockwise around the stadium (as seen from above), but I cannot explain why. The speed is approximately 12 meters per second, which seemingly depends on the time required for a spectator to react by standing after seeing an adjacent group of spectators stand.

1.130 • Body armor

How does the fabric type of body armor stop small-arms munitions (handgun bullets and fragments from bombs or grenades)? Why doesn't it stop a knife?

Answer When a high-speed projectile strikes body armor, the fabric stops the projectile and prevents penetration by quickly spreading the projectile's energy over a large area. This spreading is done by longitudinal and transverse pulses that move radially from the impact point, where the projectile pushes a cone-shaped dent into the fabric. The longitudinal pulse, racing along the fibers of the fabric ahead of the denting, causes the fibers to thin and stretch, with material flowing inward into the dent. One such radial fiber is shown in Fig. 1-46. Part of the projectile's energy goes into this motion and stretching. The transverse pulse, moving at a slower speed, is due to the denting. As the projectile increases the dent's depth, the dent increases in radius, causing the material in the fibers to move in the same direction as the projectile (perpendicular to the transverse pulse's direction of travel). Part of the projectile's energy goes into this motion. Some of the energy is dissipated by the rubbing of the fibers where they cross one another in the weave or, in body armor consisting of multiple layers, by the stretching and breaking of the fibers.

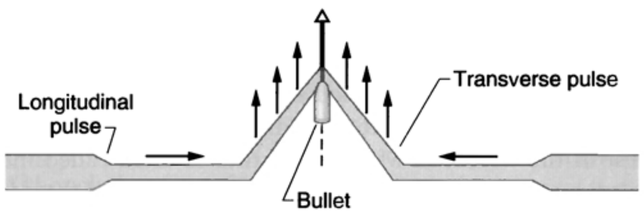


Figure 1-46 / Item 1.130 Dent in body armor due to projectile.

Fabric body armor does not stop a knife because the knife point can easily penetrate the fabric between the fibers, and the sharp edge can then cut the fibers as the knife continues to move forward. You might think that mail, the flexible armor worn in the days of fighting knights, would work better, but it was designed to stop the broad slash of a sword, not the concentrated projection of a knife point.

1.131 • Archer's paradox

No matter how well aimed an arrow is, once it is released and begins to move past the bow's stock, it will point off the target by as much as 7°. Yet it still heads toward the point of aim. The deviation of the arrow is even stranger if the arrow is followed in slow motion. Although it rests against the stock when aimed, the arrow never again touches the stock once released. Instead of sliding along the stock, it snakes around it. What accounts for the behavior, and how does the arrow still find its mark?

When the longbow was used in combat, why was the arrow prepared with a ball of beeswax formed on its point?

Answer Suppose that the arrow is on the left side of the stock. Just as it is released, both the string and the stock push its ends leftward, and the arrow buckles and then begins to oscillate left and right. The oscillations allow the arrow to snake around the stock without losing any energy through rubbing and without the feathered end striking the stock. Although the tip of the arrow does not always point toward the target during the oscillations, the flight is still in that direction. Soon after the arrow clears the bow, the oscillations die out, and then the tip points in the intended direction.

For an arrow to snake properly around the stock, it should be able to undergo one full oscillation by the time it leaves the string. The requirement demands a certain flexibility of the arrow. If it is too flexible, the oscillations are too slow and the feathered end hits the stock. If it is too stiff, the oscillations are too fast or the extent of the sideways motion is too small, and then the arrow fails to leave the bow with its full energy due to rubbing or a collision of the feathered end.

Reportedly, a ball of beeswax was placed on the tip of an arrow so that the arrow might better pierce the armor of a soldier. The reason given is that because the ball strikes the armor first, the collision causes the arrow to become more perpendicular to the armor just as the point of the arrow reaches the armor. Thus, the arrow is less likely to glance off the armor and more likely to penetrate it.

1.132 • Oscillating plants

A tree can be broken or uprooted if it is bent over by the gale of a hurricane or typhoon. How can it be in just as much danger in a substantially smaller wind?

Answer Any given tree will sway with what is called its *natural frequency*, in which the base is fixed in place, the top sways the most, and intermediate points sway by intermediate amounts. The value of the natural frequency depends on the length of the tree, the strength of the tree material (its ability to bend), and the air drag on its branches and leaves. Although a single gust of wind can set the tree swaying, the motion soon dies out and is unlikely to bend the tree over enough to break or uproot it. Those dangers come when a series of gusts hit the tree at a rate that is close to the tree's natural frequency, a condition said to be *resonance*. The situation is then like you pushing with a modest force on a playground swing carrying a child. If you push with the natural frequency of the swing, you can gradually build up the extent of the swinging. For gusts and trees, the swaying can also be built up.

Of course, wind gusts do not occur at a fixed rate but if their average frequency falls close to the resonant frequency of a tree, the swaying may be enough to break or uproot the tree. However, if the tree is surrounded by other trees, not only is the tree partially shielded from the gusts but also the energy of its motion is gradually lost to the rubbing of limbs with those other trees. Any tree, whether clustered or isolated, will also lose energy to the air drag on the foliage and to the stretching and compression of its stems.

Crop plants are also subject to resonant swaying by wind gusts, and so they too can be broken or uprooted by persistent gusts coming at a rate roughly at the resonance frequency. For corn stalks, that is a frequency of 1 to 2 hertz, somewhat higher than for trees.

1.133 • Oscillating tall buildings

The impact of wind on a tall building can cause the building to oscillate, which can be irritating or even nauseating to the building occupants. Making the building stiffer to decrease the deflection due to the wind is not practical or economical. How then can you reduce the oscillations to an acceptable level?

Answer One way to decrease the oscillations is to mount a spring–block device on the roof, with the spring aligned with the prevailing direction of the wind. One end of the spring is attached to the roof; the other end is attached to a block that can move along a track parallel to the spring. The frequency at which the block would naturally oscillate on the end of the spring is adjusted until it matches the frequency at which the building naturally sways. Then, when the building sways, the spring is stretched, causing the block to oscillate at the same frequency. However, the block's oscillation is delayed from the building's oscillation so that the two oscillations are exactly out of step. For example, when the building sways to the left, the block is oscillating to the right and thus tends to offset the building's sway.

Some buildings have double spring–block oscillators, one spring–block oscillator mounted on the block of a larger spring–block oscillator. The oscillations of the smaller oscillator are fine-tuned by an electronic circuit monitoring the building oscillations. Other buildings have a water oscillator in which water oscillates from side to side out of step with the building. To diminish the sway of the Petronas Tower in Kuala Lampur, Malaysia, which is 101 stories (508 meters) tall, a pendulum with a 680 000 kilogram ball is mounted on the 92nd floor.

1.134 • Diving from a springboard

In springboard diving, a skilled diver knows how to make a running dive: The diver first takes three quick steps along the board to start the board oscillating and then leaps to the free end of the board so as to be catapulted high into the air. A novice diver can imitate that procedure but fail miserably to be catapulted upward and might even be knocked off the board. What is the "secret" of a skilled diver's high catapult?

Answer A competition diving board sits on a fulcrum about one-third of the way out from the fixed end of the board. In a running dive, a diver takes three quick steps along the board, out past the fulcrum so as to rotate the board's free end downward. As the board rebounds back through the horizontal, the diver leaps upward and toward the board's free end. A skilled diver trains to land on the free end just as the board has completed 2.5 oscillations during the leap. With such timing, the diver lands as the free end is moving downward with greatest speed. The landing then drives the free end down substantially, and the rebound catapults the diver high into the air.

1.135 • Fly casting

If you throw a fishing fly as hard as you can, it travels only a short distance because of air drag. How, then, can you cast a fly a great distance with a rod and reel? Surely, the task is even more difficult because the line also meets air resistance, and yet the procedure gives a large speed to the fly.

Answer To cast, you bring the rod up and somewhat past the vertical to toss the fly and line to the rear, and then you pull the rod sharply forward to hurl them forward. Your force on the fly and line is effectively at the tip of the rod. Were you to throw them by hand with an identical force, you would do little work and give them little kinetic energy because the distance your hand moves is small. Since the tip of the rod moves through a larger distance, your work and the energy you give the fly and line are larger.

Once the tip of the rod is forward and stationary (Fig. 1-47*a*), the kinetic energy and speed of the fly increase even though you no longer do any work. To see the increases, first note the shape of the line just then (Fig. 1-47*b*): It extends forward from the tip of the rod, curves upward and toward the rear, and then extends back almost horizontally

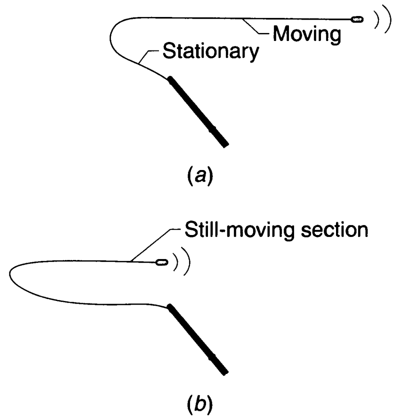


Figure 1-47 / Item 1.135 A fishing line cast forward. (*a*) Most of the line is moving. (*b*) Less of the line is moving.

to the fly. The first section is stationary because the rod is stationary, while the last section is moving along with the fly. As the fly moves forward, more of the line is in the stationary section, and so the kinetic energy becomes concentrated in the fly and the length of line that is still moving. When the fly reaches the forward-most point, it has all of the kinetic energy and moves quickly, much faster than if you threw it by hand. If you are holding some of the line loosely just then, the fly can pull it out and thus travel far out over the water.

Air drag limits the travel distance of the line. That is the reason why anglers strive for a small loop in the line so that the loop runs into less air. They also strive for an asymmetric loop with a forward-pointing top and less-curved bottom. The air drag on the bottom part of such a loop produces a vertical lift on the line that allows a longer cast. This is the technique used by anglers in competition fly casting.

Some anglers believe that the bending of the rod on the preliminary backward cast of the line is the primary source of energy for the fly during the forward cast, but studies reveal that such a contribution is small. However, the flexibility of the rod is important in the placement of a cast and in the handling of a fish. The stiffness of a rod is measured by the amount of the load required on the tip of the rod to bend the rod by a certain amount. Anglers usually choose a stiffer rod when fishing for large fish because they don't want the pole to bend over. The frequency of a rod is measured by the rate at which it will oscillate when the butt end is clamped in place and the tip is first deflected by a small amount and then released. High-frequency rods, said to be "lively," are often preferred for long casts. Low-frequency rods offer more control and are used to place a fly accurately.

1.136 • The Falkland Islands battle, Big Bertha

During World War I, British and German navies battled near the Falkland Islands, which is at a latitude of about 50° S. Although the British shots were well aimed, they mysteriously landed about a hundred meters to the left of their targets. Were the gun sights off? Seemingly not, for they had been precisely set back in England. What was wrong?

During the German shelling of Paris in that war, a huge artillery piece nicknamed Big Bertha hurled shells into the city from 110 kilometers away. Had not the Germans taken scientific principles into account, their shots would have missed the mark by almost 2 kilometers.

When the Germans first began to test long-range artillery, they were surprised to find that if a shell is fired at a large angle, larger than 45°, it went much farther, perhaps twice as far as when 45° was the angle. Since in many common situations a launch at 45° produces the maximum range for a shot, why were their shells going farther with a larger angle?

Answer We usually invent a fictitious force, the *Coriolis force*, to account for the apparent deflection of a long-range shell that is actually due to Earth's rotation during the shell's flight. The apparent deflection is rightward in the Northern Hemisphere and leftward in the Southern Hemisphere, and it is larger at larger latitudes and zero at the equator.

When a long-range shell is launched, it has not only the velocity due to the launch but also a certain velocity due to the rotation of Earth at the location of the launch. During the shell's flight, the target continues to circle around Earth's axis because of the rotation. If the target's motion is not taken into account, the shell will miss the target. For an example in the Northern Hemisphere, suppose the target lies due north of the shell's launch site. Both the target and the launch site circle eastward around Earth's axis, but the target, being at a higher latitude, follows a smaller circle than does the launch site. Since both sites must complete a full circle in a day, the target moves slower than does the launch site. When the shell is launched due north, it also has the same eastward speed as the launch site. During its flight, it travels eastward faster than does the target and so it ends up to the east of the target. In the perspective of someone at the launch site, the shell is deflected eastward—that is, toward the right of the target.

Gunners allow for the deflection through trial and error but the correction to the gun sights depends on latitude and is in the opposite directions in the two hemispheres. The British guns were set well for the latitude of England but woefully wrong for the southern latitude of the Falkland Islands. With the long flight of the shells from Big Bertha, the Germans knew to correct for the Coriolis deflection—during a shell's flight, Paris moved.

When the Germans fired long-range shells at an angle larger than 45°, the shells traveled through the thin reaches of the atmosphere, which reduced the air drag on them, and so the shells went surprisingly farther.

1.137 • Jack and the beanstalk to space

Is there any way to put a satellite into orbit and then drop a line from it to the ground so that material can be hoisted to the satellite? Is there any way that the satellite could be moved away and the disconnected line then remain in place? (You would then have a "beanstalk" but no giant.)

Answer If the satellite is in an equatorial orbit and at the proper altitude so that it rotates around Earth just as fast as Earth turns, then in principle a line could be lowered to Earth and an elevator system could even be rigged. If the satellite is higher, the effective centrifugal force on it would pull on the line—the arrangement would then be a *skyhook* that could lift materials on the line without need of an elevator system. A strong, lightweight line might actually be left standing free, like the fabled beanstalk, if the effective centrifugal force balanced the line's weight, but calculations show that the line would need to be about 143 million meters long, a bit much.

If the satellite is in an orbit that leaves the lower end of the line skimming over Earth, and if the line is elastic, then it might provide a virtually free means of transportation. A passenger compartment could be added to the line's lower end and, as the line stretched out because of the pull by the satellite, the compartment would hop into the atmosphere and then come down again after traveling a great distance. Although during the ascent the compartment's pull against the satellite would reduce the satellite's energy, most of the energy would be given back during the descent when the compartment pulls the satellite along its orbit. To allow for inevitable energy losses, the satellite might be equipped with a small rocket.

1.138 • Spring fever and the standing of eggs

Try standing a raw egg on its end. Chances are that it will just topple over. Do you have any better chance of standing it up on the vernal (spring) equinox as some people believe?

Answer To understand the vernal equinox, imagine a plane that extends through Earth's equator and out to the Sun. Also imagine that the Sun orbits Earth instead of the other way around. In this arrangement, the Sun's orbit is slanted with respect to the extended plane, and the Sun passes through the plane twice a year. One of those days is the vernal equinox. According to rumor, the gravitational pull by the Sun on objects on Earth, particularly an egg, is somehow different on that day. The rumor is just untrue.

So why then does the rumor continue? One reason may be that a few people make a concerted effort on the vernal equinox, and on that day only, to stand up eggs. (Those people must be pretty bored.) If they gain moderate success on that day, then they claim there is something special about gravity then. Were the idea true, surely you will feel the difference—your mass is larger than an egg's and so you should feel the stabilizing pull from the Sun all that much more. Needless to say, you feel no different on the vernal equinox and probably do not even know when it passes.

If you find an egg that will stand on end, that end will likely be slightly flat, though perhaps only in a small region. A sneaky way to stand up most any egg is the following: Make a small mound of salt, lightly press the blunt end of the egg down into the mound, adjust the egg so that it is upright, and then carefully blow salt away from the egg. The few salt crystals that remain are wedged between the egg and the table and provide enough support to keep the egg upright. Someone unaware of what you have done might not even see the remaining crystals; you could then attribute the egg-standing to, say, an increased flux of cosmic rays. (Why not? It makes as much sense as attributing the stunt to the vernal equinox.) You could also cheat by flattening the end of an egg with sandpaper.

Here's another way that sometimes works. Shake the egg so as to rupture the membrane holding the yolk. Then hold the egg upright on a table for a few minutes to allow the yolk to settle into the bottom end and thereby lower the center of mass of the egg. The bottom-heavy egg might then continue to stand up when you release it.

The habit of standing up eggs on the first day of spring appears to have begun in China thousands of years ago. Since then, an uncountable number of eggs have been stood on that particular day. You might think that such success proves that the day is special. Well, no. The first day of spring on the Chinese calendar is about 90 days before the vernal equinox.

1.139 • Moon madness

Most people believe that the number of births, car accidents, admissions at hospital emergency rooms, aggressive acts, and a whole host of other human activities increase during a full Moon. Just how would the Moon cause this lunar effect—is the effect due to the gravitational force of the Moon, is it psychological, or is nonexistent?

Answer Can gravitation be the cause? No, the gravitational pull on you due to the Moon is imperceptibly small. Were it noticeably large, then you would feel the effect as the Moon rose in the sky and you thereby move somewhat closer to it, increasing the Moon's gravitational pull on you. Do you feel lighter as the Moon climbs the sky? No, of course not.

Could a tidal effect due to gravitation be the cause? The Moon certainly has an appreciable and easily seen effect on oceans by causing the tides. Do people somehow respond to the same effect? No, the tides are due to the variation of the Moon's (and Sun's) gravitational force across the width of Earth. That variation over such a large distance produces a bunching of water. As Earth turns, some ocean regions turn through this bunching and experience high tide. The variation of the Moon's gravitational force across the width (or length) of a person is too small to produce any similar tidal effect. So, this too is not the answer.

But why even consider gravitation? The term full Moon means that the full face of the Moon (in our perspective) is illuminated by the Sun. That extent of illumination would in no way alter the gravitational force on us due to the Moon.

So, one might guess that the lunar effect is psychological—people are somehow driven into a frenzy because of the added illumination at night, even if they happen to live in bright city lights or not go out at night.

Alas, if you plot the number of births, car accidents, admissions at hospital emergency rooms, aggressive acts, or other human activities versus the phase of the Moon, you actually will find no peak at full Moons. The lunar effect is just a legend, even among professional health workers who should know better.

1.140 • Gravity hill

Scattered around the world are places where gravity seems to pull a car up a hillside. One location is just outside Mentor, Ohio. When I coast down the hillside with my car in neutral, the car gradually slows to a stop and then begins to travel back toward the crest of the hill. Can gravity actually pull upward in such places? (If you visit one of these hills, be extremely cautious that you are not hit by another car—a driver will not expect to find a stopped or slowly moving car.)

Answer The effect is an illusion, but it can be so convincing that the experience is unnerving. (When I first sampled the illusion near Mentor, one of my daughters, then a child, was in the car. Although she knew little about gravity, she knew enough to burst into tears as the car rolled uphill.) If you sight along the surface of the road, the illusion disappears and you see the true inclines of the road. You may find that there is a shallow dip in the overall moderate slope of the hill. (Be careful of other cars.) When the car rolls backwards and toward the crest, it is actually rolling back into the dip. When you sit in the car, the dip is imperceptible and the illusion of rolling up the hillside is strong. If the trees alongside the road are tilted appropriately, they can enhance the illusion.

The illusion of a wrong tilt of a section is sometimes due to a much stronger tilt of the road before and after the section. In one example, if the near and far road sections are strongly downhill and the middle section is only moderately downhill, that middle section may appear to be uphill. The apparent horizontal can also affect the perception of tilt: For example, imagine a horizontal road that curves off to the left just in front of a hillside that hides the true horizon. You get the impression that as the road approaches the hill, it curves downward because the apparent horizon is at the hilltop and thus high.

1.141 • Falling through the center of Earth

Imagine a hole that extends along the rotation axis of Earth, from one pole to the other. If you were to fall into such a hole, how long would you take to reach the opposite end, and if you did not somehow escape then, what would happen to you? Would matters be any different if the hole went through Earth elsewhere?

A shorter version of such a tunnel has been suggested for transportation in heavily traveled regions, such as between New York and Washington, D.C. A straight tunnel would be dug between the two cities and track laid. When a train is released at one end of the track, it would require almost no energy from an engine to reach the opposite end of the track. What would propel it, and how much time would the trip require?

In *Pole to Pole*, an early science fiction story by George Griffith, three people attempt to make a trip through Earth by using a naturally formed (and of course fictional) hole that extends through the North and South Poles. Beginning at the South Pole, their capsule first falls toward the center of Earth while being slowed by balloons that are filled with helium or hydrogen. As the story goes, the gravitational force on the passengers becomes alarmingly large as they approach the center of Earth and then, exactly at the center, it momentarily disappears.

The later ascent toward the North Pole proves slower than anticipated, and the balloons are again employed to give lift, but calculations by the onboard scientist reveal that the capsule will rise only to a certain height and there it will slow to a stop, trapping the passengers. Even ditching heavy machines fails to lighten the load sufficiently. In desperation, the scientist lowers himself through a bottom hatch, briefly clings by his hands, and then drops away from the capsule. The loss of his mass is enough to allow the capsule to reach the end of the tunnel where the remaining two passengers escape. (Scientists are often wont to sacrifice themselves for the benefit of others.) Is the story sound?

Answer Suppose that you fall into a straight tunnel connecting the poles. Freeze the picture after you have fallen to a certain radius from the center. Imagine a sphere with that same radius and centered on Earth's center. The mass inside the sphere pulls on you but the mass outside the sphere effectively does not, because for every outward pull by an outside section on your side of Earth, there is a matching inward pull by some other outside section on the opposite side of Earth.

Now continue the fall. As you approach the center, the radius of your location and the size of the remaining mass contained in a sphere of that radius shrink, and so the gravitational pull on you also shrinks. When you pass through the center, the pull is momentarily zero. The ascent through the rest of the tunnel is a reverse of the descent. Assuming ideal conditions, such as no air drag, equal distances for descent and ascent, and the miraculous idea that you could somehow survive the heat and other lethal conditions in Earth's core, you would come to a stop just as you reached the opening at the end of the ascent.

The time of full passage would be about 42 minutes. (The result assumes that the density of Earth is uniform. If the core is denser than the rest of Earth, the result is several minutes less.) If you did not escape, you would bob back and forth in the tunnel forever.

If the tunnel were located somewhere else, it would have to be curved if you were not to crash into its sides. The trouble is that you begin the descent with whatever rotational speed the ground has at the opening to the tunnel. As you fall toward the center, you pass into sections with less rotational speed and will run into the side of the tunnel.

The straight-line tunnel between cities is nearest the center of Earth at the tunnel's midpoint. A train would essentially fall down the first half of the track and then climb back up the second half. Extra energy would be needed only to overcome friction and air drag. The trip would take 42 minutes, the same as in the pole-to-pole tunnel.

I leave the details of the science fiction story for your analysis.

1.142 • Stretching of plastic shopping bags

When you load up a plastic shopping bag with groceries and then carry the bag by the loops at the top of the bag, why will the loops initially withstand the load but then, several minutes later, begin to stretch, perhaps to the point of tearing?

Answer If you suspend a load from the lower end of a spring hanging from a ceiling, the spring will stretch by a certain amount and then stay stretched. Plastic, which consists of polymers, is different. If you suspend a load from the lower end of a plastic strip, the strip will initially stretch like the spring but thereafter it will gradually stretch more in what is called *viscoelastic creep.* The mechanism of this creep can vary from polymer to polymer but a simplistic explanation is this: The polymer consists of many long and entangled molecules, somewhat like a pile of spaghetti strands. When the polymer is put under load, these molecules gradually disentangle somewhat because they are pulled in the direction of the load. The gradual reorientation of the molecules allows the plastic to gradually stretch. If the plastic stretches enough, it may also narrow perpendicular to the direction of the load in what is called *necking.* You can easily see necking in the plastic retainer for a beverage six-pack. Pull the retainer off the beverages and then pull it in opposite directions with your hands until it necks.

1.143 • Giant's Causeway and starch columns

Giant's Causeway in Northern Ireland is an ancient lava (basalt) bed that now consists of basalt columns of various heights. The columns are stunning because in cross section they are polygonal, with many being hexagonal. How could the once-fluid lava break up into vertical, polygonal columns? You can produce similar columns with a mixture of water and cornstarch dried by a heat lamp.

Answer As lava slowly cools, randomly positioned cracks (fractures) develop at the top surface and then extend into the bulk of the lava. The cracks occur because as the lava cools, it tends to contract, which puts the lava under *stress* (a tendency to pull apart). When the stress is so large that it overwhelms the strength of the lava, the lava ruptures into a crack, reducing the stress. Where a developing crack happens to extend toward an existing crack, the stress along the existing crack steers the developing crack to make a perpendicular intersection.

After this first stage of crack formation, a secondary system of cracks develops in the lava. These cracks may each start in a straight line but as they extend into the bulk of the lava, they tend to split (*bifurcate*). Depending on the rate at which the lava cools, the intersection of the secondary cracks with the first-stage cracks tends to split the lava into columns that are pentagonal or hexagonal in cross section.

You can see similar first-stage cracks and secondary cracks in many situations, such as drying mud layers. You can also study the crack formation in a controlled way with a mixture of water and cornstarch. As water diffuses (spreads) through the mixture and then evaporates, the mixture attempts to contract and thus is under stress and tends to form cracks. Depending on the rate at which water evaporates, the secondary cracks can produce pentagonal and hexagonal columns of dried cornstarch.

1.144 • Broken fingernails

If you tear a fingernail, why does the crack tend to veer left or right across the nail rather than travel down the nail?

Answer After you tear a nail at its exposed edge, the crack tends to travel in a direction that requires the least energy to separate cells from one another. The nail consists of three layers: the lower layer is moderately hard keratin, the thicker middle layer is harder keratin, and the upper layer is softer keratin. The strength of the nail is largely determined by that middle layer, which consists of long, narrow cells that run left and right across the nail. Less energy (about half as much) is needed to separate two lines of those cells from each other than to break across many lines of the cells. Thus, the crack tends to veer left or right rather than traveling down the nail.

1.145 • Crumpling paper into a ball

Take a sheet of paper and crumple it between your hands, squeezing it into a ball. Quickly you reach the point where you cannot collapse the ball further. Yet, 75% of the ball is just air. What stops you from crushing the ball further?

Answer As you crumple the paper, you form *curved ridges* (folds) and *conical points* (peaks). Energy from you is required to rearrange the fibers of the paper into these new configurations, and force from you is needed to overcome the friction between the fibers and between pieces of the paper that rub together. Here's another way of saying all this: Energy is stored in the places where the paper is stressed. If you unfold the sheet, you can see the lines and regions of permanent distortion due to the stress.

To collapse a crumpled ball more, you must collapse the existing ridges and also create new ones, which requires more energy from you. The rearrangement of the fibers now becomes more difficult. Eventually you reach the stage where further collapse requires more energy and force than you can supply. Still, if you were to put the ball under a heavy load, it would gradually collapse further over the next few weeks or even the next few years. The fibers gradually move in a *plastic flow* as if they were in a hot plastic that was somewhat fluid.

1.146 • Playful to tragic examples of explosive expansion

One day R. V. Jones of the University of Aberdeen happened upon a beaker of water outside a lab in Oxford while carrying a pistol. For amusement he fired at the beaker, expecting it to shatter into a heap of fragments as a beaker should when hit by a bullet. Instead, it disappeared. He later lectured on why.

Years afterward the Royal Engineers of Aberdeen set out to topple a tall industrial chimney with the physics of his lesson plan. They placed an explosive charge inside the bottom of the brick chimney and then filled the chimney with 2 meters of water. They expected that the explosion would blow out the foundation and send the chimney to the ground. Well, they were half right. The lowest 2 meters of the chimney certainly blew away, but so cleanly that the rest of the chimney dropped neatly and stably onto the remains of the old base. The Royal Engineers then had an even worse problem on their hands.

Why did the beaker and the lowest 2 meters of the chimney get blown away so completely?

A series of stunning photographs by "Doc" Edgerton of MIT, some of the early strobe photographs, reveals the response of a common lightbulb penetrated by a bullet. When the bullet enters the bulb, it reduces the glass at the entrance point to a powder and then some of the powder is propelled back toward the weapon. Shouldn't considerations of force and momentum require that the powder be sent solely in the direction the bullet is traveling?

When President John F. Kennedy was assassinated, some of the brain debris was sent back along the rear of his car in the general direction of Lee Harvey Oswald, who is believed by most investigators to have fired the lethal shot. However, some investigators believe that the rearward spray of debris is actually evidence that another shot must have come from a second sniper on a grassy knoll some distance in front of the car. Must that be the case?

Answer When a bullet hits an empty beaker, the glass around the entrance and exit points shatters into a powder while the rest of the glass is broken into larger pieces as fracture lines travel around the sides of the beaker. If the beaker is filled with water, the water cannot expand upward fast enough to accommodate the space required by the bullet and the effect of its shock wave, and so the water pushes outward on the beaker's walls, reducing the glass to a powder all around and hurling the grains away in all directions. So it went with the bricks in the lowest 2 meters of the chimney when the explosive device suddenly demanded additional volume.

The back-splatter of powdered glass in Edgerton's demonstration is also due to the expansion of a fluid, the small amount of gas contained by the bulb. I don't mean to trivialize or even objectify President Kennedy's death, but the spread of brain debris on the back of the car was most likely due to the response of the fluid in the brain to the sudden impact of Oswald's bullet.

1.147 • Why a hanging picture becomes crooked

If you hang a picture with a short length of cord passing over a support such as a nail, chances are that it will eventually be crooked. What makes it unstable? Is there anything you can do to stabilize it other than tying the cord to the nail or using two, widely spaced nails?

Answer When the cord is short, the picture is unstable because any chance disturbance will allow it to lower the center of its mass distribution by hanging crooked. You can eliminate the instability by substituting a long cord. The minimum length involves the angle between the sections of the cord at the nail and the angle at the left and right between diagonals across the picture (Fig. 1-48). When the angle between the diagonals is less than the angle at the nail, the picture is unstable. By substituting a longer cord, you decrease the angle at the nail. When it is smaller than the angle between the diagonals, the picture cannot lower its center of mass by becoming crooked and thus is stable.

1.148 • A two-spring surprise

Find two springs that are approximately equal in length and strength and arrange for them and three lengths of string to support a block as shown in Fig. 1-49. One of the strings con-

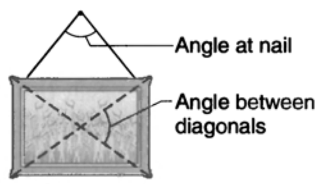


Figure 1-48 / *Item 1.147* Angles are important to the picture's stability.

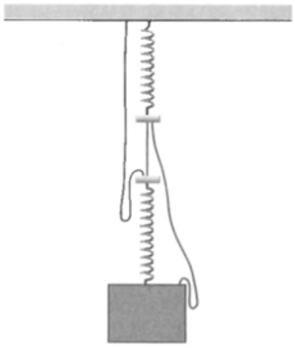


Figure 1-49 / *Item 1.148* Arrangement of two springs and limp strings.

nects the springs and is under tension. The other two strings are of equal lengths but are slightly too long to help support the block and are thus limp.

If you cut the short, interconnecting string so that the longer strings must then help support the block, does the block descend?

Answer When you cut the short string, two factors determine the new level of the block. One factor is that the block now hangs from the two longer strings; since those strings were originally limp and are now under tension, the block tends to be at a lower level. The second factor has to do with how much the springs are stretched. In the original arrangement, each spring supported the full weight of the block, but in the new arrangement, each supports only half that weight. So, in the new arrangement, the springs are now stretched less, which tends to move the block upward. Provided that the longer strings are not too long, this second factor wins out and the block ends up higher than initially.

1.149 • Stability of a pop can

The stability of a can of pop or beer on a table is measured by the energy needed to tilt the can from its normal resting position up to where its center of mass lies directly above the edge still on a table. Is a full can more or less stable than an empty one? Is the can most stable for some particular height of the liquid? The question might be important if the table happens to be on a shaky airplane flight or train ride or if a bartender attempts to slide the can across the surface of a bar.

Answer A completely filled can is more stable than an empty one. Although the center of mass is at mid-height for both cases, the extra mass in a full can means that more energy is needed to tilt the can to the point where it will topple onto its side.

If you slowly drain liquid from a can, three factors influence the can's stability. The center of mass drops until the liquid surface reaches it, and then the center of mass begins to rise. The mass of the liquid decreases as the liquid is removed. And when the can is tilted, the remaining liquid flows so that its top surface remains horizontal. Consideration of these factors shows that a typical can of beer or pop is most stable when the height of the liquid is slightly larger than the radius of the can.

1.150 • Wilberforce pendulum

The strange pendulum shown in Fig. 1-50 is named after L. R. Wilberforce, a British physicist who investigated it in 1894. It consists of a spring attached to a small object with adjustable arms. When the spring is pulled down and released, the object first bobs up and down, but the motion is soon replaced with a rotational motion of the object. Thereafter the motion is periodically exchanged between the spring and rotational motions. The arms on the object are needed because if the apparatus is to display this exchange of motion, the frequency of the purely spring-like oscillations must match the frequency of the purely rotational motion. To make that so, the arm lengths need to be adjusted. Why does the *Wilberforce pendulum* behave so strangely?

Answer The Wilberforce pendulum is similar to the coupled pendulums described in a previous item. Here the normal modes of motion are the oscillations of the spring and the rotation of the object. The modes are coupled because when the spring oscillates and changes length, the coiling and uncoiling requires that it also rotate. The rotation is initially slight but soon it gains all of the energy. As the object then rotates, it coils and uncoils the spring, which changes the spring's length. The variation is initially small but soon it steals all of the energy. Then the process of transfer repeats itself.

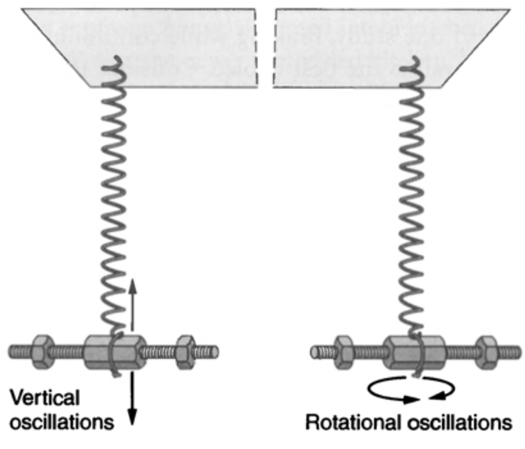
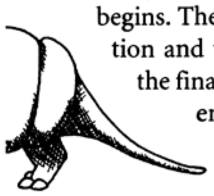


Figure 1-50 / *Item 1.150* Wilberforce pendulum alternates between vertical oscillations and rotational oscillations.

1.151 • Drag racing starts

In drag racing there are two measures of interest on a quarter-mile course: the final speed and the elapsed time. To prepare for the race, why does a driver gun the engine so that the rear wheels spin? Why does the procedure decrease the elapsed time for the run but does not appreciably increase the final speed?

Answer The rear tires are spun so that some of the material melts. After cooling for a few seconds, the material is sticky and so adds to the traction of the wheels when the race begins. The increased traction allows a large initial acceleration and thereby reduces the elapsed time in the run, but the final speed is largely set by the power limitation of the engine—that is, the maximum rate at which the engine can provide energy.



1.152 • Turn or stop

It is difficult to find any physics with more real-world impact than that which involves your possible death. For example, suppose you suddenly discover that you are driving straight for a brick wall at a T-intersection. Should you apply your brakes fully, turn left or right at full speed, or turn while applying the brakes?

Suppose instead that you spot a box ahead of you on a stretch of highway. To avoid hitting the box should you apply your brakes fully or attempt to steer around the box?

If your car and another car are headed toward an intersection along perpendicular streets and with identical speeds, should you and the other driver brake fully without changing direction, or should you each swerve away from each other so that the cars end up leaving the intersection along adjacent paths?

Answer Let's ignore all practical matters such as brake fade, reaction time, and nonuniform road conditions. Then, according to one study, braking while continuing to head toward the wall is the best choice. Consider the situation where the frictional force on the tires is maximum and just barely brings you to a stop in front of the wall. A circular turn onto the side street would require a force on the tires that is twice as large, because extra force is needed to make the car turn from its initial travel. So, if you elect to turn, the force would overwhelm the friction, and you would slide, spin, and eventually hit the wall. Even if you braked while turning, you would still hit the wall.

Whether you can steer around a box depends on the ratio of its width to the distance between you and the box when you begin to act. The marginal case is when the width is about half the distance. For a wider box, studies suggest you should brake fully while headed straight toward the box. For a smaller box you can steer around it.

In the situation where two cars are about to collide in an intersection, it may be best for the drivers to swerve. However, the danger is hardly diminished because the cars then leave the road and plow through whatever is in their way.

1.153 • Slipping past a bus

A bus slows to make a turn at an intersection, but there is enough room in your lane adjacent to the bus's lane for your car to slip by the bus (Fig. 1-51). Is that a wise thing to do?

Answer As the bus turns, its rear effectively pivots around the rear wheels and swings out in a direction that is opposite the turn. Unless the turn is gradual, the rear of the bus might move into your lane by a meter or so and thus strike your car if you are trying to slip by. The sharper the bus is turned, the more its rear encroaches on your lane.

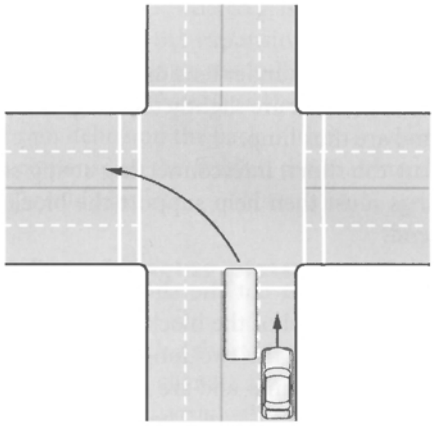


***Figure 1-51** / Item 1.153* Car slipping past a turning bus.

1.154 • Compression region in sticky tape

For many types of sticky tape, as you pull the tape from the roll, a short region of compression (where the tape is noticeably pressed onto the roll) forms just ahead of where the tape leaves the roll. You might see the compression region better if you stick two tape strips together and then slowly peel them apart. What causes the compression line?

Answer As the tape is pulled from the roll, the separated portion rotates away from the roll, about the line where the tape separates from the roll. The tape is stiff enough for this rotation of the separated portion to cause a rotation of the portion that is about to be separated, squeezing the gummy adhesive below it down onto the roll. When you stop separating tape from the roll, you eliminate the rotation and so the region of compression disappears.

1.155 • Bobsled in a curve

In bobsledding, the goal is, of course, to complete the run from the top of the course to the bottom in the least time. Often the winner is decided by a fraction of a second, a margin that may be only one part in 1000. In the straight sections the idea is to slide as smoothly as possible. What strategy should be used in a turn? When you enter the turn, should you steer the sled up high on the slope or keep it as low as possible? Is there a danger of a spill (and so a crash) for either case?

Answer Imagine taking a circular turn on a flat track. In order to turn, a centripetal force must act on you toward the center of the circle. The faster you take the turn, the larger the centripetal force must be. That force is provided by the friction on the sled that counters the sled's tendency to slip sideways. (It is the friction that is perpendicular to the runners on the sled, not the friction along their lengths, which tends to slow the sled.) If you come into the turn with too much speed, the friction is overwhelmed and you slip sideways and crash.

A turn on a bobsled track is banked so that the speed can be high. The bank tilts the supporting force on you and the sled from the ice surface. The tilt is toward the center of the circle so that the support force provides additional centripetal force. Now you might take the turn fast without slipping sideways, provided that you ride up on the bank.

However, you do not want to climb the bank any more than is necessary for three reasons. (1) The higher you go, the farther you must travel to complete the turn, and so you add to the travel time. (2) If you go high, both the friction along the length of the runners and the air drag have longer to act on the sled, and so you come out of the turn with a smaller speed than if you had stayed low. (3) Going high with too small a speed may result in a spill because of the tilt.

1.156 • Too quick to slide

The novel apparatus in Fig. 1-52 consists of a ring that is free to slide along a rod. The upper end of the rod (at the pivot) is forced to oscillate horizontally through a small distance. If the oscillations are slow, the ring slides off the rod, but if they are quick, the ring stays on the rod in spite of its weight. What holds it on the rod?

Answer Were the pivot stationary or oscillated slowly, gravity would, of course, pull the ring off the rod. But when the oscillations are rapid, gravity lacks the opportunity. The pivot moves the slowest near the extreme ends of its oscillations and the fastest in the center. So, most of the time the rod is at a slant. Suppose the slant is leftward (the pivot is leftmost). Although gravity attempts to slide the ring down the rod and toward the right just then, before the ring can move, the pivot shifts to the right and the rod slants rightward. Now gravity tries to move the ring down and to the left, but, again before the ring can move, the rod changes orientation.

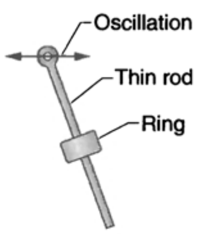


Figure 1-52 / *Item 1.156* Oscillation can keep the ring on the rod.

1.157 • The home of the Little Prince

The mysterious visitor that appears in the book of this enchanting parable, *The Little Prince*, was said to come from a planet that was barely larger than a house. What would life be like on such a planet—for example, could the Little Prince walk about on the planet?

Answer The source of this whimsical item, J. Strnad, considers a planet somewhat larger than the one in the celebrated book and finds that even walking on the planet would be quite difficult because of the tiny gravitational pull. If the Prince were to move faster than 11 centimeters per second, he would be launched into space, unable to return, and if he moved slower but still faster than 80 millimeters per second, he would be sent into orbit around the planet. Someday astronauts will need to cope with such conditions if they mine house-size asteroids.

1.158 • Parachuting with a pumpkin

In 1987, as a Halloween stunt, two skydivers passed a pumpkin back and forth between them while they were in free fall just west of Chicago. The stunt was great fun until the last skydiver with the pumpkin opened his parachute. The action caused the pumpkin to be ripped from his hands. Unfortunately, the pumpkin then plummeted about half a kilometer, ripped through a roof of a house, slammed into a kitchen floor, and splattered all over the newly remodeled kitchen. What caused the skydiver to lose control of the pumpkin?

Answer When the skydiver opened his parachute, the parachute exerted a sudden, large, upward force on him to reduce his downward velocity. The force was more than enough to rip him away from his pumpkin, and the poor pumpkin then fell to its death in that house just west of Chicago.

1.159 • Pulling in a feisty fish

If a fish is small, you might be able to reel it in by simply rotating the handle on the reel and winding up line, but if it is large and full of fight, what should you do to bring it in?

Answer Pulling in a fish involves a battle of torques. When you point the rod toward a strong, feisty fish, you must apply a large force to the reel's handle if you are to generate enough torque to rotate it. The problem is the short lever arm that you work with—it is the distance between the handle and the center around which it turns. You have an easier time if you grab the rod above the reel and pull so as to rotate the rod around its lower end. If the fish is strong, you can prop the lower end on a pivot and then pull with both hands. Either way, you work with a larger lever arm, and so less force is required of you. After you raise the tip of the rod, you gradually lower it again as you wind up line.

If you wish to wear out a fish, holding it in check is easier with a rod that bends because that condition shortens the distance between your hand and the tip of the rod and decreases the torque created by the fish. You then need less torque from your hands to keep the rod in place.

1.160 • Fiddlesticks

Fiddlesticks is a toy consisting of a plastic ring that rotates around a wooden rod. If you hold the rod vertically with the ring at the top and then spin the ring, it will gradually move down the rod. Why does its rate of descent slow and the spin increase during the fall? If you quickly invert the rod before the ring reaches the bottom, you can keep the motion going indefinitely.

Answer If you allowed the ring to roll down an inclined plane, it would progressively turn faster during its descent, with the increased energy for rotation coming from the decreased potential energy. The ring on the rod essentially rolls down the rod in a similar fashion, but on the inside surface of the ring rather than the outside. At any given instant, the ring is at a slant, with part of its inner surface touching the rod. In the next instant, the point of touch has moved around the rod and also down it (Fig. 1-53). The point of touch continues to spiral down the rod. As the ring descends, it converts potential energy into the kinetic energy for the spinning.

The rate of descent is set by the pitch of the spiral, which is fixed by the slanted orientation of the ring. As the ring spins faster, it becomes more horizontal, and the pitch of the spiral and the rate of descent both decrease.

If two rings are set spinning near the top of the rod, the higher ring might happen to catch up with the lower ring. When they touch, the higher ring bounces upward from the collision, spiraling upward.

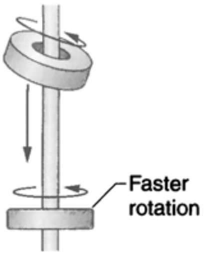


Figure 1-53 / Item 1.160 The ring is initially slanted and spinning slowly. Lower down, it is less slanted and spinning faster.

1.161 • Rotor on a notched stick

A rustic toy that is certain to spark controversy consists of a rotor on a notched stick and a second stick that is rubbed along the notches (Fig. 1-54). The wood rotor is supported by a pin that runs through a hole in the rotor and into one end of the notched stick. Holding your forefinger on one side of the notched stick and your thumb on the opposite side, you stroke the second stick over the notches. If you press hard with your forefinger, the rotor turns in one direction; if instead you press hard with your thumb, the rotor turns in the opposite direction.

When you show the toy to someone unfamiliar with it, you can slyly shift the pressure between thumb and forefinger to reverse the rotation. There is no end to the causes you can attribute to the reversal, such as variation in the cosmic ray intensity.

How does the toy work?

Answer If you apply no pressure on the sides of the notched stick, the vibrations only wiggle the rotor. But when you press against one side, the pressure retards that side's response to the vibrations. The asymmetry in the response of the two sides forces the pin to travel around an elliptical path, and then the friction between the rotor and the pin makes the rotor spin around in the same direction. When you shift the pressure to the opposite side of the stick, the pin travels around the ellipse in the opposite direction, and so the rotor's spin is reversed.

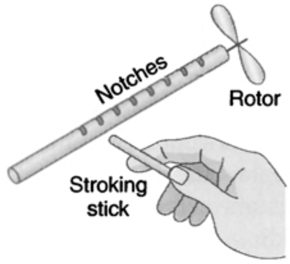


Figure 1-54 / Item 1.161 Rotor spins on the pin after the stick is set oscillating.

1.162 • Shot put and hammer throw

At what angle should a shot be put to maximize the range? Is it 45° as some textbooks claim? If not, is the deviation due to air resistance the shot encounters during the flight?

At what angle should the hammer in a hammer throw be launched? Why does the athlete spin around prior to the release of the hammer, while also moving forward? Just before the release, why is the hammer pulled toward the athlete's body?

Answer If the shot were launched by a machine at ground level, the theoretical optimum angle would be 45°. If it were launched by a machine at the typical release height in shot putting, the theoretical optimum angle would be about 42°. However, most shot putters prefer a smaller angle, perhaps as small as 29°, because the release is then physically more efficient and the shot is launched with greater speed. Although the smaller angle tends to decrease the shot put range, the greater launch speed more than makes up for that decrease. (Air resistance has little effect.)

To build up the kinetic energy of the hammer prior to its release, the athlete twirls the hammer around several times (with feet planted) and then begins to spin several times along with the hammer while also moving across the launching circle in order to add even more speed to the hammer. The hammer's motion is not horizontal. Rather, the hammer rises to a high point when the athlete faces the direction of the intended launch, and then the hammer falls to a low point in just the opposite direction. During the fall, the athlete, with both feet momentarily planted, pulls in the direction of travel of the hammer and thus adds to the kinetic energy.

As the athlete almost completes the last spin and reaches the edge of the launching circle, the hammer is suddenly pulled toward the body to increase its speed. (The situation is like an ice-skater bringing in arms and a leg while spinning on point—the action increases the rate of spinning.) The hammer is then released at about shoulder height. Thus, the hammer should be released at an angle somewhat less than 45° because of that initial launch height.

1.163 • Jumps during downhill ski race

If an experienced skier who is coming down a hill notices that the slope suddenly steepens along the way, the skier will crouch and then jump upward to lift the legs and become airborne before reaching the increase in slope. Why doesn't the skier wait until reaching the increase in slope to use the slope to become airborne?

Answer If the skier does not jump prior to reaching the sudden increase in slope, but instead uses that increase to become airborne, then the skier travels farther through the air and thus falls farther to land on the snow. The longer fall results in a more jarring landing, which might easily topple the skier.

1.164 • Pulling a tablecloth beneath dishes

Pulling a tablecloth out from a set of dishes is a classic classroom demonstration. When I was still dating and faced with trying to start a conversation on a first date, I would often perform the stunt for my date, only I would not use common dishes or glassware, but instead would partially fill lab beakers and flasks with wine. The technique always got the conversation going. However, if you should try the demonstration on one of your dates, be aware that showing it is not enough. To keep the conversation moving, you need to explain how the demonstration works. How does it work?

Answer If you pull smoothly and rapidly on the tablecloth, you immediately reduce the friction between it and the dishes. Such reduction is common. When two surfaces begin to slide over each other, the friction between them is generally smaller than when they are on the verge of sliding. In the case of the tablecloth, all or part of the reduction stems from the skipping the dishes undergo. Since they do not fully touch the cloth at all times, the friction on them is smaller, and the cloth can slide out from underneath. However, that smaller friction will still move the dishes in your direction. The longer you pull, the more the dishes will move, which is another reason for you to pull rapidly so as to reduce that time.

SHORT STORY

1.165 • Pulling with teeth

On April 4, 1974, John Massis of Belgium managed to pull two passenger cars of New York's Long Island Railroad by clamping his teeth down on a bit that was attached to the cars with a rope and then leaning backward and pushing against the railway ties with his legs. The cars weighed about 80 tons, or 700 000 newtons, but since Massis did not lift the cars, it was their mass that was important. Somehow he was able to move a mass of about 71 000 kilograms through a measurable distance. (In a physics classroom the concept of work being the product of the force and the distance an object is moved is sometimes left cold, but Massis instilled new life, albeit bizarre, into the concept.)

1.166 • Jerking chair

If you are in a chair on a common, smooth floor, you can move yourself and the chair over the floor with a series of jerks and without touching the floor with your feet. But an initially stationary object (here, you and the chair) cannot move unless there is some "outside" (external) force acting on it. What is the force that propels you and the chair?

Answer To move yourself and the chair, you first suddenly and strongly push your hands down and toward the rear on the chair. The downward force increases the compression of the chair against the floor, allowing more friction between the chair and the floor, which prevents the chair from sliding backward. Your push against the chair also propels your body forward. Once you are moving, suddenly pull upward and forward on the chair. The upward pull reduces the compression of the chair on the floor and thus also the friction between the chair and the floor, allowing the chair to slip forward. So, the outside force that moves you is actually the friction encountered in the first stage of the procedure.

1.167 • Lifting a person with fingers

You may have seen the following stunt in a magic show: A performer chooses three people from the audience to assist him in lifting a fourth, somewhat heavy person also chosen from the audience. The stunt requires that the magician and his three new assistants lift the fourth person from a chair while each use only a single index finger. The magician places his finger below an armpit of the seated person. Each of the assistants similarly places an index finger: one is below the other armpit, one is below the left knee, and one is below the right knee. With a great effort, the magician and three assistants try to lift the seated person, with no success—he is just too heavy.

To apply some magic, the magician and the assistants place their hands on the head of the seated person and then press down with a little pressure. This pressure presumably reduces the weight of the seated person. The fingers are then repositioned for a lift, which is attempted on a signal from the magician. This time, the seated person is easily lifted.

What's going on? Obviously, if a little downward pressure on my head could reduce my weight, I would never have to worry about being even a bit overweight.

Answer During the first attempt at the lift, the three assistants and the magician happen to lift in an uncoordinated manner, with some forces being applied sooner than others. The unequal forces at the four points on the body of the seated person merely topples that person to one side because of the torque those unequal forces produce, and then there is little chance that the lift can be made. Indeed, the magician can help initiate this toppling.

During the second attempt the four forces are applied simultaneously, due to the coordinating signal from the magician. There is then no torque on the seated person, and with that person's weight now shared equally between the four people, the person can be lifted with a reasonable effort.

1.168 • Rockets, and a problem with an iceboat

Suppose that an initially stationary rocket is ignited while in space. Can it reach a speed that is larger than the speed by which its propellant is issued? Does its final speed depend on whether the fuel burns slowly or quickly? Why are ground-launched rockets made to fire in stages? (The idea originated in China around 1000 A.D.) Is there some optimum number of stages? Could a single-stage rocket be made that is powerful enough to launch a satellite into orbit or send people to the Moon? How feasible was the plan in one of the Jules Verne novels where a manned capsule was fired like a ball from a large cannon sunk into the ground?

You are on a small iceboat on a wide, flat expanse of very slippery ice that you wish to cross. Strewn around the shore of the ice are rocks. You decide to load some of them into the boat so that you can propel the boat by throwing the rocks from the boat and toward the shore, but you have room for only a certain total mass of rocks. To give the iceboat the greatest final speed, should you choose many small rocks or a fewer number of larger rocks? That is, should you throw a large or small amount of mass with each toss? For argument, assume that you always hurl the rocks, large or small, with the same speed relative to you and the boat.

Answer The rocket can be made to go faster than the speed at which material is issued from it provided that the ratio of the rocket's initial mass to its final mass exceeds 2.72 (which is equal to the exponential of 1.0). The rate at which the fuel is burned makes no difference on the rocket's final speed. A single stage rocket cannot launch a payload from Earth into orbit because it cannot reach the required final speed of about 11.2 kilometers per second. So, rockets are built with stages. When the lowest stage has exhausted its fuel, it is dropped off so that its mass need not be lifted any higher, and then the next stage is ignited. There is an optimum number of stages, about four or five for common rockets, due to the expense of additional stages.

The people in Verne's story would have been killed by the acceleration they experienced.

You will give the iceboat a greater final speed if you throw a large number of small rocks instead of a fewer number of large rocks. To see the point, first consider throwing only one large rock and then consider throwing two smaller rocks, each with half the mass of the larger rock. In the second scheme, the first rock gives a certain forward speed to the boat and also to the second rock that you still hold. That means that when you throw the second rock, the increase in the boat's speed is greater than when you threw the first rock.

SHORT STORY

1.169 • Earth to Venus

The first attempt at sending a man to Venus came in Baltimore, Maryland, in 1928. Robert Condit and two assistants built a rocket from angle iron and sailcloth. It was powered by gasoline that was vaporized and sprayed into steel tubes and then ignited by spark plugs.

Condit was to make the trip alone, carrying along some food, water, two flashlights, and a first aid kit. Guidance was not a concern because he planned to aim the craft carefully when he took off. When he got to Venus he was to deploy a 25-foot silk parachute to slow his descent. How exactly he was to get back was not too clear, but if there was no food or water on the planet, he did not intend to stay long.

On the day of the test firing, Condit climbed into the craft and turned on the engine to go up a quarter-mile, just to check it out. Great billows of fire and smoke erupted from the steel tubes, but there was no liftoff. Condit increased the flow of gasoline, and the fire became so arresting that it stopped the traffic on the street. But there was still no liftoff. Condit kept at it until he finally ran out of fuel.

He never reached Venus, or otherwise you would already know his story.

1.170 • A choice of hammers

To cut into wood or soft stone with a chisel, should you use a wood or steel mallet? Which is best if you are to cut into something much harder, such as granite? Why does a steel hammer serve better than a wood one to drive a nail into wood?

Answer When the material is soft and requires only a small force to penetrate, the idea is to transfer as much energy as possible to the cutting. In that case a wood mallet serves best because, although it delivers only a moderate force to the chisel and so to the material, it transfers much of its energy. When the material is hard, the cut is more difficult to make, and so force is more important. A steel hammer delivers a large force because it is massive and because it bounces from the chisel. However, the strike of the hammer against the chisel is elastic; that is, little energy is transferred and most is kept by the hammer.

A steel hammer is, of course, also the choice for driving a nail. A wood mallet deforms when it strikes the head of a nail, wasting some of the mallet's energy.

1.171 • Pressure regulator

A conventional pressure cooker consists of a pot that is tightly sealed except for a central tube that is mounted with a loosely fitted cylinder. The cylinder has three holes drilled in its side, each with a different diameter. I set the pressure in the pot by choosing which of the holes is to rest on the tube. But how does the procedure work? After all, the weight of the cylinder is not changed by a different choice of hole.

Answer The steam that is generated inside the pot pushes upward against the weight of the cylinder. The pressure that is maintained in the pot roughly matches the pressure needed to support the cylinder. When the pressure of the steam becomes too large, it lifts the cylinder and allows steam to escape so that the pressure inside the pot is brought back to the desired level. If you choose a wide hole in the cylinder, the weight of the cylinder is spread over the large cross-sectional area of the hole, and so the pressure needed to lift the cylinder is small. A smaller hole gives a larger pressure in the pot.

1.172 • Sliding a stick across fingers

Hold a meter stick horizontally on your index fingers, with the fingers at opposite ends of the stick, and then move your fingers uniformly toward each other. Does the stick slide uniformly? No, it alternates between sliding on one finger and then the other, changing several times before the fingers reach the center of the stick. Why?

Answer In spite of appearances, the initial conditions on the fingers are not symmetric. You inevitably pull slightly harder with one finger—say, the right one—and overcome the static friction on it from the stick, and so it begins to slide beneath the stick. The friction on it is then *kinetic friction*, which is initially smaller than the *static friction* on the left finger. But as the right finger moves toward the center, the portion of the stick's weight that it supports increases, and so does the sliding friction, until the friction there exceeds the friction on the left finger. Then the right finger stops and the left finger begins to slide. Soon the left finger supports so much weight that it stops and the right finger begins to move again. The cycle is repeated until your fingers get near the stick's center, and then the stick tends to topple off your fingers.

SHORT STORY

1.173 • Giant tug-of-war

Harrisburg, Pennsylvania, June 13, 1978: Some 2200 students and teachers attempted to set the world's record for a tug-of-war. The braided-nylon rope was 600 meters long, 2.5 millimeters thick, and built to withstand a force of 57 000 newtons (13 000 pounds). However, soon after the contest began, the rope suddenly snapped. The contestants near the center then relaxed their grip but the ones farther away continued to pull, and so the rope quickly slid through some of the hands. At least four students lost fingers or fingertips from the friction.

1.174 • Shooting along a slope

Suppose that you set the sights on a rifle for a certain distance while at a shooting range. If you then shoot at a target at the same distance but either up or down a slope, will the shots land true, too high, or too low?

Answer Perhaps surprisingly, the shots land high when you shoot either up or down the slope. To correct the sights, you must multiply the distance to the target by the cosine of the slope's angle with respect to the horizontal.

1.175 • Starting a car on a slippery road

When the road is slick and a car has a manual shift, should you start the car's motion in first or second gear?

Answer Since the road is slick, the friction on the tires is easily overwhelmed, in which case the tires will slip. To avoid slippage, you initially want only a small torque applied to the wheels. You might be able to use first gear if you let out the clutch smoothly and gingerly. Otherwise, you should shift to second gear to reduce the torque.

1.176 • Balancing a tire

When a new tire is mounted on a wheel, it must be *balanced*, which is a procedure in which a small lead weight is attached to the rim. If the tire is not balanced, it will not roll smoothly but will shimmy or bump against its mount. Both problems are due to the fact that the wheel's mass is not uniformly spread around the center—the wheel acts as though it has an extra mass at some spot inside it. When the wheel is balanced, the lead mass offsets that extra mass, and then the wheel runs smoother.

One way to balance the wheel is to lay it down on a tilt-table stand with a bubble balance. The wheel and stand are then like a playground see-saw in that the extra mass creates a tilt in one direction. You place a lead mass on the opposite side of the tilt and then trim the weight with cutters until the stand is level, which is indicated by the bubble being centered in the balance. This technique is called a *static balance.*

In a *dynamic balance* the wheel is spun horizontally around its center. The extra mass on one side makes the wheel wobble, but when a lead mass is added to the rim and trimmed appropriately, the wobble disappears.

Are the two techniques of balancing equivalent? That is, do they each eliminate both bump and shimmy?

Answer The two techniques for balancing are not equivalent. The static balance eliminates bumping; the dynamic balance eliminates shimmy. Although the lead mass may end up in the same location, it will be trimmed to different sizes in the two techniques.

To see the difference, first consider the see-saw arrangement of a static balance. The extra weight on one side of the wheel creates a torque that attempts to rotate the wheel in one direction around its center. The size of the torque depends on the size of the extra mass and on how far horizontally it is from the center. The lead mass creates a torque in the opposite direction. Since it must be on the wheel's rim, its distance from the center is fixed. So, to balance the two torques, you start with a lead mass that is too large and then trim it until its torque matches the other torque. When the wheel is put on the car, it will not bump against its mount.

Shimmy depends on how deeply the extra mass lies buried inside the wheel. Again consider the wheel when it is horizontal. If it is to spin smoothly, it must rotate around the vertical axis through its center. However, the buried extra mass makes it rotate around an axis that is tilted from the vertical—the wheel wobbles. To right the spin axis, a lead mass is attached somewhere on the rim as previously, but it now must have a different size, and its location could also be different. Although it eliminates the wobble, it no longer exactly balances the see-saw play of torques, and there is still some bumping. Because the residual bumping is usually small, a dynamic balance is considered to be the better of the two balancing techniques.

1.177 • Carnival bottle swing

While touring a sideshow, you happen upon a stand in which the game is to knock over a bottle with a pendulum bob that is suspended at the bottle's level. The fellow (the *carnie*) running the game explains that you are not allowed to swing the bob directly at the bottle; instead you must arrange for the bob to hit the bottle on its return swing. Doesn't sound too hard, does it? With a few practice swings, you should win a prize, right?

Answer The game is dishonest because the bob will always orbit the bottle if it clears the bottle on the forward swing. For it to hit the bottle on the return swing only, its angular momentum would have to change during the travel, and yet there is no torque on it to do that. However, you might be sneaky and twist up the string before you release the bob. Then, the bob rotates around its center during its swing and can encounter forces from the passing air that are similar to those that account for a curve ball in baseball. Those forces can alter the return swing so that the bob hits the bottle. (You had best be careful, though, because an angry carnie is an unpleasant sight.)

1.178 • Hanging goblet, ready to crash

Tie a glass goblet or some other somewhat heavy object to a small and lighter object, such as a rubber eraser, by means of a meter length of cord. Hold a pencil horizontally, drape the cord over it, and then pull the lighter object toward your left or right until the goblet is just underneath the pencil and the lighter object is approximately horizontal with the pencil. If you now release the lighter object, what happens? Silly question, I know. The heavy goblet will drag the cord (and eventually the lighter object) over the pencil as it falls, until the goblet smashes on the floor. Right?

Answer Once you release the lighter object, it begins to fall while also being pulled toward the pencil by the cord because of the falling goblet. The combined motion means that the lighter object rotates around the pencil with a decreasing radius. The situation is then somewhat like an ice-skater pulling in the arms while spinning on point—the angular speed (spin) increases in order to maintain the angular momentum. Here, the angular momentum must also be maintained because there is no torque to change it. So, the rotation rate of the lighter object increases, which increases the tension in the cord, slowing the goblet's fall. Once the lighter object has rotated several times around the pencil, the force on the goblet is enough to halt the goblet's descent, and so the goblet never reaches the floor.

1.179 • Breaking a drill bit

If a high-speed drill bit is lowered too firmly onto a work surface, why does the bit break?

Answer The forces on the ends of the bit tend to buckle the bit slightly. If the rotation speed is greater than some critical value, that slight bulge is quickly enhanced to the point that the bit snaps.

1.180 • Swinging watches

A windup pocket watch, popular in earlier times, kept good time when worn but not when the watch was hung from a support by its chain. Then the watch might gain or lose 10 minutes or more per day, while it also mysteriously swung itself like a pendulum. One investigator reported the bizarre sight of a wall full of watches hanging by their chains and swinging merrily. What accounts for such untimely behavior?

Answer The pendulum motion is brought about by the rotational oscillations of a balance wheel (part of the timing mechanism) when the frequency of the wheel's oscillations is near the frequency at which the case swings. When frequency of the wheel is somewhat lower than the frequency of the swinging, the two motions are out of step and the watch gains time. When the frequency of the wheel is somewhat higher than the frequency of the swinging, it loses time.

SHORT STORY

1.181 • Flattening the Golden Gate Bridge

On its 50th anniversary in 1987, the Golden Gate Bridge was opened to pedestrians who walked across it in celebration of the magnificent bridge. A surprising number of people showed up. When 250 000 were packed rather tightly on the bridge, its midsection became flat instead of forming the normal arch, and some of the supporting cables became slack. The bridge also began to sway sideways (as experienced with London's Millennium Bridge in 2001). That day of celebration turned out to be an unscheduled integrity test of the Golden Gate Bridge. Thankfully it passed the test.

1.182 • Hunting by railway vehicles

In a traditional design for a train, the wheels are *coned* (slanted), constrained to remain on a rail by an interior flange, and are linked in pairs by an axle. The rails, which have a round top, usually lean slightly inward. When the train moves along straight track, why do the compartments or cars sway from side to side, a motion that is called *hunting*?

Hunting not only limits the speed of a train, but it also tends to deform both rail and roadbed. Because the resulting wear is not even on the left and right sides, the cars pulled by an engine are occasionally turned around so as to even out the wear on the two sides.

Answer If the car shifts, say, to the right, then a wheel on the right rides on a large radius while one on the left turns on a smaller radius, due to the slanted shape of each. Since the wheels are rigidly connected to each other, they turn at the same rate, but the difference in the turning radii means that the wheel on the right travels farther along the track than the wheel on the left in a given amount of time. The difference in the speed along the track skews the axle and the car runs crooked along the track until it is left of center. The situation is then reversed. If the oscillations continue, the train is said to "hunt" in the sense that it "seeks" a stable location.

A chance deflection can initiate the hunting, but frictional forces created by distortion on the rail and wheel due to the train's weight can also start the oscillation. If the train's speed is below some critical value, the oscillations from each deflection die out. But if the speed is higher, the oscillations build and only the flanges can save the train from derailment. Sometimes the oscillations are so extreme that the wheel climbs off the rail in spite of the flanges.

1.183 • Oscillating car antenna

Some types of vertical car antenna, especially the whip type, may begin to oscillate as you drive. Why does the antenna oscillate in the pattern of Fig. 1-55*a* for low to moderate speeds and in the pattern of Fig. 1-55*b* for higher speeds?

Answer If we mounted the antenna in a vise and somehow made it oscillate, it would oscillate in what are called *resonant modes* (or patterns) and at *resonant frequencies*. We are said to set up *resonance* when our oscillations set up one

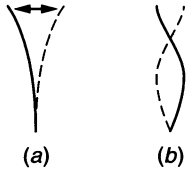


Figure 1-55 / Item 1.183 **Oscillating car antenna at (*a*) low speed and (*b*) higher speed.**

of the patterns. The simplest pattern is called the *fundamental mode*, which oscillates at the lowest resonant frequency (Fig. 1-55*a*). In this pattern, the bottom of the antenna does not move (because it is fixed in place), the top moves the most, and the intermediate points move at intermediate distances. The next more complicated pattern, the *first overtone mode*, has a point of no oscillation located somewhat down from the top. When the antenna is on a moving car, the passing air tends to create vortexes on the back side of the antenna. The variations in air pressure due to the vortexes tend to make the antenna oscillate. At low to moderate speeds, the fundamental mode is set up. At greater speeds, with vortexes being shed by the antenna at a greater rate, the first overtone mode is set up.

1.184 • A ship's antiroll tank

A ship's rolling is often just unsettling, but if the waves strike the side of the ship with the same frequency as the roll that is introduced, the rolling can be built up to a dangerous extent. (Such a match of frequency is an example of *resonance*; a similar buildup of oscillations can be seen if you push a child on a swing each time the child swings back to you.) To lessen the danger, some ships in the past were outfitted with a tank that ran across the ship's width and was partially filled with water. The dimensions of a tank were chosen so that the sloshing of the tank water had the same frequency as the rolling of the ship. Doesn't that seem precisely wrong, because won't the sloshing then augment the rolling?

Answer Suppose that the waves push on the right side of a ship at the ship's resonant frequency. The roll of the ship is not instantaneous but, because of the ship's mass, lags behind the push by about a quarter step—that is, a fourth of a full roll to the left and right. Similarly, the sloshing in the tank lags behind the roll of the ship by another quarter-step, which makes it a half-step behind the push on the ship. So, when the waves try to rock the ship to the left, the sloshing tries to rock the ship to the right, and the ship tends to remain upright.

Antiroll tanks were used primarily on German ships around the 1900s. Although they worked well on a regular seaway, they proved unworthy when the waves were irregular, and in some cases they actually enhanced the rocking.

1.185 • Road corrugation

Many unpaved road surfaces are initially made smooth but soon develop patterns of shallow hills and valleys, with separations of 0.5 to 1 meter, along the paths taken by the wheels of cars. The periodic pattern cannot be due to weather erosion as common chuckholes are. What produces the patterns? Why aren't the patterns eliminated and the road smoothed by the impact of the wheels on the hills? Similar corrugations can be found on train and trolley rails and on the downhill paths taken by skiers. Do the patterns migrate along the road, rails, and paths?

Answer A corrugation pattern on a road begins once an irregularity first appears in the initial smoothness. When a tire hits the irregularity with sufficient speed, it might hop slightly and then dig into the road when it comes down. Even if the tire does not actually leave the road surface, the tendency to hop first momentarily relieves the weight on the tire and next drives the wheel down extra hard. The downward push digs out a shallow valley from which the tire then must climb, and so it tends to hop again. With additional cars traveling over the surface, the pattern is enhanced and extended down the road but does not migrate.

1.186 • Seeing only one side of the Moon

Why do we see only one side of the Moon? (There is a variation in what we see, but not by much.) Since the Moon orbits Earth, shouldn't we see its entire surface?

Answer The strength of Earth's gravitational field varies with distance from Earth. That means that the gravitational field on the far side of the Moon is weaker than on the near side. This variation in the field has created slight tidal bulges in the Moon, one on the far side and one on the near side, so that the Moon is not spherical. Because of these bulges, Earth's gravitational field causes the Moon to rotate around its center as it orbits around Earth. The result is that the Moon always presents (roughly) the same face toward Earth. Many other natural satellites in the solar system also point the same face toward the planet they orbit.

1.187 • Intelligence satellites

When activities at some region on Earth's surface are to be monitored from space, intelligence satellites photograph the region. The satellites are timed so that when one satellite no longer looks down on the region, another one takes over. Wouldn't it be easier to keep one satellite over the region, traveling around in orbit just as fast as the interesting region turns around Earth's axis of rotation? That may seem a better strategy, but for most regions on Earth it is impossible to arrange. Why, and where does the easier strategy work?

Answer An orbiting satellite is held in orbit by the gravitational pull on it from Earth. That pull is always directed toward the center of Earth, and so the orbit must be around the center. That fact eliminates the possibility of a satellite staying over, say, New York City, because the orbit would then be around the northern half of Earth rather than Earth's center. However, a satellite, said to be a *geostationary satellite*, could stay over a point on Earth's equator because the orbit would then be around the center. The satellite would have to be placed at the proper altitude (about $\frac{1}{10}$ of the distance to the Moon) so that it orbited just as fast as the point on the equator turned around Earth's axis of rotation. For any other point on Earth's surface, an intelligence satellite must photograph along a slanted line.

1.188 • Air drag speeds up satellite

Most satellites orbit Earth in the thin reaches of the atmosphere and experience a small amount of drag. The drag should slow a satellite just as air drag on a coasting car slows the car. However, in the satellite's case, the drag increases the speed. How can a retarding force result in an increase in speed and thus kinetic energy?

Answer The drag reduces the satellite's total energy, which consists of both kinetic energy and potential energy, and the satellite gradually drops into a smaller orbit. With the fall, the satellite's potential energy decreases, but only half of the decrease is converted into thermal energy by the friction from the atmosphere. The other half goes into the kinetic energy, the increase in speed being necessary because of the smaller orbit. Upon inspection, the result may not be so surprising—normally when things fall toward Earth, their speed increases.

1.189 • Moon trip figure eight

When a spaceship is sent to the Moon, why is its path in the form of a distorted figure eight instead of an ellipse that encompasses Earth and the Moon?

Answer The figure eight path requires less energy by the ship because for much of the trip the ship stays close to the line between the centers of Earth and the Moon. Since along that line the gravitational pulls from Earth and the Moon compete, the net force on the ship is smaller than if the ship is in an elliptical orbit. So, less energy is required to overcome the net force.

1.190 • Earth and Sun pull on Moon

Since the Moon is captured in orbit around Earth, the gravitational pull on it from Earth must dominate the pull from the Sun, right? Well, actually, no, because the Sun's pull is more than twice as large as Earth's pull. Why then don't we lose the Moon?

Answer The Sun's force does dominate the Moon's motion: The Moon orbits the Sun. The smaller force from Earth acts as a perturbation to the main motion and produces loops in the orbit. We can make sense of the motion by simply saying, "The Moon goes around Earth while Earth goes around the Sun."

1.191 • Gravitational slingshot effect

If a space capsule moves near enough a planet, it might undergo a *gravity assist* or *slingshot effect* in which it gains energy. But isn't the idea faulty? Imagine monitoring the capsule from the planet. As the capsule approaches, it certainly should gain energy due to the gravitational pull from the planet, but isn't the gain nullified as the capsule recedes?

Answer The problem in the interpretation presented lies in your location—the planet that you are on is moving. From that view, the capsule will seem to gain no energy. But take the view of someone at rest with respect to the Sun. Such an observer would see the capsule gravitationally attracted to the planet. If the capsule passes near the planet on the rear of the planet's orbit, the capsule is effectively dragged along the orbit by the planet and so the capsule gains energy. The planet loses an equal amount of energy but the change is immeasurable because of the planet's huge mass, while the energy increase of the capsule is appreciable because of the capsule's much smaller mass.

1.192 • Making a map of India

In the past when India was surveyed, the measures were reportedly slightly inaccurate because the plumb line did not hang exactly along the vertical, especially in the northern part of the country. Why might the story be credible?

Answer The mass at the lower end of the plumb line can be pulled toward the Himalayas through several arc seconds by the gravitational pull from the mass of the mountains. In other regions, a nonuniform distribution of mass introduces similar errors.

1.193 • Shaving with twin blades

If one shaves with a razor having twin blades, is there an optimum speed at which the blades should be drawn across the skin, or should the blades be drawn as quickly as possible or as slowly as possible?

Answer When the first blade encounters a hair that extends from the skin, it snags the hair at the skin's surface and then drags the hair along the skin in the direction of the blade's motion, pulling the buried base of the hair upward from its original position. At some point during this dragging, the first blade slices off the length of hair that initially extended above the skin.

The remaining length of hair then springs back to its original orientation and next begins to retract into the skin. If the second blade catches the hair after it has sprung back and before it is retracted, then the blade can remove even more of the hair, delaying the next need of a shave. To get such a close shave, the razor should not be moved so quickly that the spring-back does not occur or so slowly that the retraction is completed. The optimum speed is about 4 centimeters per second, but the value will vary between shavers because of different properties of the skin and hair (especially the elasticity).

1.194 • The handedness of river erosion

There are arguments that on the average the right bank of a river in the Northern Hemisphere suffers more erosion than the left bank, while in the Southern Hemisphere just the opposite is true. Although the effect is certain to be small and masked by other factors, why might the idea be correct?

Answer Earth's rotation can produce an apparent deflection of flowing streams, rightward in the Northern Hemisphere and leftward in the Southern Hemisphere. The deflections are not true deflections because we watch the streams from a rotating surface. However, they can be quite apparent in large-scale motions, such as the air flow around weather systems, giving the familiar counterclockwise rotation around a hurricane in the Northern Hemisphere. The flow of a large river, such as the Mississippi River, might also display the apparent deflection.