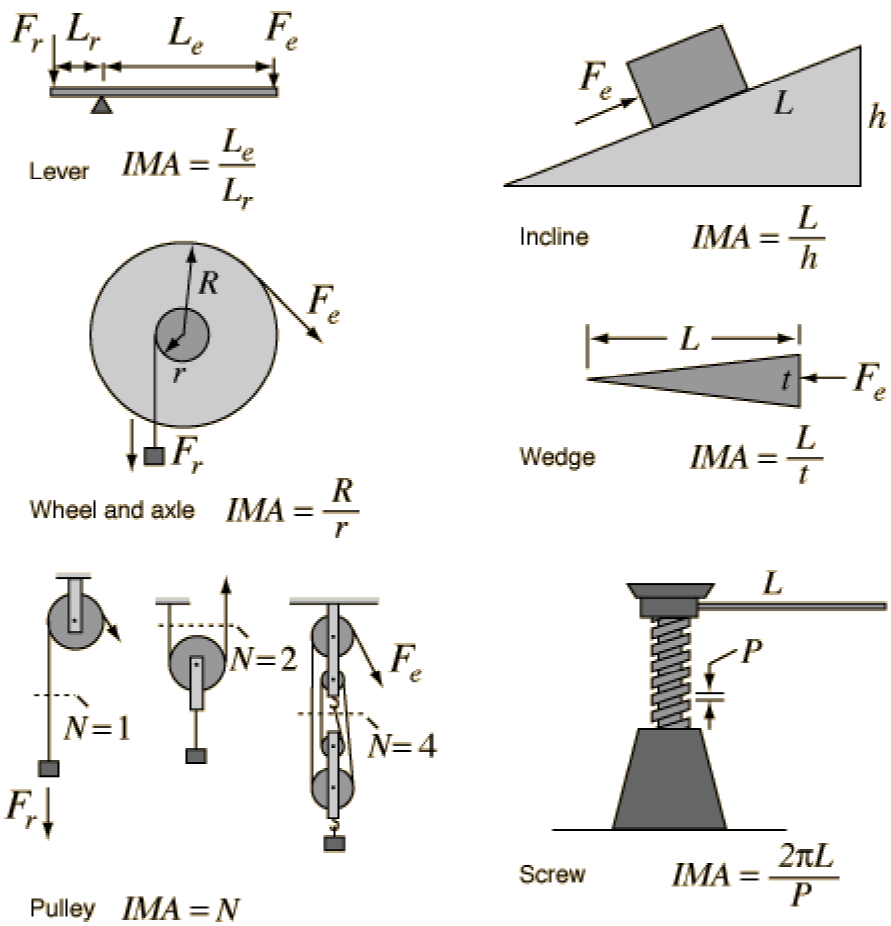
Simple Machines

It is traditional to point to a set of simple machines from which more complex machines can be fashioned. One way to characterize a "simple" machine is to say that it has no internal source of energy. It may nevertheless be very useful in that it multiply the input force to accomplish a task. The factor by which it multiplies the force is often called the "mechanical advantage". If you idealize the machine by neglecting friction, then you can state an "ideal mechanical advantage" or IMA for the machine. A typical grouping of simple machines is shown below.



Since we know by conservation of energy that no machine can output more energy than was put into it, the ideal case is represented by a machine in which the output energy is equal to the input energy. For simple geometries in which the forces are in the direction of the motion, we can characterize the ideal machine in terms of the work done as follows:

Ideal Machine: Energy input = Energy output

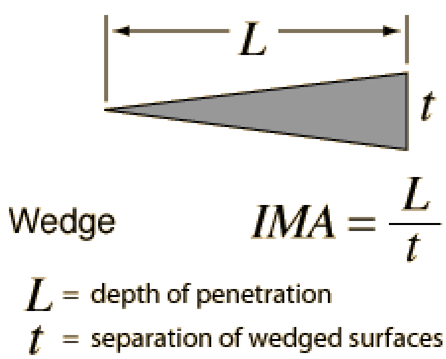
Work input = $F_e d_{input} = F_r d_{output}$ = Work output

From this perspective it becomes evident that a simple machine may multiply force. That is, a small input force can accomplish a task requiring a large output force. But the constraint is that the small input force must be exerted through a larger distance so that the work input is equal to the work output. You are trading a small force acting through a large distance for a large force acting through a small distance. This is the nature of all the simple machines above as they are shown.

Of course it is also possible to trade a large input force through a small distance for a small output force acting through a large distance. This is also useful if what you want to achieve is a higher velocity. Many machines operate in this way.

The expressions for the ideal mechanical advantages of these simple machines were obtained by determining what forces are required to produce equilibrium, since to move the machine in the desired direction you must first produce equilibrium and then add to the input force to cause motion. Both force equilibrium and torque equilibrium are applied.

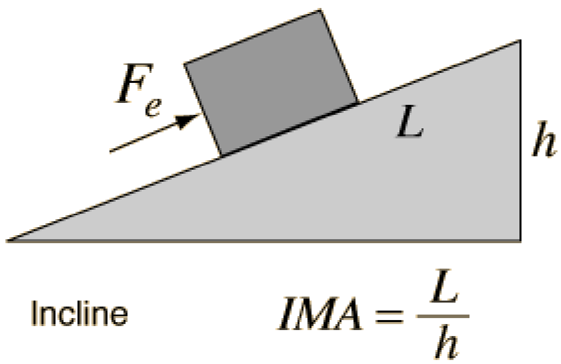
The Wedge



The wedge is one of the so-called "simple machines" from which many more complex machines are derived. The wedge embodies the same principles as the incline in the sense that a smaller force working over a longer distance can produce a larger force acting through a small distance. As a double incline, its ideal mechanical advantage is the ratio of the depth of penetration L to the amount of separation achieved t. Note that the input force for a simple incline works along the incline, i.e., the hypotenuse of the triangle. For the wedge, the working force drives the wedge inward, and the driving force times the depth of penetration is the input work to the machine.

The ideal mechanical advantage has little meaning in this case since in practical use, there is usually a large amount of friction. Nevertheless, the wedge is of great usefulness. A thin wedge of steel can create enormous forces for lifting or splitting when driven into a crack or crevice.

The Incline

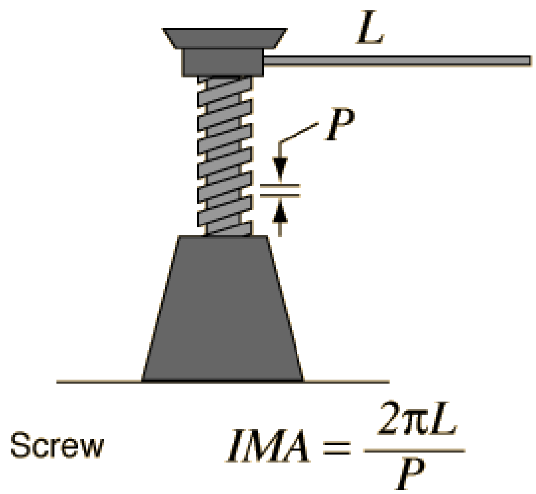


The incline is one of the so-called "simple machines" from which many more complex machines are derived. By pushing an object up a slanted surface, one can move the object to height h with a smaller force than the weight of the object. If there were no friction, then the mechanical advantage could be determined by just setting the input work (pushing the object up the incline) equal to the output work (lifting the object to height h).

The resistance force F_r =mg, the weight of the object. It takes work mgh to overcome that resistance force and lift the object to height h. By doing work on it we give it gravitational potential energy mgh. By exerting F_e to push the object up the incline, we do the same amount of work in the ideal frictionless case. So setting the works equal $F_eL = F_rh$, we arrive at the ideal mechanical advantage $F_r/F_e = L/h$ shown in the illustration.

Another approach to the incline is just to calculate the amount of force F_e required to push the object up a frictionless incline. If the forces are resolved as in the standard incline problem, you find that the required force is $F_e = mg\sin\theta = mgh/L = F_r\,(h/L)$.

The Screw

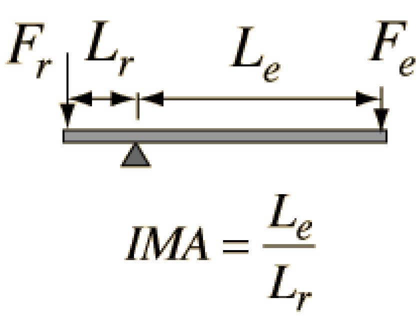


The screw is one of the so-called "simple machines" from which many more complex machines are derived. A screw is essentially a long incline wrapped around a shaft, so its mechanical advantage can be approached in the same way as the incline.

When a screw is turned once, it advances by the distance between adjacent screw threads. This distance is commonly called the "pitch" of the thread. As depicted in the illustration, the handle also adds a lever. Analysed from the point of view of work, the handled is moved one circumference $2\pi L$ to lift the load by the amount P. So the ideal mechanical advantage is $2\pi L/P$.

The ideal mechanical advantage is of little meaning here since there is typically a lot of friction. But the screw is of enormous usefulness for the lifting of heavy loads and for use in screw fasteners which can exert great forces to hold objects together.

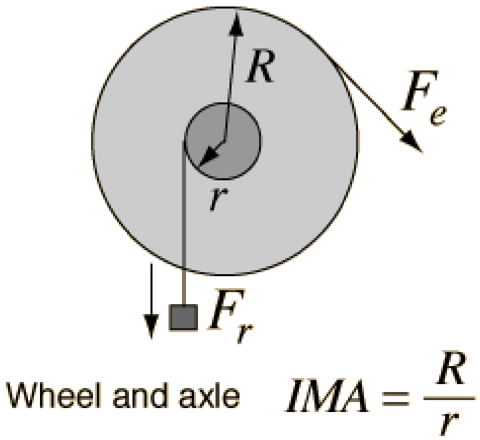
The Lever



The lever is one of the so-called "simple machines" from which many more complex machines are derived. With a lever, one can obtain a multiplication of force, but of course not a multiplication of energy. The multiplication of force can be seen to arise from the equilibrium of torques, where an input force F_e with a long lever arm L_e can balance a larger resistance force F_r with a short lever arm L_r.

A rigid lever can approach an ideal machine since there is very little loss. From torque equilibrium we see that a resistance force F_r can be balanced by a smaller effort force $F_e = (L_r/L_e)F_r$. This is often stated in terms of the ideal mechanical advantage $F_r/F_e = L_e/L_r$ shown in the illustration.

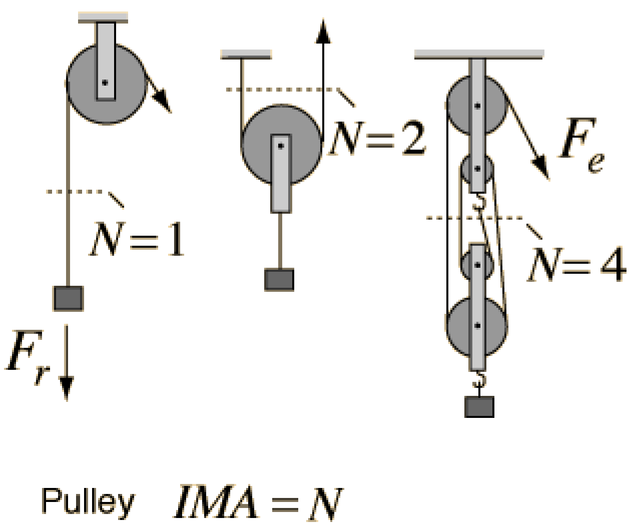
Wheel and Axle



The wheel and axle combination constitutes one of the so-called "simple machines" from which many more complex machines are derived. The principle of operation is essentially a lever, since it depends upon the effort force F_e having a longer lever arm than the resistance force F_r The ideal mechanical advantage is just the ratio of those lever arms R/r.

The clear advantage of the wheel and axle over a simple lever is that the distance of travel is limited only by the amount of rope or cable that you can wrap around the wheel or axle.

The Pulley



The pulley is one of the so-called "simple machines" from which many more complex machines are derived. With a single fixed-axis pulley, the ideal mechanical advantage is just N=1. You get the convenience of being able to redirect the effort force F_e, so that you can stand clear of the load. With a suspended pulley as in the middle illustration, the upward forces in the two ropes is equal, and therefore each supports half of the load, giving an IMA of N=2.

With a four-pulley set as shown, you have four ropes supporting the load, so the effort force F_e that establishes the rope tension is just one-fourth of the load in the ideal case, so IMA=4. All these force relationships are obtained from the force equilibrium condition, which in this case just amounts to "forces up = forces down" at any cross-section of the system.