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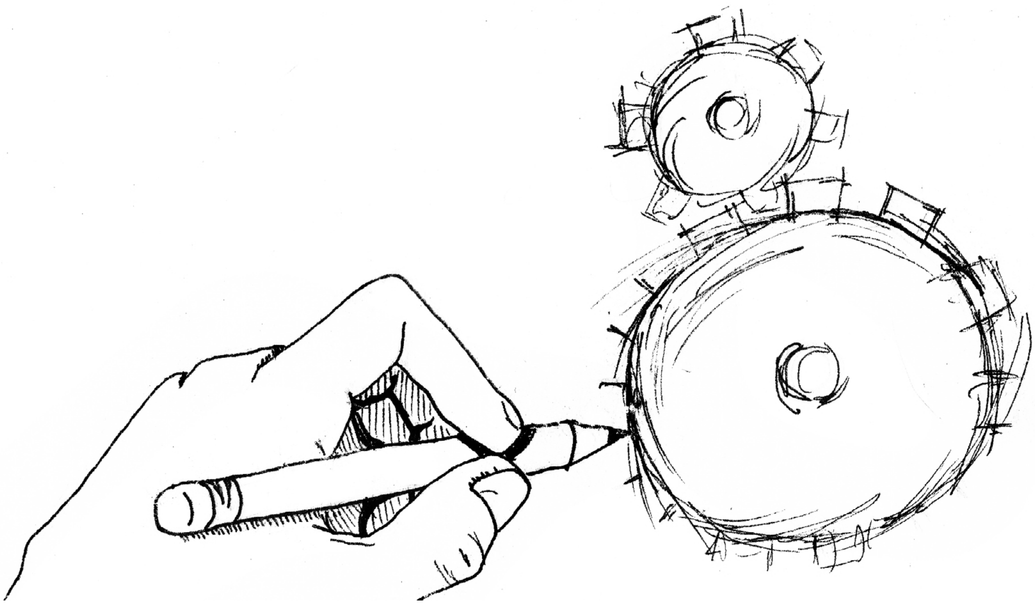
Introduction to Mechanisms and Machines



Mechanical systems come in many shapes and forms, and they have various definitions. Before we can start making machines, we need to know what we're talking about:

- A *mechanism* is an assembly of moving parts.
- A *machine* is any device that helps you do work, from a hammer to a bicycle. A hammer is a machine because it makes your arm longer, so you can do more *work*.

In this book, we use the mechanical definition of work:

$$Work = Force \times Distance$$

Force (*F*) equals *mass* (*m*) times *acceleration* (*a*), and is written as $F = ma$ (also known as Newton's second law).

For example, imagine that you're stomping on a bunch of grapes to make wine. The force the grapes feel when you stand still is equal to your weight, but the force the grapes feel when you stomp is your weight plus the acceleration your muscles give to your foot. The grapes would feel less force, however, if you were stomping them on the moon, which has just one-sixth of the Earth's gravity. *Mass* refers to the amount of stuff you're made of, which doesn't change. Gravity and acceleration depend on where you are and what you're doing. So, mass is the stuff, and weight is the force that the mass exerts.

Six Simple Machines

The four main uses of machines are to:

1. **Transform energy** A windmill transforms energy from the wind into mechanical energy to crush grain or electrical energy to power our homes.
2. **Transfer energy** The two gears in a can opener transfer energy from your hand to the edge of the can.

3. **Multiply and/or change direction of force** A system of pulleys can lift a heavy box up while you pull down with less effort than it would take to lift the box without help.

4. **Multiply speed** The gears on a bicycle allow the rider to trade extra force for increased speed, or sit back and pedal easily, at the expense of going slower.

It turns out that all complicated machines are made of combinations of just six classic simple machines: the lever, pulley, wheel and axle, inclined plane, screw, and gear. These machines are easy to spot all around us once you know what to look for.

1. Levers

You can consider a *lever* a single-mechanism machine. It's a mechanism, by our definition, because it has moving parts. It's a machine because it helps you do work.

A lever is a rigid object used with a pivot point or fulcrum to multiply the mechanical force on an object. There are actually three different classes of levers. Each kind of lever has three components arranged in different ways:

1. Fulcrum (pivot point)
2. Input (effort or force)
3. Output (load or resistance)

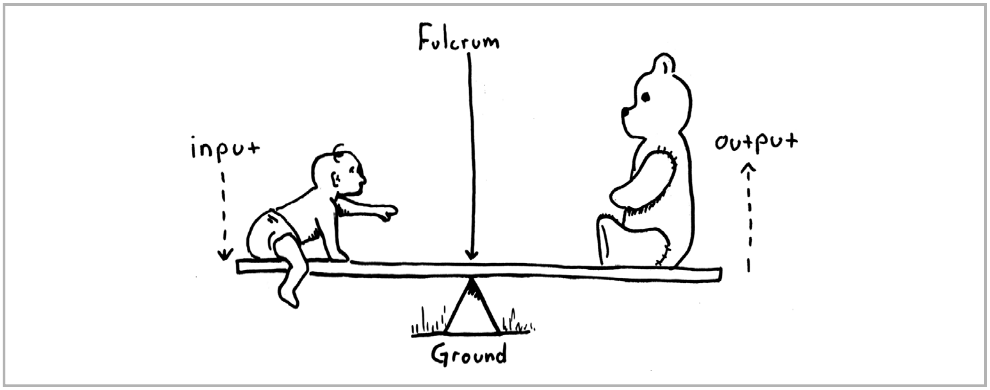
First Class Levers

In a first class, or simple, lever, the fulcrum is between the input and output. This is the classic seesaw most people think of when they hear the word *lever*, as shown in Figure 1-1.

Things can balance on a seesaw in three ways:

1. The two things can weigh exactly the same amount, and be spaced exactly the same distance from the fulcrum (the way it looks in Figure 1-1).
2. You can push down on one side with the same amount of force as the weight on the other side. Your parents may have done this with you on seesaws when you were a kid.

FIGURE 1-1 The classic playground seesaw is an example of a first class lever.



3. The two things can have different weights, and the lighter one must be farther from the fulcrum in order to balance. If you've ever been on a seesaw with someone heavier than you, you've probably done this without thinking about it. If you were the lighter one, you backed up as far as you could to the edge of the seesaw, and your heavier friend probably scooted in toward the pivot point.

In order to apply these balance rules to machines, let's replace the word *thing* with *force*. But first, meet Fido and Fluffy.

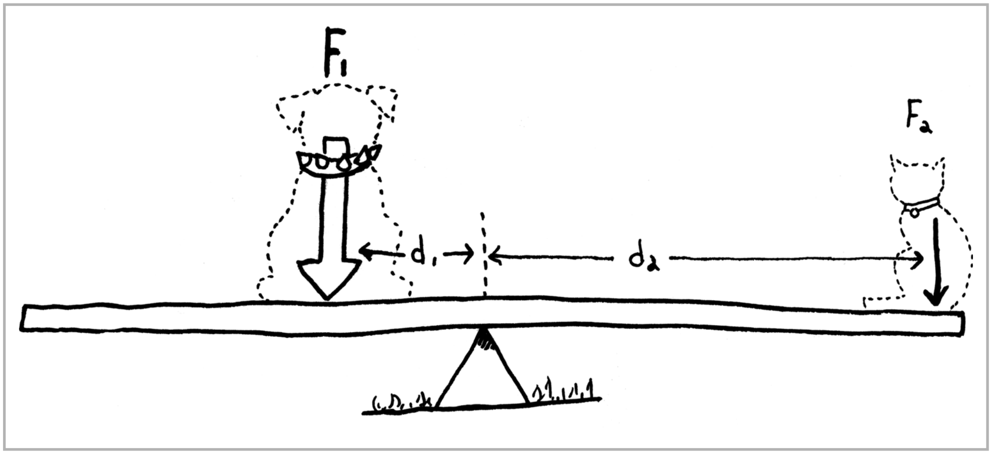
Fido is a big dog. Fluffy is a small cat. Because their names both start with *F*, I'll use F_1 for Fido and F_2 for Fluffy when I abbreviate them. Fido is heavier, so his arrow (F_1) on the left side of Figure 1-2 is bigger. He is sitting at a certain distance (d_1) from the fulcrum. Similarly, Fluffy (F_2) is at a distance d_2 from the fulcrum on the right side. In order to balance the seesaw, F_1 times d_1 must equal F_2 times d_2:

$$F_1 \times d_1 = F_2 \times d_2$$

You can see from Figure 1-2 and the equation that if $F_1 = F_2$, and $d_1 = d_2$, then the seesaw will look like Figure 1-1 and balance. But if Fido (F_1) is a 50 pound (lb) dog, and Fluffy (F_2) is a 10 lb cat, then they must adjust their distances to the fulcrum in order to balance. Let's say that Fido is 3 feet (ft) away from the fulcrum (d_1 = 3 ft). How far away from the fulcrum does Fluffy need to be to balance? Now our equation looks like this:

$$50 \text{ lbs} \times 3 \text{ ft} = 10 \text{ lbs} \times d_2$$

FIGURE 1-2 Balanced first class lever with different forces



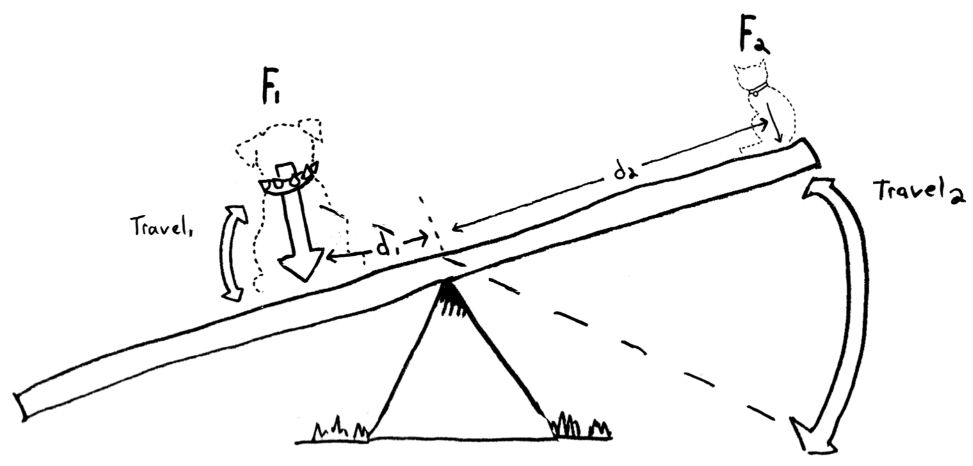
In order to balance the equation (and the seesaw), d_2 must be 15 ft. Although Fido and Fluffy helped us illustrate this point, the forces F_1 and F_2 can be anything—boxes, birds, buildings . . . you name it.

So, the lighter cat can balance a dog five times her weight if she just scoots back farther. You'll also notice that if Fido and Fluffy start seesawing, or pivoting on the fulcrum, Fluffy will go up higher because she is farther from the pivot point. I'll call the distance from the ground to Fluffy's highest point the *travel* (see Figure 1-3).

So the lightweight cat can lift the heavy dog, but she must travel farther to do it. This is how levers give us *mechanical advantage*: A smaller force traveling through a longer distance can balance a heavier force traveling a shorter distance. We could also say the lighter cat is using a 5:1 mechanical advantage to lift the heavy dog by being five times farther from the fulcrum. In our example, the travel of the light cat Fluffy (F_2) is five times that of the heavy dog Fido (F_1).

There are many places you can see levers at work every day. A hammer claw acts as a first class lever when pulling a nail out of a board (see Figure 1-4). You pull at the far end of the hammer handle with a light force, so a big force pulls the nail out with the hammer claw that is just a short distance from the hammer head. The hammer head creates a pivot point that acts as the fulcrum.

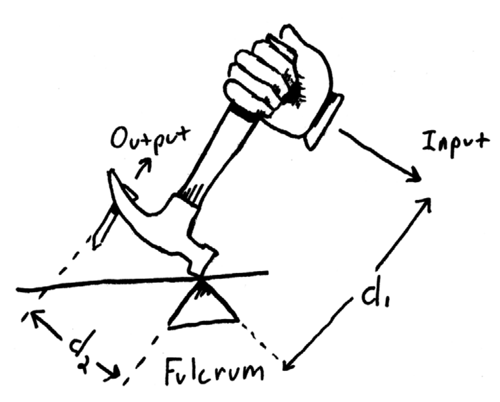
FIGURE 1-3 Levers utilize mechanical advantage to balance forces.



Here are some other examples of levers:

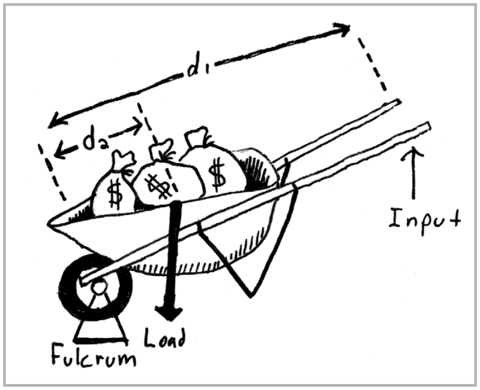
- A crowbar is a first class lever in the same way as a hammer claw.
- Oars on a boat work as first class levers.
- If you've ever used a screwdriver to pry the lid off a paint can, you were using the screwdriver as a first class lever.
- A pair of scissors is like two first class levers back to back. Scissors designed to cut paper don't have much of a built-in mechanical advantage, but think of the long handles of garden shears or bolt cutters. The long handles make the cutting force much higher—that's mechanical advantage at work!

FIGURE 1-4 A hammer being used as a first class lever



Can you think of some other first class levers?

FIGURE 1-5 The wheelbarrow as a second class lever



Second Class Levers

In a second class lever, the output is located between the input and the fulcrum. The classic example of this is the wheelbarrow. As you can see in Figure 1-5, the stuff in the wheelbarrow is the output or load, and we use the handles as the input.

We can use the same equation as for first class levers to figure out the balance of forces. Let's say we have a 50 lb load (F_2) of bags of gold in the wheelbarrow, and the distance from where the bags of gold are to the wheel is 1 ft (d_2). If the handles are 5 ft long from the grip to the wheel (d_1), how hard do we need to pull up to lift the bags of gold? Let's put what we know into our equation:

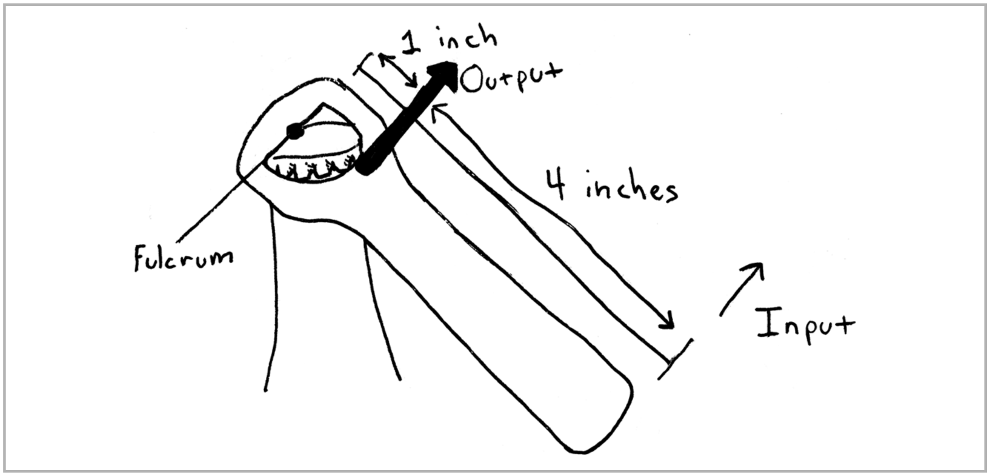
$$F_1 \times 5\text{ ft} = 50\text{ lbs} \times 1\text{ ft}$$

So in order to lift the bags of gold, we must pull up on the handles with at least 10 lbs of force (F_1). See that? We can move 50 lbs of bags of gold with only 10 lbs of pull force, for another 5:1 mechanical advantage—the same as we saw with Fido and Fluffy on the seesaw.

Another household item that uses a second class lever is a bottle opener. In Figure 1-6, you can see the input, fulcrum, and output identified. The handle of the bottle opener goes through a lot of travel to get the cap of the bottle off, but the force at the lip of the bottle cap is relatively high. A nutcracker is another example of a second class lever. Can you think of any other second class levers?

First and second class levers are *force multipliers*, which means they have good mechanical advantage. The trade-off in both cases is that the input, or effort, must move a greater distance than the output, or load.

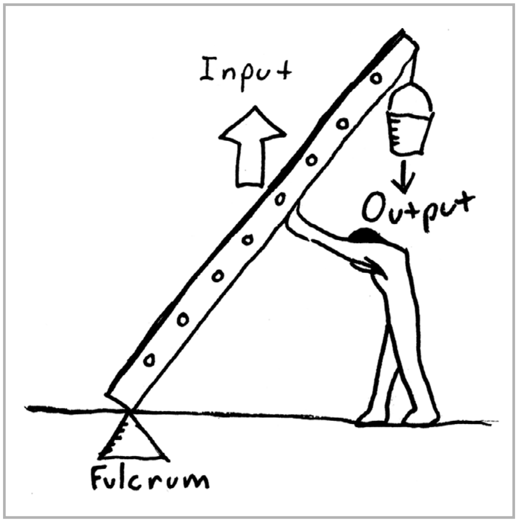
FIGURE 1-6 A bottle opener as a second class lever



Third Class Levers

In a third class lever, the input is applied between the fulcrum and the output, as shown in Figure 1-7. This is known as a *force reducer*.

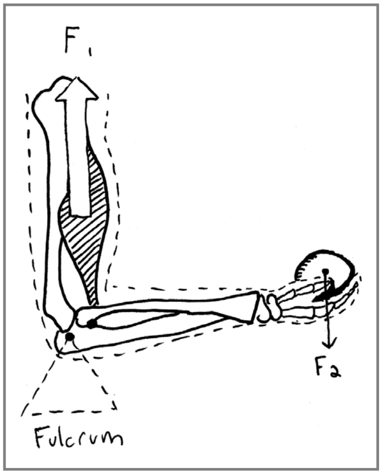
FIGURE 1-7 Using a ladder as a third class lever



Why would you want a machine that reduces force? Most of the time, it's used when this arrangement is the only option available to lift or move something, due to space or other constraints. Although a higher force is needed at the input, the advantage of a third class lever is that the output end moves faster and farther than the input.

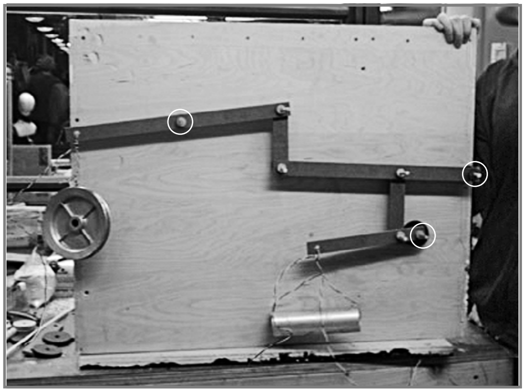
Your arm is a good example of a third class lever. As you can see in Figure 1-8, your bicep muscle is attached between your upper arm near your shoulder and forearm just past your elbow. Your bicep must work hard to lift even a small weight in your hand, but the weight can travel through a long distance since it's far from the pivot point at your elbow. A triangular arm that allowed your bicep to attach near your wrist would be more efficient, but it would have a very limited range of motion. Fishing rods and tweezers also work as third class levers.

FIGURE 1-8 Your arm as a third class lever



You can also combine levers into linkages, which we'll talk more about in Chapter 8. For now, take a look at a project from some former students of mine, shown in Figure 1-9. The two weights are being balanced by a first, second, and third class lever all at once. The fulcrums of each are circled. Can you tell which one is which? (Go to http://itp.nyu.edu/~laf333/itp_blog/2007/03/lever_madness.html to confirm your answer.)

FIGURE 1-9 Lever madness (credit: Lesley Flanigan and Rob Faludi)



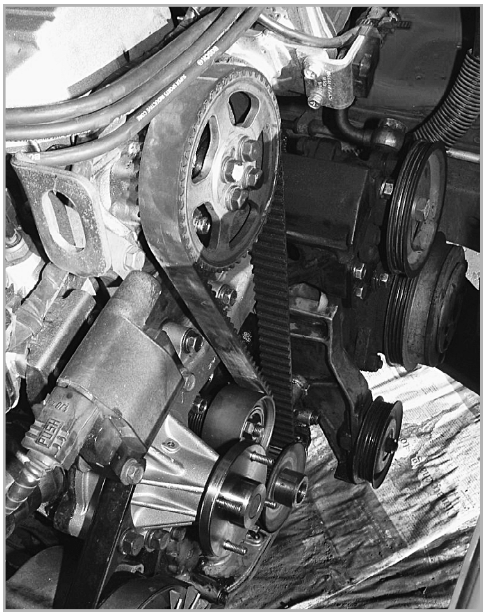
2. Pulleys

A *pulley*, also known as a *sheave*, *block* (as in block and tackle), or *drum*, is basically a wheel with a groove along the edge for a rope or belt. It's another simple machine we can use to gain mechanical advantage in a system. The two types of pulley systems are closed and open.

Closed Systems

I will call a pulley system on a fixed-length rope or belt that's constantly tight a *closed system*. A common example of this is the timing belt in a car, as shown in Figure 1-10. Timing belts use pulleys with little teeth on them that mesh with matching teeth on the belt. This helps the motor drive the belt without slipping, called *positive drive*, because the belt and the teeth on the pulley mesh together.

FIGURE 1-10 Timing belt on the engine of a car as a closed pulley system



You can find a similar system inside cameras that use 35mm film. The holes on the edge of the film actually match up with little teeth on the pulley wheel the film wraps around.

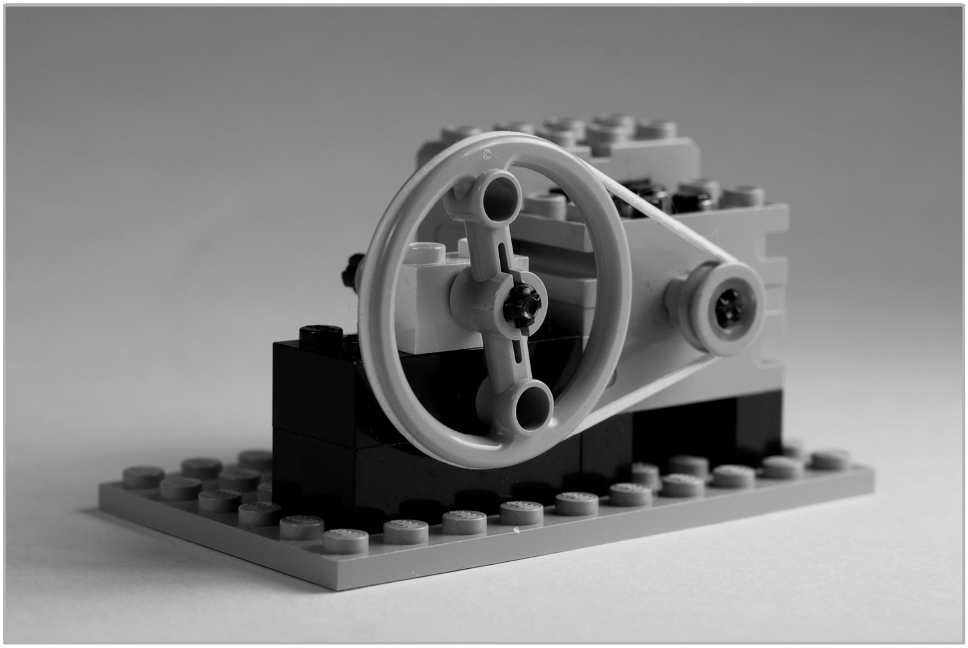
Closed pulley systems can also use smooth belts and pulleys that are spaced so the belt is tight enough not to slip on the pulleys. This is called *friction drive*, because the belt is made to fit tight around the pulleys so the friction between the pulleys and belt stops it from slipping. LEGO systems use pulleys with belts that are color-coded depending on length, as shown in Figure 1-11.

Closed pulley systems are used to translate rotational motion between axes. There is a mechanical advantage only if the *driven*, or *input*, pulley is smaller than the *output pulley*, as shown in Figure 1-11.

Any pulleys in between the input and output are called *idlers*, because they don't do anything other than redirect the belt. Sometimes the idlers are spring-loaded, or mounted such that they are adjustable, so the tension on the belt can be controlled.

The mechanical advantage of closed system pulleys is easier to calculate than with levers. It's just the ratio of the pulley diameters. If a 1 inch (in) diameter pulley is stuck on a motor and drives a 3 in diameter pulley, the mechanical advantage is 3:1. This means that the system can turn something that's three times harder to turn than the motor could by itself.

FIGURE 1-11 LEGO motor using a friction drive pulley system. The large pulley is 1 7/8 inches and the small one is 3/8 inch, which creates a 5:1 mechanical advantage.



Open Systems

Open systems are what most people think of when pulleys come to mind, but will be less useful to you when making projects like the ones in this book. In an open system, one end of the rope or belt is open or loose. A good example of this is a flag hoist. A flag hoist is just a pulley attached to the top of a long flag pole with a rope going around it, so you can stand on the ground and pull down on the rope to raise the flag. One pulley *fixed* in place like this does not magnify force or give you a mechanical advantage. The rope moves the same distance that the flag does when pulled. However, it does allow you to change the direction of movement.

On the other hand, one *unfixed* pulley does magnify force. Unfortunately, as with levers, we don't get something for nothing. The ability to decrease the effort we put in comes at the expense of needing to pull the rope or belt on the pulley a longer distance. As shown in Figure 1-12, an unfixed, movable pulley (also called a *runner*) gives us a 2:1 mechanical advantage. Because each length of the rope carries half the weight, the weight is twice as easy to pull up as it would be to lift the weight alone. The trade-off is that you must pull the rope twice as far as the distance you want the weight to move, since your effort is cut in half.

This last configuration is never very convenient. In order to be able to lift something standing on the ground, most people would prefer to pull down instead of up. By adding another pulley to the system, we maintain the 2:1 mechanical advantage but change the pull force direction to be more convenient. The arrangement in Figure 1-13 is called a *gun tackle* and does exactly that.[1]

The next logical step in this progression is to get a mechanical advantage of 3:1. There are at least two ways to do this. One is called a *luff tackle*. This uses a compound pulley (two independent pulleys in the same housing). Notice in the left image of Figure 1-14 that the weight is suspended by three parts of rope that extend from the movable single pulley at the bottom. Each part of the rope carries its share of the

FIGURE 1-12 One unfixed pulley, or runner, gives a mechanical advantage.

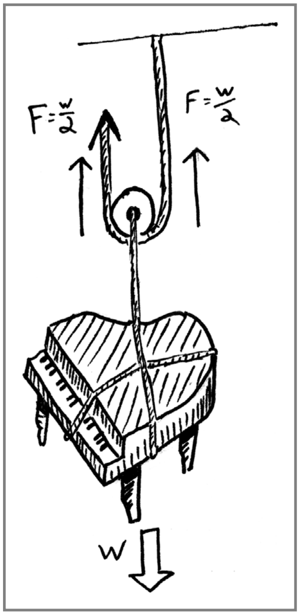


FIGURE 1-13 A gun tackle arrangement gives a 2:1 mechanical advantage, and a convenient pull direction.

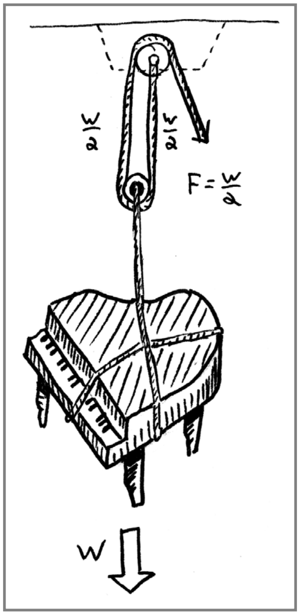
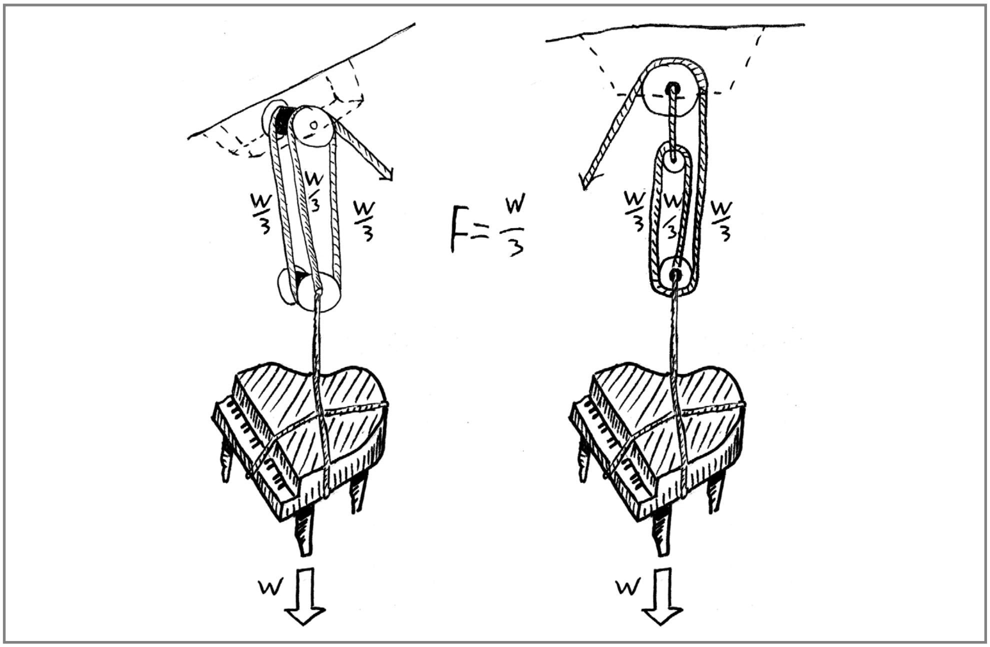


FIGURE 1-14 Pulley arrangements that give a 3:1 mechanical advantage



weight being suspended. So in this case, each part of the rope carries one-third of the weight, and that is the mechanical advantage we feel when pulling on the rope: It's three times easier to lift the weight using this arrangement than it would be to lift the weight on our own. That's a 3:1 mechanical advantage.

> ***TIP*** ***If you count the number of parts of rope going to and from the movable pulley that suspends the weight, you can figure out the mechanical advantage. If there are three pieces of rope going to and leaving one movable pulley, the mechanical advantage is 3:1.***

Another way to get the same 3:1 mechanical advantage is by using three simple pulleys, rather than one simple and one compound pulley. You can see this arrangement in the right image of Figure 1-14. The more pulleys you add to the system, the more mechanical advantage you can get.

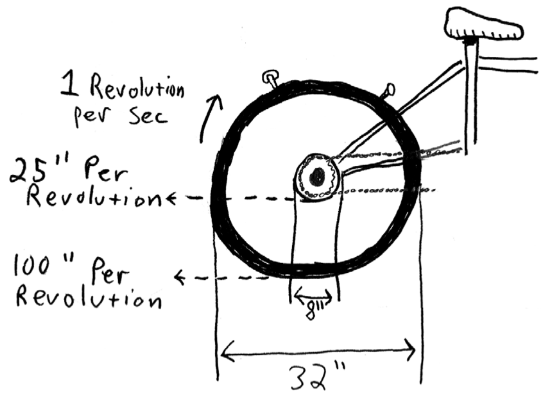
Pulley systems can get pretty complex and allow you to do things like lift a piano to guide it into a second-story window with significantly reduced effort (though you might be pulling for a very long time).

Speed and Velocity

Speed is how fast something is moving. It's measured in distance over time. Velocity is the same thing, just in a specific direction. Common units are miles per hour (mph) or feet per second (ft/s). If you tell someone to drive 60 mph north, you are actually expressing a velocity. *Rotational velocity* (also called *angular velocity*) is exactly what it sounds like: the speed of something spinning. This is commonly expressed in revolutions per second (rps) or revolutions per minute (rpm) and distinguished from straight-line velocity (v) by using the symbol ω (the Greek letter omega). *Tangential velocity* describes the speed of a point on the edge of the circle, which at one split second in time is moving tangentially to the circle. See Figure 1-15 to visualize this. In the bicycle example, think of rotational velocity as the speed the rear wheel spins by itself, and tangential velocity as the speed of the bike along the ground.

As an example, let's say you ride a bicycle with a cog attached to the rear axle that has an 8 in diameter, and your tire is 32 in across. Circumference is equal to π (or 3.14) multiplied by diameter, so the circumferences of the sprocket and wheel are about 25 in and 100 in, respectively. This means that if you pedal at the rate of 1 rps, a tooth on the sprocket travels 25 in per second, while a corresponding spot on the wheel travels through 100 in. So the point on the wheel has a tangential velocity four times higher than the sprocket, even though they have the same rotational velocity of 1 rps. If the wheel shrunk down to the size of the sprocket, you would need to pedal really fast to get anywhere (and look pretty funny doing it). So instead, use the 1:4 *mechanical disadvantage* to help you cover more ground.

FIGURE 1-15 The rear sprocket on a bicycle wheel magnifies the speed of the wheel.



3. Wheel and Axle

You have probably never thought of the steering wheel in a car as a machine, but that's exactly what it is. The large diameter of the steering wheel is fixed to an axle, which acts on the steering system to turn the wheels. Let's say the steering wheel has a diameter of 15 in, and the axle it is fixed to has a diameter of 1 in. The ratio of input to output size here is 15:1, and that's our mechanical advantage. (For more on how steering systems work, check this link: www.howstuffworks.com/steering.htm.) Similarly, a screwdriver with a thick grip handle is much easier to use than one with a handle the size of a pencil.

You can use a wheel and axle to magnify force, as in the steering wheel example, or to magnify speed, as in the wheels of a bike. A bicycle's rear cog is fixed to the rear axle, so when you pedal, the chain turns the rear cog that turns the rear wheel. This is the opposite setup as in a steering wheel. In a steering wheel, you turn a big thing (steering wheel) to make it easier to turn a small thing (steering wheel axle). In a bicycle, you turn a small thing (rear cog) in order to turn a big thing (rear wheel). You don't gain mechanical advantage in this setup, but you do gain speed.

4. Inclined Planes and Wedges

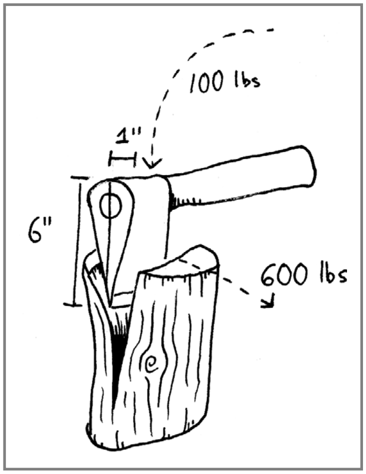
If you've ever done the move yourself from one home to another, you might have used a ramp coming off the back of the moving truck to help you roll boxes on and off the truck bed. This ramp, or *inclined plane*, is a simple machine.

Let's say you have a 100 lb box of books you need to load into the truck. If you lift it yourself, you obviously need to lift the whole 100 lbs to get the box into the truck. However, if you use a 9 ft long ramp that meets the truck at 3 ft off the ground, you can set the books on a dolly and roll them up the ramp. Since you are rolling 9 ft to go up 3 ft, instead of just lifting the box 3 ft straight up, the ramp gives you a 3:1 mechanical advantage. So with the ramp, you can get the books into the truck with only one-third of the force of lifting it directly. The mechanical advantage of a ramp is the total distance of the effort exerted divided by the vertical distance the load is raised.

You've also probably used an inclined plane to prop open a door. A few horizontal kicks to a triangular wooden stopper drive it under the door, and the vertical force created by the inclined plane keeps the door propped up and open.

A *wedge* is like two inclined planes set base to base. Wedges can be found on knives, axes, and chisels. If you drive an axe into a piece of wood, as shown in Figure 1-16, the mechanical advantage is the length of the blade divided by the width of the base. In this case, you see a 6:1 mechanical advantage. That means that if you swing the axe and it has a downward force of 100 lbs when you hit the wood, the splitting force that the wood feels coming off the axe is 600 lbs on each side.

FIGURE 1-16 An axe uses a mechanical advantage to split wood.



5. Screws

A *screw* is really just a modification of an inclined plane. There are two main types of screws:

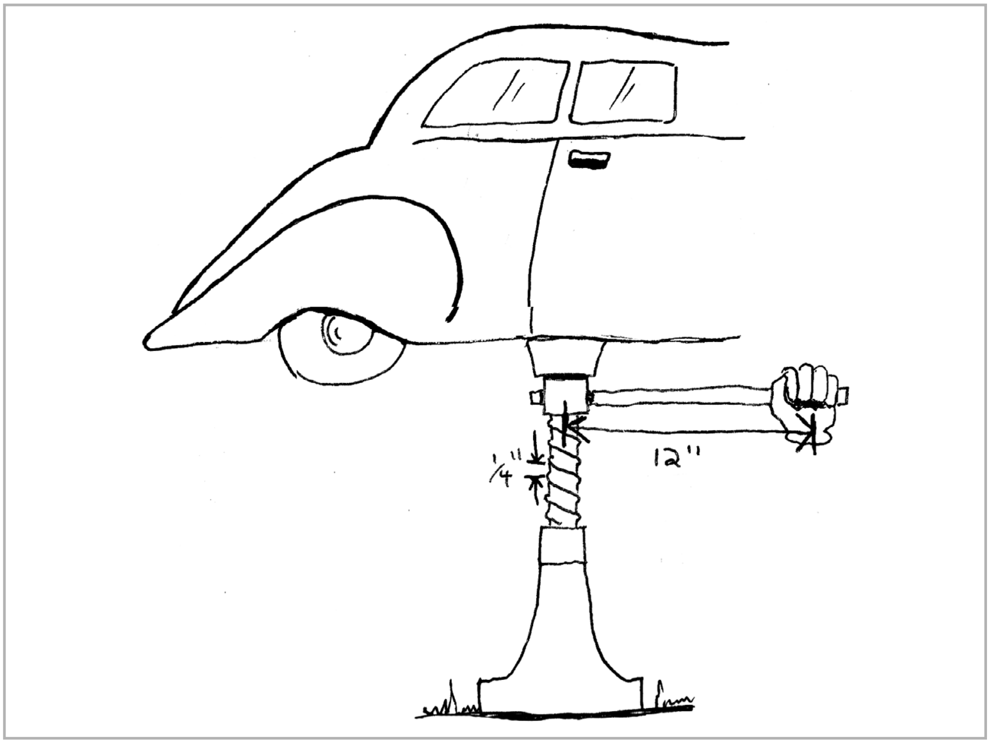
1. Screws used for fastening parts together.
   Fastening screws use their mechanical advantage to squish two or more pieces of material together.

2. Screws used for lifting or linear motion (called *power screws*). Power screws have a slightly different geometry thread to allow them to lift or push an object that slides along the threads, like in the screw jack in Figure 1-17.

TRY THIS ***Cut a piece of 8 1/2 × 11–in paper in half along the 11-in side, and then cut one of the remaining pieces diagonally from corner to corner. Next, line up the shorter side of the triangle with a pencil and start wrapping the triangle around the pencil. Notice the spiral shape? This shows how a screw is a modification of an inclined plane—the triangle.***

As with any simple machine, the mechanical advantage is the ratio of what you put in to what you get out. One example of a power screw is a screw jack that you might use to prop up your car before changing a tire. Let's say the screw jack has a handle length of 12 in, as shown in Figure 1-17. The pitch of the screw is the distance between threads, and is the distance the screw will move up or down when turned

FIGURE 1-17 Screw jack used to lift a heavy load

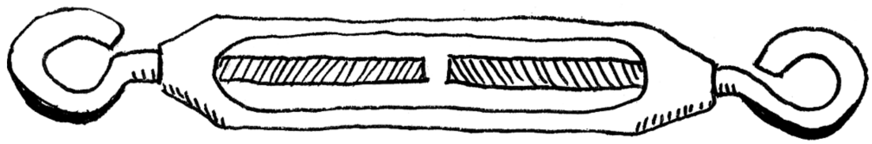


one full revolution. In our example, let's use 1/4 in. To use the screw jack, we need to turn the 12-in handle through a full circle for the jack to raise up 1/4 in. The end of the handle traces out a circle with a radius of 12 in., and the circumference equals 2π multiplied by the radius ($C = 2 \times \pi \times R$). So, our mechanical advantage is the input ($2 \times \pi \times 12$ in) divided by the output (1/4 in), which is about 300!

Power screws like in our screw jack example can achieve very high mechanical advantages in a compact space, so they are great for lifting jobs when rigging up a pulley system wouldn't be practical. A lot of this mechanical advantage is lost to friction, and we'll talk more about that in Chapter 4.

Another place you may have seen power screws at work is in turnbuckles. These are used to tension ropes and cables that are already secured. As indicated in Figure 1-18,

FIGURE 1-18 A turnbuckle can be used to tighten or loosen the tension in a cable.



the turnbuckle has left- and right-hand threads. Most screws that you've encountered have a standard right-hand thread, which means they get tighter as you turn them clockwise, or to the right. Left-hand threads get tighter when you turn the screw to the left, or counterclockwise. By using one of each, the turnbuckle can either draw in both sides at once to tighten or loosen both sides simultaneously. This same idea can be used in leveling mechanisms as well. You can also find power screws in C-clamps and vises.

You'll also find power screws in positioning systems where precise location, rather than mechanical advantage, is the main concern. These types of systems use motors to turn a power screw that positions a table or other mechanism horizontally or vertically. You can see these systems in 3D printers and precision lab equipment. (For some good examples of power screws, visit www.velmex.com/motor_examples.html.)

6. Gears

Gears are used to magnify or reduce force, change the direction or axis of rotation, or increase or decrease speed. Two or more gears in line between the input and output are known as a *drive train*. Drive trains that are enclosed in housings are called *gearboxes* or *gearheads*. The teeth of the gears are always meshing while they are being turned, so a gear drive train is an example of a positive drive.

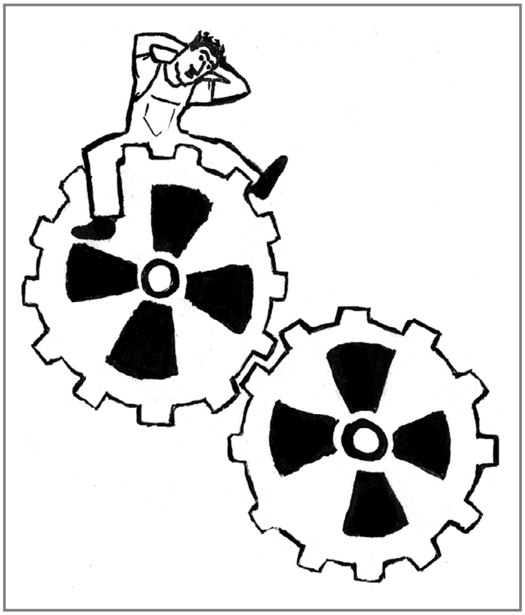
Gear Types

There are many different types of gears and ways to use them. We'll cover the details in Chapter 7. Here, we'll take a look at the five basic types of gears: spur, rack-and-pinion, bevel, worm, and planetary.[2]

Spur Gears The most commonly used gear is called a *spur gear*. Spur gears transmit motion between parallel shafts, as shown in Figure 1-19. Individual spur gears are primarily described by three variables:

1. Number of teeth (*N*)
2. Pitch diameter (*D*)
3. Diametral pitch (*P*)

FIGURE 1-19 Spur gears in a drive train



The last two variables sound alike, which can be confusing, because they represent very different things. The *pitch diameter* of a spur gear is the circle on which two gears effectively mesh, about halfway through the tooth. The pitch diameters of two gears will be tangent when the centers are spaced correctly. This means that half the pitch diameter of the first gear plus half the pitch diameter of the second gear will equal the correct *center distance*. This spacing is critical for creating smooth running gears.

The *diametral pitch* of a gear refers to the number of teeth per inch of the circumference of the pitch diameter. Think of it as tooth density—the higher the number, the more teeth per inch along the edge of the gear. Common diametral pitches for hobby-size projects are 24, 32, and 48.

NOTE ***The mating gears can have different pitch diameters and number of teeth, but the number of teeth per inch, or diametral pitch (P), must be the same for the gears to mesh correctly.***

Rack-and-Pinion Gears A *pinion* is just another name for spur gear, and a *rack* is a linear gear. A rack is basically a spur gear unwrapped so that the teeth lay flat, as shown in Figure 1-20. The combination is used in many steering systems, and it is a great way to convert from rotary to linear motion. Movement is usually reciprocating, or back and forth, because the rack will end at some point, and the pinion can't push it in one direction forever.

Another common example of a rack-and-pinion gear is a wine bottle opener—the kind shown in Figure 1-21. The rack in this case is circular, wrapped around the shaft that holds the corkscrew. The handles are a pair of first class levers that end in pinion gears, and they go through a lot of travel when you push them down to give you the mechanical advantage needed to lift the cork out of the bottle easily.

FIGURE 1-20 Rack-and-pinion gears

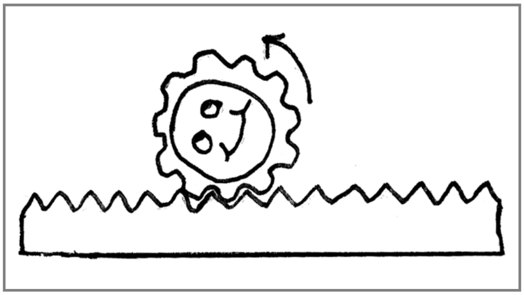
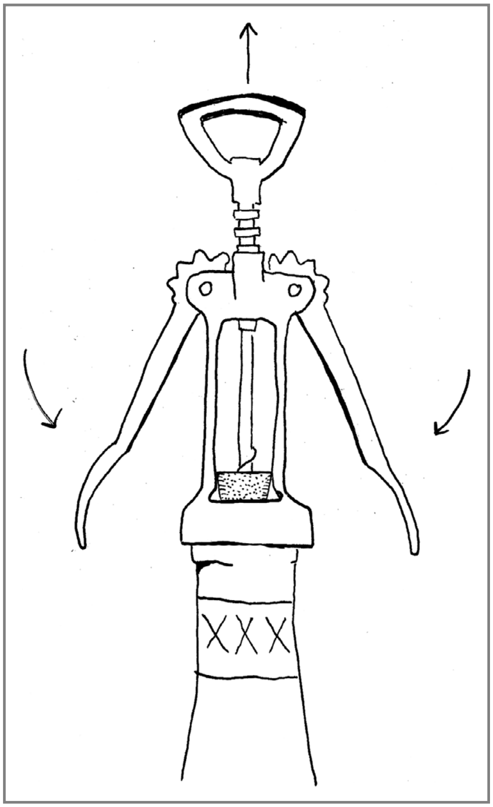


FIGURE 1-21 This corkscrew uses a type of rack-and-pinion gear and levers.

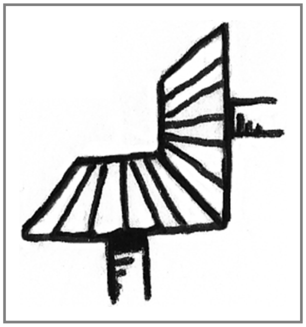


Bevel Gears *Bevel gears* mesh at an angle to change the direction of rotation. A *miter gear* is a specific kind of bevel gear that is cut at 45° so that the two shafts end up at a 90° angle, as shown in Figure 1-22.

Worm Gears *Worm gears* actually look more like a screw than a gear, as shown in Figure 1-23. They are designed to mesh with the teeth of a spur gear.

One important feature of the worm gear is the mechanical advantage it gives. When a worm gear (sometimes just called the *worm*) rotates one full revolution, the mating gear (sometimes called the *worm gear*) advances only one tooth. If the mating gear has 24 teeth, that gives the drive train a 24:1 mechanical advantage. (This is technically only true for single-lead worms; for a two-lead worm, two full revolutions are needed to turn a mating gear one tooth.) Of course, the mating gear will be moving very slowly, but a lot of times, the trade-off is worth it.

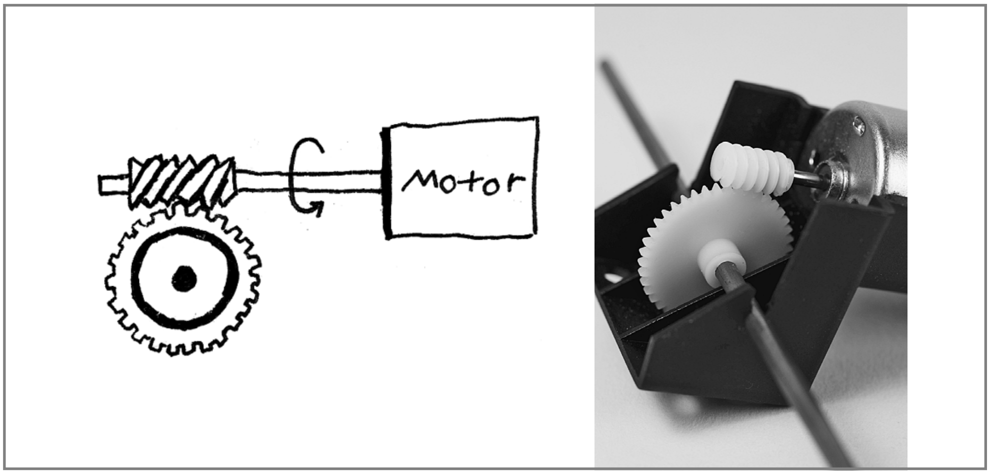
FIGURE 1-22 Bevel gears



Another great feature of worm gears is that the majority of the time, they don't *back drive*. This means that the worm can turn the worm gear, but it won't work the other way around. The geometry and the friction just don't allow it. So, a worm gear drive train is desirable in positioning and lifting mechanisms where you don't want to worry about the mechanism slipping once a certain position is reached.

Planetary Gears *Planetary*, or *epicyclic gears*, are a combination of spur gears with internal and external teeth. They are mostly used in places where a significant mechanical advantage is needed but there isn't much space, as in an electric screwdriver or a drill. You can even layer planetary gear sets to increase the

FIGURE 1-23 Worm gears



mechanical advantage. (howstuffworks.com has an excellent write-up on the topic, which you can find at www.science.howstuffworks.com/gear7.htm.)

Gear Ratios

Gears of different sizes transmit a mechanical advantage, similar to how pulleys work. As always, the mechanical advantage is the ratio of how much we put in to how much we get out.

The smaller of two gears in a set is usually called a *pinion*, and is the one being driven. Let's say we have a 20-tooth pinion attached to a motor shaft. Then a 100-tooth spur gear (of the same diametral pitch, of course) mates with the pinion to rotate an adjacent shaft. The pinion must rotate five times to turn the output gear once, so the mechanical advantage is 5:1.

When the gear train is being used to *magnify force*, the input gear will always be smaller than the output gear. This setup is great when you have a motor and need to multiply the work it can do by itself, or when you need to slow the motor's output to a speed that fits your application.

To use a gear train to *magnify speed*, reverse the gears so the big gear is the input gear. The gear train is at a mechanical disadvantage in this configuration, but since one turn of the input gear on the motor turns the mating gear five times, the speed of the output is magnified by five.

So, take a look around you and see what kind of mechanisms you can find that have gears in them. How about that old clock, your blender, or a can opener? The kitchen is a great place to go looking for all sorts of useful mechanisms.

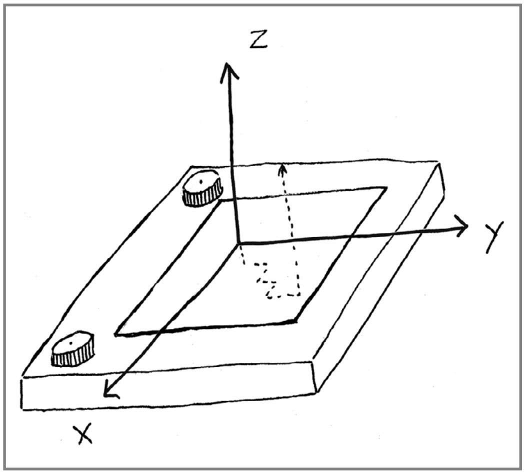
Design Constraints and Degrees of Freedom

The principle of *minimum constraint design*[3, 4] is one of the first things I teach my students. It has been around for over a century, but it's rarely taught in schools. Most designers and engineers learn it through trial and error. That process takes time, and if you're reading this book, you probably don't want to mess up designs for years to gain that experience firsthand. So here's the short version: *Don't constrain any design or moving part in more ways than necessary*. That's it. Let's examine this concept a little more in depth.

Degrees of Freedom

Every object has six different ways it can move: three straight line motions, called *translations*, and three *rotations*. This is usually shown on a coordinate system, as in Figure 1-24.

FIGURE 1-24 Coordinate system of axes and planes



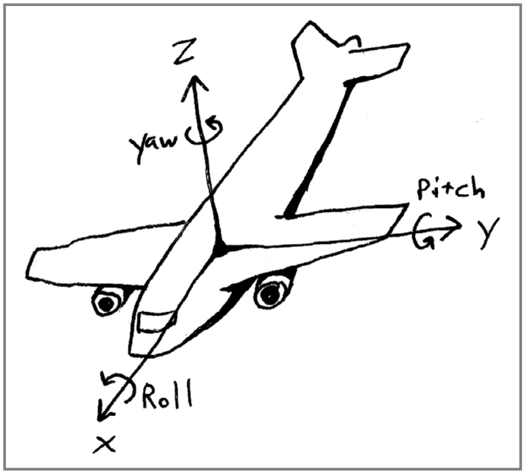
If you stand straight up and picture the origin (the middle where all the lines meet) of this coordinate system at your belly button, it will be easier to understand the movement. You can jump up and down (translation along the Z axis), shuffle side to side (translation along the Y axis), or walk forward and backward (translation along the X axis). Every linear movement is a combination of X, Y, and Z translations.

For example, if you walk forward diagonally, you are moving in X and Y. Remember the Etch A Sketch? It has two knobs: one that controls horizontal, or X motion, and one that controls vertical, or Y motion. To make a diagonal line, you spin both knobs at once. You could say that you are drawing in the XY plane, because your motion is part X and part Y movement. You can do this with your body if you walk forward and to the right diagonally. The axes in Figure 1-24 also define three planes: the XY plane, YZ plane, and XZ plane. Can you think of a way to move in the XZ plane?

In addition to these three translations, any object can spin around any of these three axes. If you spin around in place, you are rotating about the Z axis. If you bend forward and backward at your waist, you're rotating your body about the Y axis. And if you bend to the side, you are rotating about the X axis.

Rotations may be easier to picture on an airplane, where they have more specific names, as shown in Figure 1-25. When a plane tilts its wings with respect to the horizontal, it is rotating about the X axis, called *roll*. When then nose dips up or down, it's rotating about the Y axis, called *pitch*. And when it rotates around the Z axis to go into a turn, it's called *yaw*. Remembering the names of these three rotations isn't important. Just keep in mind that all movement is a combination of three translations and three rotations.

FIGURE 1-25 Rotations on an airplane are given specific names.



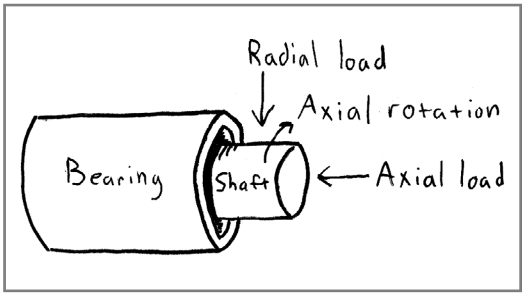
Before we move on, I want to introduce two more simple terms used to describe motion:

1. *Axial* refers to along an axis. Axial rotation is around an axis (either clockwise or counterclockwise). Axial load or force is applied parallel to an axis.

2. *Radial* refers to perpendicular to an axis. A radial load or force is applied perpendicular to an axis.

Figure 1-26 illustrates these concepts.

FIGURE 1-26 Axial and radial motion and forces



Minimum Constraint Design

Have you ever sat at a table that wobbled every time you rested your elbow on it? Most of us have, and we've also probably tried to stop the wobble by putting some napkins or coasters under the offending wobbly side. What you may not have realized at the time was that the table most likely had four legs. You see, a three-legged table can't wobble. Sure, it can fall over, but it can't wobble that annoying half an inch that the four-legged table can. That's because three points define a plane, and four points is one too many. Any time you have four points that are trying to coexist on a flat surface, you have issues. At least one of those legs will need to have some "give" in it. That's what you were adding when you squished the napkins under the wobbly table.

Using three points to define a plane is what is called good *minimum constraint design*. You can see this concept in tricycles made for young children who are not known for their superior balancing abilities, as well as in camera tripods.

Sometimes there are reasons to add more than the minimum number of constraints. For example, a car has four wheels. I just said that you only need three points to define a plane. What gives? All four wheels of the car do! Because the four points, or wheels in this case, are made of air-filled rubber, they can "give" and distribute the weight of the car evenly between them, without ever experiencing the four-legged table wobble. Also, a four-wheeled vehicle is less susceptible to tipping over than a three-wheeled one. This is what we call an example of acceptable *redundant constraint design*, because the fourth wheel is redundant. Keep this concept in mind when you are making anything. It is sure to save you loads of time reworking mechanisms, and I will point out good minimum constraint design in the projects throughout this book.

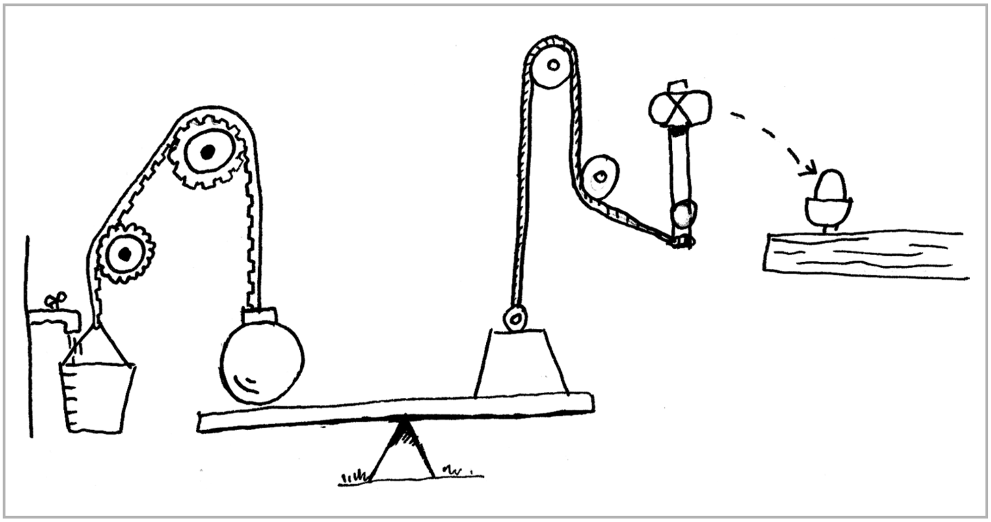
For good examples of minimum constraint design, check out any moving LEGO kit. These kits are designed well, with just enough parts to get the job done, and the parts themselves are made precisely to stick together or slide through each other with just the right amount of clearance. For bad examples, or overconstrained designs, try to assemble furniture from IKEA or any other budget retailer. Inevitably, the holes in the desk legs don't line up, the wooden pegs are too tight to go all the way in, or some other part is sized in a way that it creates an unacceptable redundant constraint and causes you a headache. Put the extra effort in on your own projects to avoid such scenarios.

Project 1-1: Rube Goldberg Breakfast Machine

Rube Goldberg was an engineer turned cartoonist who is best known for his cartoon series depicting complex contraptions that perform simple tasks in extraordinarily complex ways. In fact, the adjective *Rube Goldbergian* is defined as "accomplishing by complex means what seemingly could be done simply."[5]

Omega Engineering (www.omega.com), a company that specializes in automation equipment, uses Rube Goldberg cartoons in its ads as a comical way to show that its products are more efficient at automating tasks than the Rube Goldbergian way. These cartoons epitomize the idea that there is always more than one way to accomplish a task (see Figure 1-27). This is certainly true when it comes to making mechanisms, and it's important to realize that the first solution to a problem that comes to mind may not be the simplest or the best.

FIGURE 1-27 Rube Goldberg machine



The objective of this project is to build a Rube Goldberg machine that cracks an egg in no less than five steps. This can be done quickly and cheaply with material you find around the house, but the means to the end is limited only by your imagination and budget. I've included an example in case you're stuck, but I encourage you to ignore it and develop your own project. The idea is to get you working with your hands and making something to accomplish a specific task, without thinking too much about it.

The rules for this project are as follows:

- The majority of the egg and no more than half the shell should end up in the final receptacle.
- Limit yourself to a 3 × 3 ft area for the entire machine.
- Starting the machine is the only human interaction allowed. For example, this could be a button press, pushing a toy car over a ledge, or removing a stopper.
- From the time you initiate movement, your egg must be cracked in 5 minutes or less.
- Each step, or energy transfer, must be unique and contribute to the goal. For example, you can't have a golf ball roll down a ramp, spin five pinwheels, and then trigger a knife to cut the egg. That's boring. Also, the pinwheel spins don't contribute to the final goal of egg cracking.

I have assigned this project to my students at New York University (NYU) in the first class for the past few years, and it's always a hit. My favorite example of a successful Rube Goldberg machine to date is one that was designed to suck the egg out of the shell using a large syringe (check out the video at www.flickr.com/photos/fxy/3260972797/; credit Xiaoyang Feng, Mike Rosenthal, and Ithai Benjamin). You can browse the student pages from 2008 onward at http://itp.nyu.edu/mechanisms, as well as the rest of the Internet, to find other examples of Rube Goldberg machines. I've included a simple example here to get you started. So get to work!

Shopping List:

- 1 sheet 1/4-in thick clear acrylic, approximately 15 × 31 in (Ponoko.com stock)
- 1/4-in diameter, 36-in long wooden dowel
- Multitool with knife and file
- Mousetrap
- Paint-stirring stick
- Fishing line or other thin string
- Rubber bands
- Duct tape roll
- Small bowl
- Spoon or fork
- Egg(s)

Recipe:

1. See www.makingthingsmove.com for the link to download the templates from Thingiverse. This template was designed to be laser cut from the 1/4-in clear acrylic that Ponoko.com stocks and configured to fit on its P3 template. Register for Ponoko.com, and order the design cut out of your chosen material. You can also use the template to cut pieces out of cardboard or foam.

2. Use the knife on the multitool to score the wooden dowel into eleven 2 1/2-in long sections. Snap off the pieces at the score marks and file the edge. Set aside the remaining few inches.

3. Place all 2 1/2-in dowels in the back side template (refer ahead to Figure 1-29).

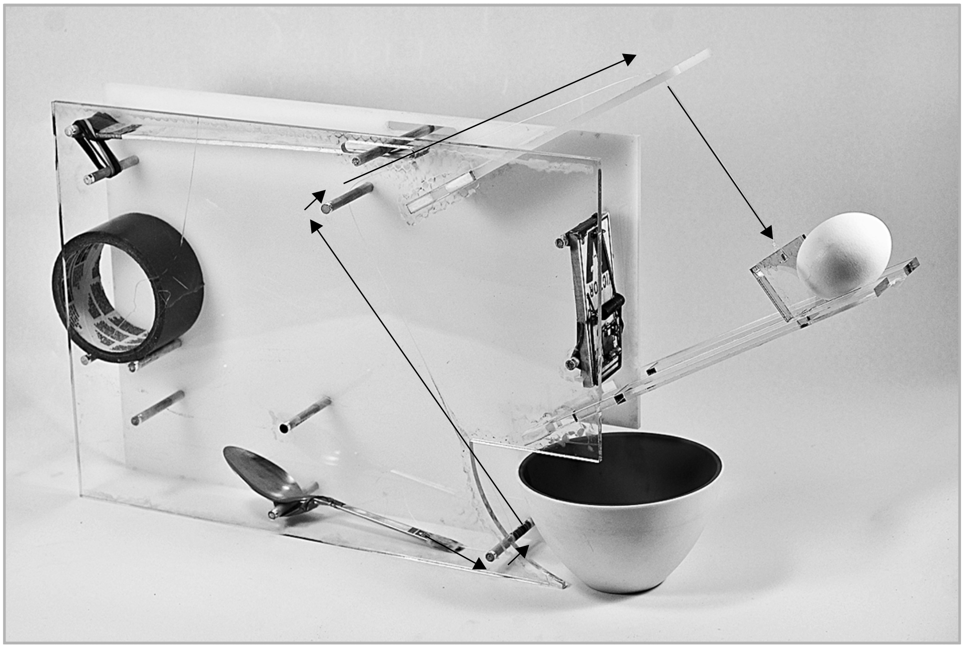
4. Loop rubber bands around the dowel just below the top-left dowel, as shown in Figure 1-28.

5. Tape the spoon or fork to the bottom-center dowel so that it can pivot when the duct tape roll falls and hits it.

FIGURE 1-28 Fixing the paint stick in place with rubber bands

6. On the handle side of the fork or spoon, duct tape a ~2 ft length of fishing line.
7. Put the front side template onto the 11 dowels while sandwiching the string guide piece (see Figure 1-29).
8. Route the fishing line as shown by the arrows in Figure 1-29. Then tie it to the hole in the egg gate.
9. Slide in egg ramp pieces to slots in the front and back template. Secure with tape if necessary.
10. Fix the wooden paint stick by looping the rubber bands around the end and securing with duct tape (refer to Figure 1-28). Hold it in position by sliding the remaining 1/4-in wooden dowel length into the slot (see Figure 1-29).
11. Duct tape the mousetrap to the two far-right dowels in the orientation shown in Figure 1-29.

FIGURE 1-29 Final assembly of Rube Goldberg breakfast machine



12. Carefully set the mousetrap.
13. Place the egg gate in the egg ramp and position the egg behind it. The string should be tight enough that when the duct tape roll hits the spoon or fork, that small amount of movement in the string dislodges the egg gate.
14. Now it's showtime! Slide the wooden dowel out of the top slot. Watch the paint stick slap the duct tape roll, which lands on the spoon, which yanks the string, which pulls out the egg gate, and allows the egg to fall and trigger the mousetrap.
15. Cook the egg and enjoy your breakfast!

References

1. U.S. Bureau of Naval Personnel, *Basic Machines and How They Work* (New York: Dover Publications, 1971).

2. David Macaulay, *The Way Things Work* (Boston: Houghton Mifflin, 1988).

3. Lawrence J. Kamm, *Designing Cost-Efficient Mechanisms: Minimum Constraint Design, Designing with Commercial Components, and Topics in Design Engineering* (New York: McGraw-Hill, 1990). Also published in paperback by the Society of Automotive Engineers, Inc., 1993.

4. James G. Skakoon, "Exact Constraint," *Mechanical Engineering* magazine (http://memagazine.asme.org/Articles/2009/September/Exact_Construction.cfm).

5. Merriam-Webster Online Dictionary, "Rube Goldberg" (www.merriam-webster.com/dictionary/rube%20goldberg).