

SIMPLE MACHINE ELEMENTS*

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Abstract

The simple mechanical elements that comprise complex machines, like robots, are described.

Complex machines are made up of moving parts such as levers, gears, cams, cranks, springs, belts, and wheels. Machines deliver a certain type of movement to a desired location from an input force applied somewhere else. Some machines simply convert one type of motion to another type, such as rotary to linear. While there is a seemingly endless variety of machines, they are all based upon simple machine elements. The elements discussed here include inclined planes, levers, wheels and axles, pulleys, and screws.

It is important to remember that all machines are limited in their efficiency by friction. No machine is 100 percent efficient in its efforts, so the mechanical advantage gained will require additional energy to accomplish the task. For more information on friction, see this module¹

1 The Inclined Plane

An **inclined plane** decreases the force required to raise an object a given height by increasing the distance over which that force must be applied, see Figure 1. Imagine lifting something twice your weight to a 4 foot high shelf. Now imagine rolling the same mass up a gently sloping surface. The latter would be much easier. Inclined planes are commonly put to use in cutting devices and often two inclined planes are put back to back to form a wedge. In a wedge, forward movement is converted into a parting movement acting perpendicular to the face of the blade. A zipper is simply a combination of two lower wedges for closing and an upper wedge for opening, as shown in Figure 2.

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¹"Introduction" <<http://cnx.org/content/m11106/latest/>>

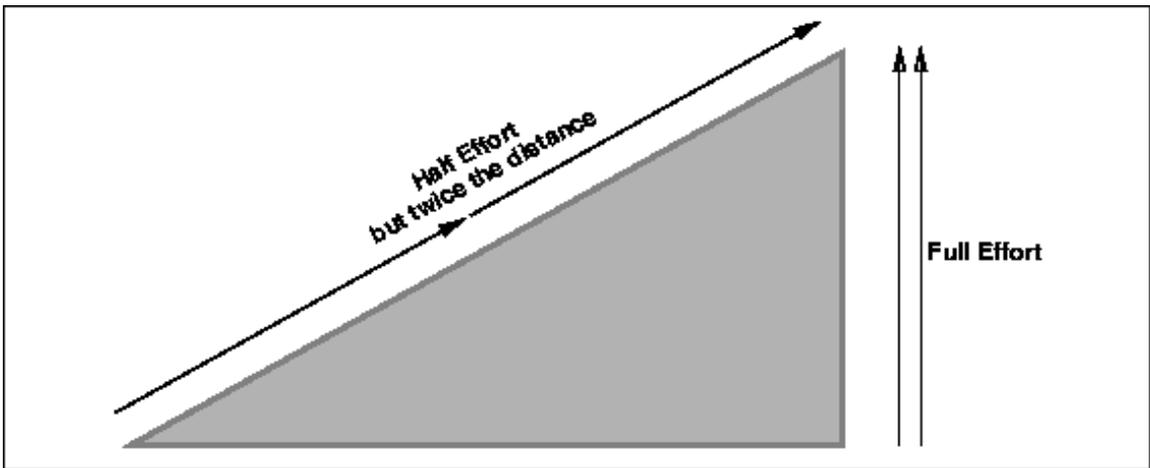


Figure 1: Inclined Plane

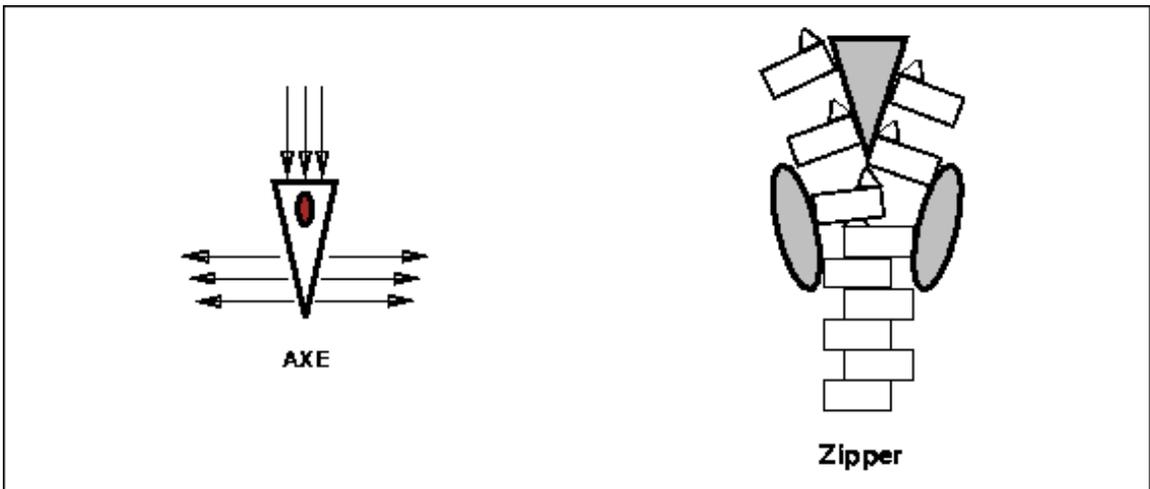


Figure 2: The Inclined Plane at Work

1.1 The Screw

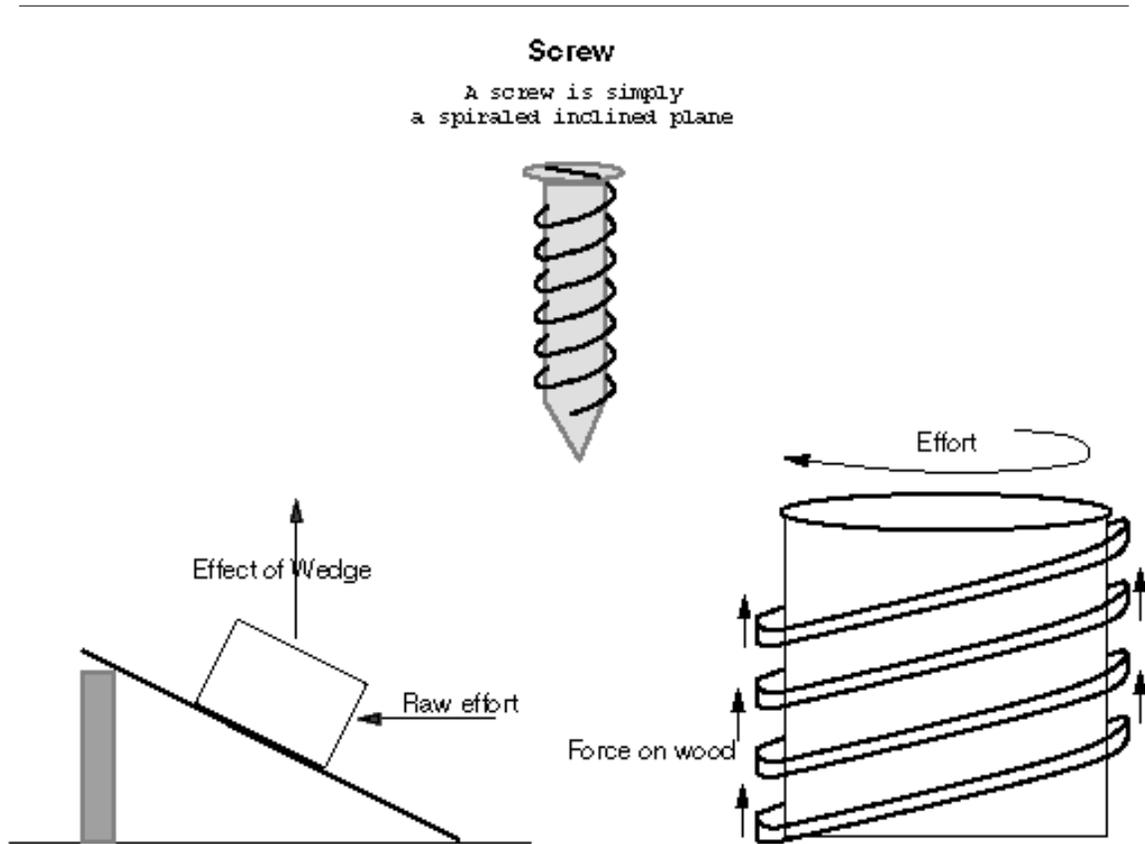


Figure 3: The Screw

The **screw** is basically an inclined plane (see Figure 3) wrapped around a cylinder. In an inclined plane, a linear force in the horizontal plane is converted to a vertical "lifting" force. With a screw, a rotary force in the horizontal plane is converted to a vertical "lifting" force.

When a wood screw is turned, the threads of the screw push up on the wood. A reaction force from the wood pushes back down on the screw threads and in this way the screw moves down even though the force of turning the screw is in the horizontal plane. Screws are known for high friction, which is why they are used to hold things together. A worm gear is sometimes used in machines, but they also have high friction that can waste considerable power.

2 Levers

A **lever** has three points of interest: the fulcrum, the load, and the effort applied to the lever. The **fulcrum** is the point around which the lever pivots rotationally. The **load** is what we wish to manipulate with the lever, and the load is described by its position relative to the fulcrum, and the force (magnitude and direction) it exerts at that point. The **effort** is also a force that has a magnitude and a direction, and a position with respect to the fulcrum. A lever is used to change the direction of movement, and to trade the

magnitude of the effort for the distance over which the effort is applied.

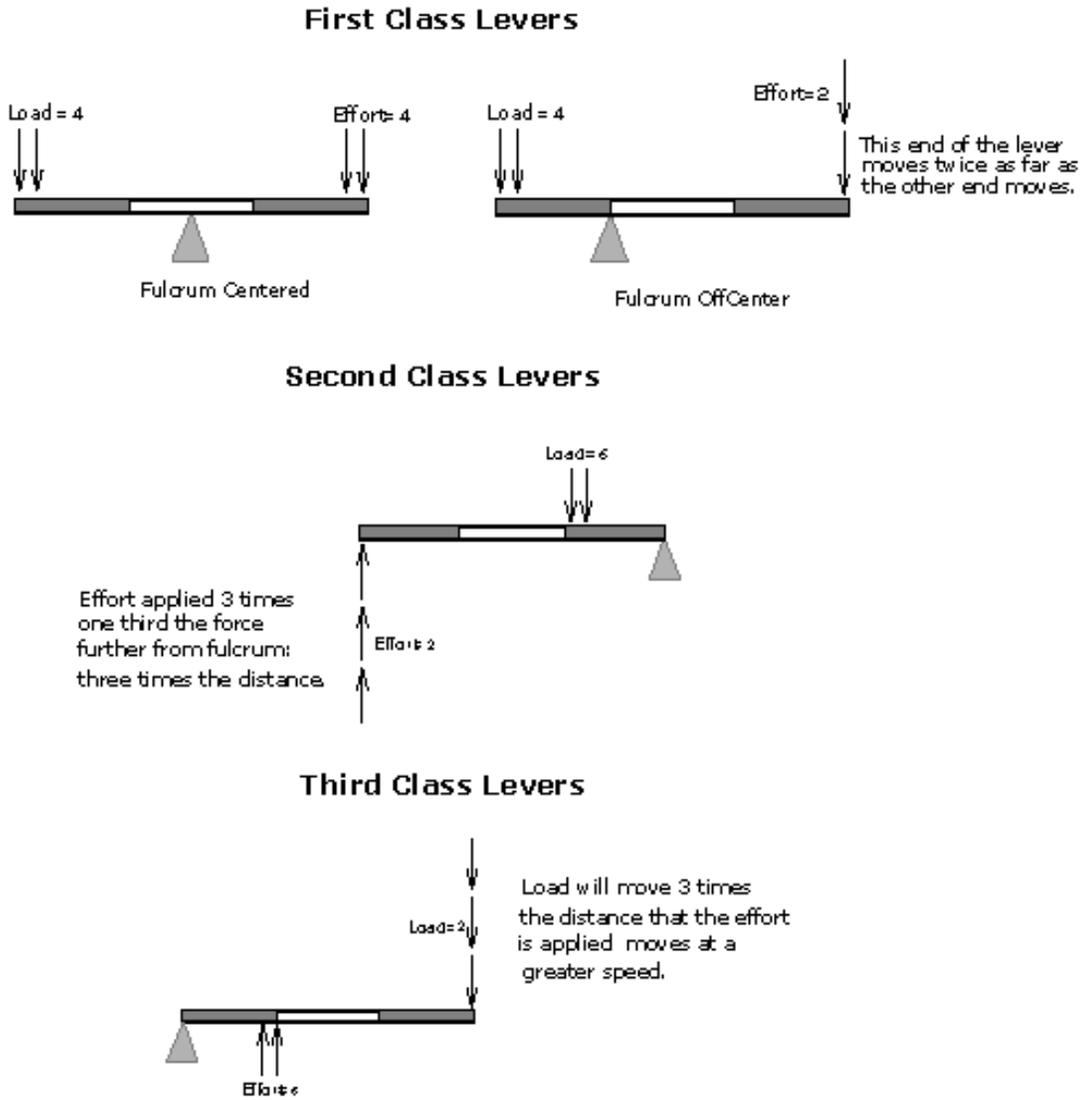


Figure 4: Classes of Levers

As shown in Figure 4, there are three different classes of levers defined by the relative positions of the fulcrum, effort, and load. A **first class lever** has the fulcrum positioned between the effort and the load. Examples of first class levers include: a balance, a crow bar, and scissors. In a **second class lever** the load is placed between the fulcrum and the effort. Examples of second class levers include: a wheelbarrow, a bottle opener, and a nutcracker. **Third class levers** place the effort between the fulcrum and the load. Examples of a third class lever are a hammer, a fishing rod, and tweezers. Most machines that employ levers

use a combination of several levers, often of different classes.

3 The Wheel and Axle

Both levers and the inclined plane lower the force required for a task at the price of having to apply that force over a longer distance. With wheels and axles the same is true: a powerful force and movement of the axle is converted to a greater movement, but less force, at the circumference of the wheel. In a circular geometry, **torque** is a more useful concept than force and distance. You can learn more about torque here². The **wheel and axle** can be thought of as simply a circular lever, as shown in Figure 5. Many common items rely on the wheel and axle such as the screwdriver, the steering wheel, the wrench, and the faucet.

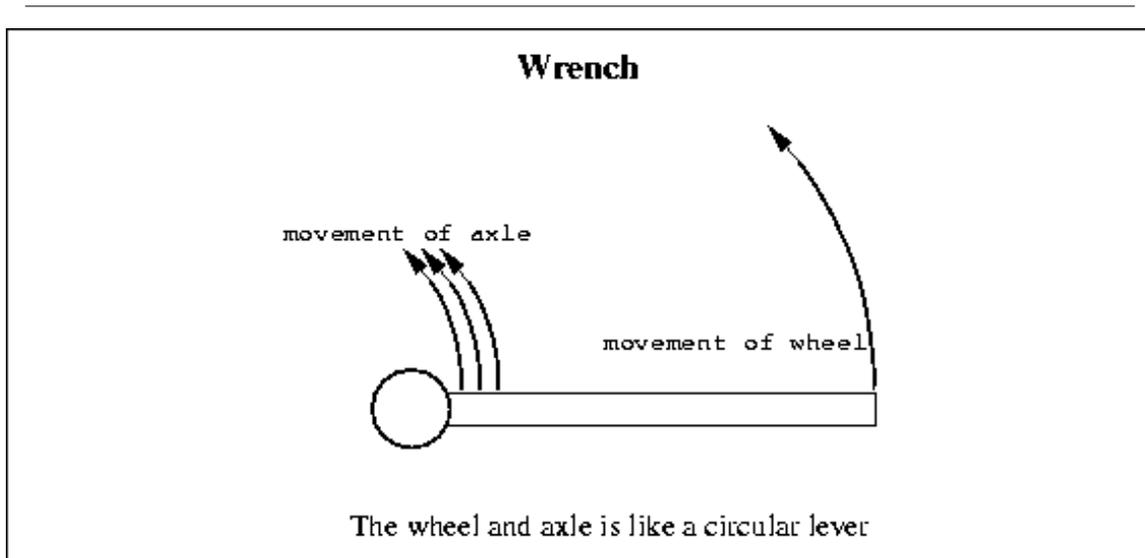


Figure 5: The Wheel and Axle

3.1 Gears and Belts

A wheel and axle assembly becomes especially useful when combined with gears and belts. **Gears** can be used to change the direction or speed of movement, but changing the speed of rotation inversely affects the force transmitted. A small gear meshed with a larger gear will turn faster, but with less force. There are four basic types of gears: spur gears, rack and pinion gears, bevel gears, and worm gears. **Spur gears** are probably the type of gear that most people picture when they hear the word. The two wheels are in the same plane (the axles are parallel). With **rack and pinion gears** there is one wheel and one rack, a flat toothed bar that converts the rotary motion into linear motion. **Bevel gears** are also known as pinion and crown or pinion and ring gears. In bevel gears, two wheels intermesh at an angle changing the direction of rotation (the axles are not parallel); the speed and force may also be modified, if desired. **Worm gears** involve one wheel gear (a pinion) and one shaft with a screw thread wrapped around it. Worm gears change the direction of motion as well as the speed and force. **Belts** work in the same manner as spur gears except that they do not change the direction of motion.

²"Introduction" <<http://cnx.org/content/m11106/latest/>>

In both gears and belts, the speed and force is altered by the size of the two interacting wheels. In any pair, the bigger wheel always rotates more slowly, but with more force. On both the big and the small gear, the linear velocity at the point of contact for the wheels is equal. If it was unequal and one gear were spinning faster than the other at the point of contact then it would rip the teeth right off of the other gear. As the circumference of the larger gear is greater, a point on the outside of the larger gear must cover a greater distance than a point on the smaller gear to complete a revolution. Therefore the smaller gear must complete more revolutions than the larger gear in the same time span. (It's rotating more quickly.)

The force applied to the outer surface of each wheel must also be equal otherwise one of them would be accelerating more rapidly than the other, and again the teeth of the other wheel would break. However, the forces the forces applied to the axles are not equal. Returning to the concept of levers, we know that the distance from the fulcrum at which the force is applied effects the force applied at another point, and a wheel and axle works like a lever. Equal forces are being applied to each wheel, but on the larger wheel that force is being applied at a greater distance from the axle. Thus, for the larger wheel, the force on the axle is greater than the force on the axle of the smaller wheel.

4 Cams and Cranks

Both cams and cranks are useful when a repetitive motion is desired. **Cams** make rotary motion a little more interesting by essentially moving the axle off-center. Cams are often used in conjunction with a rod. One end of the rod is held flush against the cam by a spring. As the cam rotates the rod remains stationary until the "bump" of the cam pushes the rod away from the cam's axle. Cams can be used to create either a linear repetitive motion such as the one illustrated in Figure 6, or a repetitive rotational motion such as using a cam and a rubber band.

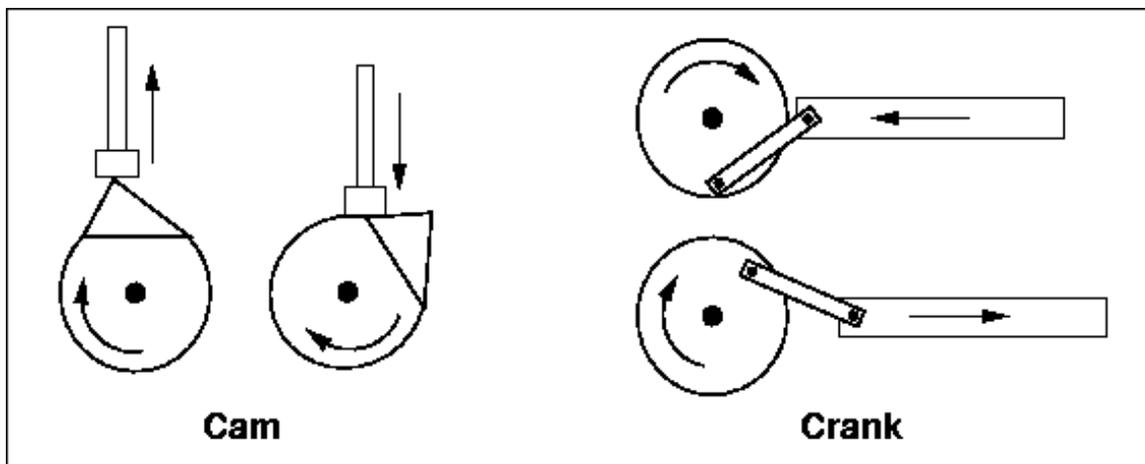


Figure 6: Cams and Cranks

Cranks convert rotary motion into a piston-like linear motion. The best examples of cranks in action are the drive mechanism for a steam locomotive and the automobile engine crankshaft. In a crank, the wheel rotates about a centered axle, while an arm is attached to the wheel with an off-centered peg. This arm is attached to a rod fixed in a linear path. A crank will cause the rod to move back and forth. If instead the rod is pushed back and forth, it will cause the crank to turn. On the other hand, cams can move their rods, but rods cannot move the cams.

5 Pulleys

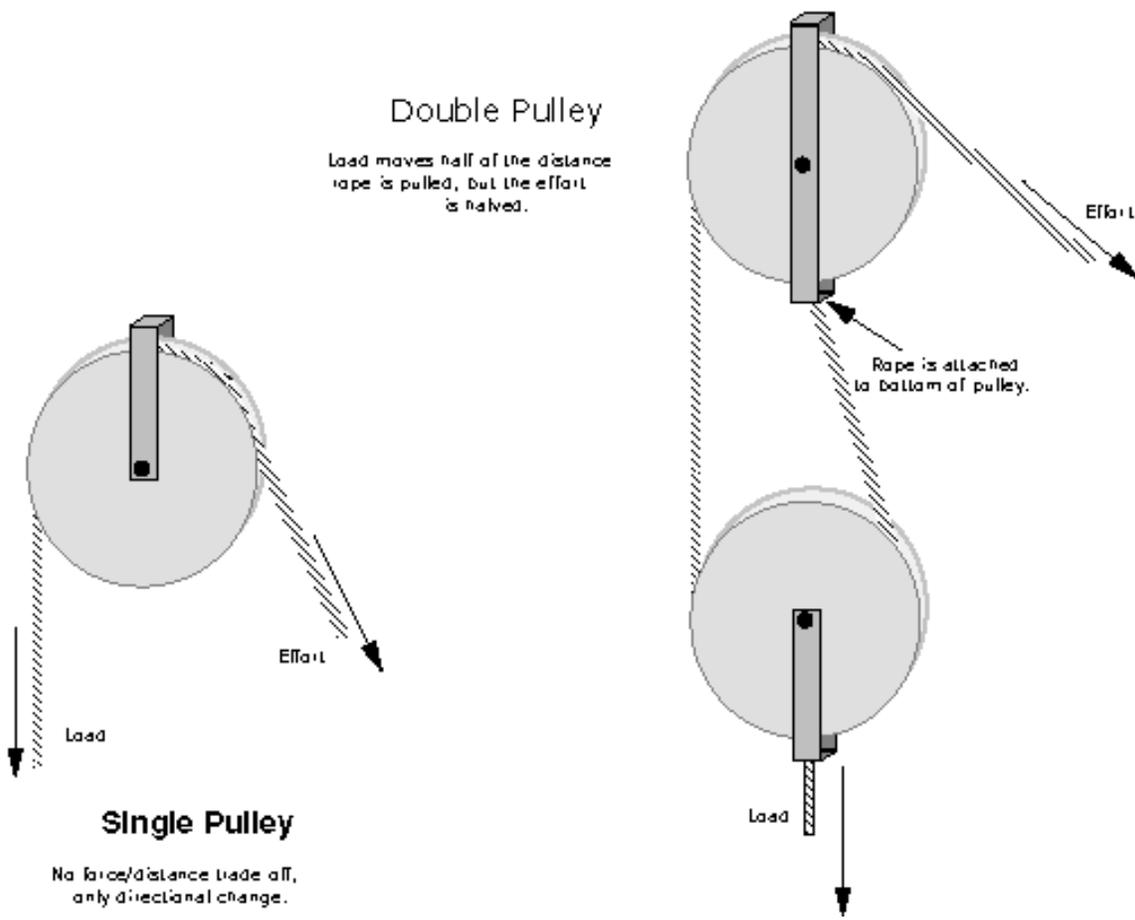


Figure 7: Pulleys

Pulleys can be used to simply change the direction of an applied force or to provide a force/distance tradeoff in addition to a directional change, as shown in Figure 7. Pulleys are very flexible because they use ropes or chain to transfer force rather than a rigid object such as a rod. Ropes can be routed through virtually any path. They are able to abruptly change directions in three-dimensions without consequence, except, of course, additional friction. Ropes can be wrapped around a motor's shaft and either wound up or let out as the motor turns.

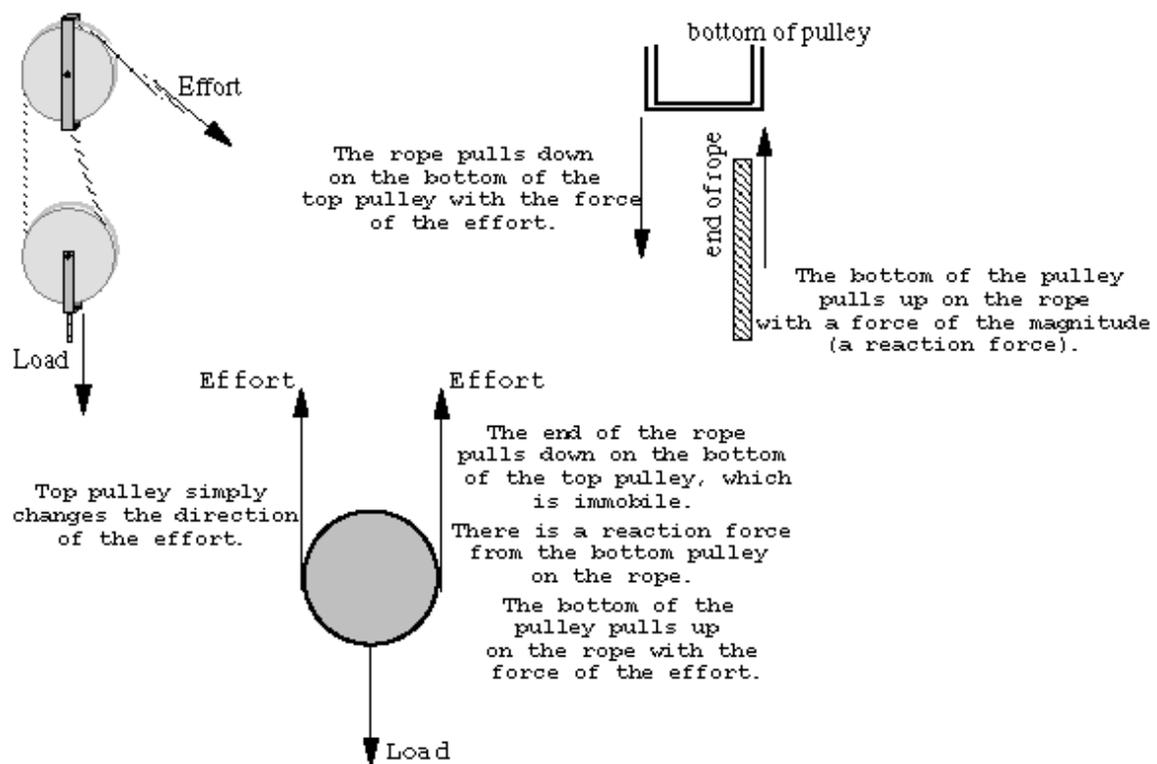


Figure 8: How Compound Pulleys Work

Figure 8 illustrates how a compound pulley 'trades' force for distance through an action/reaction force pair. In a double pulley, as the rope passes over the pulley the force is transmitted entirely but the direction has changed. The effort is now pulling up on the left side of the bottom pulley. Now, for a moment forget that the end of the rope is tied to the bottom of the top pulley. The mechanics are the same if the rope is fixed to the ceiling. The important thing is that the end of the rope is immobile. The effort is once again transmitted entirely as the rope passes over the bottom pulley and there is a direction change. The end of the rope is attached to the ceiling so the rope is pulling down on the ceiling with the force of the effort (and half of the force of the load). We assume that the ceiling holds up, so this must mean that there is a force balancing out this downward force. The ceiling pulls up on the rope as a reaction force. This upward force is equal to the effort and now there is an upward force on the right side of the bottom pulley. From the perspective of a free-body diagram the compound pulley system could be replaced by tying two ropes to the load and pulling up on each with a force equal to the effort.

The disadvantages of pulleys, in contrast to machines that use rigid objects to transfer force, are slipping and stretching. A rope will permanently stretch under tension, which may affect the future performance of a device. If a line becomes slack, then the operation of a machine may change entirely. Also, ropes will slip and stick along pulley wheels just like belts. One solution to the problems associated with rope is to use chain. Chain is pliable like rope, and is able to transfer force through many direction changes, but the chain links are inflexible in tension, so that the chain will not stretch. Chains may also be made to fit on gears so that slipping is avoided.