Chapter 5 Thermal Energy and Friction

Figure 5.1 A racecar locking its brakes. The tires are smoking from the heat generated by friction with the road. (Photo credit: CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=192252)

Section 5.1 Friction

Friction is a word that is often used outside of physics, in a completely different context. If there is a lot of friction in your relationship with someone, that means you always feel like you are fighting with them, and the situation can get pretty hot. Bringing the word “friction” into the context of physics, things are pretty much the same. Friction is a force that always fights against motion. And it transforms kinetic energy into thermal energy, so situations again can get pretty hot.

Let’s consider hammering a nail into a board. You can’t (usually) push a nail into a board with just your hand. The force of friction between the nail and the board, pushing back against you, is too strong. But if you use a hammer, you can generate enough force to push the nail into the board. Once the nail starts moving, it doesn’t just keep going through the board. It stops quickly, again because the friction doesn’t want it to go into the board—it is opposing the motion.

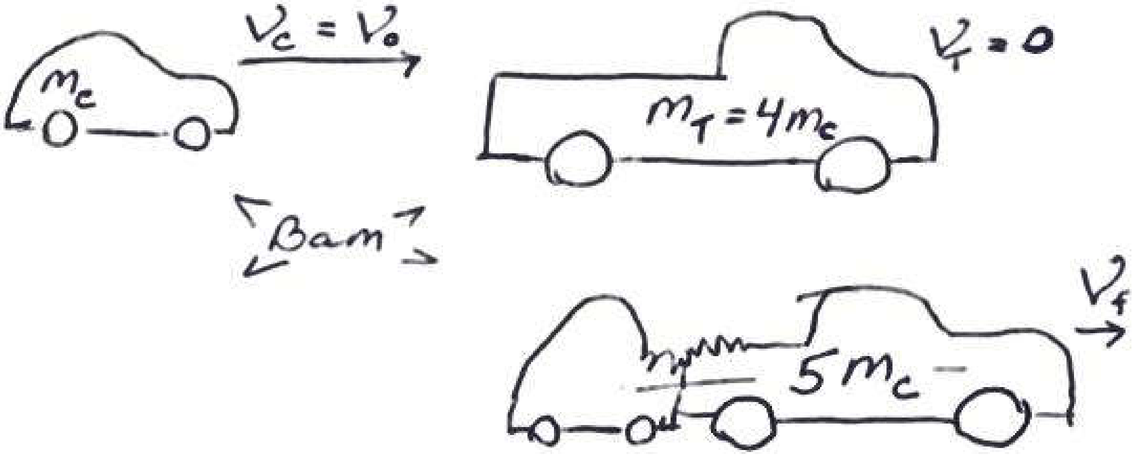
What if you then realize that you have put the nail in the wrong place, so now you have to pull the nail back out. Again, you (usually) can’t pull a nail out of a board just with your hands. You have to use the claw part of the hammer again to generate enough force to pull the nail out because of the friction between the nail and the board. So when you tried to push the nail in, the friction pushed back at you, and when you tried to pull the nail out, the friction pulled back at you. That’s what it means to say that the force of friction always fights against motion.

Section 5.2 **Thermal Energy**

Have you ever touched a nail immediately after you've hammered it into the board and then pulled it back out? What did you notice? The nail gets really hot! All of that work that you did giving the nail kinetic energy to go into the board, and all of the work you did giving the nail kinetic energy so it would come back out, changed into thermal energy. That's an example of how friction transforms kinetic energy into thermal energy.

Any time that there is a collision and something deforms, thermal energy is created, whether that thing is wood deforming to allow a nail to enter or the bumper of a car. Let's look again at the collision of a car and a truck that we have already seen in Section 3.4. This time we will ask a different question:

A 1000 kg car moving at 20 m/s strikes a stationary 4000 kg truck. The two stick together and continue moving on the very slippery ground. Was any thermal energy produced in this collision? If so how many Joules of thermal energy was produced? If not, how can you be sure no thermal energy was produced?



We will need two different lenses to answer this question. First, the momentum lens can give us the final velocity of the car-truck wreckage, since there are no external forces and momentum is conserved. And second, by using the energy lens we can find the initial kinetic energy and the final kinetic energy. Since there are no other types of energy in this problem, any energy difference between the initial and final energy must have been "lost" as thermal energy, ***E_{th}***.

Since we already used the momentum lens in Section 3.4, let's just refer to the answer we already found instead of solving the problem again. We found that the final velocity of the car-truck wreckage was 4 m/s. So...

$$E_K(\text{before collision}) = E_{th} + E_K(\text{after collision})$$

$$\frac{1}{2}m_c V_o^2 + \frac{1}{2}m_T \cancelto{0}{V_T^2} = E_{th} + \frac{1}{2}(m_c + m_T)V_f^2$$

$$E_{th} = \frac{1}{2}m_c V_o^2 - \frac{1}{2}(m_c + m_T)V_f^2$$

$$E_{th} = \frac{1}{2}(1000\,\text{kg})(20\,\text{m/s})^2 - \frac{1}{2}(5000\,\text{kg})(4\,\text{m/s})^2$$

$$E_{th} = 200{,}000\,\text{J} - 40{,}000\,\text{J} = 160{,}000\,\text{J}$$

Yes, thermal energy was created. In fact, 160,000 J, four fifths of the initial energy, was transformed into thermal energy!

Let's try and answer a question related to the nail going into the board.

Exercise 5.1 **You are using a 0.6 kg hammer to drive a nail into a wooden stud in the wall of a house. You swing the hammer at 8 m/s, and each hit drives the nail 2 cm into the wood. Assume that the mass of the nail is very small compared to the mass of the hammer. After each swing, the hammer, nail, and wood are all motionless.**

a. Draw pictures of what is happening just before the hammer hits the nail and after the collision is over but the hammer is still touching the nail. Include all of the information that you can from the question in your drawings.

b. How much thermal energy is created each time the hammer hits the nail? Do it just like in the example above. Look at kinetic energy before and kinetic energy after. Ignore any other forms of energy (like sound or gravitational potential)

c. What is the change of momentum of the hammer during the collision? Isn't momentum supposed to be conserved? Where did it go?

d. What is magnitude of the acceleration of the hammer as it comes to rest during the collision? Assume that the hammer experiences constant acceleration from the time it hits the nail until the time the hammer and nail stop moving.

e. What was the force on the hammer during the collision?

f. How much time did the collision last as the nail was driven into the wall?

Is friction good or bad? We have non-stick frying pans so eggs don't stick—so in that case friction is bad. But the treads on hiking boots are made of rubber so they DO stick—in that case friction is good.

Exercise 5.2 **Give two examples of times or places when friction is desirable, and two examples when friction is NOT desirable. (Note: it might help if you think about when you would benefit from using something like oil that would reduce friction, and when you would benefit from using something like rubber that tends to increase friction.) Can you come up with a general rule for why friction is sometimes good and sometimes bad?**

Section 5.3 Vectors

Up to this point we've used a lot of words (force, work, friction, energy, …) that are not uncommon in daily usage, but in physics we may have slightly different or more specific definitions of what these words mean. Now we meet a word that is rarely used except in a scientific context: vector. A vector is simply something that has both a magnitude and a direction. This is actually a concept that you are already familiar with. A negative sign is something that keeps the magnitude (size) of something the same but reverses its direction. If your boss tells you that your pay is going to change by 30%, that could be very good or very bad depending on whether that means your pay is going *up* 30% or *down* 30%. Same magnitude of change, but opposite direction!

Friction is something that opposes motion, which means that if motion is to the right, friction is to the left. The force of friction can be represented by a vector. In fact, you already drew force vectors with arrows back in Section 1.4. All forces are actually vectors, and many other things as well, including momentum, velocity, acceleration, and even displacement (change in position).

When there is more than one force acting at the same time, we will want to know what the total (or net) force is. In the previous work we have done, we haven't tried to add forces together to get a total. How would that be done?

Imagine giving somebody directions by drawing a map with an arrow 20 meters long pointing East. You have just made a displacement vector to tell the person where to go. Something like this:

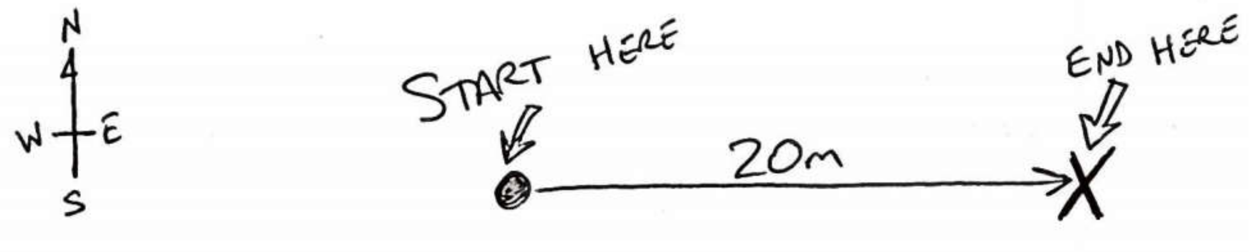


Figure 5.2: A displacement vector pointing East

But what if you wanted the person to go 20 meters East AND 20 meters South? You could simply add another arrow to your drawing, this one pointing South. What would your map look like? One of these?

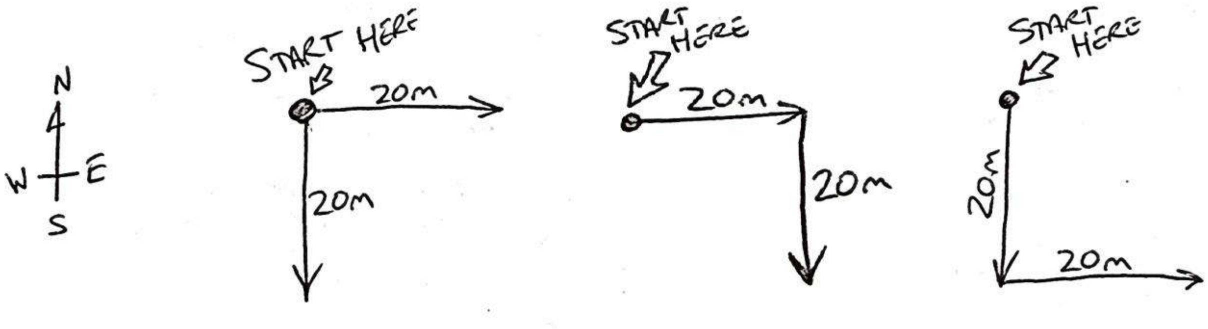


Figure 5.3: Adding vectors, sometimes done correctly and sometimes incorrectly!

Which one? Is there more than one that is correct? Hopefully you see that in the first option, on the left, there is not a clear ending point. It seems that you are telling the person to either go East OR go South. Or maybe go East, then come back and go South? This isn't a good way to look at combining the directions into something that makes sense.

What about the second one? This time it seems clear that the person should first go 20 m East and then turn and go 20 m South from that same point. So they will end up somewhere South-East from the starting point. This is a better way to look at combining the directions.

And what about the third option? This time it appears that you want the person to first go South and then turn and go East. So it seems different from the second option, but if you compare the places where the person ends up, you can see that in fact it gives the same result.

This is how you should add vectors. It is best if you try to draw the arrows in a way that they are roughly proportional to the right size to make your drawing as useful as possible. **To add vectors, draw them so that the tail of each starts at the tip of the previous one.** And it actually doesn't matter which one you start with. You should end up in the same place no matter what. Just like adding 3+4 is the same as adding 4+3. Let's try it with some forces. Imagine a game of tug-of-war with two equal teams, each able to pull with a force of 4000 N.

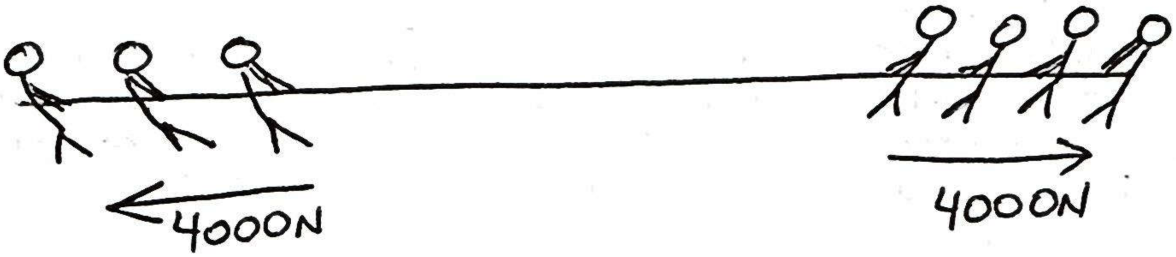


Figure 5.4: A game of tug-o-war. The teams are evenly matched in terms of the amount of force they can apply to the rope, even though the team on the right has more people.

The net force of the two teams pulling against each other can be represented like this:

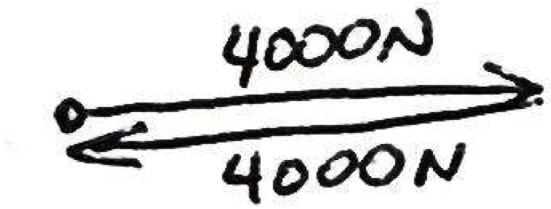


Figure 5.5: The net force of the tug-o-war game in the figure above. 4000 N to the right plus 4000 N to the left ends up back at zero. No net force.

The second arrow ends right back where the first one started. So with all of those people generating as much force as they can, the net force they get for all of that effort is zero. Nobody is going to win this game of tug-of-war! You can represent it in an equation form as well. You simply have to define one direction as being positive. For example, in this case we could make positive point to the right. Then negative is to the left. The total force is the sum of all of the forces:

What if another person, who is able to pull with a force of only 200 N, comes to join the team on the left? In that case, the net force would be 200 N to the left, or -200 N. Even though this one person is pulling with a relatively small force (the other three team members together are pulling 20 times as much as this fourth person), it is enough to create a net force to let the team on the left win. Net force to the left is going to create an acceleration to the left, so if they started with zero velocity the rope will start going left.

Section 5.4 When the force opposes the motion

What happens when the force points in the direction opposite the motion, as it does with friction? We've already seen at least one example of force pointing opposite the direction of motion: when something is launched straight up into the air. What happens? The thing that was thrown upward slows down and eventually stops in the air, and then it starts coming back down.

A force is supposed to cause acceleration, right? F = ma. And we usually think of acceleration as something that increases speed. The "gas pedal" in a car can also be called an "accelerator." And that makes sense, because it makes the car speed up. But it is actually also possible for an acceleration to slow something down. That's exactly what happens when the speed is in the opposite direction from velocity. It even works with the equation we introduced in Section 4.1, $= \frac{\Delta v}{\Delta t}$. The change in time, on the bottom, is always positive. We live in a universe where (as far as we know) time can never go backward. But let's look at the change in velocity. If something is slowing down, that means the final speed is less than the initial speed. So the change is a small final speed minus a larger initial speed. And something small minus something big is going to be less than zero, so negative. **So if an object is moving in the positive direction and acceleration is negative, it will slow down. And the opposite is also true: If an object is moving in the negative direction and acceleration is positive, it will slow down.**

Often people will refer to slowing down as "deceleration." We won't use that word in this class, because it will actually introduce some difficulties. If we wanted to define acceleration as increasing speed and deceleration as decreasing speed, what would happen when the initial speed is zero? Is acceleration now in both directions? And when we start looking at circular motion, it will become even more complicated. An object moving in a circle at constant speed is accelerating, because the direction of the velocity is constantly changing. That's where the ideas of centripetal (and centrifugal) force will come in. If we say that acceleration increases speed and deceleration decreases speed, we will need yet another word to describe this situation where the speed doesn't change. So we are better off just using acceleration as the word to describe any of these things.

Exercise 5.3 **You and your bicycle together have a mass of 80 kg. You are going full speed, 4 m/s, across level ground when suddenly you see a line of ants crossing the road 6 meters in front of you.**

- **a. You love ants and don't want to squish any, so you slam on your brakes, creating a force of friction of 700 N between your tires and the road. Are the ants safe? Remember to check whether your answer makes sense.**
- **b. Can you actually bike at 4 m/s? Is that a reasonable number?**
- **c. How far would you travel before stopping if the road were wet, which reduces the force of friction to 500 N between your tires and the road?**

That is the motion lens, and the momentum lens is similar. A force pointing in the same direction as the momentum will increase the magnitude of the momentum. A force pointing in the opposite direction will decrease the magnitude of the momentum. And if two objects have momenta in opposite directions, we have to take the directions into account. For example, the total momentum of two people running toward each other across a field would be zero if each of them had the same momentum. That also means that if there is a collision where the two objects stick together, the final speeds may be lower than any of the initial speeds.

Exercise 5.4 **A 1000 kg car driving at 40 m/s collides with a 3000 kg truck driving at 20 m/s. The vehicles stick together and skid off on the very slippery road. Find both the final velocity of the car-truck wreckage and also the amount of thermal energy created for each of these two situations. Be sure to use the strategies we learned in Section 3.1.**

- **a. The car rear-ends the truck driving in the same direction.**
- **b. The car and truck have a head-on collision, driving in opposite directions.**

What about the energy lens? When something is moving, we are talking about kinetic energy. If a force is in the same direction as the velocity, the speed will increase. And that means the kinetic energy will also increase. But if the force is in the opposite direction of the velocity, the speed will decrease, so the kinetic energy will also decrease.

Do you remember the definition of work? It is the change in energy. So what this means is that **a force that acts in the direction of the motion will increase the kinetic energy, doing work on the object** (work is positive). But if the force is in the direction opposite of the motion, the kinetic energy decreases. Since change in energy is negative, that means the work is also negative. So **a force that opposes the motion of an object actually removes energy from the object, or we can say that the object does work on whatever was causing the force** (work is negative).

If you are not sure if work was done on the object (positive work) or if work was done by the object (negative work), you can ask yourself how the energy of the body changed. For instance, if you carry a 20 kg mass 100 m across a soccer field, you may feel you've done lots of work because you're tired. However, you have not changed the energy of the mass; you have only changed its position. You have displaced the mass horizontally, but the force you put on it is upward, perpendicular to the change in position, so no work is done. Remember that work is force times distance in the same direction! Not perpendicular. But what if you carried the mass up a hillside 100 m, increasing your elevation by 30 m? Now you know you've done work because the mass has more gravitational potential energy. The change in energy could also be kinetic. If the mass was carried horizontally but ended up moving at 10 m/s when you let go of it and it wasn't moving at first, you've done work on it. So work is positive. If, on the other hand, it was moving 10 m/s and you caught it and set it down, you have actually removed energy from the mass, so work is negative.

Exercise 5.5 **If an 80-kg paratrooper makes a HALO (High-altitude, Low-open) parachute jump from a plane that is 10,000 m above the earth. Ignore any sideways motion as the paratrooper jumps—let's just worry about the vertical direction for now.**

a. What is the speed of the paratrooper just before he hits the ground, neglecting air resistance?

b. In fact, there is enough air resistance that the paratrooper's actual speed just before hitting the ground would be 60 m/s if he did not open his parachute. How much thermal energy is generated in the air as the paratrooper falls? What percentage of the initial gravitational energy is lost to thermal energy?

c. If all goes well, the paratrooper would actually open his parachute, making his speed just before hitting the ground drop to only 5 m/s. What fraction of the initial gravitational potential energy is lost to thermal energy in this case?

d. Is the air resistance doing work on the paratrooper, or is it removing energy?

Exercise 5.6 **A 20 g bullet moving at 500 m/s is fired upward into a 1-kg wood cube. It sticks into the cube and the two fly up into the air because of the impact.**

a. What is the speed of the block and bullet as they start to fly upward together?

b. How much thermal energy was lost in the collision?

c. Neglecting air resistance, how high with the block and bullet fly upward before they are stopped by gravity?

Section 5.5 **Static friction**

So far we have just talked about friction while something is moving. There can also be a force of friction when something is not moving. This is called static friction. If you place a child on a waterslide, the child slides down freely. That is because the friction opposing the motion down a waterslide is very small. But you could also place the same child on a hillside with the same slope as the waterslide without worrying about sliding down. Maybe rolling, but not sliding! That is because static friction is holding the child in place.

Determining the size of static friction is a bit tricky. If you push against a boulder with a force of 500 N and the boulder doesn't move, it is likely static friction that is keeping it in place. If you are pushing against it but it won't move, the acceleration is zero but the force you are applying is not zero. According to Newton's Laws, that must mean that the static friction that is fighting against you is exactly as large as the force you are applying. That's how static force works. If nothing is trying to move an object, the static force is zero. But as soon as a force is applied, a static force with the exact same magnitude but the opposite direction immediately appears to prevent the motion. If you push hard enough, you can eventually overcome the static force, because it will have some maximum possible value depending on the surfaces and the mass of the object. At that point, the static friction stops and the kinetic friction we have already been learning about takes over. Normally the maximum static friction is a bit larger than the kinetic friction. That is why it is usually harder to start sliding something across the floor than it is it keep it sliding after it has already started to move.

Exercise 5.7 **A 1000 kg car is at rest on a level road and the brakes are locked up, so the wheels can't turn. I am not far from home, only 1 km, so I decide to just skid it home. The maximum static friction between the wheels and the road is 12,000 N, and the frictional force after it starts sliding is 8,000 N. Draw force diagrams, and find the net force and the acceleration of the car for each of the following:**

a. The car is just sitting there without anybody or anything trying to push it.

b. I get behind the car and push with a horizontal force of 500 N.

c. I attach the car to a tow truck and pull with a force of 10,000 N.

d. I attach the car to a tow truck and pull with a force of 14,000 N.

Exercise 5.8 **How much work is done on the car from Exercise 5.7 as you skid it home?**
