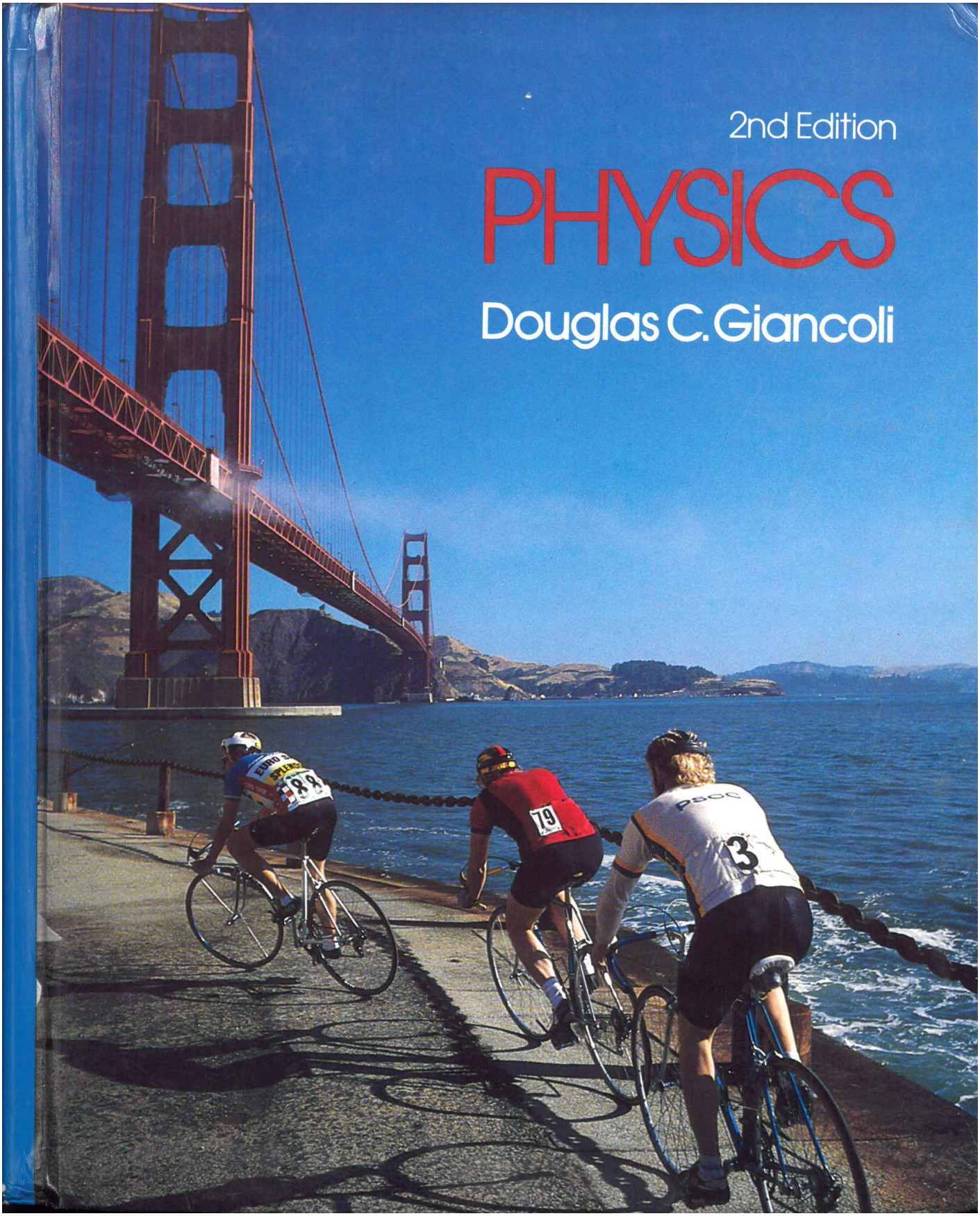

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8 BODIES IN EQUILIBRIUM; ELASTICITY AND FRACTURE

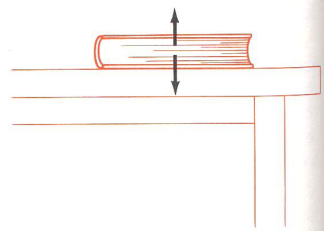
8-1 ▮ Statics—the study of forces in equilibrium

In this chapter we will study a special case of motion—when the net force and torque on an object or system of objects are zero. In this case either the object or system will be at rest, or the center of mass of the object or system will be moving at constant velocity. We will be concerned mainly with the first case, when the object or objects are all at rest. Now you may think that the study of objects at rest is not very interesting since the objects will have neither velocity nor acceleration; and the net force and the net torque will be zero. But it is just this last aspect that makes this subject of *statics* interesting: true, the *net* force on an object at rest is zero, but this does not imply that no forces act on it. In fact it is virtually impossible to find a body on which no forces act at all. Objects within our experience have at least one force acting on them (gravity) and if they are at rest then there must be other forces acting on them as well so that the total net force is zero. An object at rest on a table, for example, has two forces acting on it, the downward force of gravity and the force the table exerts upward on it, Fig. 8-1. Since the net force is zero, the upward force exerted by the table must be equal to the force of gravity acting downward. (Do not confuse this with the equal and opposite forces of Newton's third law which act on different bodies; here both forces act on the same body.) Such a body is said to be in **equilibrium** (Latin for 'equal forces") under the action of these two forces.†

The subject of statics is concerned with the calculation of the forces acting on bodies which are in equilibrium. The techniques for doing this find application in a wide range of fields. A knowledge of the forces in muscles and joints is of great value in medicine and physical therapy, and is also valuable in the study of athletic activity. Architects and engineers must be able to calculate the forces on the structural members of a building, for any material will break or buckle if too much force is applied.

Let us take a simple example of the addition of forces applied to orthodonture.

FIGURE 8-1
The book is in equilibrium; the net force on it is zero.



† A body in equilibrium at rest is said to be in *static equilibrium* whereas a body moving uniformly at constant velocity is in *dynamic equilibrium;* we consider mainly the former case.

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EXAMPLE 8-1 The wire band shown in Fig. 8-2 has a tension T of 2.0 N along it. It therefore exerts a force of 2.0 N on the tooth (to which it is attached) in the two directions shown. Calculate the resultant force on the tooth due to the wire.

SOLUTION Since the two forces are equal, their sum will be directed along the line that bisects the angle between them, which we have labeled the y axis. The x components of the two forces add up to zero. The y component of each force is (2.0 N)(cos 70°) = 0.68 N and adding the two together we get a total force of 1.36 N. Note that if the wire is firmly attached to the tooth, the tension to the right, say, can be made larger than to the left and the net force would correspondingly be directed more toward the right.

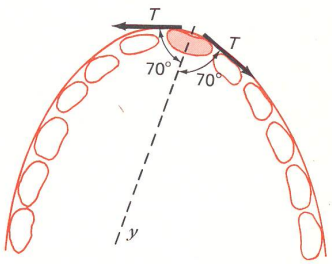


FIGURE 8-2
Forces on a tooth, Example 8-1.

Although it is intended that the tooth in this example should move, it moves very slowly and is essentially in equilibrium. The net force on it is therefore zero. The gums, then, must exert a force of 1.36 N on the tooth in a direction opposite to that exerted by the wire. In a similar way the force exerted on the leg by the traction apparatus shown in Fig. 8-3 can be calculated to be 320 N. Notice that if the pulleys are essentially frictionless, there is a tension of 20 kg (9.8 m/s^2) = 200 N all along the cord; thus there are two 200-N forces acting at 37° angles on the central pulley and on the leg and the resultant is 320 N acting to the right. Now the leg is in equilibrium so there must be another 320-N force acting on the leg to keep it at rest. What exerts this force?

8-2 ▮ The conditions for equilibrium

For a body to be at rest, the sum of the forces acting on it must add up to zero. Since force is a vector, the components of the net force must each be zero. Hence, if the forces on the object act in a plane, a condition for equilibrium is that

$$\sum F_x = 0, \qquad \sum F_y = 0. \tag{8-1}$$

If the forces act in three dimensions (a situation we will not consider) then the third component must be zero as well, $\sum F_z = 0$. We must remember that

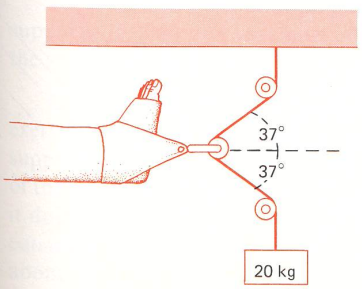


FIGURE 8-3
Traction apparatus exerts force on a leg.

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if a particular force component points along the negative x or y axis, it must have a negative sign. Equation 8-1 is called the *first condition* for equilibrium.

EXAMPLE 8-2 Calculate the tension in the two cords used to support the 200-kg chandelier shown in Fig. 8-4.

SOLUTION The three forces, $\mathbf{F}_1$, $\mathbf{F}_2$, and the 200-kg weight of the chandelier, act at the point where the three cords join. We choose this junction point (it could be a knot) as the object for which we write $\sum F_x = 0$, $\sum F_y = 0$. (Note that we don't bother considering the chandelier itself since only two forces act on it, gravity downward and the equal but opposite force exerted upward by the cord, both of which equal $mg = 1960$ N.) There are only two unknowns and we can solve for them using Eq. 8-1. We first resolve $\mathbf{F}_1$ into its horizontal (x) and vertical (y) components. Although we don't know the value of $\mathbf{F}_1$ we can write $F_{1x} = F_1 \cos 60°$ and $F_{1y} = F_1 \sin 60°$. $\mathbf{F}_2$ has only an x component. In the vertical direction we have only the weight of the chandelier = (200 kg)(g) acting downward and the vertical component of $\mathbf{F}_1$ upward. Since $\sum F_y = 0$, we have:

$$\sum F_y = F_1 \sin 60° - (200 \text{ kg})(g) = 0$$

so

$$F_1 = \frac{(200 \text{ kg})(g)}{\sin 60°} = (230 \text{ kg})(g) = 2260 \text{ N}.$$

In the horizontal direction,

$$\sum F_x = F_2 - F_1 \cos 60° = 0.$$

Thus

$$F_2 = F_1 \cos 60° = (230 \text{ kg})(g)(0.500) = (115 \text{ kg})(g) = 1130 \text{ N}.$$

The magnitudes of $\mathbf{F}_1$ and $\mathbf{F}_2$ determine the strength of cord or wire that must be used. In this case, the wire must be able to hold at least 230 kg.

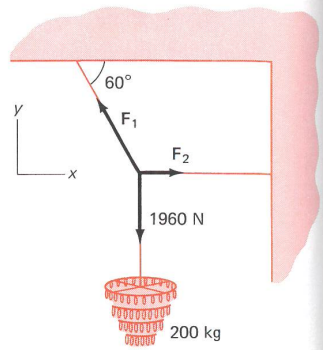


FIGURE 8-4
Example 8-2.

Although Eq. 8-1 must be true if an object is to be in equilibrium, it is not a sufficient condition. Figure 8-5 shows an object on which the net force is zero. Although the two forces labeled **F** add up to give zero net force on the object, they do give rise to a torque which will rotate the object. Referring to Eq. 7-12, we see that if a body is to remain at rest, the net torque applied to it must be zero. Thus we have the *second condition* for equilibrium: that the sum of the torques acting on a body must be zero:

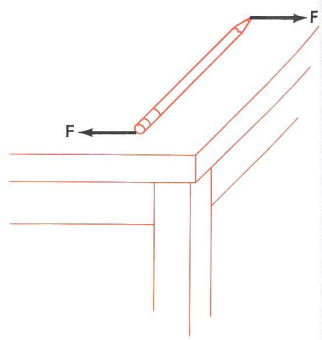
$$\sum \tau = 0. \qquad (8\text{-}2)$$

This will assure that the angular acceleration, α, about any axis will be zero; if the body is not rotating initially ($\omega = 0$) it will not start rotating. Equations 8-1 and 8-2 are the only requirements for a body to be in equilibrium.

We will consider cases in which the forces all act in a plane† (we call it the xy plane). In this case the torque is calculated about an axis that is per-

† If the forces are not in a plane, the situation is more complicated; there will be three force equations plus three torque equations (torque calculated about three mutually perpendicular axes). We won't usually be concerned with such complicated situations.

FIGURE 8-5
Although the net force on it is zero, the pencil will move (rotate). A pair of equal forces acting in opposite directions but at different points on a body (as shown here) is referred to as a *couple*.



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pendicular to the xy plane. The choice of this axis is arbitrary. Since $\tau = I\alpha$ for a rigid body about any fixed axis (Eq. 7-12), $\tau = 0$ about any fixed axis if the body is in equilibrium ($\alpha = 0$): therefore we can choose any axis that makes our calculation easier.

This subject of statics is important because it allows us to calculate certain forces on (or within) a structure when some of the forces on it are already known. There is no single technique for attacking such statics problems, but the following procedure is helpful. (1) Choose one body at a time for consideration, and on a diagram show all the forces acting on the body and the points at which these forces act; this is called a "free-body diagram." (2) Choose a convenient coordinate system and resolve the forces into their components. (3) Using letters to represent unknowns, write down equations for $\sum F_x = 0$, $\sum F_y = 0$, and $\sum \tau = 0$, and then solve these equations. Undoubtedly the hardest step is (1): *all* the forces *on* the body must be included, but the forces exerted *by* this body on other objects must *not* be included.

It is useful to refer back to Example 8-2 to see how this procedure was followed. Notice that we did not bother to consider the forces on the chandelier (which are gravity downward and the rope pulling upward with an equal force). Since we wanted to know the tension in the two cords, we chose the junction point (or knot) of the cords as our object. Since the object is essentially a point, there would be no torques, so the torque equation was not used. Of course, one does not have to use all three equations if they are not needed.

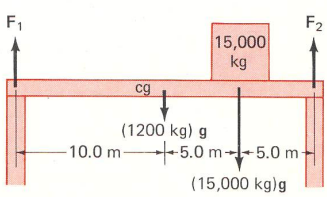
In many situations we must make use of the torque equation (8-2). Just as the components of a force are positive or negative depending on their direction, so too are torques. If a torque that tends to rotate the object counterclockwise is considered positive then a torque that tends to rotate it clockwise must be considered negative. Another way of stating the equilibrium conditions is that the sum of all clockwise torques is equal to the sum of all counterclockwise torques; and for the forces: the sum of the upward forces is equal to the sum of the downward forces, and the sum of horizontal forces to the left is equal to the sum of horizontal forces to the right.

One of the forces that acts on bodies is the force of gravity. Our analysis in this chapter is greatly simplified if we use the concept of center of gravity (cg); as we discussed in Section 6-8, we can consider the force of gravity on the body as a whole as acting at its cg. For uniform symmetrically shaped bodies, the cg is at the geometric center. For more complicated bodies, the cg can be determined as discussed in Section 6-8.

EXAMPLE 8-3 A uniform 1200-kg beam (beneath a floor, let us say) supports 15,000 kg of machinery, Fig. 8-6. Calculate the force on each of the supports.

SOLUTION We analyze the forces on the beam, since the force it exerts on each support is equal and opposite to the force exerted by that support on the beam. We call these forces $\mathbf{F}_1$ and $\mathbf{F}_2$ in Fig. 8-6. The weight of the beam itself acts at its center of gravity, 10.0 m from either end. Since it doesn't matter which point we choose as the axis for writing the torque equation, we can choose one that is convenient. If we calculate the torques about the point of application of $\mathbf{F}_1$, then $\mathbf{F}_1$ will not enter (its lever arm

FIGURE 8-6
A 1200-kg beam supports a 15,000-kg machine (Example 8-3).



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will be zero) and we will have an equation in only one unknown, F_2. Thus $\sum\tau = 0$ gives

$$-(10.0\text{ m})(1200\text{ kg})(g) - (15.0\text{ m})(15{,}000\text{ kg})(g) + (20.0\text{ m})F_2 = 0.$$

Solving for F_2 we find $F_2 = (12{,}000\text{ kg})(g) = 118{,}000$ N. To find F_1 we use $\sum F_y = 0$:

$$\sum F_y = F_1 - (1200\text{ kg})(g) - (15{,}000\text{ kg})(g) + F_2 = 0.$$

Putting in $F_2 = (12{,}000\text{ kg})(g)$ we find $F_1 = (4200\text{ kg})(g) = 41{,}200$ N.

Figure 8-7 shows a beam which extends beyond its support. Such a beam is called a *cantilever*. The forces acting on the beam in this figure are those due to the supports, $\mathbf{F}_1$ and $\mathbf{F}_2$, and the force of gravity, which acts at the cg, 5.0 m to the right of the right-hand support. If you follow the procedure of the last example to calculate F_1 and F_2 assuming they point upward as shown in the figure (see the problems) you will find that F_1 comes out negative; if the beam has a mass of 1200 kg, then $\mathbf{F}_2 = 15{,}000$ N and $\mathbf{F}_1 = -3000$ N. Whenever an unknown force comes out negative, it merely means that the force actually points in the opposite direction from what you assumed. Thus in Fig. 8-7, $\mathbf{F}_1$ actually points downward. With a little reflection it should become obvious that the left-hand support must indeed pull downward on the beam if it is to be in equilibrium (and not push upward as $\mathbf{F}_2$ does).

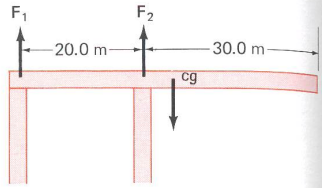
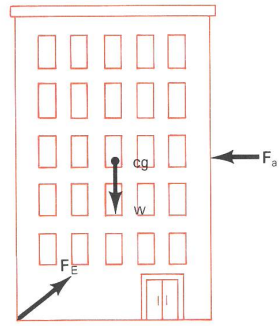


FIGURE 8-7
A cantilever.

As another example, we calculate the stability of a building under the action of wind. It is obviously an important consideration in the design of high buildings to determine if the wind will knock them over. In Fig. 8-8, the forces on the building are shown. The weight **w** acts downward at the cg (assumed to be at the center of the building). $\mathbf{F}_a$ represents the force of the air (wind), which, if we assume it acts uniformly over the whole face of the building, can be considered as a single force acting at the center of that face of the building. Finally, $\mathbf{F}_E$ represents the force of the earth on the building which counterbalances the first two forces to keep the building in equilibrium. Normally the upward and sideways force of the earth ($\mathbf{F}_E$) acts all along the base of the building. But we are interested in the worst possible situation, when the building has started to tip slightly and $\mathbf{F}_E$ acts at the last point of support, the corner of the building. The components of $\mathbf{F}_E$ can be calculated from the force equations, but what we are really interested in is whether the building will reach this rather dire situation of starting to tip over. To determine this, we must calculate torques about the potential pivot point.

FIGURE 8-8
Force on a building subjected to wind (F_a) and gravity (w); F_E is the force on the building due to the earth in the situation when the building is just about to tip.



EXAMPLE 8-4 A 50-story building is being planned. It is to be 200 m high with a base 40 m by 70 m. Its total mass will be about 1.5×10^7 kg and its weight therefore about 1.5×10^8 N. Will this building tip over in a 200-km/h wind† which exerts a force of 1450 N/m^2 over the 70-m-wide face?

† The force (in N) exerted per square meter on a flat surface by a wind of speed v (in km/h) is given roughly by $0.035\,v^2$, assuming the wind blows perpendicular to the surface.

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SOLUTION To get F_a we must multiply the force per area by the total area: $F_a = (1450\ \text{N/m}^2)(70\ \text{m})(200\ \text{m}) = 2.0 \times 10^7\ \text{N}$. We calculate the torque about the potential pivot point, the lower rear edge of the building (where F_E acts in Fig. 8-8). The wind, as we saw above, can be considered to act at the midpoint of the face, which is 100 m above the ground. The torque it produces, tending to overturn the building, is equal to $(100\ \text{m}) \cdot (2.0 \times 10^7\ \text{N}) = 2.0 \times 10^9\ \text{N}\cdot\text{m}$. The torque tending to keep the building upright is the force of gravity acting through a lever arm equal to half the width of the building, or 20 m; this torque equals $(20\ \text{m})(1.5 \times 10^8\ \text{N}) = 3.0 \times 10^9\ \text{N}\cdot\text{m}$. The building will not tip over, but it is close; a safety factor of two or more would be better.

*8-3 Applications to muscles and joints

The techniques for calculating forces on bodies in equilibrium can readily be applied to the human (or animal) body. This is of great use in studying the forces on muscles, bones, and joints for organisms in motion or at rest. Generally a muscle is attached, via tendons, to two different bones (see Fig. 8-9). The points of attachment are called *insertions*. The two bones are flexibly connected at a *joint*, such as those at the elbow, knee, and ankle. A muscle exerts a pull when its fibers contract under stimulation by a nerve, but it cannot exert a push. A muscle that tends to bring two limbs closer together, such as the biceps muscle in the upper arm (Fig. 8-9) are called *flexor* muscles; those that act to extend a limb outward, such as the triceps, are called *extensor* muscles. The flexor muscle in the upper arm is used when lifting an object in your hand; the extensor muscle is used when throwing a baseball.

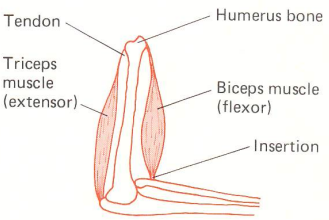
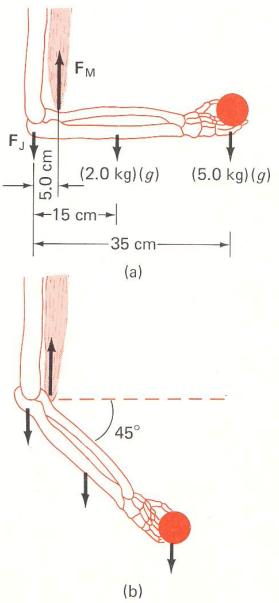


FIGURE 8-9
Diagram showing the biceps (flexor) and triceps (extensor) muscles in human arm.

FIGURE 8-10
Example 8-5.



EXAMPLE 8-5 How much force must the biceps muscle exert when a 5.0-kg mass is held in the hand (*a*) with the arm outstretched as in Fig. 8-10a. and (*b*) when the arm is at a 45° angle as in Fig. 8-10b? Assume the mass of forearm and hand together is 2.0 kg and their cg is as shown.

SOLUTION (*a*) The forces acting on the forearm are shown in Fig. 8-10a and include the upward force F_M exerted by the muscle and a force F_J exerted at the joint by the bone in the upper arm. We wish to find F_M, which is done most easily by using the torque equation, calculated about the joint so that F_J does not enter:

$$(0.050\ \text{m})(F_M) - (0.15\ \text{m})(2.0\ \text{kg})(g) - (0.35\ \text{m})(5.0\ \text{kg})(g) = 0.$$

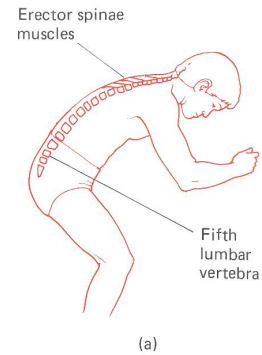
We solve this for F_M and find $F_M = (41\ \text{kg})(g) = 400\ \text{N}$. (*b*) The lever arm for the muscle is reduced to $(0.050\ \text{m})\ \sin 45° = 0.035\ \text{m}$. But the lever arms for the downward forces are reduced by the same ratio; so the same result will be obtained, $F_M = 400\ \text{N}$.

Note in the example that the force required of the muscle is quite large compared to the weight of the object lifted. Indeed, the muscles and joints of the body are generally subjected to quite large forces.

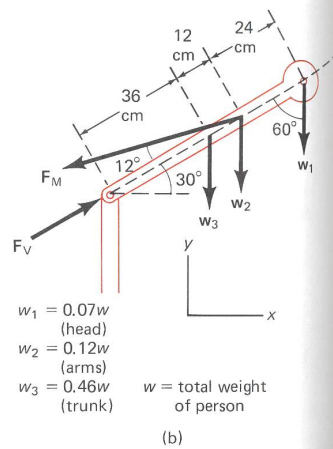
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The point of insertion of a muscle varies from person to person. A slight increase in the point of insertion of the biceps muscle from 5.0 cm to 5.5 cm can be a considerable advantage for lifting and throwing. Indeed, athletes are often found to have muscle insertions farther from the joint than the average person, and if this applies to one muscle it usually applies to all.

As another example of the large forces acting within the human body we consider the muscles used to support the trunk when a person bends forward, Fig. 8-11a. The lowest vertebra on the spinal column (fifth lumbar vertebra) acts as a fulcrum for this bending position. The "erector spinae" muscles that support the trunk act at an effective angle of about 12° to the axis of the spine. Figure 8-11b is a simplified schematic drawing showing the forces on the upper body; we assume the trunk makes an angle of 30° with the horizontal. The force exerted by the muscles is represented by $\mathbf{F}_M$; the force exerted on the base of the spine at the lowest vertebra is $\mathbf{F}_V$; and $\mathbf{w}_1$, $\mathbf{w}_2$, $\mathbf{w}_3$ represent the weights of the head, freely hanging arms, and trunk, respectively. The values shown are approximations taken from Table 6-1; the distances (in cm) refer to a person 180 cm tall, but are approximately in the same ratio of 1:2:4 for an average person of any height and the answer below is then independent of the height of the person.



(a)



(b)

FIGURE 8-11
(a) Person bending over. (b) Forces required of back muscles ($\mathbf{F}_M$) and in the vertebrae ($\mathbf{F}_V$) when a person bends over.

EXAMPLE 8-6 Calculate the magnitude and direction of the force $\mathbf{F}_V$ acting on the fifth lumbar vertebra for the example shown in Fig. 8-11b.

SOLUTION First we calculate F_M using the torque equation (Eq. 8-2) about the base of the spine; the torques are calculated using $\tau = rF_\perp = r(F \sin\theta)$ where θ is 12° for $\mathbf{F}_M$ and 60° for $\mathbf{w}_1$, $\mathbf{w}_2$, and $\mathbf{w}_3$:

$$(0.48\text{ m})(\sin 12^\circ)(F_M) - (0.72\text{ m})(\sin 60^\circ)(w_1) - (0.48\text{ m})(\sin 60^\circ)(w_2) - (0.36\text{ m})(\sin 60^\circ)(w_3) = 0.$$

Putting in the values for w_1, w_2, w_3 given in the figure, we find $F_M = 2.2w$, where w is the total weight of the body. To get the components of F_V we use the x and y components of the force equation:

$$\sum F_y = F_{V_y} - F_M \sin 18^\circ - w_1 - w_2 - w_3 = 0$$
$$F_{V_y} = 1.3w.$$
$$\sum F_x = F_{V_x} - F_M \cos 18^\circ = 0$$
$$F_{V_x} = 2.1w.$$

Then $F_V = \sqrt{F_{V_x}^2 + F_{V_y}^2} = 2.5w$. The angle θ that F_V makes with the horizontal is given by $\tan\theta = F_{V_y}/F_{V_x} = 0.62$, so $\theta = 32^\circ$.

The force on the lowest vertebra is thus $2\frac{1}{2}$ times the body weight! This force is transmitted from the "sacral" bone at the base of the spine, through the fluid-filled and somewhat flexible *intervertebral disc*. The discs at the base of the spine are clearly being compressed under very large forces.

If the person in Fig. 8-11 has a mass of 90 kg, and is holding 20 kg in his hands (this increases w_2 to $0.33w$) then F_V is increased to nearly five times the person's weight ($5w$)! (For this 200-lb person, the force on the disc would be 1000 lb!) With such strong forces acting, it is little wonder that so many people suffer from lower back pain at one time or another in their lives.

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*8-4 ▮ Simple machines: levers and pulleys

Simple machines, such as levers, pulleys, gears, and the wheel and axle, are designed to reduce the force needed to lift a heavy load. They can be analyzed using the principles we have discussed in this chapter. Consider, for example, the lever shown in Fig. 8-12. If the stone is lifted slowly, it is essentially in equilibrium, and using the torque rule ($\sum \tau = 0$), with the torques calculated about the pivot point, we see that a force of only (50 kg)(g) = 500 N is needed to lift the stone whose weight is (200 kg)(g) = 2000 N. In a sense, the force has been multiplied by a factor of 4, and we say the lever gives us a *mechanical advantage* of 4. From the geometry of the situation as shown in Fig. 8-12b, the 500-N force must be exerted through a distance of 2.0 m to raise the stone 0.50 m. Thus the work done by the person is (500 N)(2.0 m) = 1000 J, and the work done on the stone is (2000 N)(0.50 m) = 1000 J, also. In other words, the input work equals the output work (this is essentially conservation of energy).

This example has been idealized, for in practice it would be found that the force necessary to lift the 2000-N stone would be different from 500 N. This is due to two factors common to all machines: friction and the weight of the machine itself (for example, in Fig. 8-12 we would need to include the weight of the lever in calculating the torques). We therefore define an "ideal" and an "actual" mechanical advantage. The *ideal mechanical advantage* (IMA) is defined as the (output force)/(input force) for the ideal situation, which means the output work = input work, or $F'_i d_i = F'_o d_o$; the subscript "o" means output and "i" means input and the primes remind us we are talking of the force in the ideal case. From this relation we have $F'_o/F'_i = d_i/d_o$. Thus the ideal mechanical advantage is also the ratio of the distance d_i moved by the input force to the distance d_o moved by the load (the output):

$$\text{IMA} = \frac{d_i}{d_o}.$$

The *actual mechanical advantage* (AMA) is the ratio of the actual output

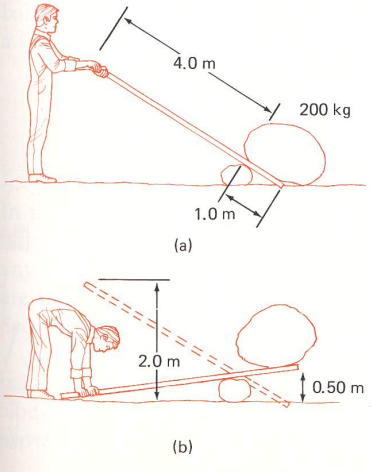


FIGURE 8-12
A simple lever.

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force to actual input force for the particular machine

$$\text{AMA} = \frac{F_o}{F_i}.$$

Finally, the efficiency of any machine, be it simple or complex, is defined as (work output)/(work input). This can be written in terms of the IMA and AMA:

$$\text{efficiency} = \frac{F_o d_o}{F_i d_i} = \left(\frac{F_o}{F_i}\right)\Big/\left(\frac{d_i}{d_o}\right) = \frac{\text{AMA}}{\text{IMA}}.$$

For example, suppose it actually took a 550-N force to lift the 2000 N stone in Fig. 8-12. The IMA = 2.0 m/0.50 m = 4.0, whereas the AMA = 2000 N/550 N = 3.6. The efficiency is then (3.6)/(4.0) = 0.90 or 90 percent.

Pulleys are often used to mechanical advantage. The pulley system shown in Fig. 8-13 has an IMA of 2.0. This is readily seen by noting that there are two ropes supporting the weight and in the ideal case each need carry only half the weight. This can also be seen from the fact, see Fig. 8-13, that $d_o = d_i/2$. For more complicated systems, such as those shown in Fig. 8-14, similar considerations will reveal that the IMA in general is equal to the number of ropes pulling up on the load. The AMA will always be less than the IMA; hence the work output will be less than the work input.

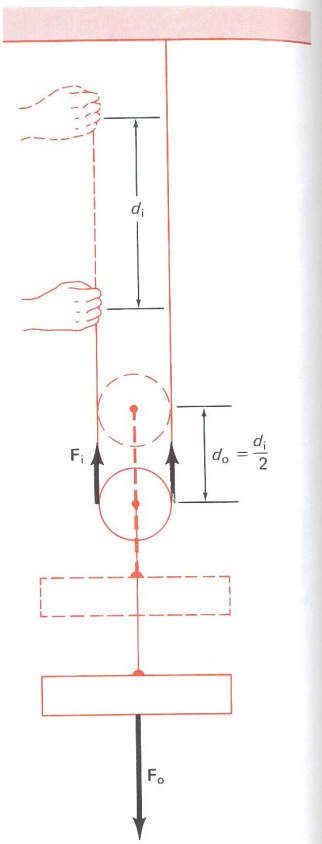
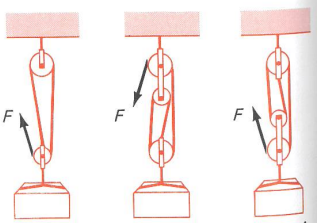


FIGURE 8-13
Simple pulley.

FIGURE 8-14
Various pulley systems.



8-5 ▮ Stability and balance

A body in static equilibrium, if left undisturbed, will undergo no translational or rotational acceleration since the sum of all the forces and the sum of all the torques acting on it are zero. However, if the object is displaced slightly, three different outcomes are possible: (1) the object may return to its original position, in which case it is said to be in **stable equilibrium;** (2) the object will move even farther from its original position, in which case it is said to be in **unstable equilibrium;** or (3) it remains in its new position, in which case it is said to be in **neutral equilibrium.** Consider the following examples. A ball suspended freely from a string is in stable equilibrium for if it is displaced to one side it will quickly return to its original position (Fig. 8-15a). On the other hand, a pencil standing on its point is in unstable equilibrium. If its cg is directly over its tip (Fig. 8-15b), the net force and net torque on it will be zero. But if it is displaced ever so slightly—say by a slight vibration or tiny air current—there will be a torque on it and it will continue to fall in the direction of the original displacement. Finally, an example of an object in neutral equilibrium is a sphere resting on a horizontal table top. If it is placed slightly to one side, it will remain in its new position.

In most situations, such as in the design of structures and in working with the human body, we are interested in maintaining stable equilibrium or

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balance, as we sometimes say. In general, an object whose cg is below its point of support, such as a ball on a string, will be in stable equilibrium. If the cg is above the base of support we have a more complicated situation. Consider a block standing on its end (Fig. 8-16a). If it is tipped slightly, it will return to its original position due to the torque on it as shown in Fig. 8-16b. But if it is tipped too far, Fig. 8-16c, it will fall over. The critical point is reached when the cg is no longer above the base of support. In general, *a body whose cg is above its base of support will be stable if a vertical line projected downward from its cg falls within the base of support.* This is a result of the fact that the upward force on the object (which balances out gravity) can only be exerted within the area of contact, so that if the force of gravity acts beyond this area, a net torque will act to topple the object. Stability in this case is relative. A brick lying on its widest face is more stable than a brick standing on its end, for it will take more of an effort to tip it over. In the extreme case of the pencil in Fig. 8-15b, the base is practically a point and the slightest disturbance will topple it. In general, the larger the base and the lower the cg, the more stable the object.

In this sense, humans are much less stable than four-legged mammals, which not only have a much larger base of support because of their four legs, but have a lower cg. The human species has had to develop special apparatus, such as certain very strong muscles, in order to deal with the problem of keeping a person upright and at the same time stable. Because of this upright position, humans suffer from numerous ailments such as low back pain due to the large forces involved as we saw in Example 8-6. When walking and performing other kinds of movement a person continually shifts the body so its cg is over the feet, although in the normal adult this requires no conscious thought. Even as simple a movement as bending over requires moving the hips backward so that the cg remains over the feet, and this repositioning is done without thinking about it. To illustrate this, position yourself with your heels and back to a wall and try to touch your toes. Persons carrying heavy loads automatically adjust their posture so that the cg of the total mass is over their feet, as shown in Fig. 8-17. However, to people who suffer from muscle weakness in the trunk or legs, or who have suffered damage to the spinal cord, even walking can be difficult. A conscious effort is required to balance the body over the feet and the slightest miscalculation can lead to a fall.

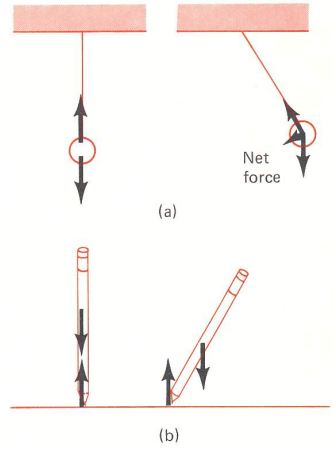


FIGURE 8-15
(a) Stable equilibrium; (b) unstable equilibrium.

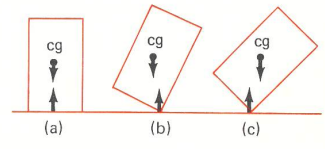


FIGURE 8-16
Equilibrium of a block resting on a surface.

FIGURE 8-17
Humans adjust their posture when carrying loads to achieve stability.



8-6 ▮ Elasticity; stress and strain

In the first part of this chapter we studied how to calculate the forces on objects in equilibrium. In this section we study the effects of these forces, for any object changes shape under the action of applied forces. If the forces are great enough, the object will break or *fracture*, and we discuss this in Section 8-7.

If a force is exerted on an object, such as the vertically suspended metal bar shown in Fig. 8-18, the length of the object changes. If the amount of elongation, ΔL, is small compared to the length of the object, experiment shows that ΔL is proportional to the weight or force exerted on the object;

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this was first noted by Robert Hooke (1635–1703). This proportionality can be written as an equation and is sometimes called *Hooke's law*†:

$$F = k\,\Delta L. \tag{8-3}$$

Here F represents the force (or weight) pulling on the object, ΔL is the increase in length, and k is a proportionality constant. Equation 8-3 is found to be valid for almost any solid material from iron to bone, but it is valid only up to a point. For if the force is too great, the object stretches excessively and eventually breaks. Figure 8-19 shows a typical graph of elongation versus applied force. Up to a point called the *elastic limit*, the object will return to its original length if the applied force is removed. This is called the *elastic region*. If the object is stretched beyond the elastic limit, it will be permanently deformed. For most common materials Eq. 8-3 is a good approximation almost up to the elastic limit and the graph is a straight line. Beyond this point, the graph deviates from a straight line and no simple relationship exists between F and ΔL. If the object is stretched much beyond the elastic limit, it will break. The maximum force that can be applied without breaking is called the *ultimate strength* of the material.

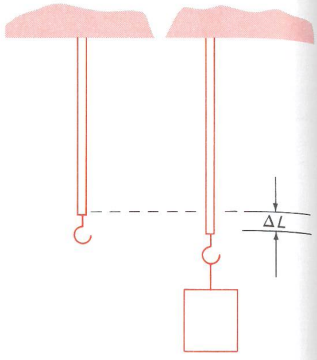


FIGURE 8-18
Hooke's law: $\Delta L \propto$ applied force.

The amount of elongation of an object, such as the bar shown in Fig. 8-18, depends not only on the force applied to it, but also on the material from which it is made and on its dimensions. That is, the constant k in Eq. 8-3 can be written in terms of these factors. If we compare bars made of the same material but of different lengths and cross-sectional areas, it is found that for the same applied force the amount of stretch (again assumed small compared to the total length) is proportional to the original length and inversely proportional to the cross-sectional area. That is, the longer the object, the more it elongates for a given force; and the fatter it is, the less it elongates. These experimental findings can be combined with Eq. 8-3 to yield the relation

$$\Delta L = \frac{1}{E}\frac{F}{A}L_0, \tag{8-4}$$

where L_0 is the original length of the object, A is the cross-sectional area, and ΔL is the change in length due to the applied force F; E is a constant of proportionality‡ known as the *elastic modulus*, or *Young's modulus*, and its value depends only on the material. The value of Young's modulus for various materials is given in Table 8-1. Because E is a property only of the material and is independent of the object's size or shape, Eq. 8-4 is far more useful for practical calculation than Eq. 8-3. From Eq. 8-4 we see that the change in length of an object is directly proportional to the product of the object's length L_0 and the force per unit area F/A applied to it. It is general practice to define the force per unit area, as the **stress:**

$$\text{stress} = \frac{\text{force}}{\text{area}} = \frac{F}{A}.$$

Also, the **strain** is defined to be the ratio of the change in length to the

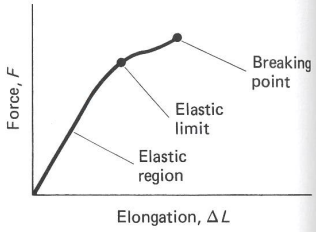


FIGURE 8-19
Applied force vs. elongation for a typical solid.

† The term "law" applied to this relation is not really appropriate—see footnote on this point in Section 5-4.

‡ The fact that E is in the denominator so that $1/E$ is the actual proportionality constant is merely a convention.

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TABLE 8-1
Elastic moduli

Material	Elastic modulus, E (N/m^2)	Shear modulus, G (N/m^2)	Bulk modulus, B (N/m^2)
Solids			
Iron, cast	100×10^9	40×10^9	90×10^9
Steel	200×10^9	80×10^9	140×10^9
Brass	100×10^9	35×10^9	80×10^9
Aluminum	70×10^9	25×10^9	70×10^9
Concrete	20×10^9		
Brick	14×10^9		
Marble	50×10^9	20×10^9	70×10^9
Granite	45×10^9	20×10^9	45×10^9
Wood (pine)			
(parallel to grain)	10×10^9		
(perpendicular to grain)	1×10^9		
Nylon	5×10^9		
Bone (limb)	15×10^9	80×10^9	
Liquids			
Water			2.0×10^9
Alcohol (ethyl)			1.0×10^9
Mercury			2.5×10^9

original length:

$$\text{strain} = \frac{\text{change in length}}{\text{original length}} = \frac{\Delta L}{L_0}.$$

Strain is thus the fractional change in length of the object and is a measure of how much the bar has been deformed. Equation 8-4 can be rewritten as

$$\frac{F}{A} = E\frac{\Delta L}{L_0} \tag{8-5}$$

or

$$E = \frac{F/A}{\Delta L/L_0} = \frac{\text{stress}}{\text{strain}}.$$

Thus we see that the strain is directly proportional to the stress.

EXAMPLE 8-7 A 1.60-m-long steel piano wire has a diameter of 0.20 cm. How great is the tension in the wire if it stretches 0.30 cm when tightened?

SOLUTION We solve for F in Eq. 8-4 and note that the area $A = \pi r^2 = (3.14)(0.0010\text{ m})^2 = 3.1 \times 10^{-6}\text{ m}^2$. Then

$$F = E\frac{\Delta L}{L_0}A$$

$$= (2.0 \times 10^{11}\text{ N/m}^2)\left(\frac{0.0030\text{ m}}{1.60\text{ m}}\right)(3.1 \times 10^{-6}\text{ m}^2) = 1200\text{ N},$$

where we obtained the value for E from Table 8-1.

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The bar shown in Fig. 8-18, is said to be under *tension* or *tensile stress*. For not only is there a force pulling down on the bar at its lower end, but since the bar is in equilibrium we know that the support at the top is exerting an equal upward force† on the bar at its upper end, Fig. 8-20a. In fact, this tensile stress exists throughout the material. Consider for example the lower half of a suspended bar as shown in Fig. 8-20b. This lower half is in equilibrium so there must be an upward force on it to balance the downward force at its lower end. What exerts this upward force? It must be the upper part of the bar. Thus we see that external forces applied to an object give rise to internal forces, or stress, within the material itself.

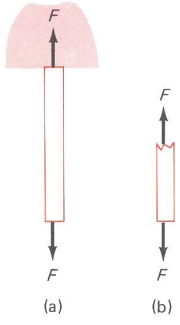


FIGURE 8-20
Stress exists *within* the material.

Strain or deformation due to tensile stress is but one type of stress to which materials can be subjected. There are two other common types of stress: compressive and shear. *Compressive* stress is the exact opposite of tensile stress. Instead of being stretched, the material is compressed: the forces act inwardly on the body. Any sort of column that supports a weight, such as the columns of a Greek temple (Fig. 8-21) is subjected to a compressive stress. Equations 8-4 and 8-5 apply equally well to compression and tension, and the values for E are usually the same.

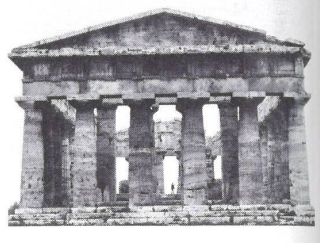


FIGURE 8-21
A Greek temple (in Paestum, Italy). (D. Giancoli).

Figure 8-22 compares tensile and compressive stresses as well as the third type, shear stress. An object under *shear* stress has equal and opposite forces applied *across* its opposite faces. An example is a book or brick firmly attached to a table top with a force exerted parallel to the top surface; the table exerts an equal and opposite force along the bottom surface. Although the dimensions of the object do not change significantly, the shape of the object does change as shown in the figure. An equation similar to 8-4 can be applied to calculate shear strain:

$$\Delta L = \frac{1}{G}\frac{F}{A}L_0 \qquad (8\text{-}6)$$

but ΔL, L, and A must be reinterpreted as indicated in Fig. 8-22c. Note that A is the area of the surface *parallel* to the applied force (and not perpendicular as for tension and compression), and ΔL is *perpendicular* to L_0. The constant of proportionality, G, is called the *shear modulus* and is generally one-half to one-third the value of the elastic modulus, E (see Table 8-1).

The rectangular object undergoing shear in Fig. 8-22c would not actually be in equilibrium under the forces shown, for a net torque would exist. If the object is in fact in equilibrium, there must be two more forces acting on it which balance out this torque. One acts vertically upward on the right, and the other acts vertically downward on the left as shown in Fig. 8-23. This is generally true of shear forces. If the object is a brick or book lying on a table, these two additional forces can be exerted by the table and whatever exerts the other horizontal force.

If an object is subjected to a pressure on all sides, its volume will be compressed. A common situation is a body submerged in a fluid; for in this case, the fluid exerts a pressure on the object in all directions, as we shall see in Chapter 9. Pressure is defined as force per area and thus is the equivalent of "stress." For this situation the change in volume, ΔV, is found to be proportional to the original volume, V_0, and to the increase in the pressure,

† If we ignore the weight of the bar.

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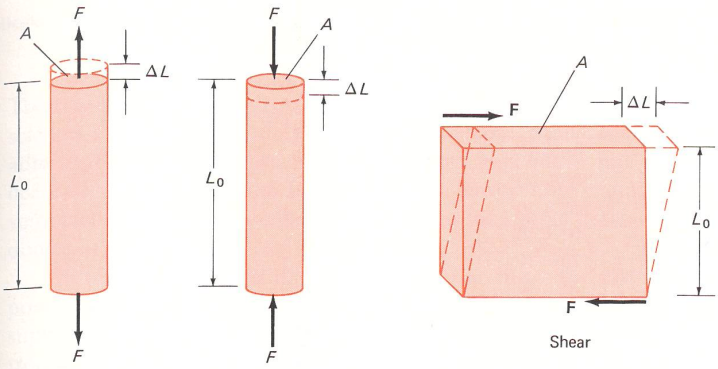


FIGURE 8-22
The three types of stress.

ΔP. We thus obtain a relation of the same form as Eqs. 8-4 and 8-5 but with a proportionality constant called the *bulk modulus*, B:

$$\frac{\Delta V}{V_0} = -\frac{1}{B}\Delta P \tag{8-7}$$

or

$$B = -\frac{\Delta P}{\Delta V/V_0}.$$

The minus sign is included to indicate that the volume *decreases* with an increase in pressure. Values for the bulk modulus are given in Table 8-1. Since liquids and gases do not have a fixed shape, only the bulk modulus applies to them.

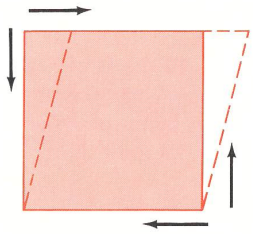
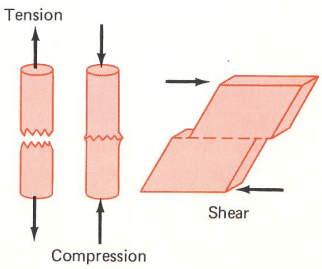


FIGURE 8-23
Balance of forces and torques for shear stress.

8-7 ▮ Fracture

If the stress on a solid object is too great, the object fractures or breaks, Fig. 8-24. In Table 8-2 are listed the ultimate tensile strength, compressive strength, and shear strength for a variety of materials. These give the maximum force per unit area that an object can withstand under each of these three types of stress. They are, however, representative values only and the actual value for a given specimen can differ considerably. It is therefore necessary to maintain a safety factor of from 3 to perhaps 10 or more—that is, the actual stresses on a structure should not exceed one-tenth to one-third of the values given in the table. You may encounter tables of the "allowable stresses" in which an appropriate safety factor has already been included.

FIGURE 8-24
Fracture as a result of the three types of stress.



EXAMPLE 8-8 (*a*) What minimum cross-sectional area should the supports have to support the beam of Example 8-3 (Fig. 8-6) assuming the supports are made of concrete and a safety factor of 6 is required? (*b*) How much will the chosen supports compress under the given load?

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TABLE 8-2
Ultimate strengths of materials (force/area)

Material	Tensile strength (N/m^2)	Compressive strength (N/m^2)	Shear strength (N/m^2)
Iron, cast	170×10^6	550×10^6	170×10^6
Steel	500×10^6	500×10^6	250×10^6
Brass	250×10^6	250×10^6	200×10^6
Aluminum	200×10^6	200×10^6	200×10^6
Concrete	2×10^6	20×10^6	2×10^6
Brick		35×10^6	
Marble		80×10^6	
Granite		170×10^6	
Wood (pine)			
(parallel to grain)	40×10^6	35×10^6	5×10^6
(perpendicular to grain)		10×10^6	
Nylon	500×10^6		
Bone (limb)	130×10^6	170×10^6	

SOLUTION (*a*) The right-hand support receives the larger force, 1.18×10^5 N. It is clearly under compression and from Table 8-2 we see that the ultimate compressive strength of concrete is 2.0×10^7 N/m^2. Using a safety factor of 6, the maximum allowable stress is 3.3×10^6 N/m^2. Since $F/A = 3.3 \times 10^6$ N/m^2 and $F = 1.18 \times 10^5$ N we can solve for A and find

$$A = \frac{1.18 \times 10^5 \text{ N}}{3.3 \times 10^6 \text{ N/m}^2} = 3.6 \times 10^{-2} \text{ m}^2 \text{ or } 360 \text{ cm}^2.$$

A support 18 cm × 20 cm will be adequate.

(*b*) We solve for

$$\frac{\Delta L}{L_0} = \frac{1}{E}\frac{F}{A} = \left(\frac{1}{2.0 \times 10^{10} \text{ N/m}^2}\right)(3.3 \times 10^6 \text{ N/m}^2) = 1.7 \times 10^{-4}.$$

Thus, if the support has a length $L_0 = 5.0$ m, $\Delta L = 0.85 \times 10^{-3}$ m, or about 1 mm. This calculation was for the right-hand support. If the left-hand support is made of the same cross-sectional area, it will compress less and this should be taken into account.

As can be seen in Table 8-2, concrete (like stone and brick) is reasonably strong under compression but extremely weak under tension. Thus concrete can be used as vertical columns placed under compression but is of little value as a beam since it cannot withstand the tensile forces that arise (see Fig. 8-25). Reinforced concrete, in which iron rods are embedded in the concrete, is much stronger in terms of stability; but the concrete on the lower edge of a loaded beam still tends to crack since concrete is weak under tension. This problem is solved with **prestressed concrete** which also contains iron rods or a wire mesh, but during the pouring of the concrete, the rods or wire are held under tension. After the concrete dries, the tension on the iron is released and this puts the concrete under compression. The amount of compressive stress is carefully predetermined so that when the design loads are applied to the beam, they reduce the compression on the lower edge but never put the concrete into tension.

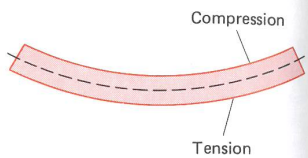


FIGURE 8-25
A beam sags, at least a little (but is exaggerated here), even under its own weight. The beam thus changes shape so that the upper portion is compressed, and the lower portion is elongated (under tension). Shearing stress also occurs within the beam.

FIGURE 8-26
Round arches in the Roman Forum. The one in the background is the Arch of Titus. (D. Giancoli).



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*8-8 ▮ Spanning a space: arches and domes

There are a great many areas where the arts and humanities overlap the sciences and this is especially clear in architecture. Many of the features we admire in the architecture of the past were introduced not just for their decorative effect but often for practical purposes. One example is the development of methods to span a space, from the simple beam to arches and domes.

It might be said that the first important architectural invention was the post-and-beam (or post-and-lintel) construction in which two upright posts support a horizontal beam. It is still used today; but until steel was introduced in the nineteenth century, the length of a beam was quite limited because the strongest building materials were then stone and brick. Hence the width of a span was limited by the size of available stones. But equally important, all of these materials—though strong under compression—are very weak under tension and shear; all these stresses occur in a beam as shown in Fig. 8-25. The minimal space that could be spanned using stone is shown by the closely spaced columns of the great Greek temples (Fig. 8-21).

The introduction of the semicircular arch by the Romans (Fig. 8-26), aside from its aesthetic appeal, was a tremendous technological innovation. It had been preceded by the so-called "triangle arch" and the "corbeled arch," but these were only slight improvements over the post-and-beam (see Fig. 8-27). The advantage of the "true" or semicircular arch is that, if well designed, its wedgeshaped stones experience stress which is mainly compressive even when supporting a large load such as the wall and roof of a cathedral. Because the stones are forced to squeeze against each other, they are thus mainly under compression (see Fig. 8-28). Note however, that the arch transfers horizontal as well as vertical forces to the supports. A round arch consisting of many well-shaped stones could span a very wide space. However, considerable buttressing on the sides was needed to support the horizontal components of the forces. The buttressing was frequently provided by heavy walls leading off to the side.

The pointed arch came into use in Europe about A.D. 1100 and soon became the hallmark of the great Gothic cathedrals. It too was an important technical innovation, and it is likely that this was at least part of the reason it was originally introduced: it was first used to support heavy loads such as the tower of a cathedral and as the central arch across the nave; the lesser arches in these "transitional" buildings often remained round. Apparently the builders realized that because of the steepness of the pointed arch, the forces due to the weight above could be brought down more nearly vertically, so less horizontal buttressing would be needed. The pointed arch reduced the load on the walls, so there could be more openness and light. The smaller amount of buttressing needed was provided on the outside by graceful flying buttresses (Fig. 8-29).

The technical innovation of the pointed arch was achieved not through calculation but through experience and intuition. The beginnings of the science of statics and building appeared during the Renaissance and was advanced by Galileo; but it was not until somewhat later that detailed calculations, such as those presented earlier in this chapter, came into use. To

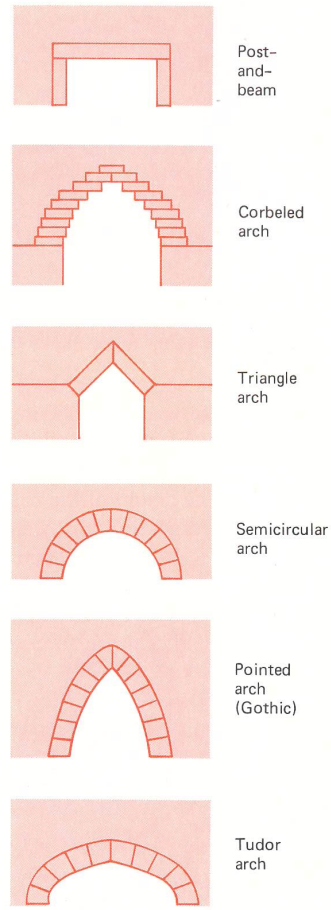
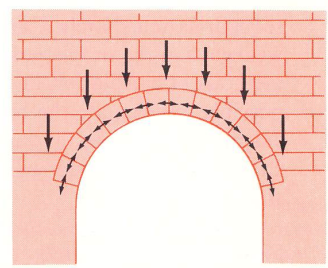


FIGURE 8-27
Various means to span a space.

FIGURE 8-28
Stones in a round (or "true") arch are mainly under compression.



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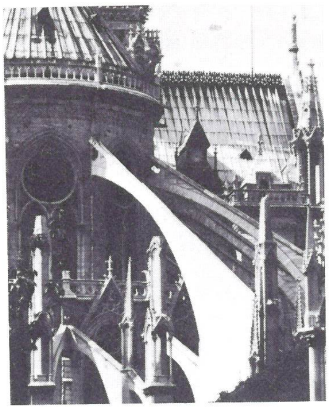


FIGURE 8-29
A flying buttress (on the cathedral of Notre Dame, in Paris). (D. Giancoli).

make an accurate analysis of a stone arch is quite difficult in practice. But if we make some simplifying assumptions, we can show why the horizontal component of the force at the base is less for a pointed arch than for a round one. Figure 8-30 shows a round arch and a pointed arch, each with an 8.0 m span. The height of the round arch is thus 4.0 m whereas that of the pointed arch is larger and has been chosen to be 8.0 m. Each arch supports a weight of 12.0×10^4 N ($= 12{,}000$ kg $\times\ g$) which for simplicity we have divided into two parts (each 6.0×10^4 N) acting on the two halves of each arch as shown. To be in equilibrium, each of the supports must exert an upward force of 6.0×10^4 N; they also exert a horizontal force, F_H, at the base of the arch, and it is this we want to calculate. We focus only on the right half of each arch; we set equal to zero the toal torque calculated about the apex of the arch due to the forces exerted on that half arch, as if there were a hinge at the apex. For the round arch, the torque equation is:

$$(4.0\text{ m})(6.0 \times 10^4\text{ N}) - (2.0\text{ m})(6.0 \times 10^4\text{ N}) - (4.0\text{ m})(F_H) = 0.$$

Thus $F_H = 3.0 \times 10^4$ N. For the pointed arch the torque equation is

$$(4.0\text{ m})(6.0 \times 10^4\text{ N}) - (2.0\text{ m})(6.0 \times 10^4\text{ N}) - (8.0\text{ m})(F_H) = 0.$$

Solving, we find $F_H = 1.5 \times 10^4$ N—only half as much! From this calculation we can see that the horizontal buttressing force required for a pointed arch is less because the arch is higher, and there is therefore a longer lever arm for this force. Indeed, the steeper the arch, the less the horizontal component of the force needs to be, and hence the more nearly vertical is the force exerted at the base of the arch.

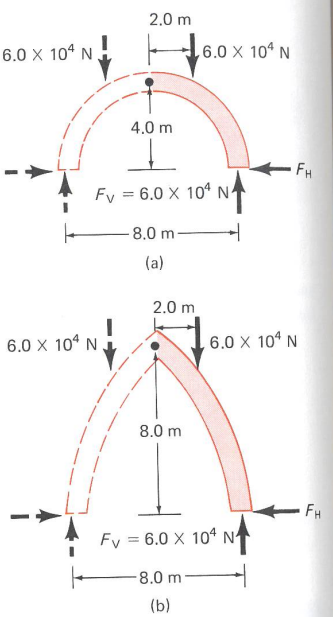


FIGURE 8-30
Forces in a round arch (a) compared with those in a pointed arch (b).

The further development of the arch was one of decline; for the subsequent flattened arches, such as the Tudor arch (Fig. 8-27), were structurally weaker than the simple pointed arch. However, with the coming of advanced methods of calculation in the nineteenth and twentieth centuries it became possible to calculate the best shape of arch for a given load condition. For example, if the load is uniform across the span, it can be shown that the stresses within the arch will be purely compressive if the arch has a parabolic shape.

Whereas an arch spans a two-dimensional space, a dome—which is basically an arch rotated about a vertical axis—spans a three-dimensional

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space. The Romans built the first large domes; their shape was hemispherical and some still stand, such as that of the Pantheon in Rome (Fig. 8-31). By the time of the Renaissance, the technique for constructing large domes seems to have been lost. Indeed, the dome of the Pantheon was a source of wonder to Renaissance architects. (Even today we do not know precisely how it was built). The problem came to the fore in fifteenth-century Florence with the designing of a new cathedral which was to have a dome 43 m in diameter to rival that of the Pantheon. A dome, like an arch, is not stable until all the stones are in place. It had been the custom to support a dome during construction with a wooden framework. But no trees big enough or strong enough could be found to support the 43 m space required for the cathedral in Florence. In 1418, after the cathedral was finished except for the dome, a competition for the design of the dome was held and was won by Brunelleschi. One problem that had to be dealt with was that the dome was to rest on a drum that had been completed with no external abutments; and there was no place to put any. Hence the dome must exert the minimum of horizontal force. Brunelleschi solved this by designing a pointed dome (Fig. 8-32), since a pointed dome, like a pointed arch, exerts a smaller side thrust against its base.

The other major problem was how to support the dome during construction. Instead of using a wooden framework, Brunelleschi built the dome in horizontal layers. Each layer was bonded to the previous one which held it in place until the last stone of the circle was placed. Each closed ring was then strong enough to support the next layer. It was an amazing feat.

To end this section we will consider the forces necessary to support a modern dome, that of the Small Sports Palace in Rome, Fig. 8-33. A dome, like an arch, is statically most stable when under compression. The 36 buttresses which support the 1.2×10^6 kg dome are positioned at a 38° angle and connect smoothly with the dome.

EXAMPLE 8-9 Calculate the components of the force, F_V and F_H, which each buttress exerts on the dome so that the force acts compressively, that is, at a 38° angle (Fig. 8-34).

SOLUTION The vertical load on *each* buttress is 1/36 of the total weight. Thus

$$F_V = \frac{(1.2 \times 10^6 \text{ kg})(9.8 \text{ m/s}^2)}{36} = 3.4 \times 10^5 \text{ N}.$$



FIGURE 8-31
The Pantheon in Rome, built in the first century. (Italian Government Travel Office).

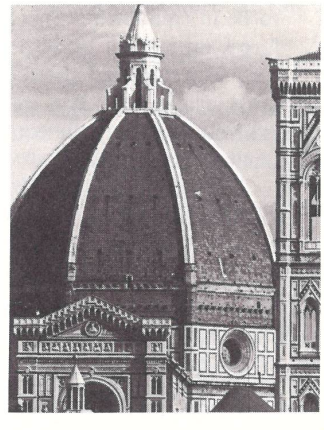


FIGURE 8-32
Brunelleschi's dome for the cathedral of Florence, Italy. (Italian Government Travel Office).



FIGURE 8-33
The dome of the Small Sports Palace in Rome, built for the 1960 Olympics. (Italian Government Travel Office).

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The force must act at a 38° angle at the base of the dome in order to be purely compressive. Thus

$$\tan 38^\circ = \frac{F_V}{F_H} = \frac{340{,}000\ \text{N}}{F_H}$$

$$F_H = \frac{340{,}000\ \text{N}}{\tan 38^\circ} = 430{,}000\ \text{N}.$$

In order that each of the buttresses be able to exert this 430,000-N horizontal force, a prestressed concrete tension ring surrounds the base of the buttresses beneath the ground.

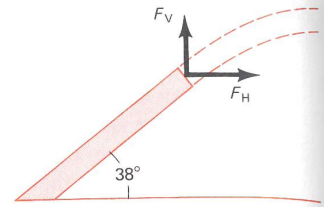


FIGURE 8-34
Example 8-9.

Summary

A body at rest, or one in uniform motion at constant velocity, is said to be in *equilibrium*. The determination of the forces within a structure at rest is the field called *statics*. The two necessary conditions for a body to be in equilibrium are (1) the vector sum of all the forces on it must be zero, and (2) the sum of all the torques (calculated about any arbitrary point as axis) must also be zero. It is important when doing statics problems to apply the equilibrium conditions to only one body at a time.

A body in static equilibrium is said to be in (*a*) *stable*, (*b*) *unstable*, or (*c*) *neutral equilibrium*, depending on whether a slight displacement leads to (*a*) a return to the original position, (*b*) further movement, or (*c*) rest in the new position. An object in stable equilibrium is also said to be in *balance*.

Hooke's law applies to many elastic solids and states that the change in length of an object is proportional to the applied force. If the force is too great, the object will exceed its elastic limit, which means it will no longer return to its original shape when the distorting force is removed. If the force is even greater, the ultimate strength of the material can be exceeded and the object fractures. The force per unit area acting on a body is called the *stress*, and the resulting fractional change in length is called the *strain*. The stress on a body is present within the body and can be of three types: *compression*, *tension*, and *shear*. The ratio of stress to strain is called the elastic modulus of the material; Young's modulus applies for compression and tension, and the shear modulus for shear; bulk modulus applies to an object whose volume changes as a result of pressure on all sides. All three moduli are constants for a given material when distorted within its elastic region.

Questions

1. Describe several situations where a body is not in equilibrium, even though the net force on it is zero.
2. A bear sling, Fig. 8-35, is used in some national parks for placing backpackers' food out of the reach of bears. Explain why the force needed to pull the backpack up increases as the backpack gets higher and higher.
3. A ladder, leaning against a wall, makes a 60° angle with the ground. When is it more likely to slip: when a person stands near the top or near the bottom?
4. Explain why touching the toes while seated on the floor with outstretched legs produces less stress on the lower spinal column than when touching the toes from a standing position. Use a diagram.
5. An earth retaining wall is shown in Fig. 8-36a. The earth, particularly when wet, can exert a significant force F on the wall. (*a*) What force produces the torque to keep the wall upright? (*b*) Explain why the retaining wall in Fig. 8-36b would be much less likely to overturn.
6. Explain why a rectangular brick can be placed so that slightly less than half its length can be suspended over the edge of a table, but no more.

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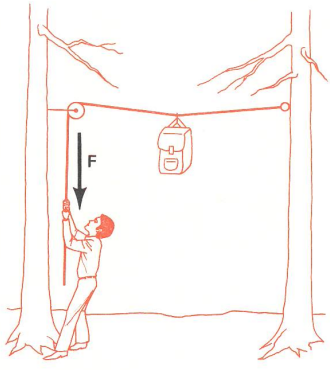


FIGURE 8-35

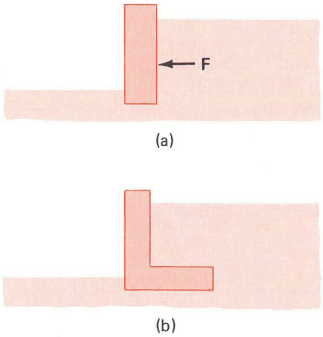


FIGURE 8-36

7. Which of the configurations of brick, (*a*) or (*b*) of Fig. 8-37, is the more likely to be stable? Why?
8. Name the type of equilibrium for each position of the ball in Fig. 8-38.
9. In what state of equilibrium is a cube (*a*) when resting on its face, (*b*) when on its edge?

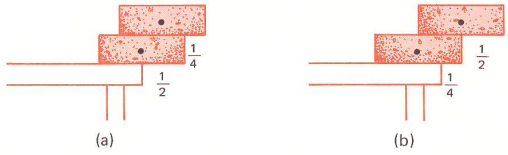


FIGURE 8-37

The dots indicate the cg of each brick. The fractions $\frac{1}{4}$ and $\frac{1}{2}$ indicate what portion of each brick is hanging beyond its support.

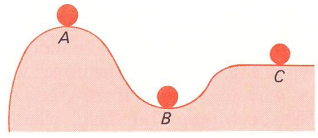


FIGURE 8-38

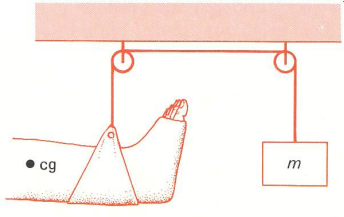
10. Why do you tend to lean backward when carrying a heavy load in your arms?
11. What purpose does a walking stick serve when you are hiking in rough country? Be specific.
12. Place yourself facing the edge of an open door. Position your feet astride the door with your nose and abdomen touching the door's edge. Try to rise on your tiptoes. Why can't this be done?
13. Why is it not possible to sit upright in a chair and rise to one's feet without first leaning forward?
14. Why is it more difficult to do situps when your knees are bent than when your legs are stretched out?
15. Examine how a pair of scissors or shears cuts through a piece of cardboard. Is the name "shears" justified?
16. Materials such as ordinary concrete and stone are very weak under tension or shear. Would it be wise to use such a material for either of the supports of the cantilever shown in Fig. 8-7? If so, which one(s)?

Problems

SECTIONS 8-1 AND 8-2

1. (I) What should be the tension in the wire if the net force exerted on the tooth in Fig. 8-2 is to be 0.50 N? Assume that the angle between the two forces is 160° rather than the 140° in the figure.
2. (I) Calculate the torque about the front support of a diving board exerted by a 60-kg person 3.0 m from that support.
3. (I) Calculate the mass m needed in order to suspend the leg shown in Fig. 8-39. Assume the leg has a mass

FIGURE 8-39



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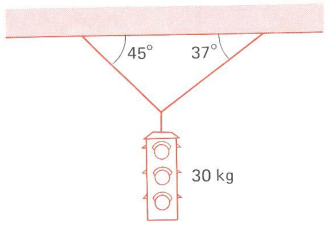
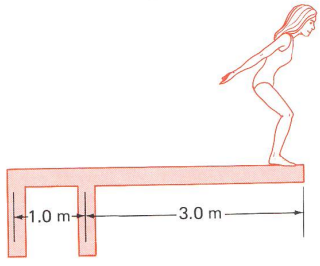


FIGURE 8-40

of 12.0 kg, and its cg is 35.0 cm from the hip joint; the sling is 77.5 cm from the hip joint.

4. (I) Two cords support a chandelier in the manner shown in Fig. 8-4 except the upper wire makes an angle of 45° with the ceiling. If the cords can sustain a force of 1000 N without breaking, what is the maximum weight chandelier that can be supported?
5. (II) Assume in Example 8-1 that the net force as calculated is 10° to the left of where it should point, if the tooth is to move correctly. If the tension to the left is 2.0 N, what should the tension to the right be to make the net force act in the correct direction?
6. (II) Find the tension in the two wires shown in Fig. 8-40.
7. (II) Calculate F_1 and F_2 for the uniform cantilever shown in Fig. 8-7 whose mass is 1200 kg.
8. (II) Calculate the net force required to topple a 60-kg rectangular retaining wall 3.0-m high and 1.2-m thick. Assume the toppling force acts 1.5 m above the base, and that the force exerted by the ground to resist toppling acts at the corner of the base (as in Fig. 8-8).
9. (II) Calculate the forces F_1 and F_2 that the supports exert on the diving board of Fig. 8-41 when a 50-kg person stands at its tip. Ignore the weight of the board.
10. (II) Repeat the problem above taking into account the board's mass of 40 kg. Assume the board's cg is at its center.
11. (II) Calculate the mass m required in Fig. 8-39 to support the leg using the result of Example 6-9 and the values given in Table 6-1 assuming an 88.5-kg person

FIGURE 8-41



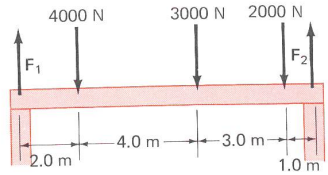
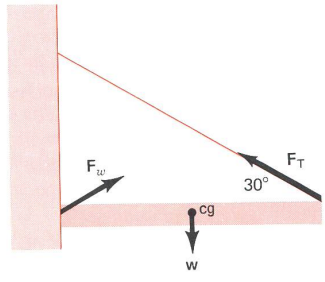


FIGURE 8-42

170 cm tall. The leg pivots about the hip joint and the support acts at the ankle joint.

12. (II) Calculate F_1 and F_2 for the beam shown in Fig. 8-42. Assume it is uniform and has a mass of 250 kg.
13. (II) Calculate the tension F_T in the wire which supports the 20-kg beam shown in Fig. 8-43 and the force $\mathbf{F}_w$ exerted by the wall on the beam (give magnitude and direction).
14. (II) A 150-cm-tall person lies on a light (massless) board which is supported by two scales, one under the feet and one beneath the top of the head. The two scales read, respectively, 29.4 kg and 32.8 kg. Where is the center of gravity of this person?
15. (II) A tightly stretched "high wire" is 50 m long. It sags 3.5 m when a 60-kg tightrope walker stands at its center. What is the tension in the wire? Is it possible to increase the tension in the wire so that there is no sag?
16. (II) The two trees in Fig. 8-35 are 12.5 m apart. Calculate the magnitude of the force $\mathbf{F}$ a backpacker must exert to hold the 15-kg backpack so the rope sags at its midpoint by (*a*) 2.0 m, (*b*) 0.20 m.
17. (II) A uniform 9.5-m-long ladder of mass 18.0 kg leans against a smooth wall (so the force exerted by the wall, $\mathbf{F}_w$, is perpendicular to the wall). The ladder makes a 20° angle with the vertical wall; and the ground is rough. (*a*) Calculate the components of the force exerted by the ground on the ladder at its base, and (*b*) determine what the coefficient of friction at the base of the ladder must be if the ladder is not to slip when a 75-kg person stands three-fourths of the way up the ladder.
18. (II) If the coefficient of friction between the ladder and the ground in the situation described in the preceding

FIGURE 8-43



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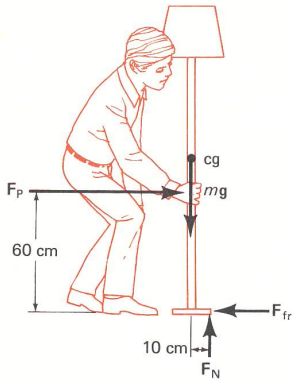


FIGURE 8-44

problem is 0.30, how far up the ladder can the person climb before the ladder starts to slip?

19. (III) A person wants to push a lamp (mass 9.6 kg) across the floor. Assuming the person pushes at a height of 60 cm above the ground and the coefficient of friction is 0.20, determine (*a*) whether the lamp will slide or tip over (Fig. 8-44). (*b*) Calculate the maximum height above the floor at which the person can push the lamp so it slides rather than tips.

20. (III) A home mechanic wants to raise the 220-kg engine out of a car. The plan is to stretch a rope vertically from the engine to a branch of a tree 25 m above. The rope passes over a firmly placed pulley 1.0 m above the engine so that when the mechanic climbs halfway up the tree and pulls horizontally on the rope at its midpoint (12 m below the branch), the engine rises out of the car. How much force must the mechanic exert to raise the engine 0.50 m? Assume the rope doesn't stretch.

21. (III) A 30-kg round table is supported by three legs placed equal distances apart on the edge. What minimum mass, placed on the table's edge, will cause the table to overturn?

22. (III) Two guy wires run from the top of a pole 2.4 m tall that supports a volleyball net. The two wires are anchored to the ground 2.0 m apart and each 2.0 m from the pole. The tension in each wire is 85 N. What is the tension in the net, assumed horizontal and attached at the top of the pole?

*SECTION 8-3

***23.** (I) If the point of insertion of the biceps muscle into the lower arm shown in Fig. 8-10a were 6.0 cm, how much mass could the person hold with a muscle exertion of 400 N?

***24.** (I) Approximately what force, F_M, must the extensor muscle in the upper arm exert on the lower arm to hold a 7.3 kg shotput (Fig. 8-45)? Assume the lower arm has a mass of 2.8 kg and its cg is 12 cm from the pivot point.

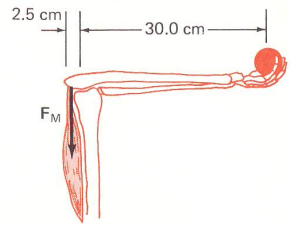


FIGURE 8-45

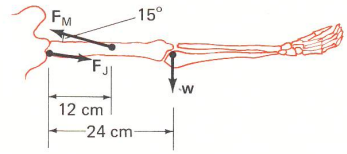


FIGURE 8-46

***25.** (II) Calculate the force required of the "deltoid" muscle, F_M, to hold up the outstretched arm shown in Fig. 8-46. The total mass of the arm is 2.8 kg.

***26.** (II) Suppose the hand in the above problem holds a 10-kg mass. What force, F_M, is required of the deltoid muscle assuming the mass is 50 cm from the shoulder joint?

***27.** (II) Calculate the magnitude of the force F_J exerted by the shoulder on the upper arm at the joint for problems 25 and 26.

***28.** (III) Calculate the magnitude of the force at the base of the spine, $\mathbf{F}_V$ in Fig. 8-11b, if a mass of 20 kg is held in the person's hands. Assume the person has a mass of 70 kg.

***29.** (III) When walking, a person momentarily puts all the weight on one foot. The cg of the body lies over the supporting foot. Figure 8-47 shows the supporting leg and the forces on it. Calculate the force exerted by the "hip abductor" muscles, $\mathbf{F}_M$, and the x and y components of the force $\mathbf{F}_J$ acting on the joint. Take the whole leg as the object under discussion.

***30.** (III) (*a*) Using the information in problem 29, calculate $\mathbf{F}_M$ and $\mathbf{F}_J$, assuming the person carries a 20-kg suitcase in each hand. Assume the cg of each suitcase lies directly below the edge of the hipbone. (*b*) Calculate $\mathbf{F}_M$ and $\mathbf{F}_J$ assuming the person carries a suitcase only in the hand on the side opposite the supporting leg. [*Hint:* first calculate the common cg of the person plus suitcase; this point will be above the foot, thus shifting the horizontal measurements from those shown in Fig. 8-47.]

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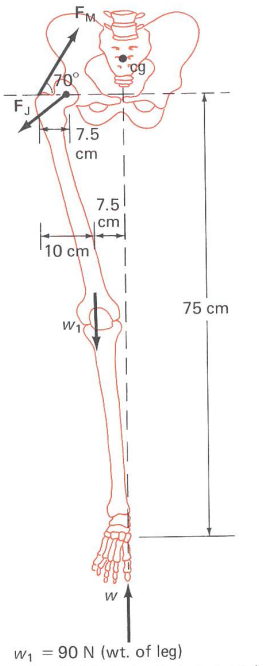


FIGURE 8-47

*SECTION 8-4

*31. (I) One kind of car jack is essentially a lever with a ratchet to hold the lifted object in place while the lever is returned for a new thrust. If the lever is pivoted 2.0 cm from the ratchet and the handle is 35.0 cm long, what is the IMA?

*32. (II) Calculate the force required in Fig. 8-12 taking into account the lever's mass of 12 kg. Assume the cg of the lever is at its center.

*33. (II) Some car jacks work on the principle of a screw. Determine the IMA of a jack in terms of the pitch (distance between threads) P, radius r_1 of the screw, and the turning radius r_2 of the jack handle. Ignore any other effects, such as that due to gears or levers in the jack.

*34. (II) Design a pulley system which can lift 80 kg with a force of (18 kg $\times$ g) assuming an efficiency of 75 percent.

*35. (II) A 38-cm long crank is attached to a spindle with a 2.5-cm radius. Assuming an efficiency of 80 percent, how much weight can be lifted on a cord wrapped around the spindle if the person can exert a steady 50-N force on the crank handle?

*36. (II) An inclined plane (such as used by the Egyptians to build the pyramids) can be considered to be a simple machine since a heavy weight can be raised by the application of a smaller force. (*a*) Calculate the IMA of a plane inclined at an angle of 15° to the horizontal. (*b*) If the coefficient of friction for a particular object on this plane is 0.40, what is the AMA?

SECTION 8-5

37. (II) The Leaning Tower of Pisa is 55 m tall and about 7.0 m in diameter. The top is 4.5 m off-center. Is the tower in stable equilibrium? If so, how much further can it lean before it becomes unstable? Assume the tower is of uniform composition.

38. (III) Four bricks are to be stacked at the edge of a table, each brick overhanging the one below it, so that the top brick extends as far as possible beyond the edge of the table. (*a*) To achieve this, show that the bricks must extend no more than (starting at the top) 1/2, 1/4, 1/6, and 1/8 of their length beyond the one below. (*b*) Is the top brick completely beyond the base? (*c*) Determine a general formula for the maximum total distance spanned by n bricks if they are to remain stable. (*d*) A builder wants to construct a corbeled arch (Figure 8-27) based on the principle of stability discussed in (*a*) and (*c*) above. What minimum number of bricks, each 0.30 m long, is needed if the arch is to span 1.0 m?

SECTION 8-6

39. (I) A marble column of cross-sectional area 2.0 m^2 supports a mass of 20,000 kg. (*a*) What is the stress within the column? (*b*) What is the strain?

40. (I) By how much is the column in the previous problem shortened if it is 10-m high?

41. (I) If the supports in Example 8-8 were 10 m high, how much would they shorten?

42. (II) How much force is required to stretch a steel piano wire of 0.050 cm diameter by 0.015 percent?

43. (II) If the two wires in Fig. 8-40 are made of steel wire 1.0 mm in diameter, what is the percentage stretch of each because of the load?

44. (II) A 15-cm-long animal tendon was found to stretch 3.1 mm by a force of 12.4 N. The tendon was approximately round with an average diameter of 8.5 mm. Calculate the elastic modulus of this tendon.

45. (II) How much pressure is needed to compress the volume of an iron block by 0.10 percent? Express answer in N/m^2, and compare it to atmospheric pressure (1.0×10^5 N/m^2).

46. (II) One liter of alcohol (1000 cm^3) in a flexible container is carried to the bottom of the sea where the pressure is 2.4×10^6 N/m^2. What will its volume be now?

47. (III) A scallop forces open its shell with an elastic material called abductin whose elastic modulus is about 2.0×10^6 N/m^2. If this piece of abductin is 3.0 mm thick and has a cross-sectional area of 0.50 cm^2, how much potential energy does it store when compressed 1.0 mm?

48. (III) A pole projects horizontally from the front wall of a shop. A 4.5-kg sign hangs from the pole at a point 2.4 m from the wall. (*a*) What is the torque due to this

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sign calculated about the point where the pole meets the wall? (*b*) If the pole is not to fall off, there must be another torque exerted to balance it. What exerts this torque? Use a diagram to show how this torque must act. (*c*) Discuss whether compression, tension, and/or shear play a role in part (*b*).

SECTION 8-7

49. (I) The femur bone in the leg has an average effective cross section of about 3.0 cm^2 ($= 3.0 \times 10^{-4}$ m^2). How much compressive force can it withstand before breaking?

50. (II) If a compressive force of 3.0×10^4 N is exerted on the end of a 20-cm-long bone of cross-sectional area 3.6 cm^2, (*a*) will the bone break, and (*b*) if not, by how much does it shorten?

51. (II) What is the minimum cross-sectional area required of a vertical steel wire from which is suspended a 250-kg chandelier? Assume a safety factor of 4.

52. (II) Assume the supports of the cantilever shown in Fig. 8-7 (mass = 7200 kg) are made of wood. Calculate the minimum cross-sectional area required of each, assuming a safety factor of 8.

53. (II) An iron bolt is used to connect two iron plates together. The bolt must withstand shear forces up to about 2000 N. Calculate the minimum diameter for the bolt, based on a safety factor of 4.

54. (II) In Example 6-4 in Chapter 6 we calculated the impulse and average force on the leg of a person who jumps 5.0 m down to the ground. If the legs are not bent upon landing, so the body moves a distance d of only about $d = 1.0$ cm during collision, determine (*a*) the stress in the tibia bone (area $= 3.0 \times 10^{-4}$ m^2) and (*b*) whether or not the bone will break. (*c*) Repeat for a bent-knees landing ($d = 50.0$ cm).

55. (II) The roof of a 7.5 m × 10.0 m room in a school is to support a uniformly distributed load of 10,000 kg (133 kg/m^2) in addition to its own mass of 4100 kg. The roof is to be supported by "2 × 4s" (actually about 4.0 × 9.0 cm) along the 10.0-m sides. How many supports are required on each side and how far apart must they be? Consider only compression and assume a safety factor of 15.

56. (III) There is a maximum height of a uniform vertical column made of any material that can support itself without buckling, and it is independent of the cross-sectional area (why?). Calculate this height for (*a*) steel (density 7.8×10^3 kg/m^3), (*b*) granite (density 2.7×10^3 kg/m^3).

57. (III) From what height must a 1.2-kg rectangular brick 15.0 cm × 6.0 cm × 4.0 cm be dropped above a rigid steel floor in order to break the brick? Assume the brick strikes the floor directly on its largest face, and that the compression of the brick is much greater than that of the steel (that is, ignore compression of the steel). State other simplifying assumptions that may be necessary.

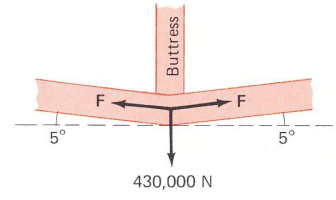
58. (III) A steel cable is to support an elevator whose total (loaded) mass is not to exceed 2200 kg. If the maximum acceleration of the elevator is 1.0 m/s^2, calculate the diameter of cable required. Assume a safety factor of 5.0.

*SECTION 8-8

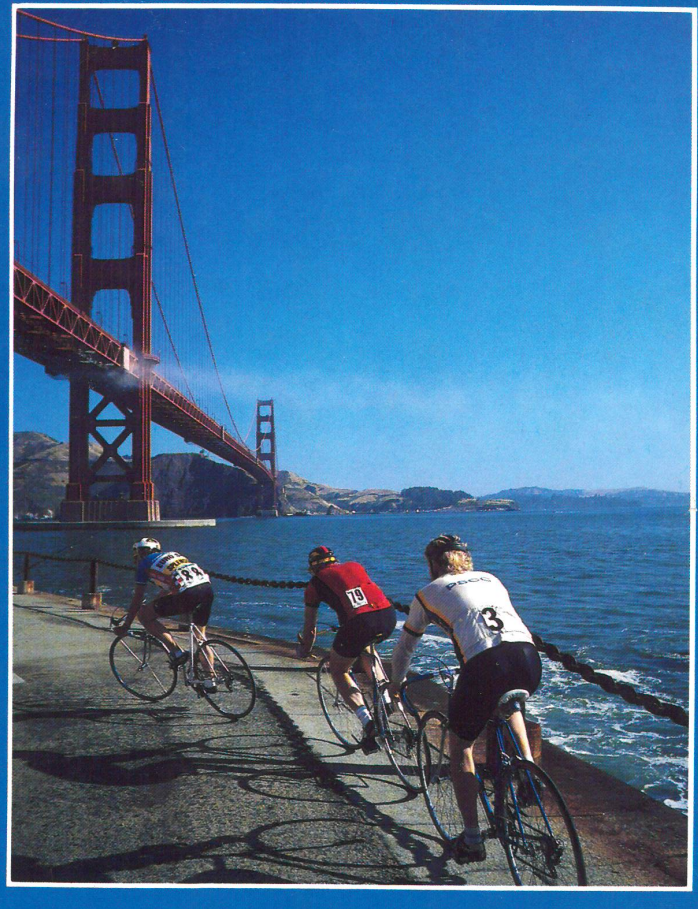
***59.** (II) How high must a pointed arch be if it is to span a space 8.0 m wide and exert one-third the horizontal force at its base that a round arch would?

***60.** (II) The subterranean tension ring that exerts the balancing horizontal force on the abutments in Fig. 8-33 is 36 sided so each segment makes a 10° angle with the adjacent one, Fig. 8-48. Calculate the tension F that must exist in each segment so that the required force of 4.3×10^5 N can be exerted at each corner (Example 8-9).

FIGURE 8-48



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