Forces and Motion Content Background Document

We experience forces in the world every day of our lives. Blocks fall from a tower; we are lifted from our crib; a ball rolls across the floor; we jump for joy. Forces cause motion so regularly in our daily life that we give little thought to figuring out just what causes changes in the motion around us. It becomes part of our intuitive sense of how the world works. Because of their vast experiences with movement and moving objects, children start school with their own set of ideas about forces and motion. By paying attention to students' thinking, taking their ideas seriously, and trying to understand their thinking, teachers can build on what children already know. These initial ideas can be used as a foundation to build remarkable understanding, even in the earliest grades.

In this document, we will try to answer a fundamental question of physical science, "Why do things start to move, slow down, speed up, stop moving or change direction?" In answering these core questions we can develop concepts that can explain and predict a wide variety of phenomena in the world.

STOP AND THINK: How would you answer that question, "Why do things start to move, stop moving, or change direction?" What is your common sense response?

If you looked the word force up in the dictionary, it would have many possible definitions, from a "force out" in baseball, to the "forces of good and evil," to the "labor force" driving our economy. None of these matches how scientists use the term, so let's clarify. In science, the term force means a ***push*** or a ***pull*** caused by the interaction of two objects that changes the motion of one or more of the objects. Many scientists add specificity to that definition to include a twist (as in the twist of a corkscrew or how you might squeeze a wet towel). Since the word force has so many possible meanings it is extremely important to clarify this scientific definition—both for ourselves and for our students—as we start our exploration of forces and motion.

Most ideas about forces and motion come from our common sense and experience. It is common sense to say that if an object is not moving, it will not start moving by itself. But our common sense does not necessarily tell us why something stops moving. It just does. We don't necessarily see something pushing or pulling it to make it stop. It is so much a part of our everyday experience that we don't even question that moving things eventually stop. But moving things in outer space will move in a straight line forever unless or until they experience an external force. What makes outer space different from Earth so that things don't slow down and stop? What makes Earth different from space so that all moving things DO eventually slow down and stop?

Similarly, common sense tells us that gravity pulls objects toward the ground. What comes up, must come down. Common sense also tells us that things that move—like a person, animal, swinging golf club or falling rock—push or pull on other objects. But can an inanimate object, like a table, wall, or floor exert a force on an object? That is a little more difficult to picture.

Then there are forces that defy our common sense. Why does a magnet attract or repel some objects but not others? Why does rubbing a balloon on your hair cause it to stick to the wall without falling? What force is holding up the balloon and allowing it to defy the pull of gravity? These phenomena almost seem like magic. How can these phenomena be explained?

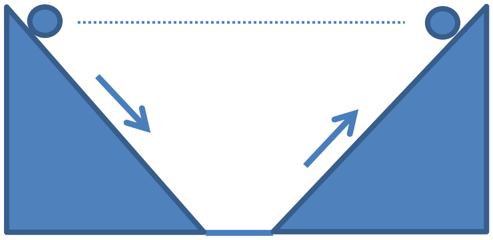
This document will challenge you to broaden and deepen your understanding of forces and motion. It is written to support and further your own content learning about how scientists define, measure, and explain phenomena in the world such as why you slip on ice or your car overheats without oil. It may also help you to understand how engineers use their knowledge of forces to solve problems in our complex world such as how to send a rocket to the moon and beyond, or how to design tall buildings to withstand the forces of high winds and shaking earthquakes. The goal is for you to develop a conceptual understanding of these ideas so you will be able to more effectively teach elementary students about forces.

The content is written with you, the teacher, in mind. It presents subject matter knowledge that is tied to the RESPeCT lessons you will be teaching, but it is at a level higher than what you will present in your classroom. After all, teachers should know more than what they teach their students!

A brief history lesson

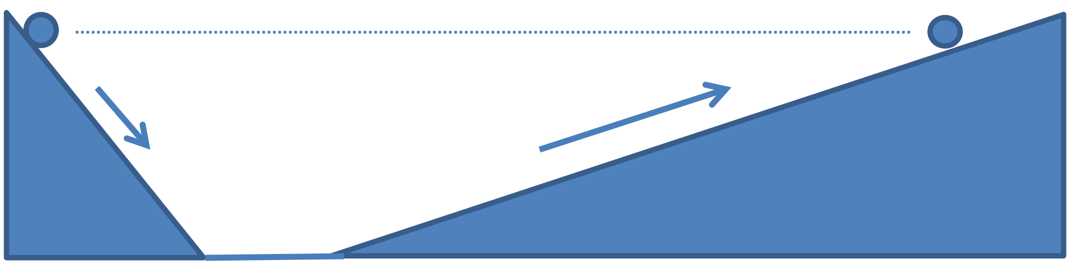
A very long time ago, people observed and tried to explain why things move. Greeks (like Aristotle) had noticed 2300 years ago that to keep something moving you had to keep pushing it (a force). If you stopped pushing, it stopped moving. From this experience they came up with the idea that the natural state of any object is to be at rest (not moving). From our everyday experience this seems to be true… but is it?

When Galileo came along in the first decade of the 17th century (also known as about the year 1610), he engaged in a thought experiment that challenged everything that people believed up to that point. He imagined rolling a very smooth ball down a ramp with a second ramp positioned at the opposite angle just beyond the first. It was something like this:



Galileo noticed that the ball could be started at a certain height on the left incline. It rolls over to the right incline and rolls up to about the same height from which it was released on the left. Of course, in real life, the ball would not make it quite to its initial height, so Galileo could not have seen this. But here Galileo was reasoning from experience and proceeding through with his thought experiment.

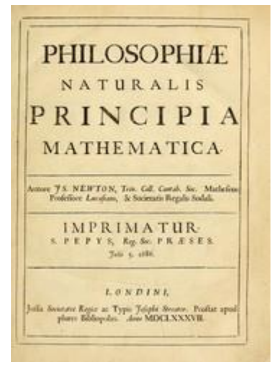
Next, Galileo thought about what would happen if the slope of the second incline was not as steep as the first. Something like this:



The ball would roll a farther distance, but just as high as it did the first time. What happens to the distance the ball travels if you reduce the slope even less? And even less again? The ball keeps traveling further and further to reach the same height as it started on the other side. What if you let the ball roll down one side, and there was no incline on the other side at all?

He realized it would roll for an infinite amount of time; the ball would not stop rolling. That is how Galileo came up with the concept of ***inertia***. Inertia is that property of matter that ***opposes changes*** in motion. If an object is in motion, it will continue moving without help from the outside. The speed of an object will not change unless you push or pull on the object.

Galileo's idea seems to be the opposite of Aristotle, but it isn't. It is just that an object that is at rest is just a special case of Galileo's idea. An object at rest will not change its speed, it will stay at rest unless it is pushed or pulled. An object in motion will not change its speed or direction, it will keep moving unless it is pushed or pulled.



Then came Newton. He also thought a lot about pushes, pulls and moving objects, and used his ideas to figure out some incredible things about our universe! In 1686, he presented his three **laws of motion** in one of the earliest and most important documents of physics, the "Principia Mathematica Philosophiae Naturalis."

Newton's first law of motion simply captures Galileo's original idea:

Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces (pushes or pulls) impelled on it.

That's just fancy language for saying that if an object is not moving, it will not start moving by itself. If an object is moving, it will not stop, change speed, or change direction by itself.

That seems to make sense from the perspective of Galileo's thought experiment. But it doesn't match our everyday experience. Objects do not keep moving by themselves. They stop. What's missing in this historic conjecturing about pushes, pulls and motion? **Friction.**

Friction

Friction affects you and the objects around you all the time. Friction is caused by the small bumps on the surface of an object hitting bumps on the surface of objects they contact. Recall that a force involves not only a single object, but an interaction between two objects. When you are coasting on your bike, friction between the bike tires and the road causes you to slow down. But friction also helps you to speed up. Tires need friction to push against the road and create forward motion. Think about trying to ride a bike on ice. The tires would spin without forward motion because there is very little friction between the tires and the icy surface.

If you looked at a piece of wood, plastic or paper through a powerful microscope, you would see the small bumps and crevices on the surface. As surfaces slide (or try to slide) over each other, the hills and valleys grind against each other and cause friction. The amount of friction between two surfaces depends on many factors, including the roughness of the surfaces and the force pushing the surfaces together. The roughness of an object is not the only contributor to friction. Frictional forces are also influenced by the electrical attraction between the molecules of substances – sort of like the stickiness that would occur if you rubbed a piece of adhesive tape over the surface of the table. When there is a lot of friction, you may see pieces of one surface sticking onto the other surface.

In general, students will be able to visualize the push of friction by seeing that rougher surfaces have more or bigger bumps and valleys, and therefore exert greater friction force.

STOP AND THINK: Consider a smooth floor like in the school's cafeteria, the rough playground hardtop and the grassy field. Which one is "bumpiest?" Which is smoother? If you were to roller skate over these three surfaces, which one would take the most effort/force? Which one would take the least effort/force?

Heavier objects push the bumps and valleys of two surfaces closer together. The hills and valleys come into closer contact, causing the friction between the surfaces to increase.

STOP AND THINK: Consider trying to push your filled-to-the-brim filing cabinet across the floor. It is really heavy and won't budge. Now consider removing all the papers from inside the cabinet. Why is it easier to move across the floor?

Let's think again about Galileo's thought experiment. The ball rolling down the incline does not roll up the other side quite as high as its starting point. Can you picture the small bumps on the ramps interacting with the small bumps on the ball? Each point of contact exerts a small push in the direction opposite of motion. Now picture the ball rolling down the ramp and across the flat surface. It will roll pretty far if the surface is relatively smooth, but it will eventually stop. Galileo, and Newton after him were imagining a world without friction. If you count friction, then Newton's first law work perfectly. The force compelling a moving object to slow down and stop is the force of friction.

Friction is caused by the interaction of two surfaces creating a push—a force—in the opposite direction of motion. The heavier an object, the greater the frictional force will be. The bumps and valleys of each surface have been pushed together increasing the force between them that resists motion.

Scientists describe different types of friction depending on the conditions where it occurs. One form of friction, called kinetic friction, occurs when objects are in motion. Kinetic friction can occur with rolling objects, like balls and wheels. Kinetic friction also describes when flat surfaces slide over one another.

Rolling Friction. Most of the lessons in the module for 2nd graders consider rolling friction, for example, the wheels of a toy car rolling over surfaces such as tile, sand paper, and carpeting.

Sliding Friction. When two flat surfaces slide over one another, such as pushing a book across the table, pushing your filing cabinet across the floor, or even pushing a car with its brakes on, it is called sliding friction. The force of sliding friction is often much larger than the force of rolling friction. Imagine how much easier it would be to push your filing cabinet across the room if were on wheels! However, this is not always the case. If both surfaces are hard, rolling friction is a smaller force. But if one of the surfaces is soft, such as deep snow, the sliding friction of skis or a sled might be a lot smaller than the rolling friction of your heavy filing cabinet. Friction depends on several characteristics of both surfaces.

Fluid Friction. Fluid friction (also known as draft force) is the resistance you feel when you move through any fluid such as water or air. The particles of water or air push back against motion in the same way that the bumps and valleys push back when two surfaces are in contact. Fluid friction is much less than rolling or sliding friction. That is why it is so much more difficult to walk on a wet floor when it has been mopped than a dry floor. The static friction between your shoe and the floor has been replaced by fluid friction between your shoe and the water leading you to slip, slide, and perhaps hit the deck!

Static Friction. When a force is applied to an object but it doesn't move (like your filled-to-the-brim filing cabinet) we say that ***static friction*** occurs. The object doesn't move because the force of friction is equal to the force of the push.

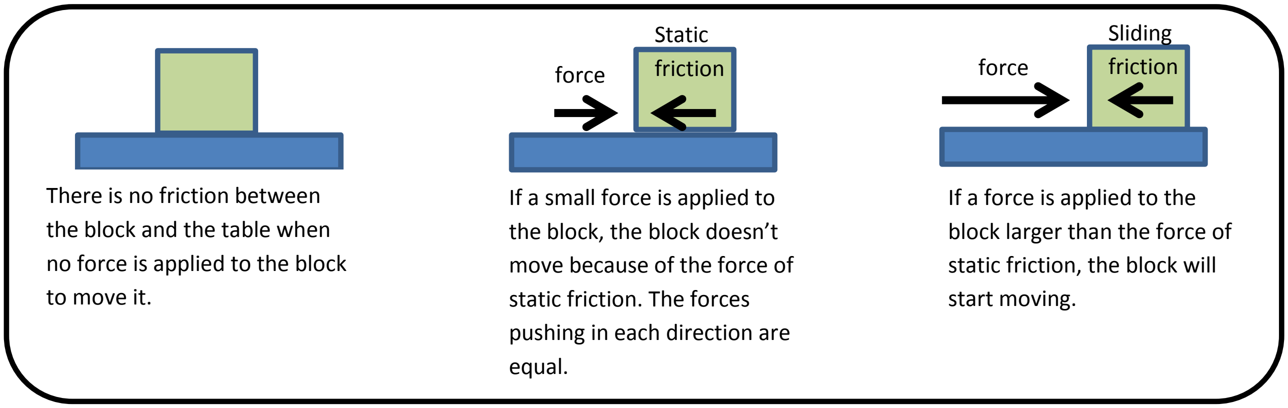


Figure 1. Examples of contact involving no friction, static friction, and sliding friction. Notice that arrows can be used to represent the strength and direction of a force. Physicists call these arrows "vectors."

Because friction pushes against motion, you may assume that friction is bad. For example, the rubbing of metal parts in a car's engine will cause the car to quickly overheat. Engineers use ball bearings to reduce friction in the engine by replacing sliding friction with rolling friction. You also add oil to slightly push the pieces of metal apart from one another to further reduce friction – and keep that oil changed regularly so small impurities do not add bumps that would increase friction.

However, without friction, many activities in our daily life might be nearly impossible. For example, tires on your car need a good tread to create the friction necessary to grip the surface of the road. You might introduce students to ways that friction positively impacts everyday activities by rubbing petroleum jelly on the classroom door and asking a student to turn the doorknob. Or have your students compare walking on an icy sidewalk in boots with a heavy tread compared to shoes with a slick surface. Could they catch a greased pig at a family picnic if there were no friction? All these examples show that friction can be helpful and harmful, but it is an inescapable part of daily life.

Net forces

Look again at figure 1 above. It shows clearly that more than one force can act on an object at the same time. In the example of static friction, the force of friction is equal to the force pushing the block, and the block does not move. If you subtract the length of the arrows from each other (because they push in opposite directions) the **net force** is zero. Consider the block in the first drawing of figure 1. It is at rest. There is no friction between the two surfaces. Does that mean there are no forces acting on the block? No! The force of gravity pulls the block toward Earth and the force of the table pushes in the opposite direction of gravity. The block doesn't move because sum of the forces acting on the block are equal and pushing in the opposite direction.

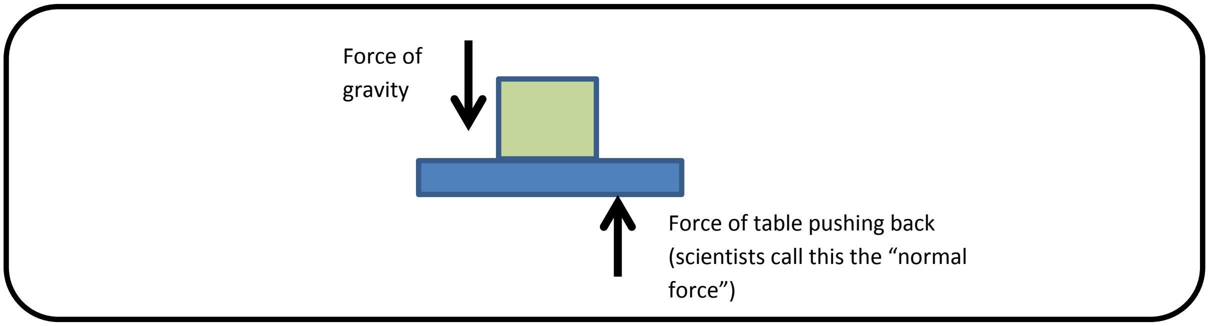


Figure 2. Net forces acting on an object at rest equal zero.

You can use the idea of adding and subtracting forces to predict all kinds of motion. Let's take the example of your filled-to-the-brim filing cabinet again. If you got a friend to help you push, and each of you pushed hard, you might be able to overcome static friction and push the filing cabinet across the room.

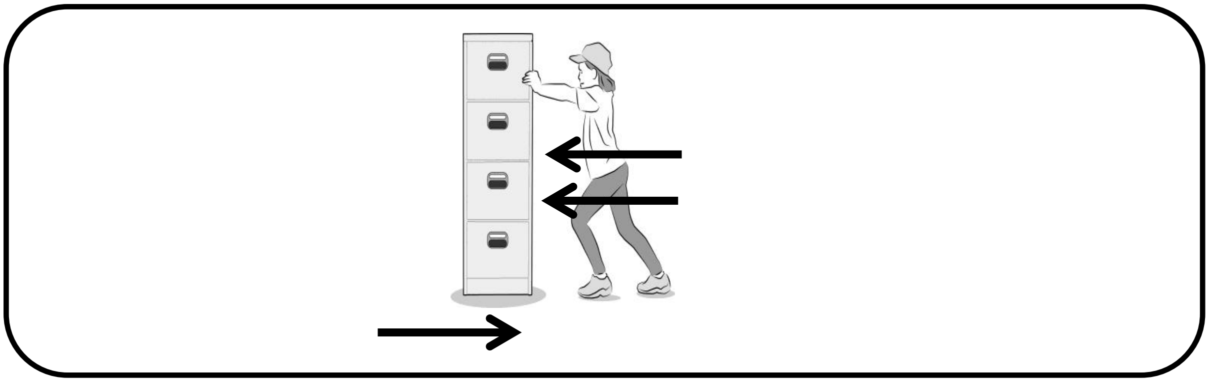


Figure 3. To calculate net force, add forces in the same direction and subtract forces in opposite directions.

Add the forces in each direction and you can predict that you will overcome static friction and the cabinet will move. The net force is calculated by subtracting the forces in one direction from the forces in the other direction.

This works even if the forces are not acting in the same direction or opposite directions, but the calculations get more complicated. Say three of the students in your classroom are fighting over the toy car during class. Each pulls in different directions. If you know the forces pulling in each direction, you can calculate and predict the direction the toy car will move.

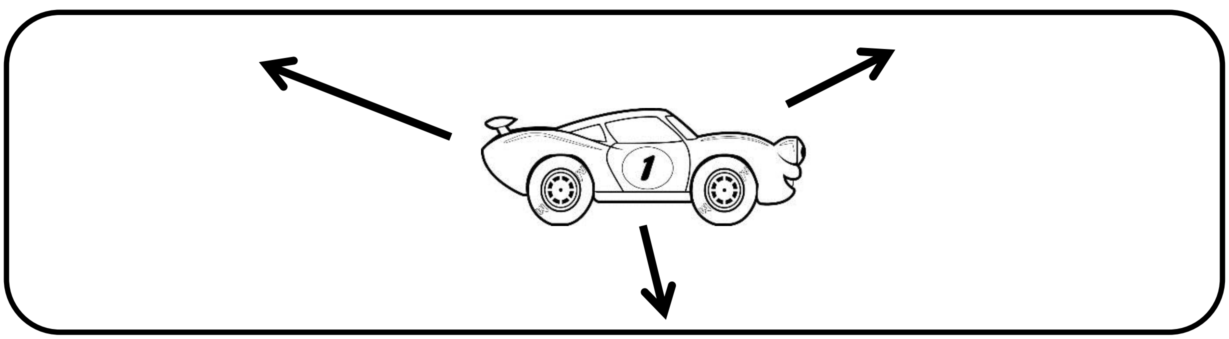


Figure 4. Net force can be calculated by graphing the arrows in each direction

Adding and subtracting force vectors (the name we give the arrows representing the strength and direction of forces) when the forces are not in the same direction or opposite direction is beyond the scope of this content deepening document. We will consider only forces acting in opposite direction—when they are subtracted from each other, or in the same direction—when they are added to each other.

One example of net forces acting on objects comes up in the opening of lesson 6. Students drop a small cotton ball in front of an electric fan. At first the cotton ball falls toward Earth. Gravity is pulling on it. Then it is pushed by the wind coming out of the fan. Gravity is still pulling on it, but a second force from the moving air pushes horizontally. The movement of the cotton ball is not straight down, nor straight across, but now angles toward the ground because of net forces on the cotton ball. The cotton ball stops when it hits the floor because of the force of friction pushes against forward motion. Students don't need to calculate the net forces, but they should see that a force pulling down and a force pushing across result in the cotton ball moving along a diagonal toward the ground.

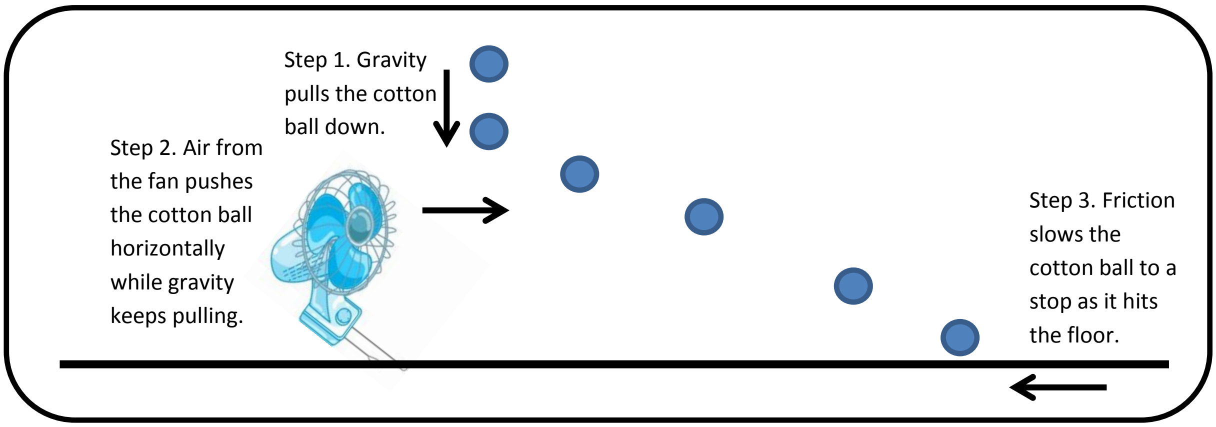


Figure 5. Multiple forces acting on a cotton ball in lesson 6.

STOP AND THINK: What are the multiple forces acting on you right now as you read this document? Do you exert a force on the pages? Is gravity pulling? Are you experiencing friction?

The key idea to keep in mind is that if a net force acts on an object at rest, the object starts moving. If a net force acts on an object that is already moving one of three things will happen:

<u>Case 1</u>: If the net force is in the same direction as the object's motion, the object's speed will increase.
<u>Case 2</u>: If the net force is in the opposite direction of an object's motion, the object will slow down and eventually stop.
<u>Case 3</u>: If the net force is at an angle with respect to the direction of an objects motion, the object will change direction towards the applied net force.

With no net forces acting on an object (another way to say that there are equal and opposite forces acting on the object), the object will maintain a constant speed and motion. If it is at rest, it will stay at rest; if it is moving, it will keep moving.

Forces and mass

How much force would it take to move a ping pong ball across the floor? Could you do it with just a puff of air? Now consider a bowling ball. How much force would it take to move it across the floor? Could you move it with just a puff of air? There are lots of factors to consider when thinking about how far or how fast an object would travel, but Newton discovered that the **mass** of an object is one of the most important.

Try to picture this this situation (figure 6) where the same force is applied to objects of two different masses.

Mass and weight are frequently confused. Whereas mass tells you how much "stuff" is there, weight tells you how much gravity pulls on that "stuff." Your weight is a force since it is a way to measure of the pull of gravity on the "stuff" that makes up you. You might have heard that if you went to the moon you would weigh a fraction of what you do on Earth. That is because the moon has less gravity than Earth. You still have the same amount of "stuff" that forms your body (your mass), but with less gravity you weigh less.

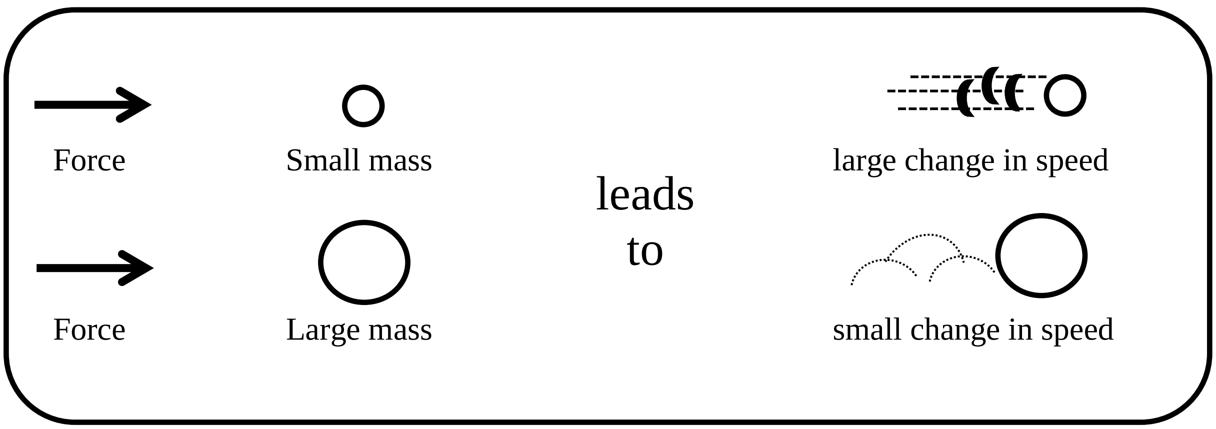


Figure 6. Equal forces acting on objects with different mass results in a different change in speed for each object.

If you wanted to cause two different objects to have the same change in speed, you object with the larger mass will require a larger force (figure 7).

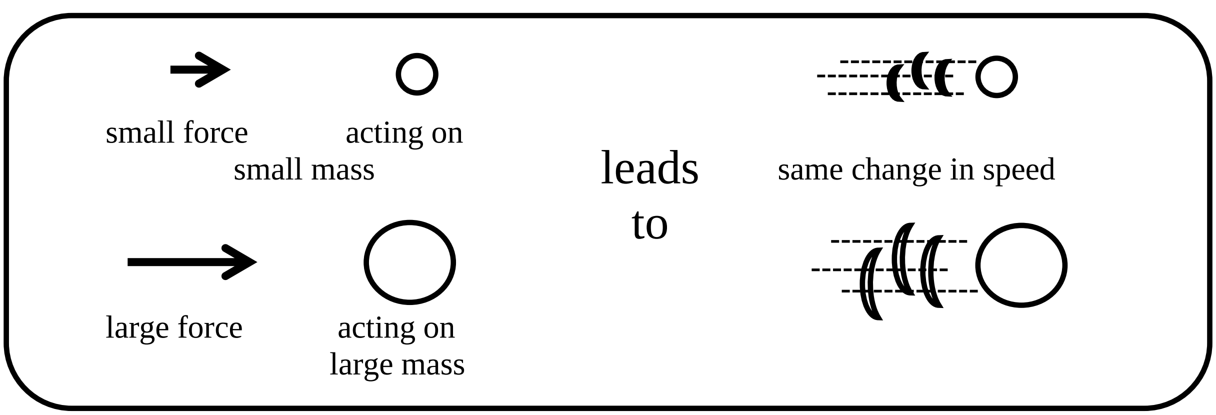


Figure 7. It takes different forces to cause the same change in speed in objects of different mass.

You might be getting the idea that there's a relationship here. The larger the mass, the more force it needs to reach the same acceleration. The same force caused less acceleration for the object with the larger mass. Newton captured this mathematical relationship in his second law of motion which states: *The acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object*.

> **Acceleration** is the word scientists use that means **a change in motion** over time. You might use the word acceleration to describe your car speeding up on the highway. But for scientists, acceleration describes any change in speed per unit of time. Getting slower is a negative acceleration. Scientists also say that changing direction is an acceleration because it is a change motion.

All that is a fancy way to say that:

FORCE = Mass x Acceleration (F = ma)

OR

ACCELERATION = Force ÷ Mass (a = m ÷ F)

In this lesson series, you will not be teaching students to calculate forces with multiplication or division. But as a teacher, you should have a conceptual understanding of how force is related to mass and impacts the resulting changes in motion. It is one of those common sense ideas that you—and your students—know intuitively. Hopefully reading about this relationship has added to your understanding.

What makes objects move differently in outer space?

All of the rules of motion on Earth apply in outer space. So, why do we see astronauts taking giant leaps on the surface of the Moon and satellites moving gracefully through space with no apparent force pushing or pulling them? There are two important differences between the conditions on Earth and conditions in outer space that affect how things move.

Gravity in space

Did you know that every bit of matter has gravity? That means that every object that has mass (like you, your car, the dust bunnies under our bed, the Moon) pulls other objects toward itself. The size of the gravitational force that an object exerts on another object is proportional to its mass. Something like Earth that has a very large mass, has a fairly strong gravitational pull. Something smaller, like the moon, exerts a smaller gravitational pull on other objects. You don't even feel the gravitational pull that you exert on other objects since it is very small. The pull of gravity depends on the mass of two objects and also the distance between objects. Once you get pretty far away from Earth, its gravitational pull doesn't affect you very much. Astronauts can make great leaps on the Moon's surface because the Moon has less gravity than Earth. But astronauts do not get pulled off the Moon toward Earth because at that distance, the pull of the Moon's gravity on their bodies is greater than the pull of Earth's gravity. But Earth's gravity, even at that distance, is enough to keep the Moon and other satellites in orbit.

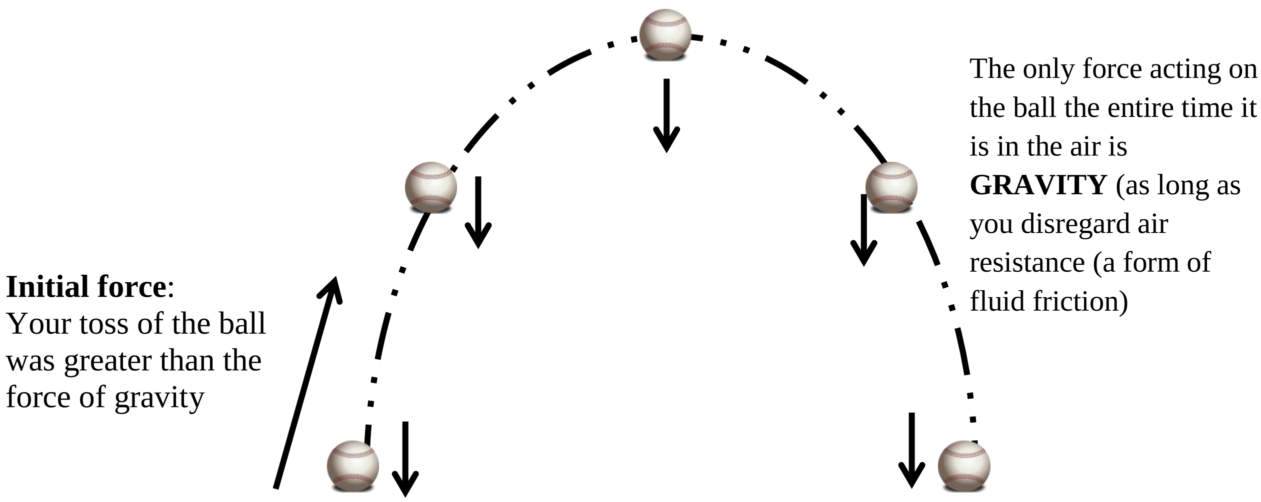
Friction in space

Friction works differently in space as well. Friction will eventually slow things moving on the moon's surface, just like it would on Earth. However, the Moon has less gravity than Earth, so bumps on surfaces are not pulled together as strongly as they would be on Earth. Therefore, the force of friction between similar objects is less on the Moon than on Earth. In contrast, if you are not on the surface of a planet or the Moon, but floating in outer space, there are no surfaces rubbing together to create friction. There is very little air or other particles to create resistance even from fluid friction. Therefore, if you are floating in space and get a little nudge, you will move in a straight line with nothing to stop you. Remember Galileo's thought experiment where the ball rolls along a flat surface forever? Galileo had never experienced conditions in outer space. But his ideas about inertia and the tendency of objects to maintain a constant speed and direction work perfectly in the outer space world without the force of friction to oppose motion.

Do things always have to touch to exert a force?

Do you remember the examples we cited in the introduction to this document that seem almost mysterious? Magnetic forces, electric forces and gravitational forces are called non-contact forces because objects do not need to touch in order to influence other objects. That is quite obvious with gravity. The pull of Earth causes objects to fall from far above its surface. Magnetic and electrical forces work similarly. These forces follow the same rules as contact forces. They cause pushes and pulls (think about Newton's first law) and the motion caused by the force is related to the mass of the object and its acceleration (Newton's second law).

Let's consider one example of non-contact forces, in this case gravity. What are the forces acting on a baseball when you toss it up in the air and it comes back down again? It seems straight forward, common sense. You threw the ball up in the air. That means you exerted an upward force on the ball. But how would you describe the forces acting on the ball once you are no longer touching it? You aren't exerting a force anymore, so why doesn't the ball turn around and come down as soon as you let go of it?



You started the baseball's upward motion with your toss. If there were no gravity (and no air resistance), the ball would continue upward forever. But something caused it to change directions and come back down to Earth. That something was gravity. Much like friction, gravity exerts a constant force on the ball pulling it toward the ground. Your initial throw was strong enough to counteract the force of gravity and get the ball moving. But once you let go of the ball, you were no longer exerting an upward force. Gravity pulled on the moving ball causing it to slow down (decelerate) along its upward path. Eventually the ball stopped (at the height of the arc). But gravity kept pulling with sufficient force to pull the ball to the ground. Because it is a constant force, the ball continues to get faster—accelerate—as it falls back to Earth. Think about Newton's equation, $F = ma$. If the force is constant and the mass is constant, then the speed must be changing. In the case of the baseball, it first decelerated (got slower) and then accelerated (got faster) as it fell to the ground.

Summing it Up

Newton's laws do a pretty good job of helping us understand, explain, and predict the world around us. They provide a framework for thinking about the forces we come in contact with every day, and those forces that don't need contact to push and pull! We can use these ideas about forces, friction, and gravity to get us to the moon, to design a roller coaster, or develop safety regulations for tires and roads. But they don't always work. It took a long time, but some smart scientists (like Albert Einstein) found situations in which Newtonian ideas about forces and motion don't work anymore. Those situations include the forces that occur on very, very small scales (like smashing electrons into protons), or at very fast speeds (like approaching the speed of light), or in very large situations (like expanding and contracting the universe).

When we think about every day, common experiences, Newton's ideas work just fine, so let's summarize:

1. Things change their motion (slow down, speed up, or change direction) because they get a push, pull, or twist – otherwise known as a **force**. A force causes changes in motion. An object at rest will start moving only if there is a force. A moving object will keep moving in the same direction unless there is a force to change that motion.

2. **Friction** is a force that is the result of tiny bumps on surfaces that resist motion. Friction could be **static** (causing an object not to move, even when you push it), **sliding** (like flat surfaces rubbing next to each other), **rolling** (like the soccer ball across the playground) or **fluid** (which refers to the resistance to motion that occurs when you move through both air and water).

3. When more than one force acts on an object, the forces are added (or subtracted for forces acting in opposite directions) to determine the **net force**.

4. There is a key relationship, both conceptually and mathematically, between net force, mass, and acceleration: **F = ma**

5. Many forces we experience are contact forces, in other words, two objects need to touch to exert a force. However **non-contact forces** such as gravity, magnetism and electrical forces do not need to have two objects touch – they can exert a force from a distance.

Back to the beginning

At the start of this document we asked the question, "Why do things start to move, stop moving, or change direction?" Has your understanding changed? Have you developed new ideas and connections that help you make sense of everyday phenomena in the world? Do you have a better understanding of why everything that goes up, must come down? Do you know why a ball rolling down a hill will keep rolling, but a ball rolling along a flat surface will not?

What new questions do you have about forces and motion? Keep track of those questions and talk to your colleagues and PD leaders to broaden, deepen, and enrich your knowledge of forces throughout this year in the RESPeCT program.