2 Motion and Machines

Chapter Outline

Motion and machines

Describing motion
- *The language of motion*
- *Forces and energy*

Making motion useful
- *Mechanical advantage*
- *Simple machines*
- *Statics: useful non-motion*

Conclusion

Outcomes

—Use the ideas of energy and force to describe how and why things move.

—Understand simple machines and mechanisms used in robotics, such as gears, pulleys, levers, belts and wheels.

—Understand basic principles in designing and building robots including the use of mechanical structures.

Motion and machines

In Chapter 1 we saw a very broad definition of what a robot is—an automated machine. The robots we'll learn about in this course will be robots that move to do useful things. Before learning about the ways robots create useful movements, we'll need to introduce the language people use to describe motion, including a discussion of energy and forces.

Machines are tools that take some energy and convert it into action, and they are put to use all around us—often without us realizing it. Even complex machines are assembled from a set of more basic parts called simple machines. The second half of this chapter focuses on simple machines, and then we'll see more complex mechanisms in Chapter 7.

machine
a tool that takes energy and converts it to action

Describing motion

Try this short experiment: find something that's moving and tell someone about its motion. What words do you use? What ideas do you hope they understand? These aren't things that normal people pay attention to, but this section will hopefully give you the ability to better describe motion in words and also using mathematical equations. Along the way, maybe you'll also learn more about why things move, which can change the way you look at the world and how things work.

Figure 1. Fun at the dunes often involves motion. How would you describe the motion depicted here?

The language of motion

Don't treat this section as "just" a vocabulary lesson. The words are important, but the way the concepts relate is more important (and, frankly, the relationships are the truly beautiful thing here). In fact, most of the words we'll define here you already know and use regularly in different contexts. When we use these words the way scientists and engineers do, we need to be careful we know what the words mean in this context. If it comes across as overly careful and picky, just know that there's a reason—everyone who describes something that happens should be able to agree on the description, so the care we take pays off as we avoid ambiguity.

$$\vec{F} = m \cdot \vec{a}$$

Figure 2. Newton's 2nd Law. Some fear it and some think it's beautiful.

Math is a natural "language" to describe motion because it can represent things in a very compact way without being ambiguous. Like a picture, an equation can be worth a thousand words. One benefit to the difficult process of learning to represent things as symbols in equations is that you find that there are similarities in many of the rules that seem to govern the universe. Sometimes you learn how to solve one problem only to find that another seemingly unrelated situation uses the same equations, and now all of your hard work is even more useful to you than it was before.

This section introduces the main players in the game of motion, along with the symbolic representation of how they relate. The math you're expected to understand is a very limited part of algebra, specifically how to manipulate an expression to solve for a variable. Also, you should be able to look at an equation that relates two variables and tell in words how one depends on the other.

motion
the change of an object's position as time passes

length
the distance between two points

Length

Motion is the change of an object's position as time goes by. To describe motion, we'll first need to define ways to talk about the two things it's based on. The first quantity that motion is based on is **length**, which is the distance between two points and helps us agree on an object's position. In order to tell someone how far something has moved from its previous position, you first need to agree on a standard reference length, and in the metric system the standard length is meters (m). We call this the unit associated with this length, and you can report any distance as a fraction (or multiple) of a meter. For example, the thickness of your hair is about 0.0001 m ($\frac{1}{10,000}$ of a meter), and the distance from the east side of the BYU-Idaho campus to the west side is about 700 m. As long as everyone agrees on what a meter is, you can have a productive conversation about the length of things.

Figure 3. A ruler can be used to measure length. This ruler measures length in inches–one of the standard lengths in the British system of units.

time
what's used to describe how long we wait between two events occurring

Time

The second quantity that motion is based on is **time**, which we'll define somewhat circularly as how much time passes between two events. The standard unit we use to measure time is the second (s), and the symbol for time is *t*. As with length, you can represent any amount of time as a multiple of this fundamental unit. It takes you about 0.2 s ($^1/_5$ of a second) to blink, and it might take you 600 s—10 minutes—to walk across campus from east to west.

Time is a strange thing to measure, though, because you can't make a ruler for time the same way you can with length. You instead have to find something that will change in a predictable way as time passes to measure time. We call these things **clocks**, and they can be based on things as simple the movement of the sun's shadow or a pendulum that swings past some point every second. You can extend the pendulum idea to the quartz tuning forks found in watches, which are designed to faithfully oscillate back and forth one time every $\frac{1}{32,768}$ s. Not coincidentally, that's $\frac{1}{2^{15}}$ s. A digital counter in the watch assumes a second has passed when 32,768 oscillations have happened, and the tuning forks are so faithful in their back and forth motion that for every year (31,556,909 s) that passes, the watch will only be wrong by a second or two. The standard second that the world uses to measure time is kept by atomic clocks, which use individual atoms as the oscillators, and they "tick" so accurately that it would take millions of years before the clock would be wrong by a second!

clock
something that can be used to measure time

Figure 4. A watch based on a spring-loaded mechanical pendulum.

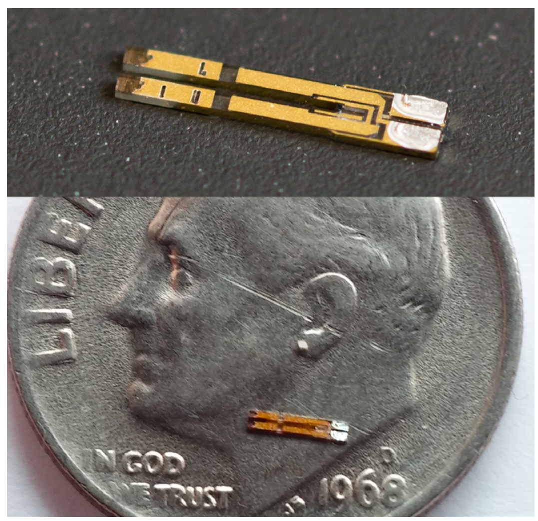


Figure 5. above: A quartz tuning fork from a digital watch. below: the same fork on a dime for scale.

Speed and velocity

As was mentioned before, motion is all about an object changing position as time changes. When the police officer asks you if you know how fast you were going, you can answer if you were paying attention to your speedometer—a device that is designed to measure one part of your car's motion: the **speed**. If you happen to watch a compass while you watch your speedometer—hopefully not while also driving!—you now know both speed and direction of your car, and we give this combination a special name: **velocity**, whose symbol is $\vec{v}$. We put the arrow over it to remind ourselves that it has a direction, and we also say that all quantities that are represented by both a magnitude (number) and direction are called **vectors**.

speed
a measure of how quickly an object's position changes

velocity
similar to speed, but also states direction of motion

vector
a quantity represented by both a number and a direction

Speed and velocity are given in units of m/s (read "meter per second"), and you'll notice that this unit is made up of units we've already met. The meter and the second are both fundamental units, which means they can't be expressed in terms of more basic units. Speed, then, is what's called a derived unit—one that is based on fundamental units. To get a feel for what 1 m/s looks like, imagine someone walking. Let's assume they start out at a position $x = 0$ m and each second they take a 1 m step in the positive x direction. This means they have a velocity $\vec{v} = \frac{1\,\text{m}}{1\,\text{s}} = 1\frac{\text{m}}{\text{s}}$ in the positive x direction.

We could use this to estimate the speed we walk. If it takes 600 s to walk across a campus that's 700 m wide, we just divide the change in position by the change in time to find the speed: 700 m / 600 s = 1.17 m/s. Apparently, 1 m/s wasn't a bad estimate for walking speed. If a car takes 60 s (one minute) to make the same trip, we would say it's moving ten times as fast: 11.7 m/s. This is the same answer we would get calculating it from scratch: 700 m/60 s = 11.7 m/s.

Acceleration

acceleration
a change in velocity: either the speed or the direction

What if you want to change your velocity? Say a pedestrian walks right in front of you as you cruise across the campus sidewalks (please don't). The ways to avoid the pedestrian are to either 1) change your speed by slowing down or 2) change your direction by swerving. In either case, we say there is an **acceleration**—by definition, a change in velocity. Since acceleration is how much velocity (m/s) changes per second (s), the units for acceleration are $\frac{\text{m}/\text{s}}{\text{s}} = \frac{\text{m}}{\text{s}^2}$.

If you need to stop your car's 10 m/s speed in 2 s to avoid hitting the pedestrian, you'll need an acceleration of 10 m/s / 2 s = 5 m/s^2, which is about half the acceleration due to gravity. Note that steering the car away from the pedestrian would also change the velocity, even if it doesn't change the car's speed. Acceleration, then, has a direction associated with it the same way that velocity does. The symbol for acceleration is $\vec{a}$.

Mass

mass
a measure of the amount of matter in an object

Mass is a measure of the amount of matter there is in an object. Matter attracts other matter through gravity, which explains why our bodies are on a desperate and futile quest to journey to the center of the earth. Matter also has the somewhat strange property that it wants to keep moving (or not moving) just like it has been moving (or not moving). As Sir Isaac Newton put it in his first law of motion, *all objects persist in their state of motion (or motionlessness) unless acted upon by an external force.*

Mass is measured in kg (read "kilograms") and has the symbol m.

Forces and energy

Forces

force
what causes a mass to accelerate

The external **force** Newton referred to is what causes acceleration. His second law of motion takes the first law a step further by stating how the motion changes—specifically, that the acceleration of an object is proportional to the force that's acting on it and in the same direction:

$$\vec{F} = m \cdot \vec{a}$$

This equation sums up in a few symbols all the words from the sentence that came before it, and the arrows even tell us that the change in velocity ($\vec{a}$) will be in the same direction as the external $\vec{F}$. Here it's important to note that the force in the equation is the net force on an object, which you find by accounting for all the forces on it, adding them up while remembering they're vectors so you have to keep track of directions, as well. For example, as you're reading this you're probably not accelerating even though there are forces acting on you. While gravity pulls you toward the earth, if you're sitting down what you're sitting on is pushing upward on you to cancel out this force and keep you stationary. Zero net force, then, doesn't mean that there are no forces acting on the object in question—it simply means that all the forces balance out.

Let's put this equation to use in the pedestrian avoidance example. Assuming your car has m = 1000 kg, which is about a ton, to get an acceleration of 5 m/s^2 backward you need a force of

$$\vec{F} = 1000\,\text{kg} \cdot 5\,\frac{\text{m}}{\text{s}^2}\text{backward} = 5000\,\frac{\text{kg} \cdot \text{m}}{\text{s}^2}\text{backward} = 5000\,\text{N backward}$$

You'll notice at that second-to-last bit that the units were getting slightly ridiculous, so we define a new unit for forces N (read "Newton"), with 1 N = 1 kg·m/s^2. This is still a derived unit, but we're hiding the nastiness in a nice little one-letter package.

Here's another example of forces and acceleration. Throw a ball in the air here on earth and you'll notice that both its speed and its direction of motion are changing. At the top of its arc, there is an instant where it might be moving horizontally, but it's not moving vertically. At that instant, it's tempting to also say that the acceleration is zero, but you can see that this is wrong if you imagine which direction it was just traveling a short time ago (up) and which direction it will be traveling a short time in the future (down). There must be an acceleration downward even in that instant that the ball is not moving vertically. Even way up there, the ball hasn't gotten very far from the center of the earth, and the force of gravity is still pulling down on it. Since this is an external net force downward, Newton's second law tells us we'll see a downward acceleration the entire time the ball is in flight.

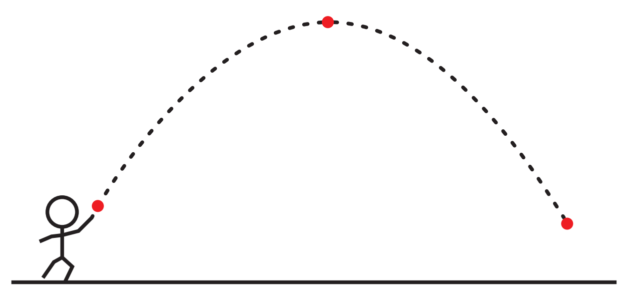


Figure 6. Throwing a ball in the air.

Energy and Work

We already mentioned that net forces cause acceleration, but carefully analyzing the motion of accelerated objects uses some complicated math called calculus, which was actually invented by Newton for just this problem but has since been put to use describing all kinds of things. Let's avoid the calculus by introducing a very tidy way to think about and describe what forces do to objects and to their motion: energy. Besides being much easier to talk about conceptually, the math in the energy picture is simplified for many situations into just arithmetic—addition, subtraction, multiplication, and division. Solving physics problems then becomes more like an exercise in accounting, but at least the math isn't much harder than what we learned in elementary school.

kinetic energy
the energy of motion

potential energy
stored energy that can be converted to motion

energy
allows one object to make another object move

work
the transfer of energy from one object to another

We'll discuss two types of energy here—kinetic energy and potential energy. **Kinetic energy** is the energy of motion. This includes the normal way we think about moving things—cars, falling water, etc.—but also includes thermal energy, which most people don't think about as being motion. Thermal energy (what we perceive as heat) is really just the effect from the motion of very small things like atoms and molecules. **Potential energy** is stored energy that can be converted into motion, and this can be categorized based on how the energy is stored; common types of potential energy are chemical, gravitational, elastic, and electrical.

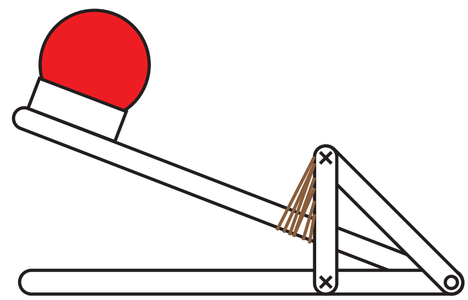
If something has **energy**, it has the ability to make an object move. For example, gunpowder has stored chemical energy, and when you burn it in a shell behind a bullet, it accelerates the bullet to some speed. When you pull the trigger on the gun, the powder in the shell burns and expands as its chemical energy is converted into kinetic (moving) energy of the gases the burning produces. Some fraction will be lost as heat or will make the gun recoil into your shoulder, but part of the energy will be used to accelerate the bullet away from you. This transfer of energy from the gunpowder to the motion of the bullet is called **work**, and we would say work is done on the bullet. In general, anytime we transfer energy from one form to another, we say that work has been done. In fact, we can be even more specific by defining work done on an object (W) as the force exerted on the object multiplied by the distance the object moves in that direction.

$$W = \vec{F} \cdot \vec{d}$$

This moving bullet in our example now has kinetic energy, but to see how this can also be used to make something move, imagine that the bullet now hits a rock, knocking pieces off the rock and making them move, as well. This shows that objects with kinetic energy can also make other objects move.

Let's look at another simple example of how we would describe a situation using energy. Grab a book and lift it up away from the ground. As you do this, even though gravity pulls down on the book, you can provide a bigger force than gravity, so there is a net force upward. There are two key things that could tip you off that you're adding energy to the book: first, that the book started out not moving and now it is moving vertically (from zero kinetic energy to some kinetic energy); and second, that the book was close to the earth and is now farther away from the earth (from low to higher gravitational potential energy). Even when you get the book as high as you want to lift it and it stops (zero kinetic energy again), there is some energy stored in the book. To see this, let go of the book and watch what happens. Gravity now acts on it as it falls over the same distance you did while lifting it, and that potential energy that you gave the book is transferred to kinetic energy and finally into sound and heat when the book hits the floor or table; this is not to mention all of the kinetic energy given to the air as the book falls through it—this must also be an inefficient way to heat your room! Note: your downstairs neighbors might kill you before you make a difference in the room's temperature.

One more fun place to see energy is in a catapult (see Figure 7). As you pull a catapult back, you are storing elastic potential energy in the rubber bands. When you let it go, the elastic potential energy is converted into kinetic energy of the projectile and it hopefully flies away from your catapult. As it flies through the air, some of its kinetic energy wants to make it leave the earth, while some of it points horizontally in the direction the catapult is shooting. There is a sweet spot where the catapult will shoot the projectile the farthest. We can see this by looking at two slightly silly cases. If the catapult shoots the projectile vertically (straight up), you'd better run when you fire it because it's not going to get anywhere horizontally. Gravity will eventually convert all the kinetic energy to gravitational potential energy at the top of the projectile's flight, then convert it back to kinetic energy as it pulls it back down to where it started, at which point your catapult has basically committed catapult suicide. If instead the projectile comes out horizontally, there is no kinetic energy in the upward direction so gravity immediately pulls the projectile to the ground and again the projectile gets nowhere. Apparently, the angle you fire the projectile is important here.



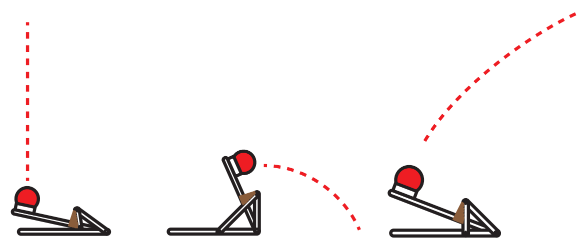


Figure 7. above: A catapult that uses rubber bands to store energy then launch a ball with it. below: three possible situations–a vertical launch, a horizontal launch, and a launch that has both horizontal and vertical components.

Another important thing to consider is how much kinetic energy you can give to the projectile. To increase the amount of energy stored ($W = F{\cdot}d$), you can either *1)* increase the force you have to work against (F) by using thicker or more rubber bands (or by doubling them up) or *2)* increase the distance you pull the catapult back (d). Both of these have implications for a catapult made from legos, since both of them will be limited by how well you can put the pieces together without having them fly apart under the stress of storing all that elastic energy.

Making motion useful

All this study of motion would be fun only to physics students if there wasn't some way to put it to use. Remember that robots are tools, and tools help us do something more easily or quicker than we can do it without them.

Mechanical advantage

Machines are designed to take energy and convert it to a more useful form. If that sounds similar to the definition for work, it's not a coincidence. Machines do work for us, and one way they do it is by taking a small input force and multiplying it to give a huge output force. This multiplying of the input force is called mechanical advantage, and you can represent it in an equation this way:

$$\mathrm{MA} = \frac{F_{output}}{F_{input}}.$$

mechanical advantage
How many times larger the output force is compared to the input force

In other words, to lift a 2000 pound piano with a 100 pound force, you need a machine that gives you a mechanical advantage of $\mathrm{MA} = \frac{F_{output}}{F_{input}} = \frac{2000\,\mathrm{lb}}{100\,\mathrm{lb}} = 20.$

A powerful way to think about mechanical advantage is in terms of energy. Possibly the most powerful idea in physics is called the law of conservation of energy. It tells us, the energy accountants, that the energy books have to balance. Despite what the guy will tell you as he tries to sell you his perpetual motion machine, no one can get more energy out of a system than they put in (or something else puts in). The same is true for machines, and we'll see in the next section how conservation of energy can be used to calculate the mechanical advantage expected for various types of **simple machines**, an object that changes the magnitude or direction of an applied force. The next section introduces some simple machines.

simple machine
an object that changes the magnitude and/or direction of a force

Simple machines

Levers

Levers use a rigid bar that is hinged at a point called the fulcrum, as shown in Figure 8. Force is applied at one side and the energy is transmitted to an object at another part of the bar. Conservation of energy lets us calculate the mechanical advantage of the lever. The energy input is just the work done moving the beam: $W = F_{input}d_{input}$. The energy output is the work done on the object at the other side and the law of conservation of energy tells us that it must be equal to the input energy: $W = F_{input}d_{input} = F_{output}d_{output}$, which can be rearranged to get $\frac{d_{input}}{d_{output}} = \frac{F_{output}}{F_{input}}$.

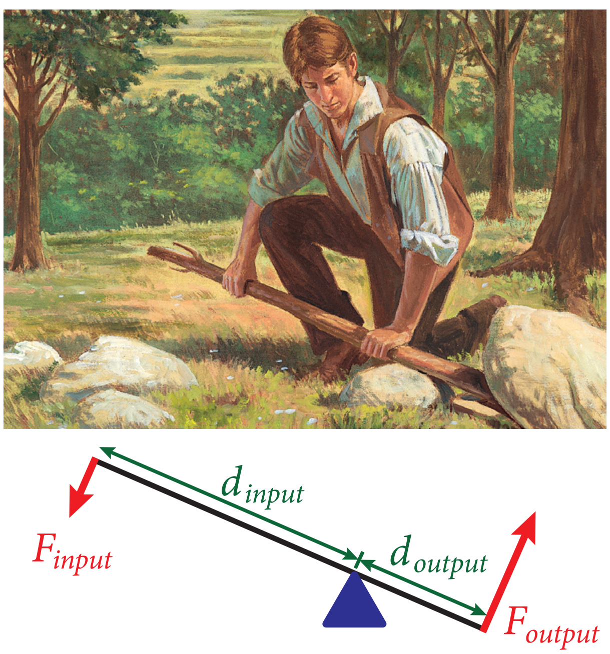


Figure 8. (top) "Having removed the earth, I obtained a lever, which I got fixed under the edge of the stone, and with a little exertion raised it up." Joseph Smith–History 1:52. (bottom) This lever changes the direction of the input force and also increases the magnitude of the force.
Photo copyright Intellectual Reserve.

But the right hand side of that equation you might recognize as the definition of mechanical advantage. One more thing to notice is that the distance the input force acts is proportional to how far from the fulcrum it's applied, which is also true for the output distance. To find the mechanical advantage of a lever, you just measure the distance from the hinge to where the input force is applied and divide that by the distance from the hinge to the output force. If the hinge is in the center of the bar as shown in Figure 9, the distances are the same, so the mechanical advantage is 1. If the hinge is 1/3 of the way from the edge and closer to the object as it was in Figure 8, d_{input} is twice as big as d_{output}, and the mechanical advantage is 2. It's good to point out here the trade-off that conservation of energy offers us: if we're willing to apply the force through a greater distance (or speed) than the object moves, the machine will multiply our force for us. The converse is true, as well, though: we could apply a bigger force on the short side of a lever and the machine will multiply the distance (or speed) instead by sacrificing force. This will show up as a theme for all our simple machines.

Inclined plane

An inclined plane is a flat ramp that is tilted at an angle. It makes lifting an object easier because if you just lift an object straight up, you have to fight all of gravity's pull downward on the object the entire distance you lift it: $W = F_{gravity} \cdot h$. If you're willing to push it up the ramp with length L, the amount of work you do is the same but now is given by $W = F_{push} \cdot L$. The mechanical advantage is $\frac{F_{gravity}}{F_{push}} = \frac{L}{h}$.

This looks surprisingly similar to the lever equation. In reality, this is only true for frictionless ramps, which are notoriously hard to walk on. This case is the best-case scenario since some of the energy input is actually going to heat up the ramp and the object. But again we see that by pushing the object through a greater distance, we gain the ability to lift heavier objects.

Wedges and screws

Wedges and screws are just other applications of inclined planes where you can get huge forces by again making the sacrifice of pushing through added distance. Compare putting a nail (like a wedge) into a piece of wood to putting a screw (like a wedge with an inclined plane wrapped around it) into a piece of wood. Where the nail needs a huge force from something like a moving hammer, using a screwdriver and the force from your hand multiplied by the mechanical advantage of the inclined plane wrapped around the screw (the screw's threads) is enough to get the same result.

Wheel and axle

The wheel and axle is a machine that relies on rotation instead of displacement like the lever did. This can be important because often we want our machine to stay in the same place. Figure 12 shows a mechanism that could be used to lift something. There is a spool of rope wrapped around an axle, and attached to the axle is a larger wheel. Someone turning the large wheel has to move all the way around the larger circumference. When the wheel turns once, the rope only moves the object up a distance equal to the circumference of the axle. The exact same trade-off occurs here as for the lever, and the mechanical advantage is $MA = \frac{r_{input}}{r_{output}}$. While a lever can only lift something

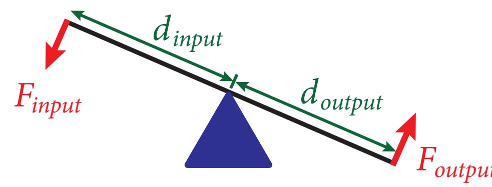


Figure 9. This lever changes the direction of the input force but has a mechanical advantage of 1, so $F_{output} = F_{input}$.

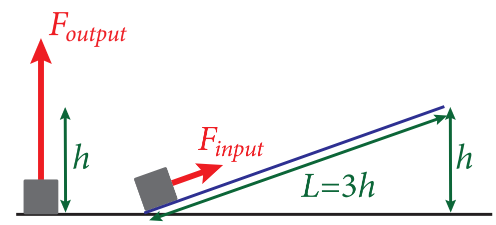


Figure 10. By pushing the object up the ramp, the required force to lift the object is three times smaller in this case.

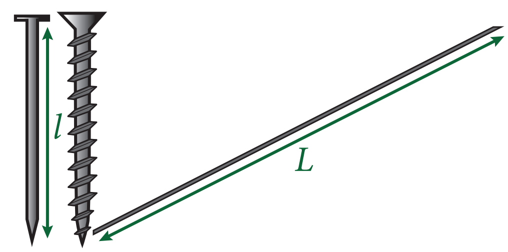


Figure 11. The tip of a nail is a wedge that opens a way for the rest of the nail. A screw's threads act like an inclined plane that pulls the screw in as it's turned. Making the screw's threads closer together increases *L* and gives more mechanical advantage.

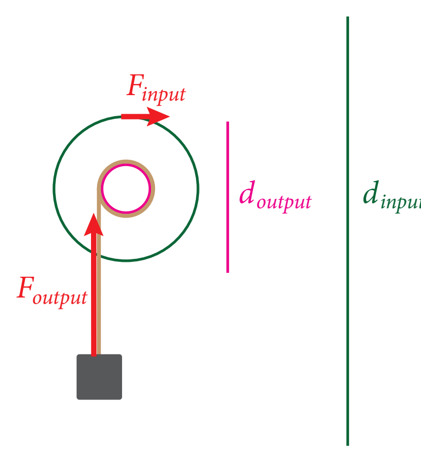


Figure 12. A wheel and axle set up to lift a heavy object. The vertical lines show the distance each force is applied for each turn of the machine (this is the circumference of each circle).

until the side you're pushing on hits the ground or something else, you can turn a wheel and axle until the rope runs out.

Gears

Gears are toothed wheels that can be connected to each other by meshing the teeth to gain mechanical advantage. You can think of them as another example of a wheel and axle, but now the axis of one wheel doesn't have to line up with the axis of the other. There's another tricky thing to think about, though, and it has to do with the fact that usually you turn the axles that the gears are connected to, and not the teeth themselves. If you turn the shaft of a big gear that's connected to a small gear, you actually move the small gear a lot (through a big angle). Whereas turning the larger wheel in the wheel and axle multiplied the input force, turning the larger gear's shaft will multiply our distance (and *divide* our force). The mechanical advantage (also known as gear ratio for gears) can be found by comparing the number of teeth in each gear. If there are twice as many teeth on one gear compared to the other, the mechanical advantage will be 2 if you turn the shaft of the small gear. Confusingly, higher gears in your car or bike actually have a lower gear ratio—lower mechanical advantage—which means you're sacrificing force for extra speed (distance). You start out in first gear because it has the highest mechanical advantage, which gives you the biggest force to get your car moving from rest.

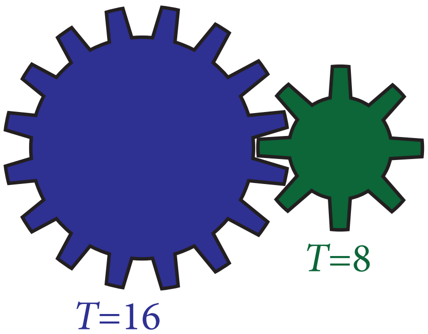


Figure 13. A set of gears. These give a mechanical advantage of 16/8 = 2 if you turn the shaft of the small gear or 8/16 = 1/2 if you turn the shaft of the large gear.

Pulleys

Pulleys are related to wheels and axles, but their mechanical advantage derives from the way you wrap rope around them. A single pulley can change the direction of the force applied to a rope or cable, but their real usefulness can be seen when they are chained together in something like the system of pulleys called a block and tackle illustrated in Figure 14. Here, if someone pulls down with force F on the rope hanging from the block and tackle, the rope wrapped around the three pulleys means the rope pulls upward in six places on the hanging mass, which gives a mechanical advantage of six. Again, the sacrifice is that you have to pull through six times as much rope as the distance the mass gets lifted.

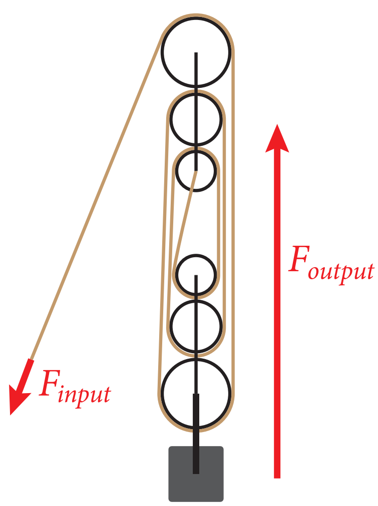


Figure 14. A block and tackle. Since the mass only goes up 1/6 the distance the rope the input force is applied to moves, the mechanical advantage is 6.

Statics: useful non-motion

We have spent so much time learning about ways to make things move, but there are many things that we'd often like to keep from moving: bridges, buildings, walls, and furniture to name a few. For this reason, there is an entire field of study devoted to ensuring things don't move and it's called **statics** (as opposed to dynamics, which is what we've focused on so far in this reading).

statics
the study of non-moving things

The key idea behind statics is stable equilibrium—which describes a system that is in a state where it has made its potential energy as small as possible. Potential energy is a little like a hot potato, and objects will spontaneously get rid of it as quickly as they can. Think back to the example of the book you lifted up in the air. The instant you let it go, it starts getting rid of its potential energy by accelerating toward the floor, where it has less potential energy. A spring has the least amount of elastic potential energy when it's the way it came out of the factory—no shorter and no longer. When you compress the spring (or stretch it out) then let it go, it will immediately go back to the way it "wants" to be: the way the factory made it. Now, keep in mind that our definition of spring here is a very loose one. Everything solid—from tree branches to bones to bars of metal—have some shape they like to form and stay that way. Deform them a little bit, and they want to go back to the way they were. Deform them a lot, and you might change the way they "want" to be, which is called a plastic deformation. We'll only focus on the ones that the objects spring back from—called elastic deformations.

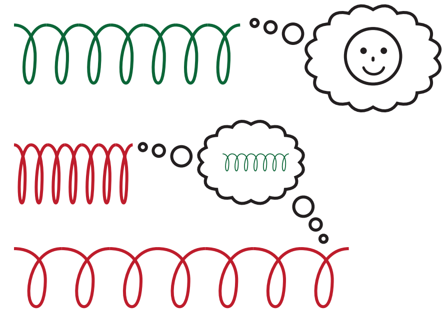


Figure 15. Springs can store potential energy. The top spring is 'happy' (has low potential energy) because it's the length that it was made. The two bottom springs have stored potential energy because they have been compressed (or stretched), and will exert a force (do work) to get back to their original length, giving up their potential energy as they do.

It's a little hard to see the connection between building bridges, stretching springs, and falling books. Given the chance, the bridge will fall down like the book. Building a bridge, then, must be all about convincing each piece of the bridge that it would be much happier staying the way it was built than falling down.

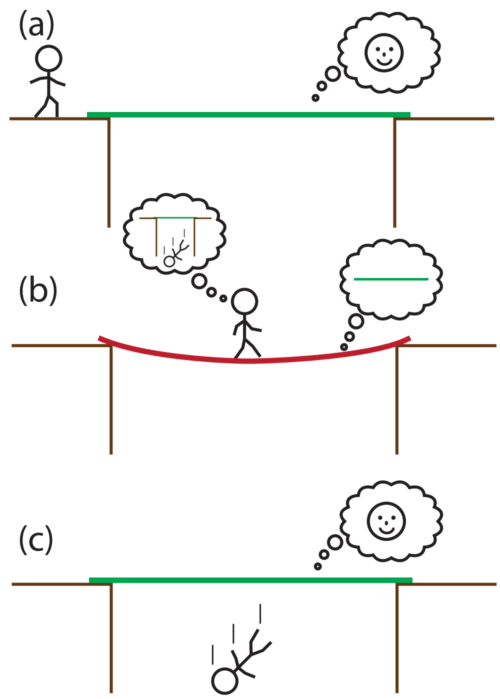


Figure 16. A cautionary tale about bridges.

Let's start by imagining the simplest bridge, illustrated in Figure 16 (a): a plank supported on either side of the span we're trying to cross. It doesn't fall down because the ground pushing up on either edge convinces those parts of the plank that they would rather be taking up space somewhere the ground hasn't already claimed. Even with something on it as in Figure 16 (b), the middle of the plank (hopefully) doesn't fall because it behaves like a spring. "Self," it tells itself somewhat colloquially, "some fool is standing on me right now but I know I came out of the factory (tree) as a straight plank. The instant he/she leaves, I'm springing back to the way I know I'm supposed to be." In fact, while the person is standing on the plank, it is trying desperately to go back to the way it came out of the plank factory, which is exactly what is keeping the person from shortsightedly trading their own potential energy for an exciting but ultimately dangerous kinetic end at the bottom of the canyon, shown in Figure 16 (c).

Another simple case would be three bars pinned together as a triangle, illustrated in Figure 17 (a). Applying downward pressure where they're pinned at the top might cause them to deform like Figure 17 (b) shows. If we apply it on the bottom bar from above while holding the top pin in place, it might look like Figure 17 (c), which looks just like our simple plank example. Again we imagine each bar as a spring, and

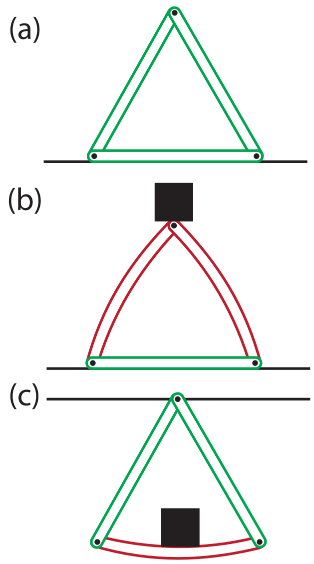


Figure 17. (a) three bars pinned together in the shape of a triangle. (b) and (c) If a load is placed on the triangle, it will deform the bars but they want to maintain their shape.

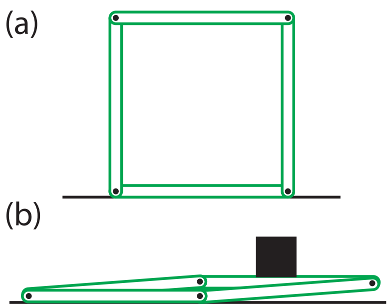


Figure 18. (a) Four bars pinned together in the shape of a square. (b) If a load is placed on the top, the bars can simply rearrange themselves to lower their potential energy.

Figure 19. Triangles supporting large cranes.

they grumble while they deform, but they're still convinced they would rather be the way they were and will snap back right when the force is removed—the elastic potential energy stored in them dwarfs the gravitation potential energy they could hope to get rid of by drooping more than they do.

It's worth talking about why triangles are used so much more often than rectangles or squares. If you pin four bars together in a rectangle and then apply some side-to-side force to the top bar, instead of deforming the bars when you apply pressure it's possible to just rotate one or two of them around the pins that are holding them together, and they can run from your applied force while the top bar falls closer to the earth and minimizes its potential energy. Here's the key: the triangle couldn't do this because of how interconnected the bars were. Three bars is a sweet spot for statics because of this—two is too few and four (or more) turns out to be too floppy (see Figure 18). You may have watched a house being built with studs parallel to each other instead of being arranged in triangles. The studs alone would not be a good static structure. But the exterior walls are then covered with sheets of plywood, so when the wall tries to move side to side, these sheets act like springs to keep the wall from changing shape. You can imagine dozens of triangles in those plywood sheets whose corners are three different screws going through the sheets and into the studs.

Let's go back to the catapult example to see how applying these ideas could get our catapult to shoot farther by improving the structural stability. The more you pin things together instead of snapping them together, the stronger the structure, which will let you store more elastic potential energy in the catapult before it rips itself apart. Bigger forces also mean you can get more speed for the launch by lowering the mechanical advantage of your catapult's lever. If you can find ways to include pinned triangles you'll have a structure that is even more solid. Look at how many pinned triangles help keep up the cranes shown in Figure 19. If you keep an eye out for triangles in stable structures, you'll find them almost everywhere.

Conclusion

Because so much of what we want done involves changing the world around us, understanding how to create motion and how to prevent motion is one of the most important steps on the way to creating useful robots. Along with the ability to move, they also need to receive instructions for each task we want them to do. Chapter 3 will discuss the basics of how to program robots.