Forces and Motion:
Content Background Document

1. Introduction

Forces govern every aspect of our physical lives. We experience these forces each moment of the day. Gravity pulls our bodies toward Earth; objects fall from high places to the ground; a baby is lifted from her crib; a ball rolls across the floor and eventually comes to a stop; children use their legs to jump or their arms to lift themselves over jungle-gym bars on the playground. Forces result in so many changes in motion in our daily lives that we give little thought to figuring out what causes them. Instead, we intuitively sense how the world works. Based on firsthand experience, children start school with their own set of ideas about forces and motion. By paying attention, taking our students' ideas seriously, and seeking to understand their thinking, we as teachers can build on what our students already know. We can use their initial ideas as a foundation for building remarkable understanding, even in the earliest grades.

In this document, we'll focus on a fundamental question of physical science: *Why do objects start moving, speed up, slow down, change direction, or stop?* By answering this question, we can develop concepts that explain and predict a wide variety of phenomena in the world around us.

STOP AND THINK

How would you answer the question, "Why do objects start moving, speed up, slow down, change direction, or stop?" What is your common-sense response?

If you look up *force* in the dictionary, you'll discover a number of ways this word can be used in everyday language. For example, people may talk about a "force-out" in baseball, the "forces of good and evil" in the world, or the "labor force" that drives our economy. But none of these examples reflect how scientists use the term. Since this word has so many different meanings, it's essential that we clarify the scientific definition before we begin our exploration of forces and motion.

In science, the term *force* means "a push or pull between two objects that causes a change in the motion of one or more of the objects." Many scientists include "twist" in the definition as well (as in twisting a corkscrew or a wet towel).

Most of our ideas about forces and motion are based on common sense from lifelong experiences. For example, common sense tells us that if an object isn't moving, it won't start moving all by itself. But common sense doesn't necessarily tell us *why* an object in motion eventually stops moving. We just know that it does, even though we may not see what makes it stop. Knowing that moving things eventually stop is so much a part of our everyday experience on planet Earth that we don't even question it. But in outer space, an object will move in a straight line forever unless or until a force outside the object—an *external force*—makes it stop.

What makes motion in outer space so different from motion on Earth? Why don't objects in space slow down and stop like they do on Earth? And why do moving objects on Earth eventually slow down and stop?

Common sense tells us that gravity pulls objects toward the ground. We know, for example, that whatever goes up must come down. Common sense also tells us that moving objects, such as people, animals, swinging golf clubs, and falling rocks, push or pull other objects. But can an inanimate or inert object, such as a table, a wall, or a floor, exert force on another object? That question is a little more difficult to answer, isn't it?

Some forces defy common sense. Why does a magnet attract or repel some objects but not others? Why does a balloon stick to the wall without falling after you rub it on your hair? What force enables the balloon to defy gravity? These phenomena almost seem like magic. How can they be explained?

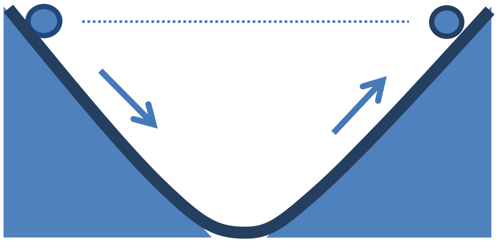
The content that follows will challenge you to broaden and deepen your understanding of forces and motion. It will also support and further your understanding of how scientists define and measure these terms, as well as how they explain everyday phenomena, such as why you slip on ice or your car overheats without oil. In addition, this document may help you understand how scientists, engineers, and mathematicians use science ideas about force and motion to solve complex problems, such as sending a rocket to the Moon and beyond or designing tall buildings to withstand high winds and earthquakes. Developing strong conceptual understandings of force and motion will also equip you to more effectively teach your students these concepts.

This document was written with you, the teacher, in mind. The subject matter is tied to the science lessons you'll be teaching, but the concepts are presented at a level higher to equip you with the tools and background you'll need to guide student learning. After all, teachers should know more about the science content than their students!

2. Motion Doesn't Want to Change

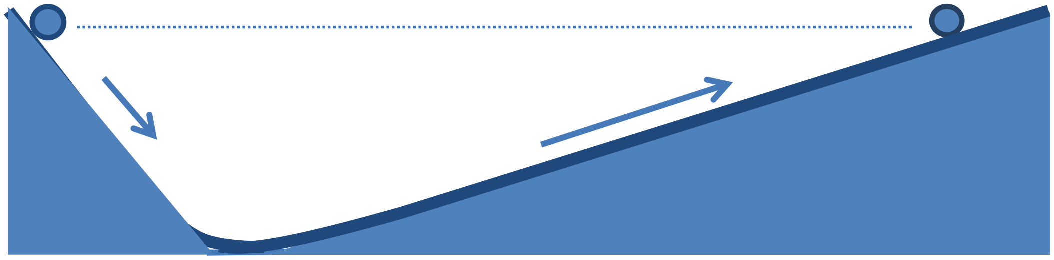
A very long time ago, people observed objects in motion and tried to explain them. More than 2,300 years ago, Greek intellectuals like Aristotle noticed that a force had to act on an object to keep it moving. If the force stopped pushing or pulling the object, it stopped moving. From these observations came the idea that the natural state of an object is to be at rest (not moving). This seems true based on our everyday experience … but is it?

Around the year 1610, Italian philosopher and mathematician Galileo engaged in a thought experiment that challenged everything people had believed about motion up to that point. He envisioned two identical ramps facing each other and a ball rolling down the first ramp and up the second ramp. His model looked something like this:



Galileo reasoned that the ball would start off at a certain height on the first ramp (the left incline), roll down that ramp and over to the second ramp (the right incline), and then roll up the second ramp to a height approximately equal to its starting height on the first ramp. Of course, in real life the ball wouldn't quite reach the initial height, but Galileo couldn't have foreseen this.

Next, Galileo thought about what might happen if the slope of the second ramp wasn't as steep as the slope of the first ramp:



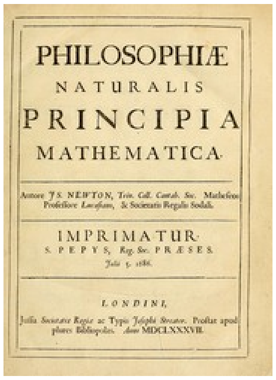
He reasoned that the ball would roll farther than in the first example but would still reach the same initial height.

Then he wondered how far the ball would roll if he kept reducing the incline of the second ramp. He reasoned that the ball would keep rolling farther and farther to reach the same initial height. But what if the second ramp was completely flat with no incline at all? Galileo reasoned that the ball would just keep rolling and never stop!

As Galileo worked through his thought experiment, he came up with the concept of inertia. *Inertia* is defined as "a property of matter that opposes changes in motion." An object already in motion will continue in motion without help from an outside force. The speed and direction of the object won't change unless an external force pushes or pulls it.

Galileo's idea seems to contradict Aristotle's, but it doesn't. It's just a different way of expressing the same concept. An object at rest will stay at rest (won't experience a change in speed) unless an external force pushes or pulls it, and an object in motion will remain in motion (won't experience a change in speed or direction) unless an external force pushes or pulls it.

After Galileo came Isaac Newton, who also explored ideas about force and motion and, in the process, figured out some incredible things about our universe! In 1686, he introduced three laws of motion in one of the earliest and most important documents on physics, the *Philosophiae Naturalis Principia Mathematica* (*Mathematical Principles of Natural History*).



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S. PEPYS, Reg. Soc. PRÆSES.

LONDINI,

Capturing Galileo's original idea, Newton stated his first law of motion in these words:

> *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 impelled on it.*

That's just fancy language for saying that if an object isn't moving, it won't start moving by itself. And if an object is already moving, it won't stop or change speed or direction by itself. An *external force* must push or pull the object to get it moving or change its speed or direction.

Based on Galileo's thought experiment, that seems to make sense, but it doesn't match everyday experience. Objects don't keep moving by themselves; they slow down and eventually stop. So what's missing in Newton's historic conjecturing about force and motion? Friction!

3. Friction

Friction is a force caused when small bumps on the surface of one object push against small bumps on the surface of another object. Friction occurs whenever two objects rub, roll, slide, or glide across each other.

You may recall that a force involves an *interaction* between two objects. When you're coasting on your bike, the force of friction between the bike tires and the road causes you to slow down. Friction always pushes against the motion of an object and ultimately leads to a reduction in speed. Friction is also the origin of traction between a wheel and the ground it's rolling over. So in addition to helping a bike slow down, friction is necessary to create forward motion as the bike's tires push against the road. Think about trying to ride a bike on ice. With little or no friction between the tires and the ice, the tires would simply spin without generating any forward motion.

If you looked at a piece of wood, plastic, or paper through a powerful microscope, you would see small bumps and crevices (like hills and valleys) on the surface. As the surfaces of two objects slide (or try to slide) over each other, these bumps and crevices grind against each other and generate friction. The amount of friction between two surfaces depends on many factors, including surface roughness and the force pushing the surfaces together. The electrical attraction between molecules of substances also causes friction, sort of like the stickiness that results from rubbing a piece of adhesive tape over the surface of a table. With extreme friction, the bumps on one surface can stick to the bumps on another surface. Friction between two moving objects also occurs in fluid. Have you ever tried running through shallow water in a swimming pool? The friction generated as water molecules slide and glide across each other makes it harder than you'd expect.

In general, students will more clearly visualize the pushing force of friction if they observe that rougher surfaces have more bumps and valleys, or bigger bumps and valleys, and therefore exert greater friction. When heavier objects come into contact, the bumps and crevices of the surfaces push together more closely, which also causes an increase in friction between the surfaces.

STOP AND THINK

Consider three surfaces: (1) a smooth floor like the kind you'd find in a school cafeteria, (2) a rough playground surface, and (3) a grassy field. Which surface is bumpiest? Which is smoother? If you were to roller-skate over these surfaces, which would require the most effort or force? Which would require the least effort or force?

STOP AND THINK

Imagine trying to push a heavy, jam-packed file cabinet across the floor. The cabinet is so heavy, it won't budge, so you remove all of the papers and try again. This time it's a breeze! Why is it easier to move an empty file cabinet across the floor?

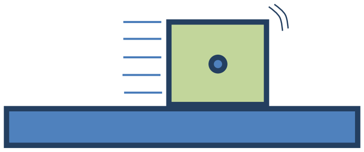
Let's revisit Galileo's thought experiment. When the ball rolls down one ramp and up the other ramp, it won't quite reach the same height as its starting point. Picture the small bumps on the surfaces of the ramps interacting with the small bumps on the surface of the ball. Each point of contact exerts a small push in the opposite direction of the ball's motion. Now picture the ball rolling down the ramp and across a flat surface. The ball will roll pretty far if the surface is relatively smooth, but it will eventually stop. Galileo and Newton envisioned a world without friction. However, if we include the idea of friction, Newton's first law of motion works perfectly. The force compelling a moving object to slow down and stop is friction!

Friction occurs when two surfaces interact, creating a pushing force in the opposite direction of an object's motion. The heavier an object, the greater the frictional force will be. As the bumps and valleys of each surface are pushed together, the motion-resisting force between the surfaces increases.

Scientists have identified different types of friction based on the conditions in which 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 or when flat surfaces slide over each other. Let's examine four types of friction.

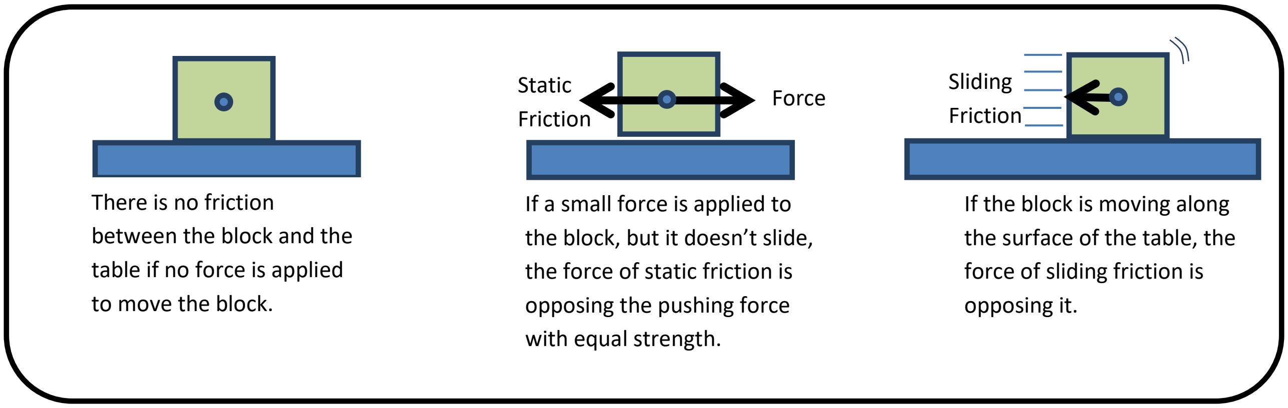
1. **Rolling friction.** Students learn about this form of friction in most of the lessons in the 2nd-grade module on forces and motion. *Rolling friction* refers to the force that resists motion when an object rolls across a surface. Rolling friction is present when the wheels of a toy car roll over surfaces like tile, sandpaper, and carpet.

2. **Sliding friction.** When two flat surfaces slide over each other, sliding friction occurs. Examples include pushing a book across a table, pushing a file cabinet across the floor, or pushing a car when the brakes are engaged. The force of sliding friction is often much greater than the force of rolling friction. Imagine how much easier it would be to push a file cabinet across the floor if it had wheels! The rolling friction would exert less motion-resisting force than sliding friction. But this isn't always the case. If both surfaces are hard, rolling friction exerts 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 a heavy file cabinet with wheels. Friction depends on various characteristics of both surfaces.



3. **Static friction.** This type of friction occurs when a force is applied to an object, but the object doesn't move. Like a jam-packed file cabinet, the object refuses to budge because the force of friction is equal to the force of the push.

4. **Fluid friction.** This type of friction (also known as *draft force*) is the motion-resisting force that occurs when the molecules of a fluid interact with each other or when a fluid interacts with other matter, such as water molecules interacting with air molecules. Fluid friction is the resistance you feel when you move through a fluid like water. The particles of water resist motion in the same way bumps and crevices on the surfaces of two objects push against each other. Fluid friction exerts much less force or resistance than rolling or sliding friction. This is why it's more difficult to walk on a wet floor than a dry floor. Fluid friction between your shoes and the water on the floor replaces static friction between your shoes and the floor, causing you to slip and slide and maybe even hit the deck!



There is no friction between the block and the table if no force is applied to move the block.

If a small force is applied to the block, but it doesn’t slide, the force of static friction is opposing the pushing force with equal strength.

If the block is moving along the surface of the table, the force of sliding friction is opposing it.

Figure 1. Examples of contact between surfaces involving no friction, static friction, and sliding friction. The blue dot represents the single point at the exact center of the object on which all forces will act. Notice that arrows can be used to represent the strength and direction of a force. Scientists and engineers call these arrows *vectors*.

Friction may sound like a bad thing because it resists or pushes against motion. For example, a car will quickly overheat if the engine’s metal parts rub or slide against each other. So engineers use ball bearings to replace sliding friction with rolling friction. The use of engine oil further reduces friction by separating the pieces of metal with a thin layer of fluid. If you forget to change your car’s oil regularly, small impurities will build up, adding surface bumps that will increase friction between the metal parts and damage the engine over time.

But without friction, it would be difficult or impossible to perform many activities in our daily lives. For example, the tires on your car need good tread to create the friction necessary to grip the road. Without adequate friction, you might find yourself fishtailing all over the road in rainy weather and end up in a ditch—or worse!

To illustrate the importance of friction in everyday activities, rub a little petroleum jelly on the classroom doorknob and ask a student to turn it. Or have students compare walking on an icy sidewalk in boots with a heavy tread versus shoes with smooth, slick soles. Or ask students, “Could you catch a greased pig at a family picnic if there were no friction?”

These examples highlight the fact that friction can be both helpful and harmful. It’s an inescapable part of daily life, unless you work on satellites in outer space or are a hockey puck on a freshly resurfaced ice-rink floor!

4. Net Forces

Look again at figure 1. Arrows called *vectors* have been used to illustrate the strength and direction of forces acting on the block in static and sliding friction. The arrows representing static friction and sliding friction are pointing in the same direction, but a shorter arrow was used to illustrate sliding friction (third diagram) because we know this force isn’t as strong as the force exerted in static friction (second diagram). Figure 1 also shows that more than one force can act on an object at the same time. In static friction, for example, the strength of the frictional force is equal to the strength of the force pushing the block, so the block doesn’t move. If you subtract the length of one arrow from the other (because they're pushing in opposite directions with equal force), the *net force* is zero. Since a zero force has no strength or direction, it can't be represented with an arrow. Instead, a zero force is represented with a dot. With zero net force, no change in motion will occur. The block will remain in place.

STOP AND THINK

What is the net force on each block shown in figure 1?

Consider the block in the first diagram in figure 1. It isn't moving or being pushed from the side, so there is no friction between the block and the table. But does that mean there are no forces acting on the block? No! The force of gravity is pulling the block toward Earth, and the force of the table is pushing against gravity in the opposite direction. The force that the table is exerting on the block isn't as obvious, since the table is just sitting there doing nothing. If the force of the table (called the *normal force*) weren't pushing up against the block, the motion of the block would change, and it would fall toward the ground. But the block's motion doesn't change because the force of gravity and the force of the table acting on the block are equal in strength and are pushing in opposite directions, resulting in a net force of zero.

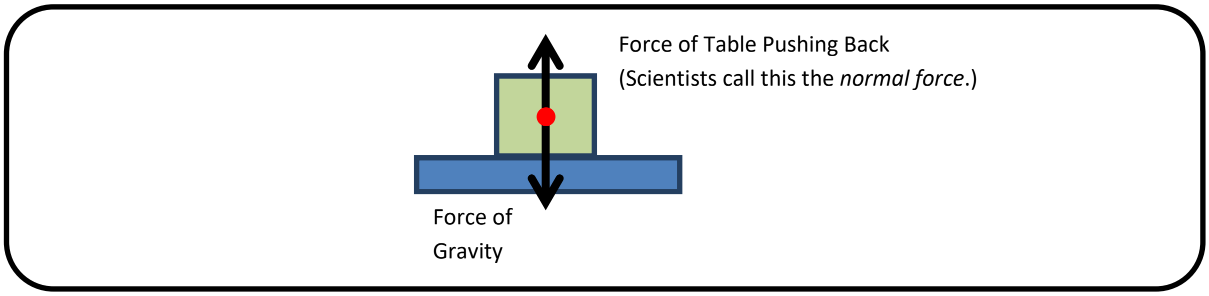


Figure 2. The net force acting on an object at rest is equal to zero.

A nonzero net force acting on an object will cause a change in motion. Think about a kid pushing on an empty file cabinet that's sitting on a carpeted floor. If the kid gives the cabinet a small push, it wouldn't move because static friction between the carpet and the cabinet would oppose the push, and the net force would be zero. But with a stronger push, the kid could overcome static friction, and the cabinet would begin sliding across the carpet (see figure 3). At that instant, a change in motion would occur (not moving to moving), and the net force would no longer be zero.

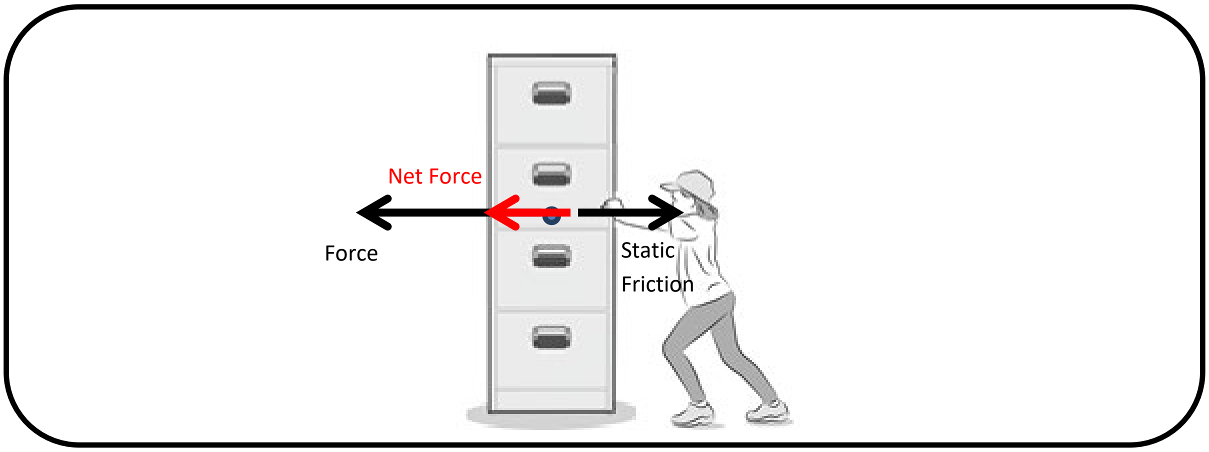


Figure 3. The net force of two opposing forces is represented by the red arrow pointing in the same direction as the longer arrow and with a length equal to the difference between the lengths of the two arrows.

This combination of forces works even if the forces aren't acting in the same direction or opposite directions, but the calculations get more complicated. Suppose you dropped a cotton ball into the airstream coming from a rotating fan (see figure 4)? At the instant you drop the cotton ball, a small downward gravitational force would be exerted on it (small because the cotton ball is light in weight) and a large force from the airstream would push against it. The net force would point mostly to the right and slightly downward. Although the cotton ball would keep moving downward when it entered the airstream, the net force would cause it to change direction and start moving to the right and slightly downward. Again, a nonzero net force causes a change in motion.

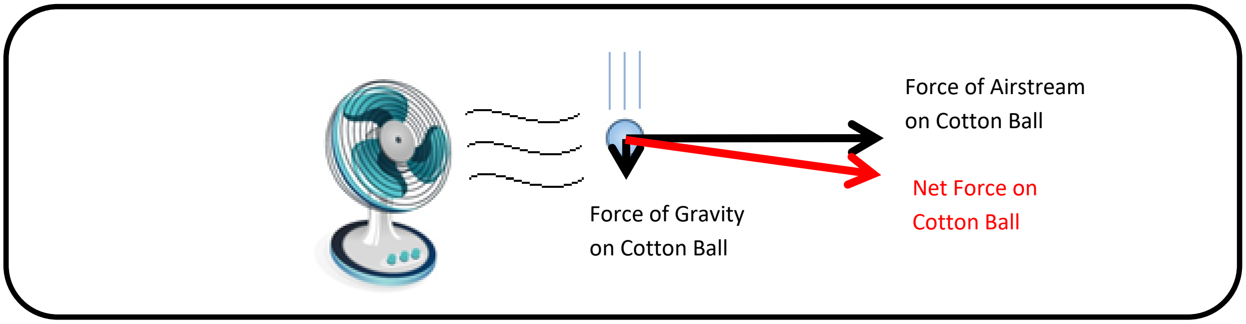


Figure 4. The net force resulting from two forces that aren't parallel to each other.

5. Tracking Changes in Motion with Cartoons

The four figures we just examined are like snapshots of moving objects at a single moment in time. In these diagrams, the motion of an object is indicated with marks that cartoonists call *motion blur*. In figure 1, for example, the motion blur (lines) indicate that only the block in the right-hand diagram is moving, while the other two blocks are at rest. To notice a change in motion, one must observe an object over time. Documenting evidence of a change in motion is best done in a video recording, which is essentially a series of snapshots taken moments apart and then played back at high speed. Each moment is called a *time step*. Smaller time steps yield a more detailed analysis of changes in motion over time. For a less detailed analysis, fewer snapshots are taken sequentially, with larger time steps. Like a comic strip, we can illustrate the motion of an object over a small series of time steps to gain a basic understanding of forces and motion.

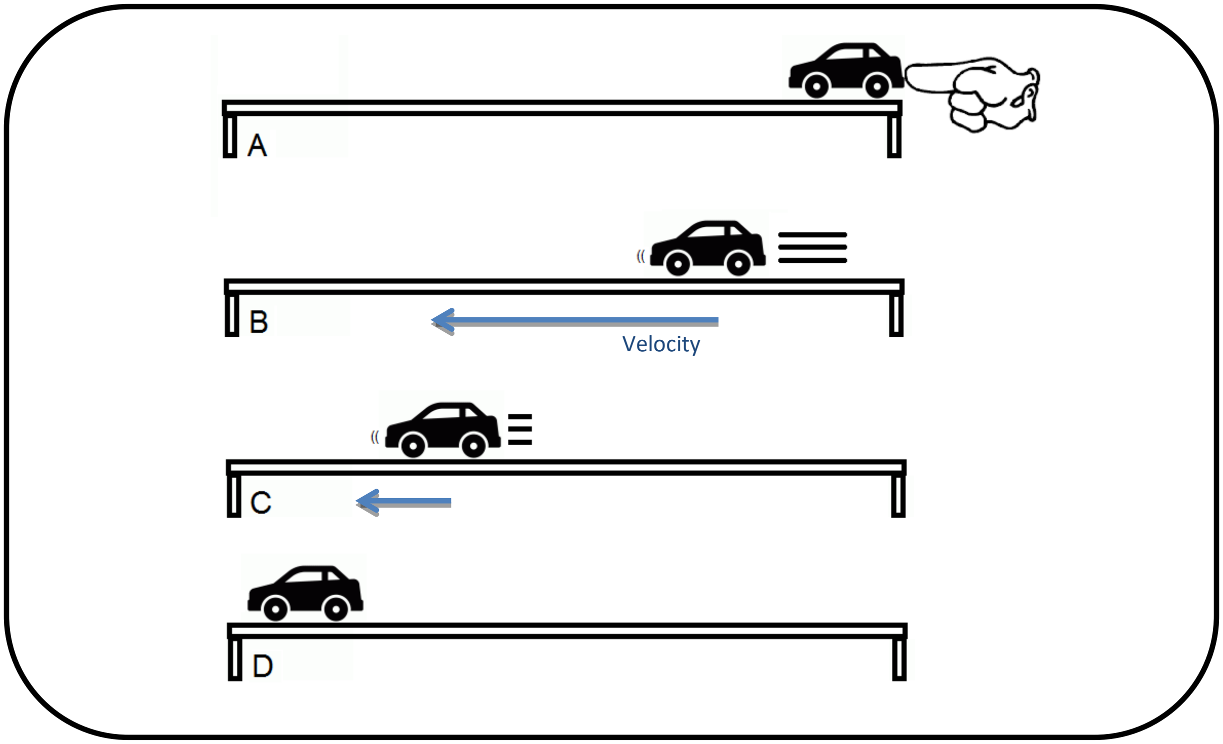


Figure 5. A toy car rolls across a table at different time intervals: (A) The car receives a push toward the left and begins to roll in that direction; (B) the car coasts at a high rate of speed after it begins moving; (C) the car slows down; (D) the car is at rest after its speed dissipates.

Scientists also use vectors (arrows that represent the strength and direction of a force) to illustrate the velocity of an object at a specific moment in time. *Velocity* is the combination of an object's speed and direction of travel. The vector used to illustrate velocity points in the object's direction of travel, and the length of the vector represents the object's speed. Shorter arrows represent lower speed, and longer arrows represent higher speed. As with forces, a velocity of zero is drawn as a dot. Like force vectors, the velocity vector of an object is typically drawn from the center of the object outward.

WARNING

Vectors can represent force, velocity, or acceleration. It's important to distinguish between these types of vectors because they're fundamentally different and can't be combined. Make sure to carefully label the vectors in diagrams, using different colors, if possible.

STOP AND THINK

Can you draw the velocity vector for the toy car
in each frame in figure 5?

Figure 6 shows the velocity vectors of a toy car rolling across a tabletop. How would you describe the change in motion occurring in frame C? If we compare this frame with the surrounding frames, we can see that the car is slowing down. The car is traveling to the left in all four frames, so the *direction* of velocity remains the same, but arrow (vector) length decreases, indicating a change in the car's speed. The change in velocity in a moment of time is called *acceleration*. As with force and velocity, scientists also use vectors to represent acceleration. The precise definition of an acceleration vector is complicated, but it can be roughly understood for one-dimensional motion (side to side or up and down), like many of the examples in this document.

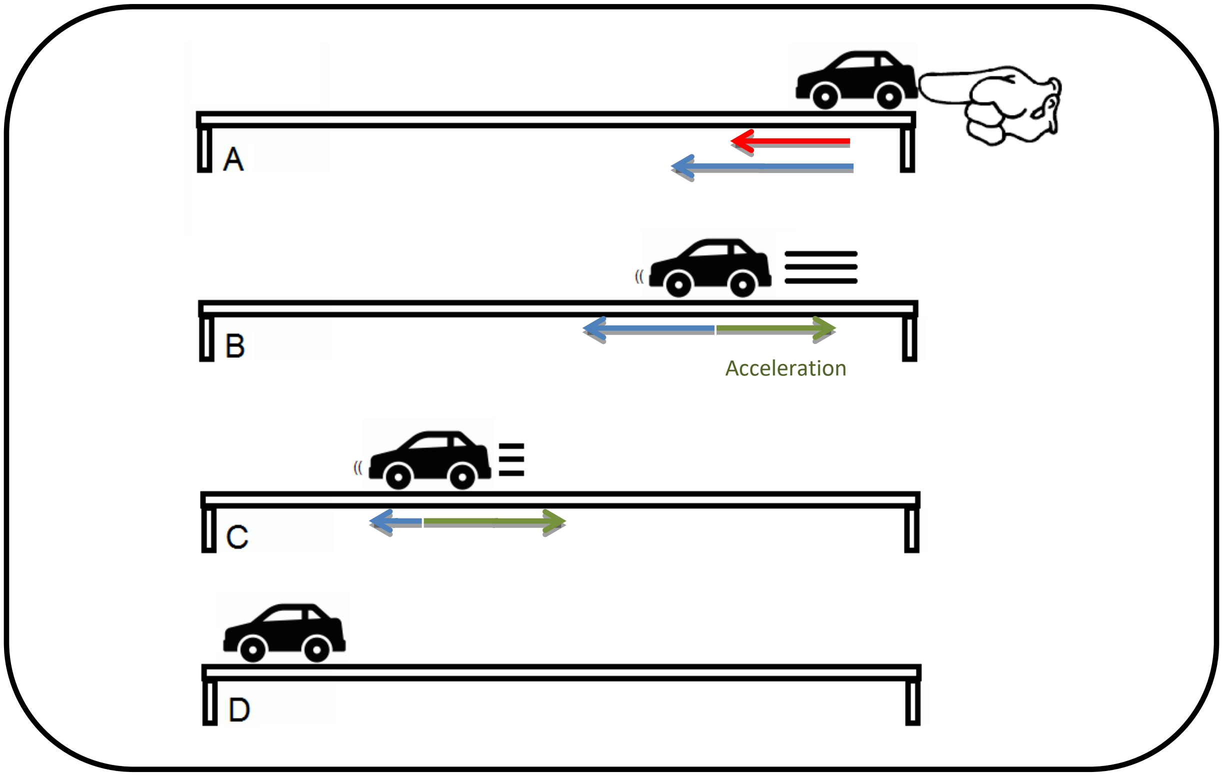


Figure 6. The toy car from figure 5 rolling across a tabletop at different time intervals: (A) A net force acts on the car, causing it to accelerate to the left; (B) the car coasts to the left while experiencing some rolling friction; (C) the car's speed decreases, and the car continues traveling very slowly to the left; (D) the car is at rest. The red vector indicates net force, blue vectors indicate velocity, and green vectors indicate acceleration. Note the zero vectors of velocity and acceleration in frame D.

Let’s examine the frames in figure 6 more closely. Scientists would represent the car’s acceleration in frames B and C with a green arrow pointing to the right, because the velocity vectors in frames A–C are pointing to the left even though their length is decreasing. If you were to align the tail ends of the velocity vectors, they would point to the right. That’s the direction of the velocity change. If the car was speeding up instead, and the length of the velocity vectors was increasing, then the acceleration vector in frames B and C would be pointing to the left. This time, if you were to align the tail ends of the three velocity vectors, they would point to the left (see figure 7).

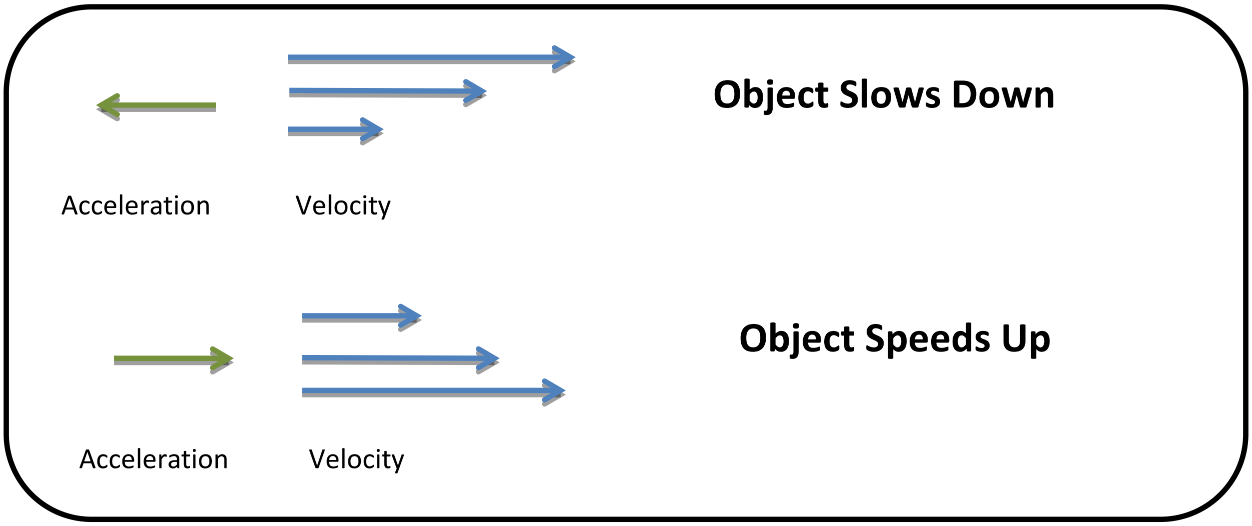


Figure 7. Acceleration vectors (green arrows) pointing in the direction of velocity change. With the velocity-vector tails aligned in each example, we see that even when all of the velocity vectors point in the same direction, the direction of each acceleration vector reflects the changes in velocity-vector lengths over time. In the first diagram, the acceleration vector points in the opposite direction of the velocity vectors when an object moving in a fixed direction slows down over time and the velocity vectors *decrease* in length. In the second diagram, the acceleration vector points in the same direction as the velocity vectors when an object moving in a fixed direction speeds up over time and the velocity vectors *increase* in length.

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WARNING

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STOP AND THINK

Consider the five-frame cartoon in figure 8.
Draw the sprinter's velocity vector (arrow) in each frame.

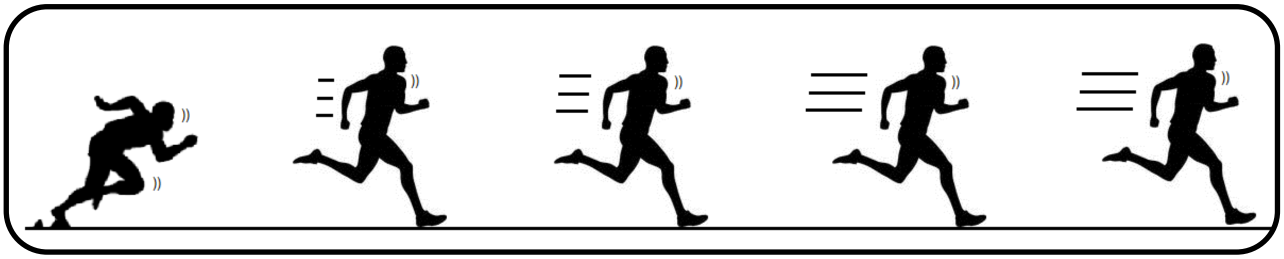
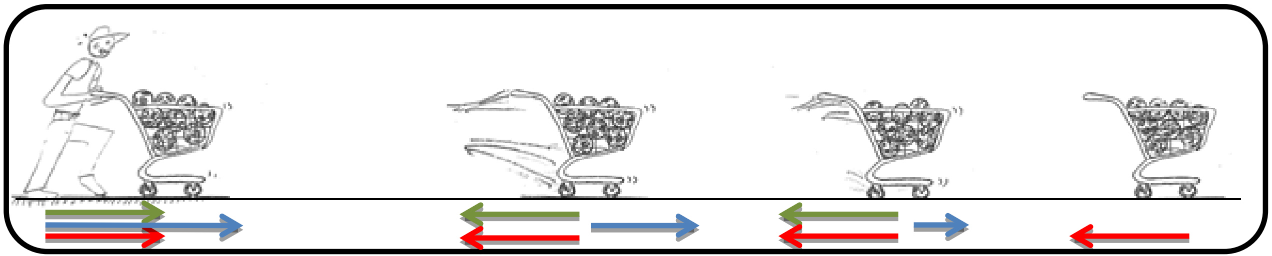


Figure 8. A sprinter comes out of the blocks, works hard to increase speed, and then achieves and maintains top speed throughout the race.

6. Explaining Changes in Motion

Figure 9 illustrates the motion of a grocery cart being pushed. Each frame shows an acceleration vector, which indicates how the motion is changing at a specific moment in time. What are the forces acting on the grocery cart in each frame? What is the *net force* on the grocery cart in each frame? You should find that the net force on the grocery cart and the cart's acceleration are in same direction in each frame. This is the first part of Newton's second law of motion: *The direction of acceleration of an object is the same as the direction of the net force on the object, compelling a change in motion.*



Courtesy of Hector Mireles

Figure 9. A man pushes a grocery cart to the right, exerting a great deal of force to change the velocity of the cart from zero to a faster velocity. When the man releases the cart, it rolls across the floor. After some distance, the cart slows down. In the final frame, the cart has lost all of its velocity and comes to a stop at the other end of the aisle.

So if we observe a change in an object's motion (i.e., if we can identify the acceleration vector at that instant), then a net force must be acting on the object in that direction. If we can identify all of the forces acting on an object and combine them to obtain this net force, we can explain why the motion is changing at that instant. For example, in the third frame of figure 9, the acceleration vector is pointing to the left because the grocery cart is slowing down as it moves to the right. The force of gravity is pulling down on the cart (toward Earth), and the ground is pushing up. Rolling friction is also applying a small force on the cart to the left, but nothing is pushing the cart to the right. This is very important to notice. Only three forces are acting on the cart at this instant. The net force on the cart is the same as the force of rolling friction on the cart because the net of the force of gravity and the normal force of the ground is zero. Thus, the net force on the cart and the cart's acceleration are in the same direction.

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WARNING

Students looking at the third frame in figure 9 often think that a force to the right is acting on the cart because the cart is moving in that direction, but this isn't the case. There is no longer any force pushing the cart. This confusion occurs because the velocity vector of the cart is pointing in that direction, and it's easy to forget that the vectors (arrows) represent distinct categories (e.g., velocity, force, acceleration). Again, it's important to carefully label the vectors in diagrams, using different colors to distinguish between vectors.

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

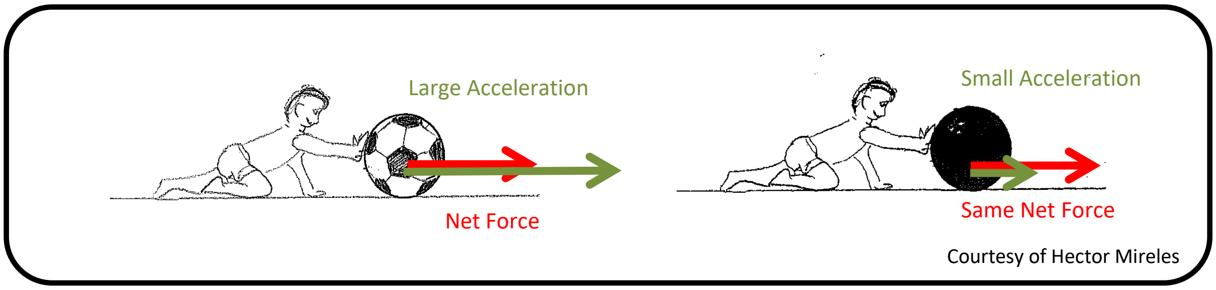
1. If the net force is in the *same direction* as the object's motion, the object will speed up.
2. If the net force is in the *opposite direction* of the object's motion, the object will slow down.
3. If the net force is at an angle with respect to the direction of the object's motion, the object will change direction toward the applied net force.

If a zero net force acts on an object, the object will maintain its velocity. If the object is at rest, it will stay at rest; if it's already moving, it will keep moving at the same speed in the same direction.

7. Force 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 how much force it would take to move a bowling ball 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 fast an object would travel, but Newton discovered that the *mass* of an object is one of the most important.

Try to picture the scenario in figure 10. The same force is applied to objects that have two different masses. A baby crawls up to a soccer ball and pushes it with a hand. The nonzero net force on the ball causes it to start rolling away from the baby. Then the baby crawls over to a bowling ball and pushes it with a hand. The nonzero net force on the bowling ball causes it to start rolling away from the baby as well. The baby, never having touched these objects before, pushes both with the same amount of force, but each ball experiences a different change in motion. The soccer ball begins rolling quickly (i.e., experiences a larger acceleration), whereas the bowling ball begins rolling slowly (i.e., experiences a smaller acceleration).



Courtesy of Hector Mireles

Figure 10. Equal forces acting on objects with different masses results in a different change in speed for each object.

What could the baby learn from this experience? To get the bowling ball rolling as quickly as the soccer ball would require a stronger push. In other words, producing the same acceleration of an object with more mass than another object requires a larger net force.

You might be getting the idea that a mathematical relationship is involved here. The larger the mass of an object, the greater the net force needed to achieve the same acceleration as an object of smaller mass. On the other hand, the same net force applied to objects with different masses results in a smaller acceleration for the object with the larger mass. Newton captured this mathematical relationship in his second law of motion. The first part of this law states that the acceleration of an object and the net force on an object are in the same direction. The second part explains how the length of the two arrows or vectors are related to each other. Here’s the full version of Newton’s second law:

> *The acceleration of an object produced by a net force is directly proportional to the magnitude of the net force, acts in the same direction as the net force, and is inversely proportional to the mass of the object.*

That’s just a fancy way of expressing this equation:

Net Force = Mass × Acceleration ($F = ma$)

OR

Acceleration = Net Force ÷ Mass

OR

$$a = F_{Net}/m$$

Newton’s second law of motion is best conceptualized by writing it in the second form shown above (Acceleration = Net Force ÷ Mass). This equation captures how an object accelerates when a net force acts on it. An object with more mass experiences less acceleration.

In this lesson series, you won't 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 change in motion. You—and your students—likely understand this relationship intuitively, but reading about it will hopefully add to your understanding.

8. What Makes Objects Move Differently in Outer Space?

If all of the rules of motion on Earth also apply in outer space, 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? To answer this question, let's consider two important differences between conditions on Earth and conditions in outer space that affect how objects move.

8.1 Gravity in Space

The pull of gravity is far less in outer space than it is on Earth, so objects don't fall in space. In fact, without a planet nearby, the gravitational force in space is almost zero.

Did you know that every bit of matter has gravity? That means every object with mass (like you, your car, the dust bunnies under your bed, and 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. So planet Earth, which has a very large mass, exerts a fairly strong gravitational pull on other objects. We use the word *weight* to describe Earth's downward pull on an object because of gravity. The Moon is smaller in mass than Earth, so it exerts a smaller gravitational pull on other objects. The gravitational pull you exert on other objects is so small that you don't even feel it.

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

The pull of gravity depends on the mass of two objects and the distance between them. The farther you are from Earth, the less Earth's gravitational pull will affect you. Astronauts can make giant leaps on the Moon's surface because the Moon has less gravity than Earth. At that distance, the Moon's gravity exerts a greater pulling force on astronauts' bodies than Earth's gravity does, which is why they don't get pulled off the Moon toward Earth. However, Earth's gravitational pull is still strong enough to keep the Moon and satellites in orbit.

8.2 Friction in Space

In outer space, there is no air resistance or friction present to act on an object. However, friction does exist on the Moon and eventually causes moving objects on the surface to slow down as they would on Earth. But the Moon has less gravity than Earth, so the forces that push the bumps on surfaces together aren't as strong as they are on Earth. As a result, the friction between two objects is less on the Moon than on Earth.

If you aren't on the surface of the Moon or some other planet, however, but are floating around in outer space, there are no surfaces rubbing together to create friction. There is very little air or other particles in outer space, or on the Moon, that would cause moving objects to experience fluid friction as they would on Earth. So if you're floating in space, and something gives you a little nudge, you'll move in a straight line forever, with nothing to stop you. Remember Galileo's thought experiment where a ball rolls across a flat surface forever? Although Galileo never applied his ideas to outer space, his concepts about inertia and the tendency of objects to maintain a constant speed and direction work perfectly in that setting without the force of friction opposing an object's motion.

9. Do Things Always Have to Touch to Exert a Force?

The introduction to this document referred to magnetic, electrical, and gravitational phenomena that seemed almost magical. Such forces are called *noncontact forces* because they don't require two objects to touch to exert an influence on each other. That's quite obvious with gravity. The gravitational pull of Earth causes objects far above its surface to fall toward the ground. Magnetic and electrical forces work in a similar way. However, each of these forces follows the same rules as contact forces, pushing and pulling objects (Newton's first law) and causing corresponding changes in motion (Newton's second law).

Let's consider gravity for a moment. What forces act on a baseball when you toss it high into the air and it comes back down again? It seems straightforward, doesn't it? You exert an upward force on the ball when you toss it into the air. But how would you describe the forces acting on the ball once you're no longer touching it? You aren't exerting a force anymore, so why doesn't the ball come back down as soon as you let go of it?

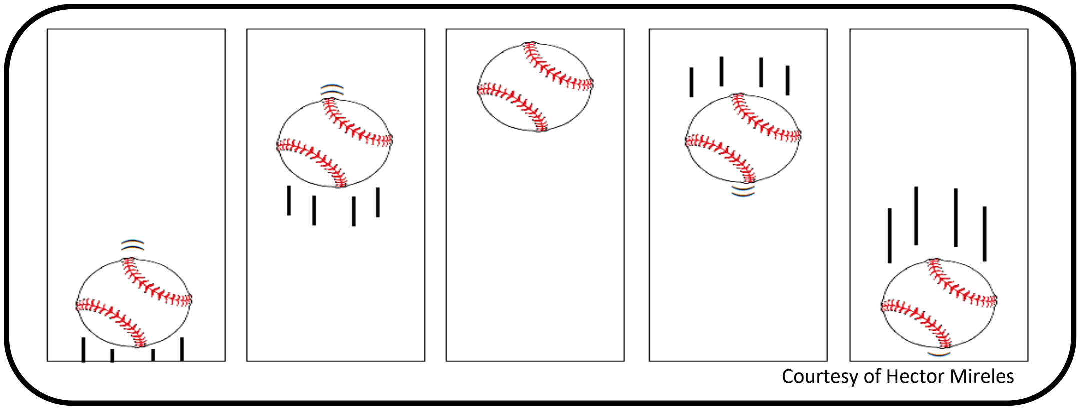

Courtesy of Hector Mireles

Figure 11. Five-frame cartoon of a baseball being tossed straight upward and falling back down.

You started the baseball's upward motion with your toss. If there were no gravity (or air resistance), the ball would continue upward forever. But a nonzero net force on the ball causes a change in motion, and it falls back to Earth. What forces are acting on the baseball in each frame of figure 11? Gravity is always creating a downward force on the ball. Air resistance (a form of fluid friction) also exerts a force on the ball, but this force is very small when the ball isn't moving fast, so it can be dismissed. Since the weight of the ball doesn't change, the length of the arrow (vector) is the same in each frame. In the first frame, the upward force from your hand is greater than the weight of the ball. So an upward nonzero net force on the baseball causes it to start moving upward. But once you're no longer touching the ball, you're no longer exerting an upward force. Yet gravity is still pulling down on the ball, so there is a constant downward nonzero net force that changes the ball's motion. The ball continues its motion away from the ground, but eventually the ball slows down, comes to a momentary stop, and then changes direction, falling toward the ground as it picks up speed.

10. Putting It All Together

Newton's laws of motion provide a framework for thinking about contact and noncontact forces, and they do a pretty good job of helping us understand, predict, and explain changes in the motion of objects in the world around us. These ideas, including the concepts of friction and gravity, are useful for everyday, common situations, such as getting astronauts to the Moon, designing a roller coaster, or developing safety regulations for tires and roads. But they don't work in every situation.

Over time, scientists like Albert Einstein discovered some situations in which Newton's ideas about force and motion don't apply, such as on a very small scale (like smashing electrons into protons) or at very fast speeds (like traveling at the speed of light) or on a very large scale (like expanding and contracting the universe).

Let's summarize Newton's ideas about motion:

1. Objects experience changes in motion (slowing down, speeding up, or changing direction) because a combination of pushes, pulls, or twists, called a *net force,* act on them. A *nonzero net force* causes a change in motion. An object at rest will start moving only if a nonzero net force acts on it, and an object in motion will keep moving in the same direction at the same speed unless a nonzero net force acts on it.
2. *Friction* is a force caused when tiny bumps on the surface of an object push against tiny bumps on the surface of another object. Friction can be *static* (preventing an object from moving even when you push it), *sliding* (such as flat surfaces rubbing or sliding over each other), *rolling* (like a soccer ball rolling across the playground), or *fluid* (resistance to motion that occurs when you move through air or water).
3. There is a key relationship, both conceptually and mathematically, between acceleration and the net force that causes it. The mass of an object determines the strength of acceleration.

$$\boldsymbol{a = \frac{F_{NET}}{m}}$$

4. Many forces we experience are *contact forces*; in other words, two objects need to touch to exert a force. However *noncontact forces*, such as gravity, magnetic forces, and electrical forces, don't require two objects to touch; they can exert force from a distance.

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11. Back to the Beginning

At the beginning of this document, we considered the question, “Why do objects start moving, speed up, slow down, change direction, or stop*?*” Have the ideas in this discussion changed your understanding of forces and motion? Have you developed new ideas and connections that can 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? Hypothetically speaking, do you know why a ball rolling down a hill will keep rolling, but a ball rolling across a flat surface won’t?

What new questions do you have about forces and motion? Keep track of these questions and talk to your colleagues and PD leaders to broaden, deepen, and enrich your science-content knowledge throughout the year.

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