Force and Motion

Force

Force is anything that tends to cause motion, change motion, stop motion, or prevent motion. This force acts on the mass of an object, so to be technically accurate, we should define it in terms of mass. But since this is a practical rather than theoretical text, we will consider the effect of gravity on the mass and use pounds and ounces of weight, rather than poundals of force.

poundal. The unit of force in the foot-pound-second system of measurement that is required to accelerate a mass of 1 pound, 1 foot per second, per second.

Mechanical Advantage

Many mechanical devices allow us to work with the force we have and afford us a mechanical advantage in which we exchange distance for force or speed. The most widely used mechanical advantage devices are the lever, the pulley, the inclined plane, and the gear train.

mechanical advantage. The increase in force or speed produced by mechanical devices such as levers, pulleys, gears, or hydraulic cylinders.

When we have a flat tire on our car, we need some way to increase the amount of force we can produce with our arms so that it will be great enough to lift the car. We normally do this with a jack. If the jack allows us to raise 350 pounds of weight by pushing down on the handle with a force of 35 pounds, the jack gives us a mechanical advantage of 10.

350 Pounds = Force out
35 Pounds = Force in
$350 \div 35 = 10$

We increase the force we use 10 times, but we do not get something for nothing. Work is the amount of force times the distance the force acts, and we must put exactly the same amount of work into the jack that we get out of it. For each stroke of the jack handle to raise the car 1 inch, we must move the jack handle down 10 inches. The amount of work the jack does is 350 pounds times 1 inch, or 350 inch-pounds. We have done exactly the same amount of work on the jack handle: We have moved a force of 35 pounds through a distance of 10 inches, or we have done 350 inch-pounds of work on the jack handle.

There are several ways we can obtain mechanical advantage and nearly all machines use one or more. *See* Figure 3-18.

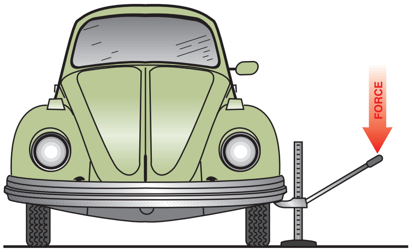


Figure 3-18. *An automobile jack is a form of lever we use to get a mechanical advantage. A small force acting downward produces a much larger force acting upward.*

The Law of the Lever

The basic lever is a rigid arm supported on a fulcrum in such a way that a force can be applied to cause rotation. We see a basic lever in Figure 3-19. A force applied to one end of the lever, the force arm, causes the other end, the weight arm, to move in the opposite direction and lift the weight.

lever. A rigid bar, free to pivot, or rotate about a point called the fulcrum. An input force is applied at one point, and an output force is taken from the lever at another point.

arm. The distance on a lever between the fulcrum and the point of application of the force or the weight.

moment. A force that causes rotation of a lever. A moment is the product of a weight and its arm.

The arm of the lever is the distance between the fulcrum and the point where the force or weight is applied. The lever is balanced when the force moment, the amount of force times the length of the force arm, is equal to the weight moment, the weight times the length of the weight arm. Moments are usually expressed in pounds-feet.

Force · Arm = Force Moment
Weight · Arm = Weight Moment

Moments try to cause rotation, and in Figure 3-19, the force moment tries to rotate the lever in a clockwise direction and is called a positive moment. The weight moment tries to rotate the lever in the counterclockwise direction and is called a negative moment.

In Figure 3-19, we see one of the more important facts about the lever: The lever is balanced when the weight moment equals the force moment. Another way to express this is that the lever is balanced when the algebraic sum of the moments is zero.

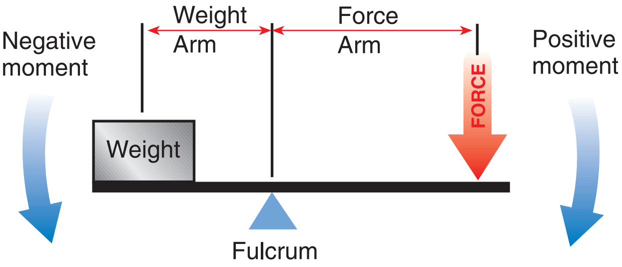


Figure 3-19. *When the lever is balanced, the sum of the moments about the fulcrum is zero.*

First-Class Lever

The lever in Figure 3-20 is a first-class lever, one whose fulcrum is between the force and the weight, with the weight moving in the direction opposite the direction of the force.

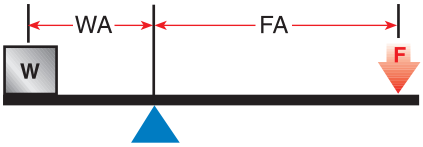


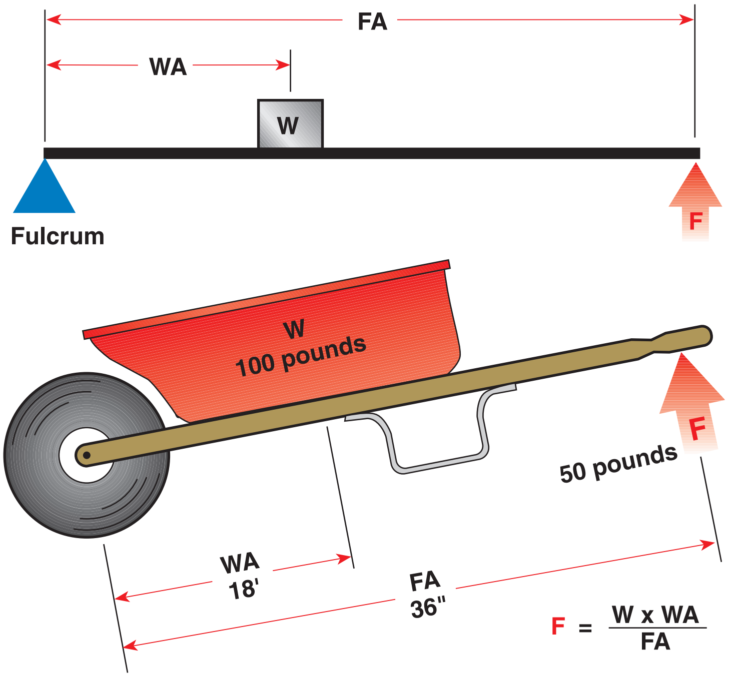
Figure 3-20. *First-class lever*

Second-Class Lever

A second-class lever is one in which the weight is between the fulcrum and the force, and the weight moves in the same direction as the force. A wheelbarrow is a good example of a second-class lever. *See* Figure 3-21.

The wheel of the wheelbarrow acts as the fulcrum, and the center of the handgrip is the point at which the force is applied. The load is the weight.

The same law of the lever applies to the second-class lever as applies to the first-class lever. The lever is balanced when the weight moment and the force moment are equal.



$$F = \frac{W \times WA}{FA}$$

$$= \frac{100 \times 18}{36}$$

$$= 50 \text{ pounds}$$

This problem can also be worked as a proportion:

Force:Weight = Weight Arm:Force Arm
Force:100 = 18:36
Force x 36 = 1,800
Force = 1,800 ÷ 36 = 50 pounds

See Page 35 for more on proportion.

Figure 3-21. *Second-class lever*

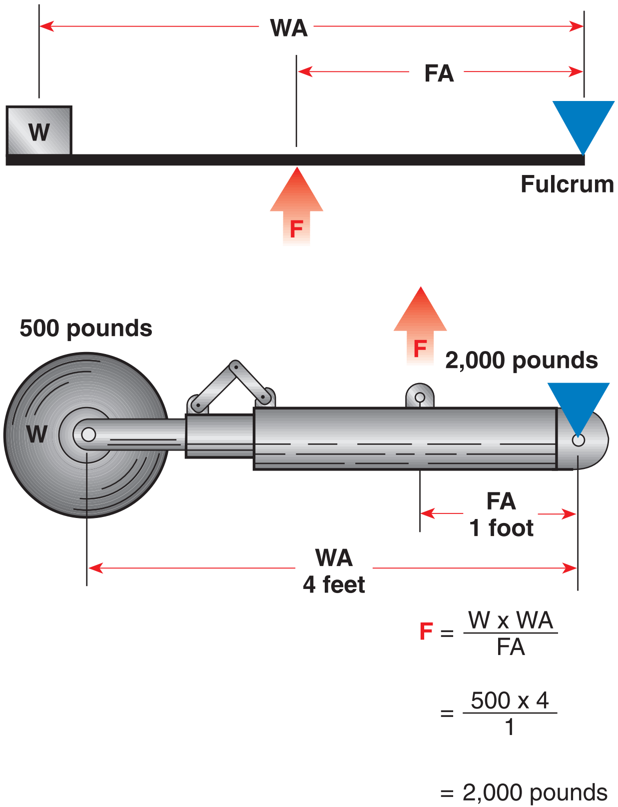
Third-Class Lever

We sometimes want to move the weight a greater distance than the force can act, or we may want the weight to move faster. To do this, we can use a third-class lever in which the force is applied between the fulcrum and the weight, and the weight moves in the same direction as the force.

In the retractable landing gear in Figure 3-22, the weight of 500 pounds has an arm of 4 feet. This gives a weight moment of 2,000 pounds-feet. This must be balanced with a force whose arm is only 1 foot.

To raise the landing gear, we must apply a force of 2,000 pounds, but we can raise the wheel 4 feet by moving the point where the force is applied by only 1 foot.

This lever requires 4 times as much force as the weight it lifts, but it moves the weight 4 times as far as the force moves, in the same length of time.

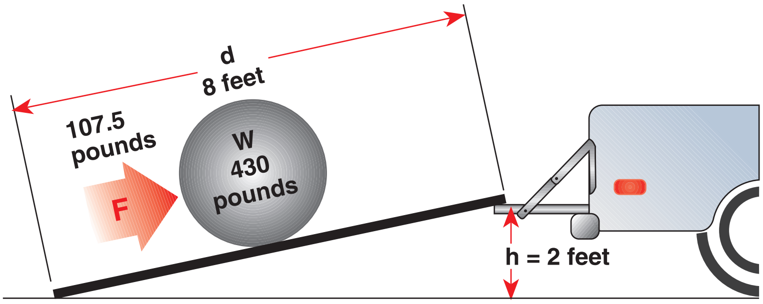


$$F = \frac{W \times WA}{FA} = \frac{500 \times 4}{1} = 2{,}000 \text{ pounds}$$

Figure 3-22. *Third-class lever*

The Inclined Plane

The inclined plane is one of the simple machines that is used to gain mechanical advantage. Suppose we want to load a drum of oil into a truck, but we do not have any form of hoist with which to lift it. We can use a long board as an inclined plane. Put one end on the bed of the truck and the other end on the ground. We can roll the drum up the board, with much less force than we would need to lift it straight up off the ground.



W = 430 pounds
h = 2 feet
d = 8 feet

$$F = \frac{W \times h}{d}$$

$$= \frac{430 \times 2}{8}$$

$$= 107.5 \text{ pounds}$$

Figure 3-23. *An inclined plane is used to gain a mechanical advantage.*

To find the amount of force needed to roll the drum into the truck, use the formula in Figure 3-23. A force of only 107.5 pounds is needed to roll the 430 pound drum into the truck. However, we will have to roll it 8 feet to raise it only 2 feet.

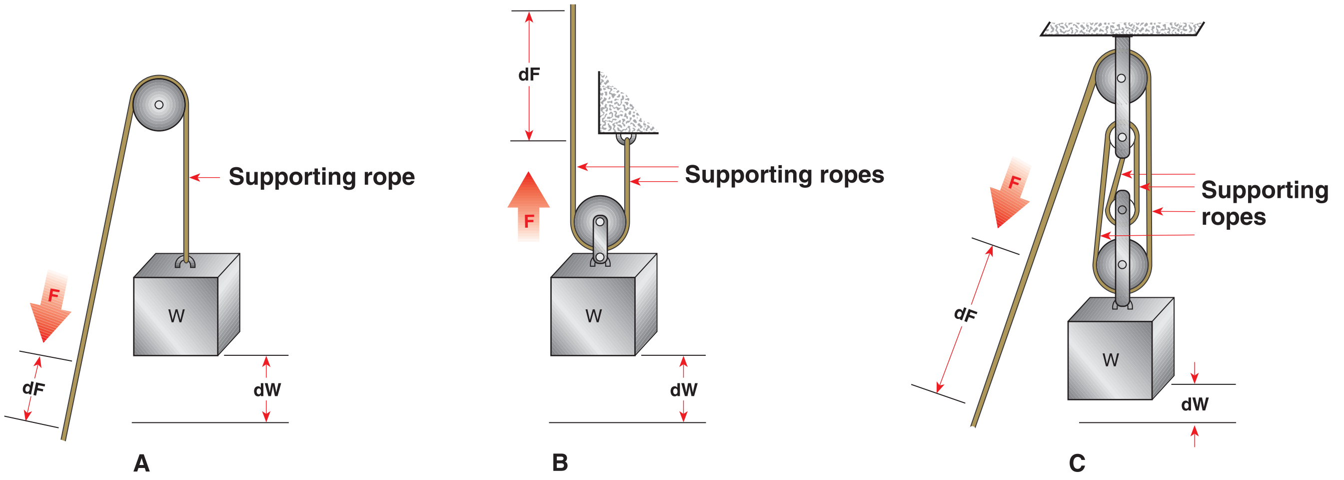
Ropes and Pulleys

One of the oldest methods of gaining mechanical advantage is by using ropes and pulleys, and we find the mechanical advantage by counting the number of sections of ropes that support the weight being lifted.

In Figure 3-24A the weight is supported by 1 section of rope. In order to lift a 100-pound weight, we need a force of 100 pounds; and if we raise the weight 1 foot, we will have to pull the rope 1 foot. The wheel, or pulley, changes the direction of the force, but it does not give any mechanical advantage.

If we attach the pulley to the weight and use 2 sections of rope to support it, as we have in Figure 3-24B, we have a mechanical advantage of 2. We need a force of only 50 pounds to lift it. But, we will have to pull 2 feet of rope to lift the weight 1 foot.

A group of pulleys, such as we see in Figure 3-24C, is called a block and tackle. Here we have four sections of rope supporting the weight. The force required to lift the load is only 25 pounds, but we must pull 4 feet of rope to raise the weight 1 foot.



A. *With one section of supporting rope, no mechanical advantage is gained.*

B. *Two sections of supporting rope give a mechanical advantage of 2.*

C. *Four sections of supporting rope give a mechanical advantage of 4.*

Figure 3-24

Gears

Gears are special wheels with notches and teeth on their outside edge. By meshing the teeth of one gear with the teeth on another, one gear can drive the other gear without slipping.

We can determine the mechanical advantage of a set of gears by counting the teeth of both gears. In the set of gears we see in Figure 3-25, the large drive gear has 90 teeth and turns in a counterclockwise direction. The smaller driven gear has 60 teeth and turns faster, and in the opposite, or clockwise, direction.

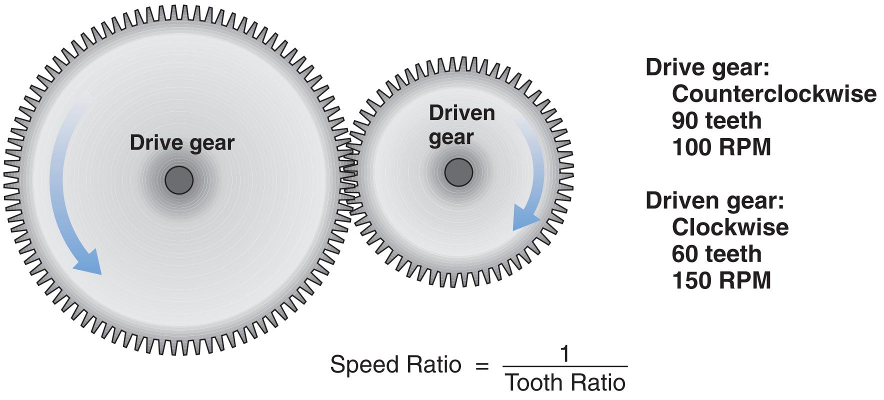


Figure 3-25. *Gears are used to change the direction of rotation between shafts and to gain a mechanical advantage.*

To find the speed of the driven gear, find the ratio of the number of teeth in the two gears. The drive gear has 1.5 times as many teeth as the driven gear, and so the driven gear will turn 1.5 times as fast as the drive gear. When the drive gear turns at 100 RPM, the driven gear will turn at 150 RPM.

Motion

Motion is the action in which objects change their position. Motion requires energy and is an essential component of work. In this section, we will discuss the difference between speed and velocity, see the way vectors can be combined, and consider each of Newton's important laws of motion.

vector. A quantity which has both direction and magnitude.

Speed and Velocity

Speed is a rate of motion, and velocity is a rate of motion in a specified direction. Speed is normally measured in units such as feet per second, miles per hour, or knots, and does not take direction into consideration. If an airplane flies north at 120 miles per hour, its speed is 120 miles per hour, but its velocity is 120 miles per hour, to the north.

Change in Speed

When an object increases its speed, it accelerates, and acceleration is measured in feet per second, per second, or feet per second2 (read as feet per second squared). When an object decreases its speed, it decelerates, and deceleration is negative acceleration. If an object falls freely in a vacuum, it is acted upon only by the force of gravity; and as it falls, it accelerates 32.2 feet per second each second it falls. This is called the acceleration due to gravity.

accelerate. To increase speed or to make an object move faster.

We use this value to find the mass of matter. We saw earlier that mass is the amount of matter in an object, and weight is the effect gravity has on the mass. We can find the mass of an object by dividing its weight, in pounds, by 32.2.

$$\text{Mass} = \frac{\text{Weight}}{32.2}$$

To find the amount of thrust a gas turbine engine is producing, first find the mass of the air flowing through the engine, then multiply this mass by the amount the air speeds up as it passes through the engine.

For example, assume that 100 pounds of air passes through an engine each second, and this air speeds up from zero feet per second to 900 feet per second. Find the amount of thrust by the formula:

$f = M \cdot a$

f = the pounds of thrust produced by accelerating the air as it passes through the engine

M = the mass of the air

a = the change in velocity of the air as it passes through the engine

$$\begin{aligned} f &= M \cdot a \\ &= \frac{100}{32.2} \cdot 900 \\ &= 2{,}795.0 \text{ pounds of thrust} \end{aligned}$$

Newton's Laws of Motion

Many of the properties of objects are explained by Newton's three laws of motion.

inertia. The characteristic of all matter that causes an object to remain in its present condition.

Newton's first law explains that when an object is at rest, it tries to remain at rest. But when it is moving, it tries to keep moving in a straight line and will not speed up, slow down, or turn unless it is acted upon by an outside force. This tendency of the object to remain in its original condition of motion is called inertia.

Newton's second law is called the law of acceleration: the amount of acceleration depends upon the mass of the object and the amount of force used. Acceleration is directly proportional to the amount of force that acts upon the object and inversely proportional to its mass.

Newton's third law is called the action-reaction law. It says that for every action, there is an equal and opposite reaction.

Circular Motion

When a bucket of water with a rope tied to its handle is swung in a circle, two interesting things happen. First, the water stays at the bottom of the bucket, which is now straight up and down, and it does not spill out. Also, the faster we swing the bucket, the heavier it becomes.

The bucket of water is obeying two of Newton's laws of motion, the first law which says that an object in motion will try to remain in motion in a straight line unless it is acted upon by an outside force; and the third law which says that for every action there is an equal and opposite reaction. *See* Figure 3-26.

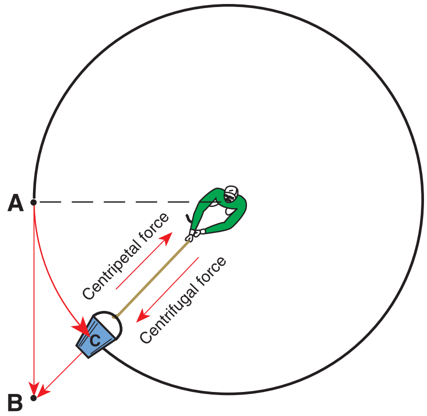


Figure 3-26. *The bucket of water is trying to obey Newton's first law and travel in a straight line from A to B. But the rope holds it along the curved path A to C. The resultant, C-B, is the centrifugal force, and this is the force that holds water in the bucket and makes the bucket heavier.*

When we start the bucket of water swinging, we put energy into it, and this energy tries to carry the bucket and the water away from us in a straight line. However, the bucket can go only as far from us as the rope allows. The rope holds it in a circular path around our body.

As the bucket is held in its circular path by the rope, it tries to travel in a straight line. The force trying to cause the bucket to travel in a straight line is opposed by the rope and is called centrifugal force. It is greater than the force of gravity that tries to pull the bucket and the water down, and it holds the water against the bottom of the swinging bucket.

As the bucket swings, centrifugal force causes the action that tries to pull it away from us. It is prevented from flying away by the force on the rope, which is the reaction. The faster the bucket swings, the greater the centrifugal force. The force on the rope opposing the centrifugal force is called centripetal force, and its magnitude is exactly equal to the centrifugal force.

magnitude. The amount of a force.

Helicopter rotor blades droop when the helicopter is parked on the ramp and the rotor is not turning. This droop is caused by gravity pulling the blades down. But as soon as the rotor starts turning, centrifugal force becomes greater than the force of gravity, and it pulls the blades straight out. *See* Figure 3-27.

Figure 3-27. *When a helicopter rotor is not turning, gravity causes the blades to droop. But when the rotor is turning, centrifugal force holds the blades straight out.*

On some small helicopters, the centrifugal force acting on the rotor is about 20,000 pounds for each blade. For some of the larger helicopters, this force can be as much as 100,000 pounds for each blade. The hub and blade grips must be strong enough to withstand this great amount of force.