COLLEGE PHYSICS

Chapter 5 FURTHER APPLICATION OF NEWTON’S LAWS: FRICTION, DRAG, AND ELASTICITY

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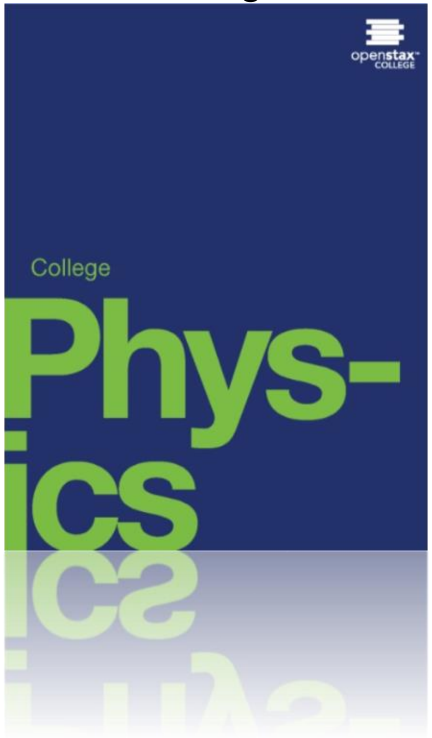


Forces of
(1) friction,
(2) air or liquid drag,
(3) and deformation.

Friction

• Friction is a contact force between systems that opposes the motion or attempted motion between them. Simple friction is proportional to the normal force N pushing the systems together. (A normal force is always perpendicular to the contact surface between systems.) Friction depends on both of the materials involved. The magnitude of static friction f_s between systems stationary relative to one another is given by

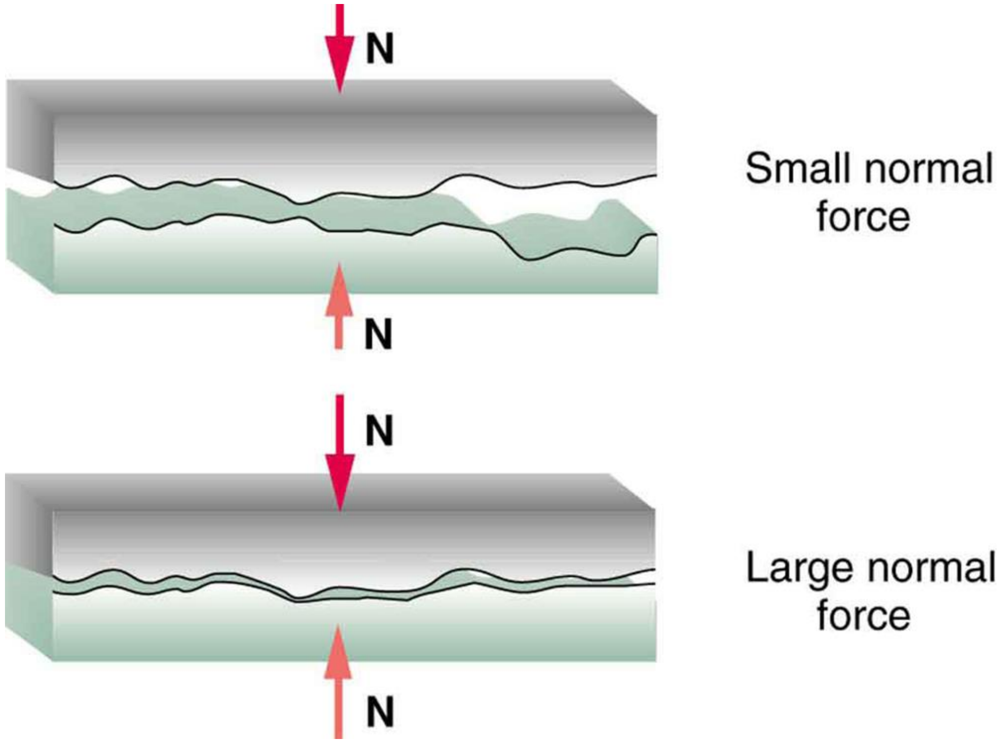
$$f_s \leq \mu_s N,$$

where μ_s is the coefficient of static friction, which depends on both of the materials.

• The kinetic friction force f_k between systems moving relative to one another is given by

$$f_k = \mu_k N,$$

where μ_k is the coefficient of kinetic friction, which also depends on both materials.

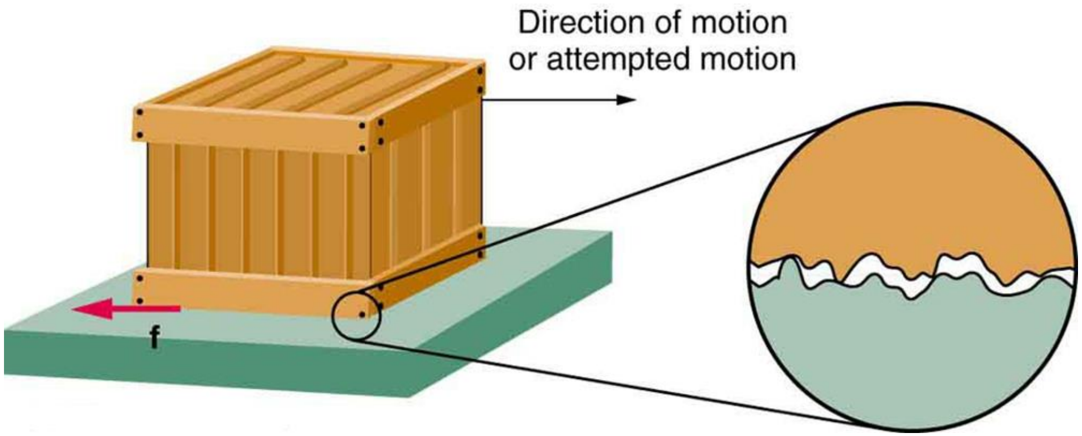


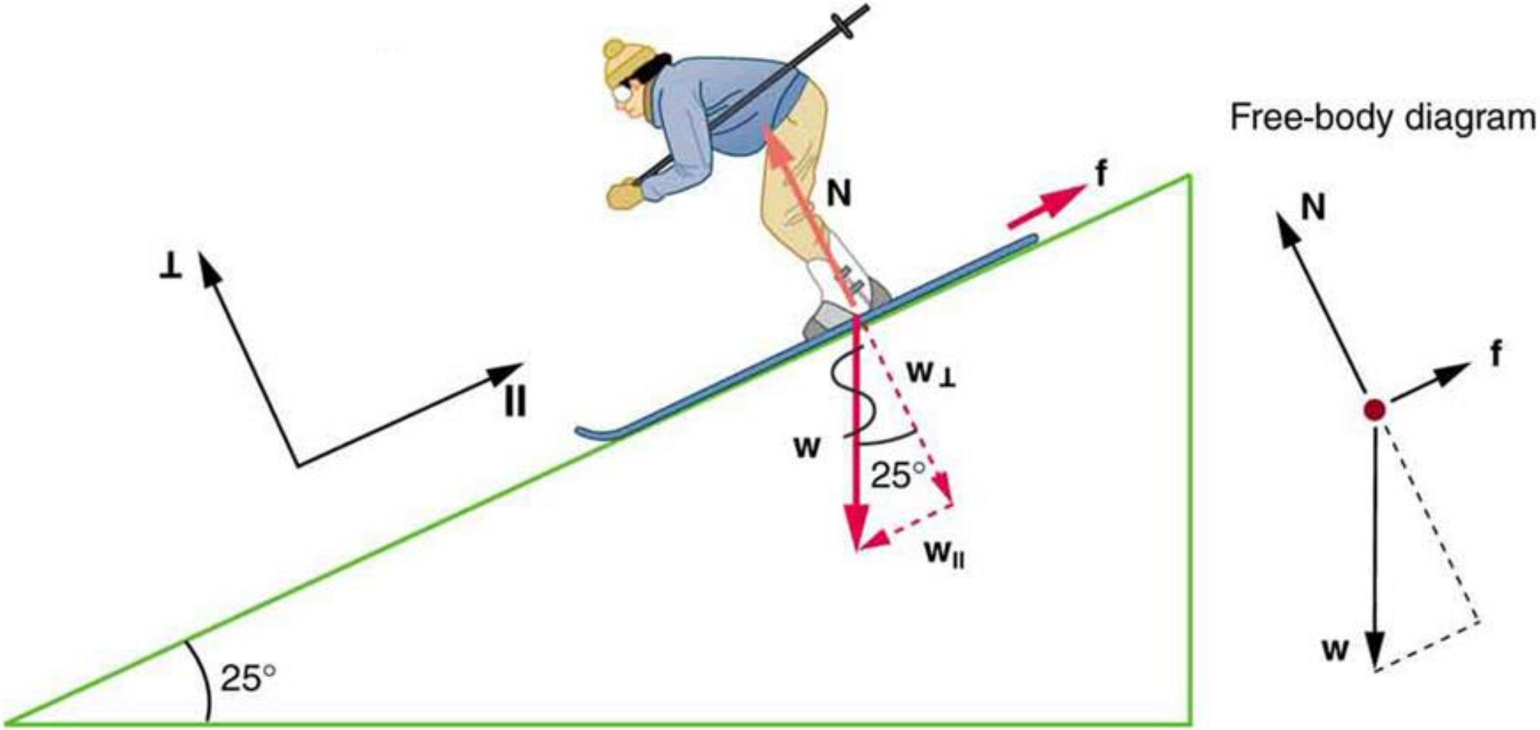
Two rough surfaces in contact have a much smaller area of actual contact than their total area. When there is a greater normal force as a result of a greater applied force, the area of actual contact increases as does friction.

KINETIC FRICTION SLOWS A HOCKEY PUCK ON ICE.

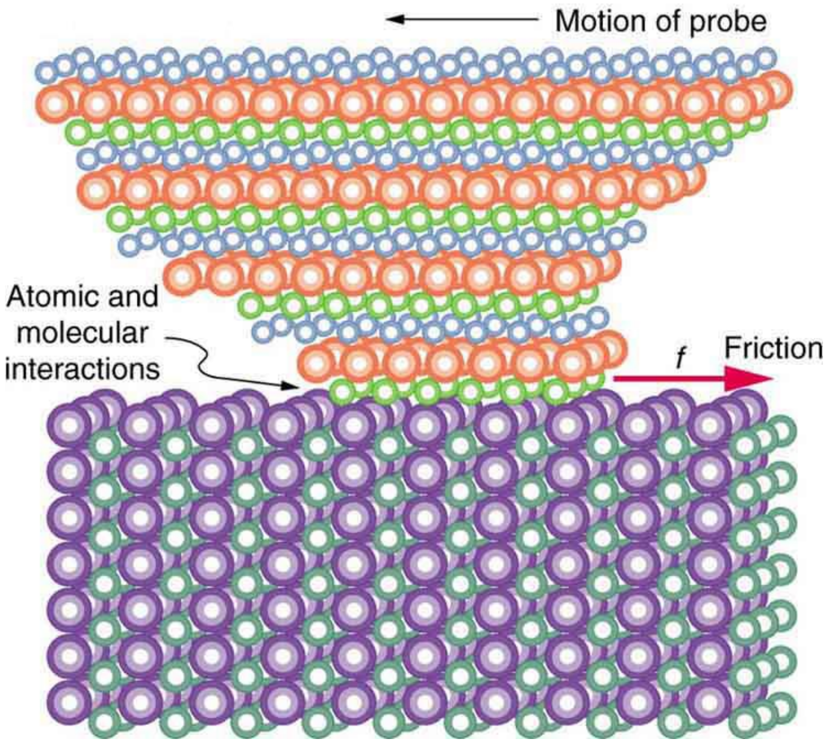
Friction arises in part because of the roughness of the surfaces in contact. In order for the object to move, it must rise to where the peaks can skip along the bottom surface. Much of the friction is actually due to attractive forces between molecules, so that even perfectly smooth surfaces are not friction-free. Such adhesive forces also depend on the substances the surfaces are made of, explaining, for example, why rubber-soled shoes slip less than those with leather soles.

$$f_{s(max)} = \mu_s N$$





The motion of the skier and friction are parallel to the slope and so it is most convenient to project all forces onto a coordinate system where one axis is parallel to the slope and the other is perpendicular (axes shown to left of skier). **N** (the normal force) is perpendicular to the slope, and **f** (the friction) is parallel to the slope, but **W** (the skier's weight) has components along both axes, namely $\mathbf{W}_{\perp}$ and $\mathbf{W}_{//}$. **N** is equal in magnitude to **W⊥**, so there is no motion perpendicular to the slope. However, **f** is less than $\mathbf{W}_{//}$ in magnitude, so there is acceleration down the slope (along the *x*-axis).



The tip of a probe is deformed sideways by frictional force as the probe is dragged across a surface. Measurements of how the force varies for different materials are yielding fundamental insights into the atomic nature of friction.

(a)

Which method of sliding a block of ice requires less force

(a) pushing

A contestant in a winter sporting event pushes a 45.0-kg block of ice across a frozen lake as shown in Figure 5.23(a). (a) Calculate the minimum force F he must exert to get the block moving. (b) What is its acceleration once it starts to move, if that force is maintained?

(a) $f_s = \mu_s N = \mu_s(mg + F\sin\theta) = F\cos\theta$

$F(\cos\theta - \mu_s \sin\theta) = \mu_s mg$, so that

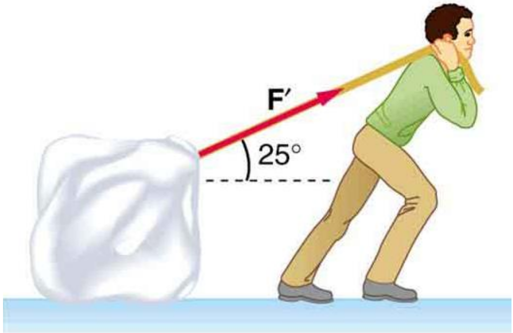
$$F = \frac{\mu_s mg}{(\cos\theta - \mu_s \sin\theta)} = \frac{(0.1)(45.0\text{ kg})(9.80\text{ m/s}^2)}{\cos 25° - (0.1)\sin 25°} = \underline{51.0\text{ N}}$$

(b) net $F = ma = F\cos\theta - \mu_k N = F\cos\theta - \mu_k(mg + F\sin\theta)$, so that

$$a = \frac{F(\cos\theta - \mu_k \sin\theta) - \mu_k mg}{m}$$

$$a = \frac{51.04\text{ N}(\cos 25° - 0.03\sin 25°) - 0.03(45.0\text{ kg})(9.80\text{ m/s}^2)}{45.0\text{ kg}}$$

$$= 0.7196\text{ m/s}^2 = \underline{0.720\text{ m/s}^2}$$



(b)

Which method of sliding a block of ice requires less force

(b) pulling at the same angle above the horizontal?

Repeat Exercise 5.18 with the contestant pulling the block of ice with a rope over his shoulder at the same angle above the horizontal as shown in Figure 5.23(b).

(a) $f_s = \mu_s N = \mu_s(mg - F\sin\theta) = F\cos\theta$

$$F(\cos\theta + \mu_s \sin\theta) = \mu_s mg$$

$$F = \frac{\mu_s mg}{(\cos\theta + \mu_s \sin\theta)} = \frac{(0.1)(45.0\ \text{kg})(9.80\ \text{m/s}^2)}{\cos 25° + (0.1)\sin 25°} = 46.49\ \text{N} = \underline{46.5\ \text{N}}$$

(b) net $F = ma = F\cos\theta - \mu_k N = F\cos\theta - \mu_k(mg - F\sin\theta)$, so that

$$a = \frac{F(\cos\ \ + \ _\text{k}\sin\ \ ) - \ _\text{k}mg}{m}$$

$$= \frac{46.49\ \text{N}(\cos 25° + 0.03\sin 25°) - 0.03(45.0\ \text{kg})(9.80\ \text{m/s}^2)}{45.0\ \text{kg}} = \underline{0.655\ \text{m/s}^2}$$

If the crate you try to push (with a force parallel to the floor) has a mass of 100 kg, then the normal force would be equal to its weight,

$$W = mg = (100\ \text{kg})(9.80\ \text{m/s}^2) = 980\ \text{N},$$

perpendicular to the floor. If the coefficient of static friction is 0.45, you would have to exert a force parallel to the floor greater than

$$f_{s(\text{max})} = \mu_s N = (0.45)(980\ \text{N}) = 440\ \text{N}$$

to move the crate.
Once there is motion, friction is less and the coefficient of kinetic friction might be 0.30, so that a force

$$f_k = \mu_k N = (0.30)(980\ \text{N}) = 290\ \text{N}$$

would keep it moving at a constant speed. If the floor is lubricated, both coefficients are considerably less than they would be without lubrication. Coefficient of friction is a unitless quantity with a magnitude usually between 0 and 1.0. The coefficient of the friction depends on the two surfaces that are in contact.

Table 5.1 Coefficients of Static and Kinetic Friction

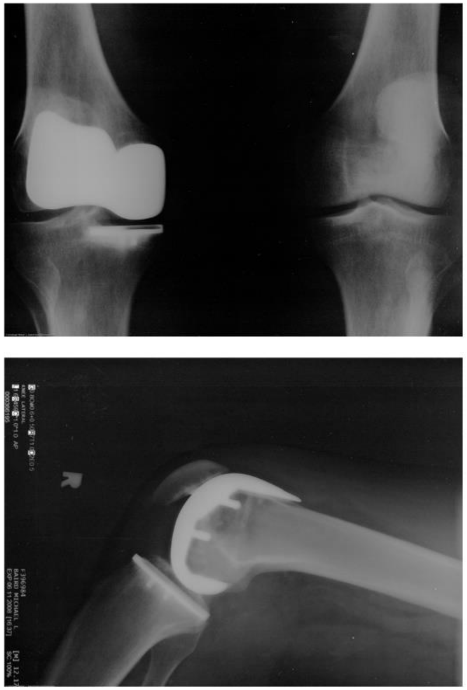
System	Static friction μ_s	Kinetic friction μ_k
Rubber on dry concrete	1.0	0.7
Rubber on wet concrete	0.7	0.5
Wood on wood	0.5	0.3
Waxed wood on wet snow	0.14	0.1
Metal on wood	0.5	0.3
Steel on steel (dry)	0.6	0.3
Steel on steel (oiled)	0.05	0.03
Teflon on steel	0.04	0.04
Bone lubricated by synovial fluid	0.016	0.015
Shoes on wood	0.9	0.7
Shoes on ice	0.1	0.05
Ice on ice	0.1	0.03
Steel on ice	0.04	0.02

Friction

1. When you learn to drive, you discover that you need to let up slightly on the brake pedal as you come to a stop or the car will stop with a jerk. Explain this in terms of the relationship between static and kinetic friction.

2. When you push a piece of chalk across a chalkboard, it sometimes screeches because it rapidly alternates between slipping and sticking to the board. Describe this process in more detail, in particular explaining how it is related to the fact that kinetic friction is less than static friction. (The same slip-grab process occurs when tires screech on pavement.)

Many people have experienced the slipperiness of walking on ice. However, many parts of the body, especially the joints, have much smaller coefficients of friction—often three or four times less than ice. A joint is formed by the ends of two bones, which are connected by thick tissues. The knee joint is formed by the lower leg bone (the tibia) and the thighbone (the femur). The hip is a ball (at the end of the femur) and socket (part of the pelvis) joint. The ends of the bones in the joint are covered by cartilage, which provides a smooth, almost glassy surface. The joints also produce a fluid (synovial fluid) that reduces friction and wear. A damaged or arthritic joint can be replaced by an artificial joint. These replacements can be made of metals (stainless steel or titanium) or plastic (polyethylene), also with very small coefficients of friction.



Artificial knee replacement is a procedure that has been performed for more than 20 years. In this figure, we see the post-op X-rays of the right knee joint replacement.

Total hip replacement surgery has become a common procedure. The head (or ball) of the patient’s femur fits into a cup that has a hard plastic-like inner lining.

Drag Forces

• Drag forces acting on an object moving in a fluid oppose the motion. For larger objects (such as a baseball) moving at a velocity v in air, the drag force is given by

$$F_D = 12 C\rho A v^2,$$

where C is the drag coefficient (typical values are given in **Table 5.2**), A is the area of the object facing the fluid, and ρ is the fluid density.

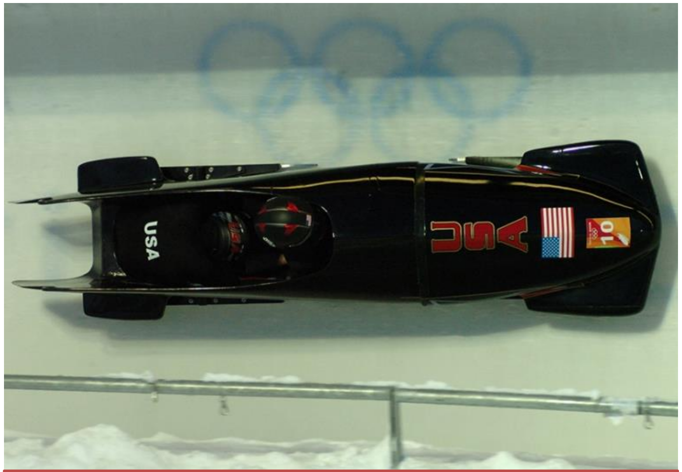
• For small objects (such as a bacterium) moving in a denser medium (such as water), the drag force is given by Stokes' law,

$$F_S = 6\pi\eta r v,$$

where r is the radius of the object, η is the fluid viscosity, and v is the object's velocity.

Athletes as well as car designers seek to reduce the drag force to lower their race times.

"Aerodynamic" shaping of an automobile can reduce the drag force and so increase a car's gas mileage.



From racing cars to bobsled racers, aerodynamic shaping is crucial to achieving top speeds. Bobsleds are designed for speed. They are shaped like a bullet with tapered fins.

NASA researchers test a model plane in a wind tunnel.

Typical values of drag coefficient *C*

Object	C
Airfoil	0.05
Toyota Camry	0.28
Ford Focus	0.32
Honda Civic	0.36
Ferrari Testarossa	0.37
Dodge Ram pickup	0.43
Sphere	0.45
Hummer H2 SUV	0.64
Skydiver (feet first)	0.70
Bicycle	0.90
Skydiver (horizontal)	1.0
Circular flat plate	1.12

At highway speeds, over 50% of the power of a car is used to overcome air drag. The most fuel-efficient cruising speed is about 70–80 km/h (about 45–50 mi/h). For this reason, during the 1970s oil crisis in the United States, maximum speeds on highways were set at about 90 km/h (55 mi/h).

Body suits, such as this LZR Racer Suit, have been credited with many world records after their release in 2008. Smoother “skin” and more compression forces on a swimmer’s body provide at least 10% less drag.

If we compare animals living on land with those in water, you can see how drag has influenced evolution. Fishes, dolphins, and even massive whales are streamlined in shape to reduce drag forces. Birds are streamlined and migratory species that fly large distances often have particular features such as long necks. Flocks of birds fly in the shape of a spear head as the flock forms a streamlined pattern.

Geese fly in a V formation during their long migratory travels. This shape reduces drag and energy consumption for individual birds, and also allows them a better way to communicate.

Some interesting situations connected to Newton's second law occur when considering the effects of drag forces upon a moving object. For instance, consider a skydiver falling through air under the influence of gravity. The two forces acting on him are the force of gravity and the drag force (ignoring the buoyant force). The downward force of gravity remains constant regardless of the velocity at which the person is moving. However, as the person's velocity increases, the magnitude of the drag force increases until the magnitude of the drag force is equal to the gravitational force, thus producing a net force of zero. A zero net force means that there is no acceleration, as given by Newton's second law. At this point, the person's velocity remains constant and we say that the person has reached his *terminal velocity* (v_t). Since F_D is proportional to the speed, a heavier skydiver must go faster for F_D to equal his weight. Let's see how this works out more quantitatively.

At the terminal velocity, $F_{net} = mg - F_D = ma = 0$

Thus, $mg = F_D$

Using the equation for drag force, we have $mg = (1/2)\rho C A v^2$

Solving for the velocity, we obtain $v = (2mg/\rho CA)$

Assume the density of air is $\rho = 1.21\ \text{kg/m}^3$. A 75-kg skydiver descending head first will have an area approximately $A = 0.18\ \text{m}^2$ and a drag coefficient of approximately $C = 0.70$. We find $v = [2(75\ \text{kg})(9.80\ \text{m/s}^2)/(1.21\ \text{kg/m}^3)(0.70)(0.18\ \text{m}^2)]^{1/2} = 98\ \text{m/s} = 350\ \text{km/h}$.

Terminal velocity becomes much smaller after the parachute opens.

Drag Forces

5. Athletes such as swimmers and bicyclists wear body suits in competition.

6. Two expressions were used for the drag force experienced by a moving object in a liquid. One depended upon the speed, while the other was proportional to the square of the speed. In which types of motion would each of these expressions be more applicable than the other one?

7. As cars travel, oil and gasoline leaks onto the road surface. If a light rain falls, what does this do to the control of the car? Does a heavy rain make any difference?

8. Why can a squirrel jump from a tree branch to the ground and run away undamaged, while a human could break a bone in such a fall?

Elasticity: Stress and Strain

- Hooke's law is given by

$$F = k\Delta L,$$

where ΔL is the amount of deformation (the change in length), F is the applied force, and k is a proportionality constant that depends on the shape and composition of the object and the direction of the force. The relationship between the deformation and the applied force can also be written as

$$\Delta L = (1/Y)(F/A)L_0,$$

where Y is *Young's modulus*, which depends on the substance, A is the cross-sectional area, and L_0 is the original length.

- The ratio of force to area, F/A , is defined as *stress*, measured in N/m^2 .
- The ratio of the change in length to length, $\Delta L/L_0$, is defined as *strain* (a unitless quantity). In other words,

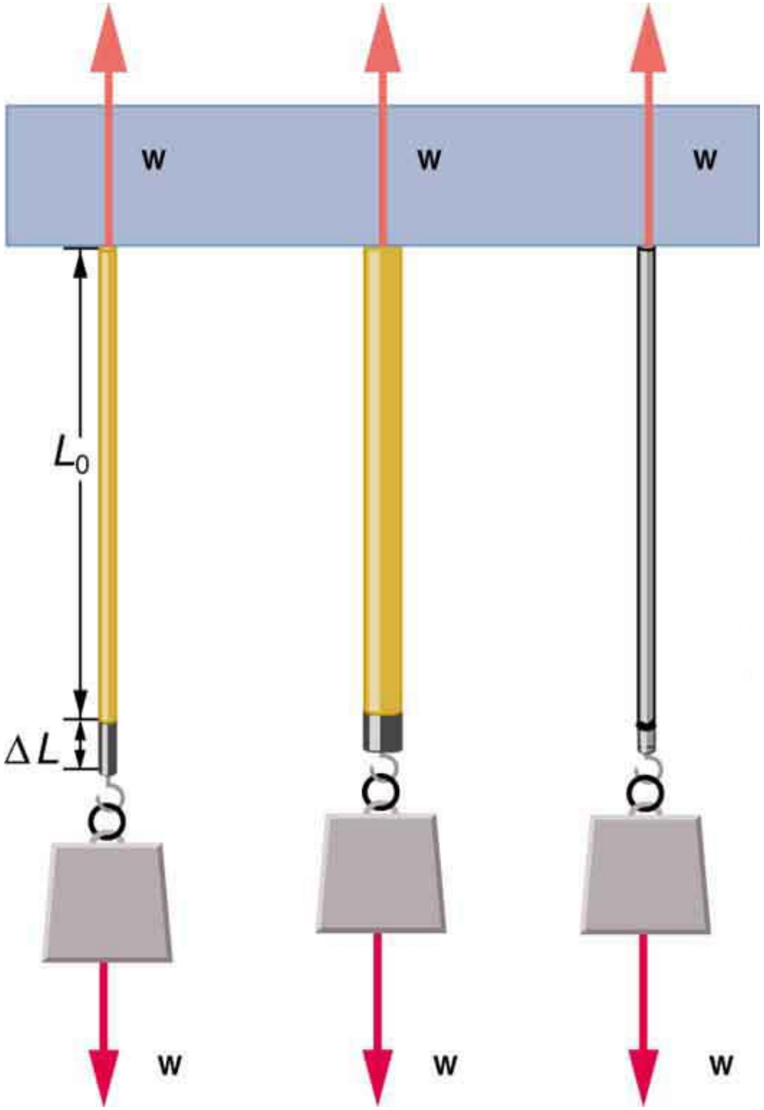
$$\text{stress} = Y \times \text{strain}.$$

- The expression for shear deformation is

$$\Delta x = (1/S)(F/A)L_0,$$

where S is the shear modulus and F is the force applied perpendicular to L_0 and parallel to the cross-sectional area A .

FIGURE 5.12

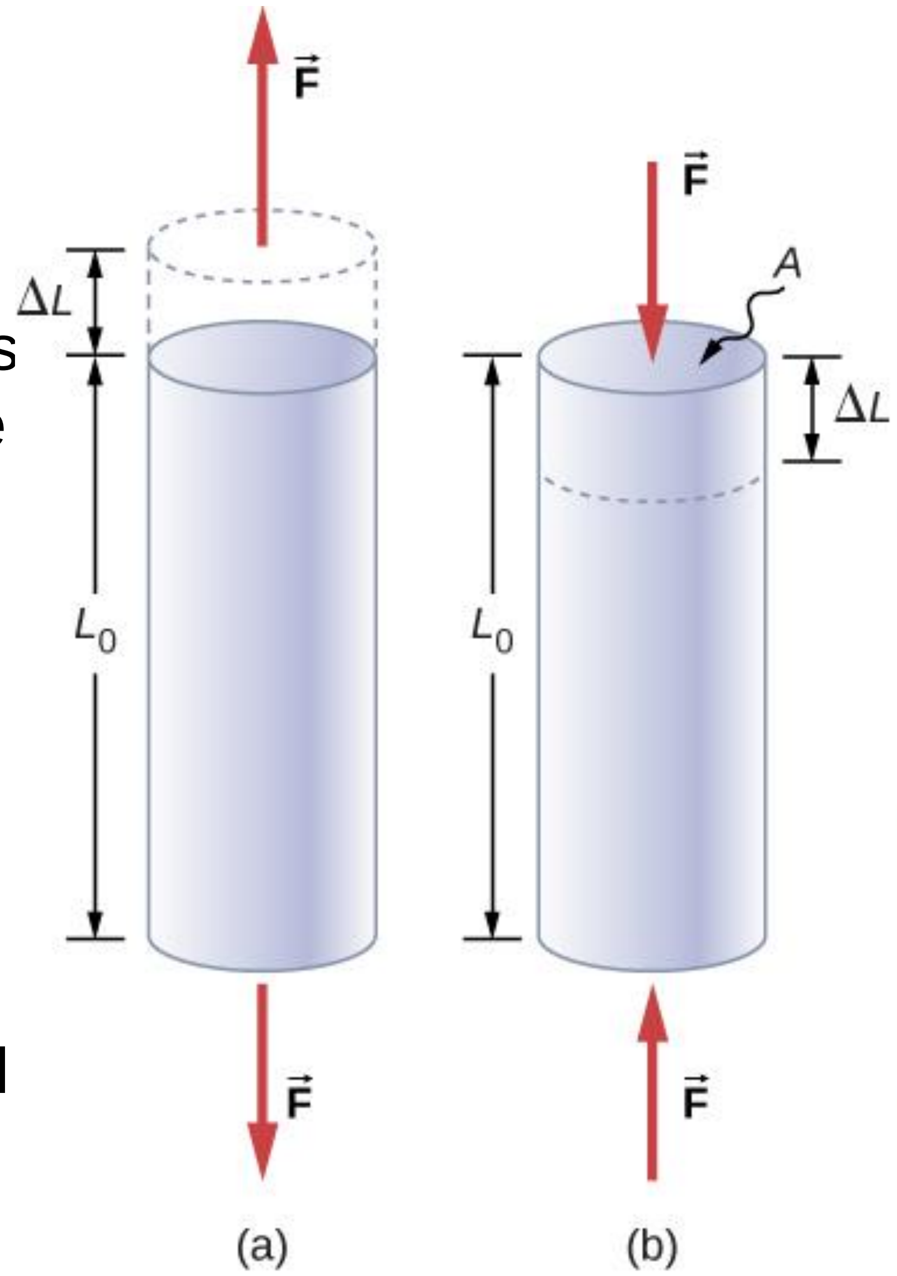


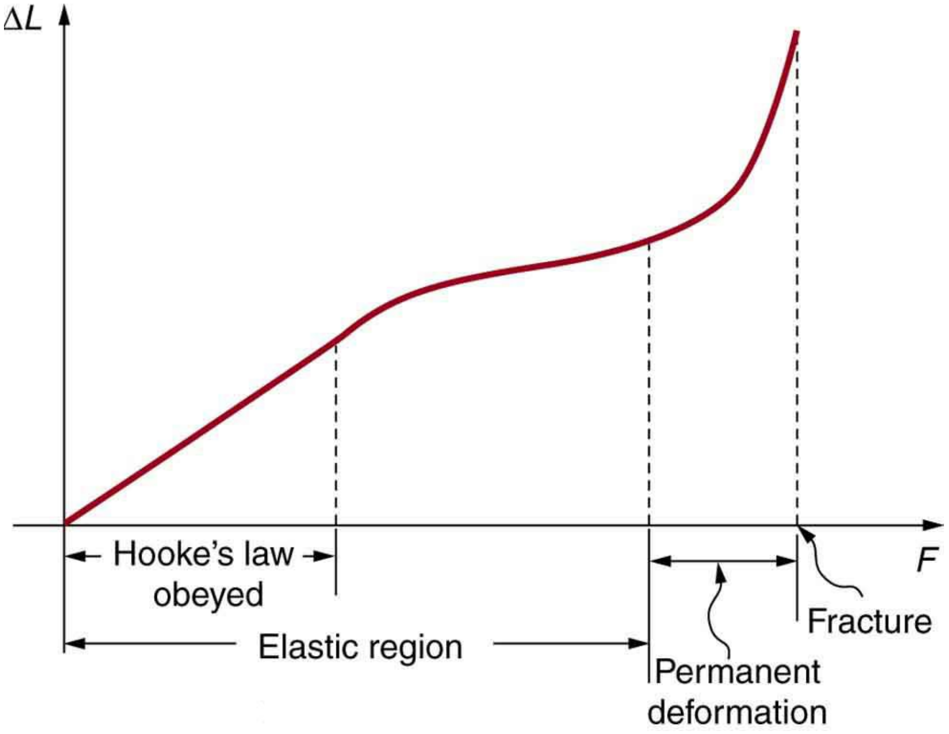
The same force, in this case a weight (*w*), applied to three different guitar strings of identical length produces the three different deformations shown as shaded segments. The string on the left is thin nylon, the one in the middle is thicker nylon, and the one on the right is steel.

(a) Tension. The rod is stretched a length ΔL when a force is applied parallel to its length.

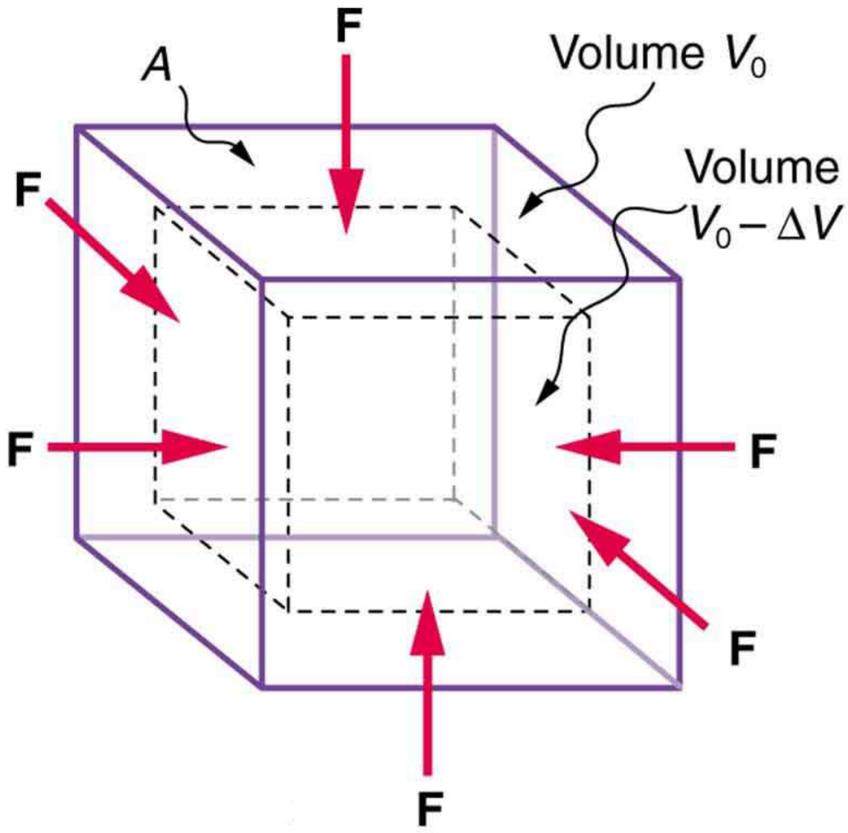
(b) Compression. The same rod is compressed by forces with the same magnitude in the opposite direction.

For very small deformations and uniform materials, ΔL is approximately the same for the same magnitude of tension or compression. For larger deformations, the cross-sectional area changes as the rod is compressed or stretched.





A graph of deformation ΔL versus applied force F . The straight segment is the linear region where Hooke's law is obeyed. The slope of the straight region is 1/k. For larger forces, the graph is curved but the deformation is still elastic— ΔL will return to zero if the force is removed. Still greater forces permanently deform the object until it finally fractures. The shape of the curve near fracture depends on several factors, including how the force F is applied. Note that in this graph the slope increases just before fracture, indicating that a small increase in F is producing a large increase in L near the fracture.



An inward force on all surfaces compresses this cube. Its change in volume is proportional to the force per unit area and its original volume, and is related to the compressibility of the substance.

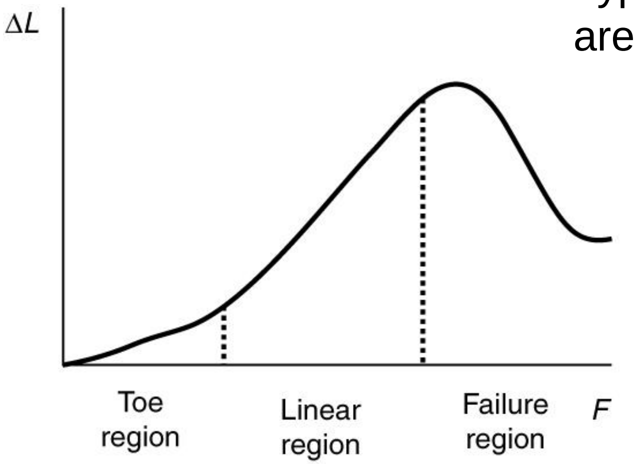
- The relationship of the change in volume to other physical quantities is given by

$\Delta V = (1/B)(F/A)V_0$,

where B is the bulk modulus, V_0 is the original volume, and F/A is the force per unit area applied uniformly inward on all surfaces.

Bones, on the whole, do not fracture due to tension or compression. Rather they generally fracture due to sideways impact or bending, resulting in the bone shearing or snapping.

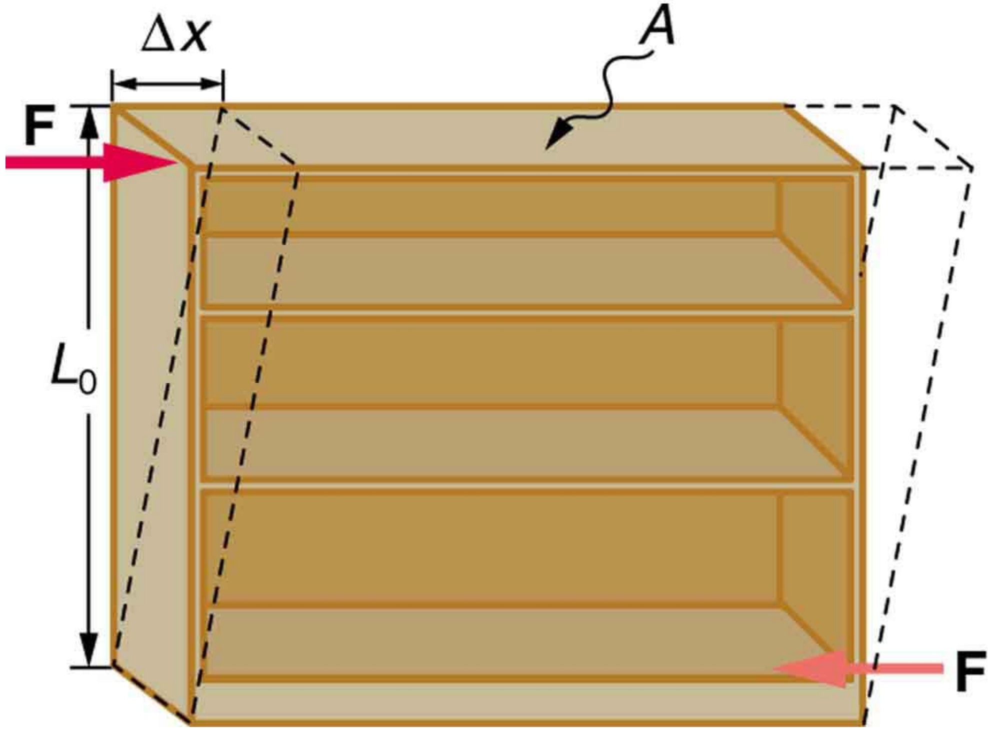
Unlike bones and tendons, which need to be strong as well as elastic, the arteries and lungs need to be very stretchable. The elastic properties of the arteries are essential for blood flow. The pressure in the arteries increases and arterial walls stretch when the blood is pumped out of the heart. When the aortic valve shuts, the pressure in the arteries drops and the arterial walls relax to maintain the blood flow. When you feel your pulse, you are feeling exactly this—the elastic behavior of the arteries as the blood gushes through with each pump of the heart. If the arteries were rigid, you would not feel a pulse. The heart is also an organ with special elastic properties. The lungs expand with muscular effort when we breathe in but relax freely and elastically when we breathe out. Our skins are particularly elastic, especially for the young. A young person can go from 100 kg to 60 kg with no visible sag in their skins. The elasticity of all organs reduces with age. Gradual physiological aging through reduction in elasticity starts in the early 20s.



Typical stress-strain curve for mammalian tendon. Three regions are shown: (1) toe region (2) linear region, and (3) failure region.

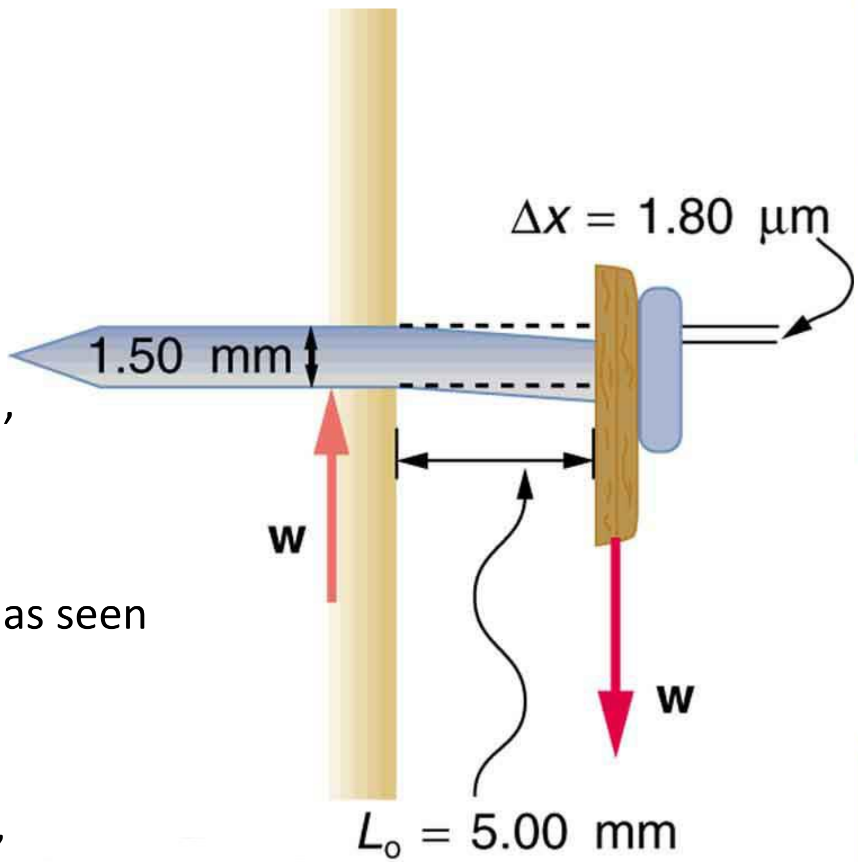
Another biological example of Hooke’s law occurs in tendons. Functionally, the tendon (the tissue connecting muscle to bone) must stretch easily at first when a force is applied, but offer a much greater restoring force for a greater strain. **Figure** shows a stress-strain relationship for a human tendon. Some tendons have a high collagen content so there is relatively little strain, or length change; others, like support tendons (as in the leg) can change length up to 10%. Note that this stress-strain curve is nonlinear, since the slope of the line changes in different regions. In the first part of the stretch called the toe region, the fibers in the tendon begin to align in the direction of the stress—this is called *uncrimping*. In the linear region, the fibrils will be stretched, and in the failure region individual fibers begin to break. A simple model of this relationship can be illustrated by springs in parallel: different springs are activated at different lengths of stretch. Examples of this are given in the problems at end of this chapter. Ligaments (tissue connecting bone to bone) behave in a similar way.

Material	Young's modulus (tension–compression) Y $(10^9\ N/m^2)$	Shear modulus S $(10^9\ N/m^2)$	Bulk modulus B $(10^9\ N/m^2)$
Aluminum	70	25	75
Bone – tension	16	80	8
Bone – compression	9		
Brass	90	35	75
Brick	15		
Concrete	20		
Glass	70	20	30
Granite	45	20	45
Hair (human)	10		
Hardwood	15	10	
Iron, cast	100	40	90
Lead	16	5	50
Marble	60	20	70
Nylon	5		
Polystyrene	3		
Silk	6		
Spider thread	3		
Steel	210	80	130
Tendon	1		
Acetone			0.7
Ethanol			0.9
Glycerin			4.5
Mercury			25
Water			2.2



Shearing forces are applied perpendicular to the length L_0 and parallel to the area A , producing a deformation Δx . Vertical forces are not shown, but it should be kept in mind that in addition to the two shearing forces, **F** , there must be supporting forces to keep the object from rotating. The distorting effects of these supporting forces are ignored in this treatment. The weight of the object also is not shown, since it is usually negligible compared with forces large enough to cause significant deformations.

Side view of a nail with a picture hung from it. The nail flexes very slightly (shown much larger than actual) because of the shearing effect of the supported weight. Also shown is the upward force of the wall on the nail, illustrating that there are equal and opposite forces applied across opposite cross sections of the nail.



Solving the equation $\Delta x = (1/S)(F/A)L_0$ for F, we see that all other quantities can be found:

$F = (SA/L_0)\Delta x$

$S = 80\times10^{9}\ \mathrm{N/m^2}$. The radius r is 0.750 mm (as seen in the figure), so the cross-section area is

$A = \pi r^2 = 1.77\times10^{-6}\ \mathrm{m^2}$

The value for L_0 is also shown in the figure. Thus,

$F = (80\times10^{9}\ \mathrm{N/m^2})(1.77\times10^{-6}\ \mathrm{m^2})(5.00\times10^{-3}\ \mathrm{m})(1.80\times10^{-6}\ \mathrm{m}) = 51\ \mathrm{N}.$

This 51 N force is the weight w of the picture, so the picture's mass is

$m = w/g = F/g = 5.2\ \mathrm{kg}.$

Discussion

This is a fairly massive picture, and it is impressive that the nail flexes only $1.80\ \mu\mathrm{m}$ — an amount undetectable to the unaided eye.

Elasticity: Stress and Strain

9. The elastic properties of the arteries are essential for blood flow. Explain the importance of this in terms of the characteristics of the flow of blood (pulsating or continuous).

10. What are you feeling when you feel your pulse? Measure your pulse rate for 10 s and for 1 min. Is there a factor of 6 difference?

11. Examine different types of shoes, including sports shoes and thongs. In terms of physics, why are the bottom surfaces designed as they are? What differences will dry and wet conditions make for these surfaces?

12. Would you expect your height to be different depending upon the time of day? Why or why not?

13. Why can a squirrel jump from a tree branch to the ground and run away undamaged, while a human could break a bone in such a fall?

14. Explain why pregnant women often suffer from back strain late in their pregnancy.

15. An old carpenter’s trick to keep nails from bending when they are pounded into hard materials is to grip the center of the nail firmly with pliers. Why does this help?

16. When a glass bottle full of vinegar warms up, both the vinegar and the glass expand, but vinegar expands significantly more with temperature than glass. The bottle will break if it was filled to its tightly capped lid. Explain why, and also explain how a pocket of air above the vinegar would prevent the break. (This is the function of the air above liquids in glass containers.)