Chapter 1 Ways to Look at the World

Section 1.1 The Big Picture

Figure 1.1 "The Starry Night," painted by Vincent van Gogh in 1889 (credit bgEuwDxel93-Pg at Google Cultural Institute, public domain)

Creation is beautiful and awe-inspiring. We humans have been attempting to describe it, capturing little pieces that we can appreciate in some meaningful way, for millennia. Some make the attempt through artwork, as in the famous painting by Vincent van Gogh in Figure 1.1. Others make the attempt through music, like Vivaldi's "Four Seasons," or Counting Crows' "Big Yellow Taxi." Still others use poetry:

古池や蛙飛びこむ水の音

furu ike ya / kawazu tobikomu / mizu no oto

an ancient pond / a frog jumps in / the splash of water

Matsuo Bashō, 1686[i]

[i] Translated by William J. Higginson in Matsuo Bashō: Frog Haiku (Thirty Translations and One Commentary), revised ed., Shoemaker & Hoard, 2003.

Some try to capture the beauty in photographs, as Ansel Adams did in Figure 1.2. Some people enjoy going for retreats to the mountains or a lake or the sea, relaxing and enjoying being in nature. Every unique perspective on the world around us helps to enrich our lives.

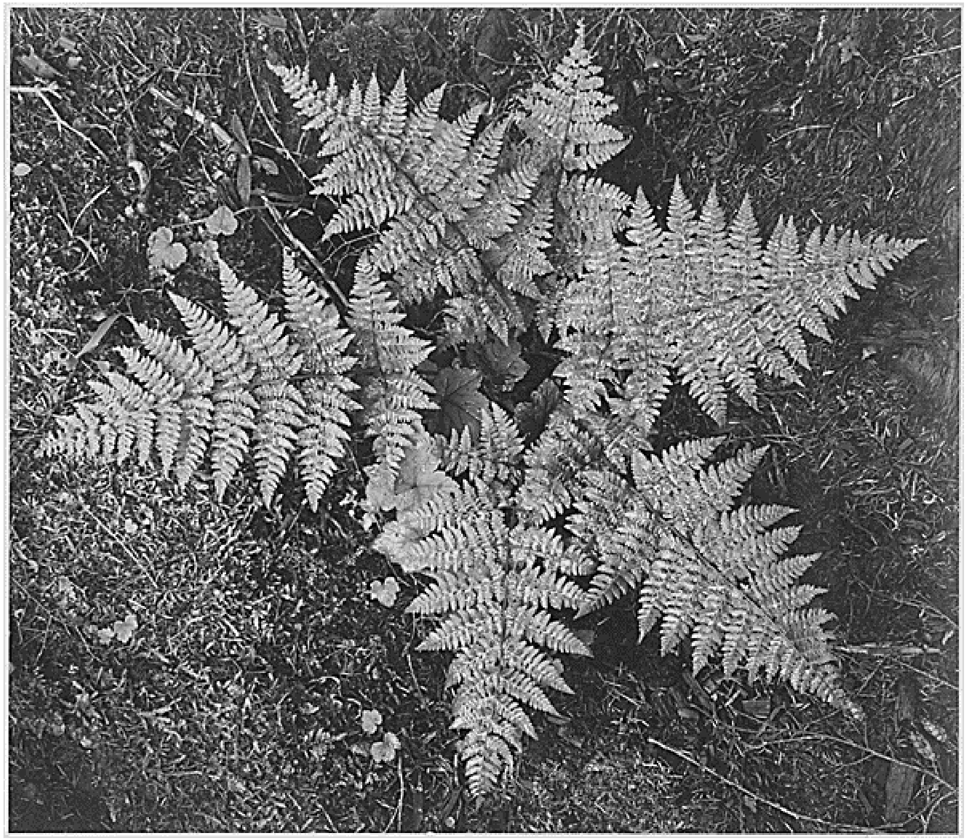

Figure 1.2 **Close-up of ferns, from directly above. (credit: Ansel Adams. Property of the U.S. Government, public domain.)**

Physics offers another perspective on the world around us, finding ways to observe, measure, and describe things that often cannot be observed with our five senses, but which can still somehow be understood, often through conceptual drawings or mathematics. In Ansel Adams' photograph, we can see patterns and symmetries in the leaves of a fern; physics can show us patterns and symmetries in the motion of a ball flying through the air. In Matsuo Bashō's writing the motion of a frog affects an ancient pond; physics can help us to understand these interactions between bodies that collide. Van Gogh's painting captures in one place objects as large as a galaxy and as small as a twig; physics looks beyond galaxies to the whole of the universe, and it looks beyond twigs to see what is inside the tiniest sub-atomic particles.

The character Sherlock Holmes in the books by Sir Arthur Conan Doyle is known for carrying a magnifying glass with a lens that he uses to discover clues about his surroundings. In this book we will use four different "lenses" to help us understand the world:

- Motion: how position and speed change over time
- Momentum: how hard it is to stop a moving object
- Force: the things that cause changes in the momentum of an object
- Energy: the ability to do work

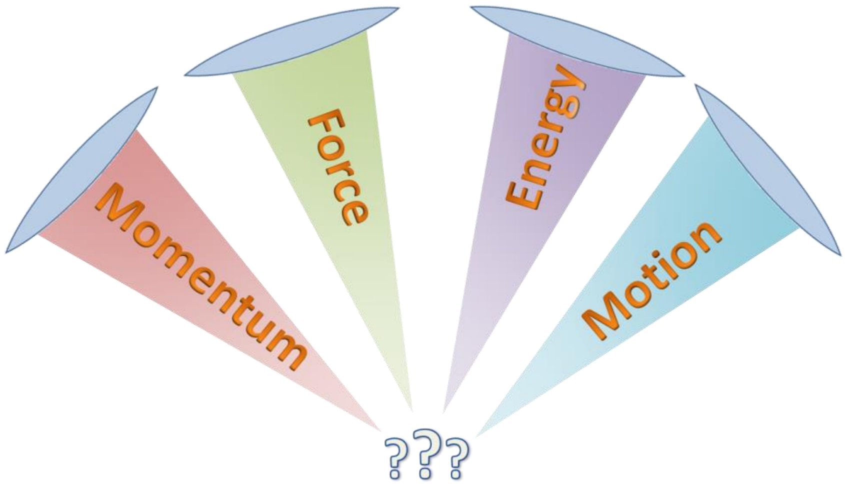

Figure 1.3 The four "lenses" of physics we will use to learn about the world around us

The way we will be learning physics is a little like the way we all learned our first language – you just dive in and start doing it. Happily, we started learning physics many years ago, because you come to your first class with some familiarity with motion, momentum, forces, and energy. Now, we will deepen your familiarity and practice working on problems.

Section 1.2 **Motion maps**

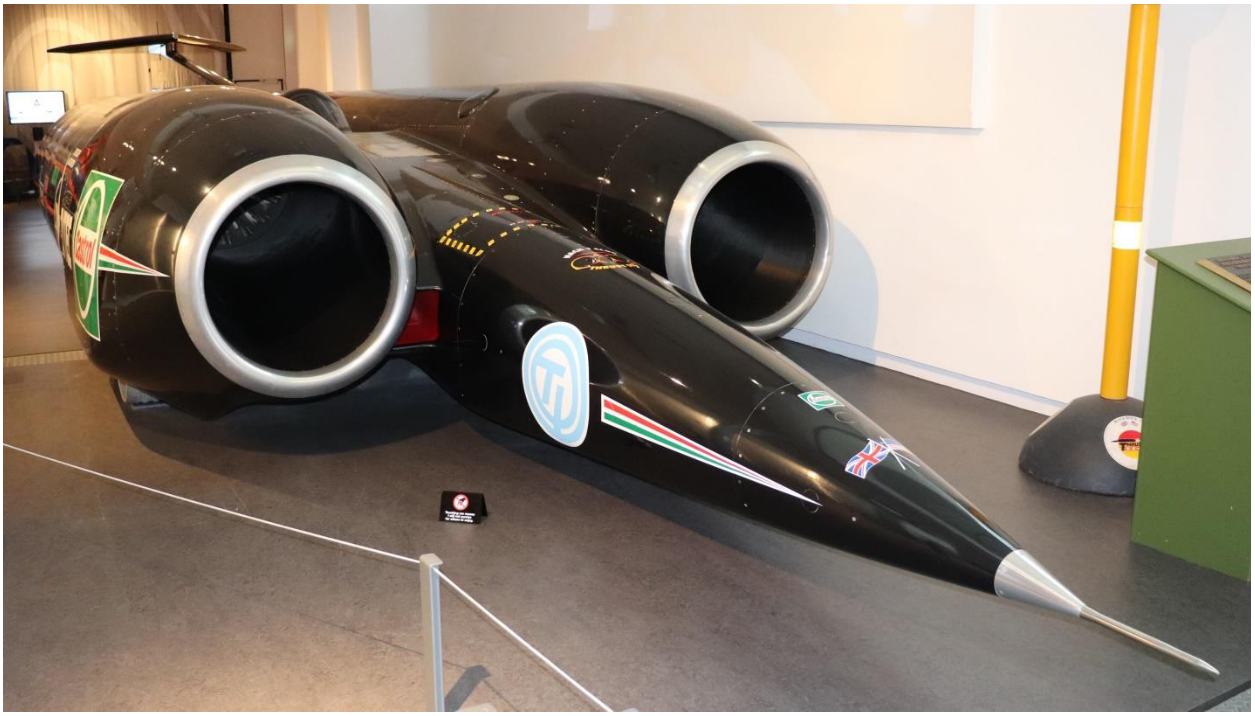

Figure 1.4 ThrustSSC, the twin turbofan jet-powered car that officially holds the Outright World Land Speed Record, having traveled at a speed of 763.035 mph over one mile in October 1997. (credit: Vauxford, from Wikimedia Commons, CC4.0)

When we consider the motion lens, we look at how the position of something changes in time, without concern for the cause of the motion. ThrustSSC' was moving quite quickly in October 1997, when it traveled across the faster than the speed of sound! But in Figure 1.4, the ThrustSSC doesn't appear to be moving at all. We can capture the motion of something by using a "motion map." It's basically a series of points that represent the position of an object at different points in time.

For example, this could be the motion map of the Thrust SSC as it broke the world record:

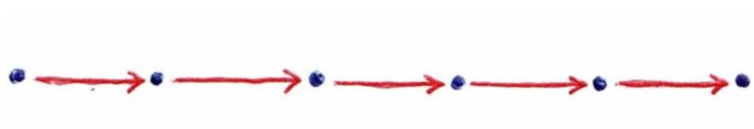

Figure 1.5 Motion map of ThrustSST setting land speed record

Each dot represents the position at a certain point in time, and the points are marked at equal time intervals of 1 second each. Five seconds to go one mile! The arrows are added in to show you the order of the dots. Starting on the left, and going to the right.

But what if we looked at more than just that record-setting time? Thrust SSC must have started off not moving, and then taken a few seconds to get up to speed. And after setting the record, it must have slowed to a stop again. So if we include a little bit more time before and after, the motion map would look something like this:

Figure 1.6 Motion map of ThrustSST setting land speed record, including time shortly before and shortly after the timed portion

See how the spacing between the dots is smaller at the beginning and the end? When the speed is slower, the space between the dots is smaller—that should make sense, because if you are moving quickly then your position will change more in one second than it would if you were moving slowly. In fact, the length of the red arrows tells you about the speed of the object at any point in time.

What if we now wanted to include even more time before and after the run? What about the time when ThrustSSC was just sitting there, getting ready to go? Or the time after it had stopped at the end? It wouldn't be helpful to just draw more dots right on top of each other on a motion map, because we wouldn't be able to see them. Instead we can stack more dots above the previous dot. So a dot that is directly above another dot, with no arrow, means that the position of the object hasn't changed from one second to the next. A dot next to another dot, with an arrow in between means that the object has moved from one position to the other along the direction of the arrow.

Figure 1.7 Motion map of ThrustSST setting land speed record, including time before it started moving and after it stopped moving

Since we can use the arrows to show direction, we can map an object moving back and forth as well. If you are pacing back and forth in a room, your motion map may look something like this:

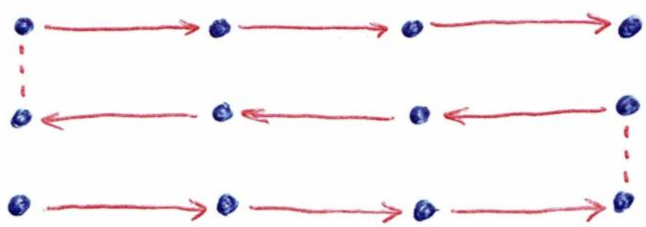

Figure 1.8 Motion map of a person pacing back and forth. The dotted lines are optional. They are added for clarity.

Vertical dotted lines are included in this motion map for clarity, as a reminder of which dots are one second apart. For example, the dot on the top left is one second after the dot directly below it. But the dot on the top right is NOT one second after the dot directly below it.

Exercise 1.1 For the dot on the top right in the motion map in Figure 1.8 of a person pacing back and forth, how many seconds is that dot after the dot directly below it? How do you know?

Exercise 1.2 Draw motion maps for each of the following:

a. **A person running a 50-yard dash. Make your motion map start two seconds before the race starts.**

b. **A car that begins stopped at a traffic light, drives slowly forward for three seconds, stops at a stop sign, drives quickly forward for three seconds, stops, and goes in reverse for two seconds.**

Section 1.3 **Momentum blocks**

Figure 1.9 A "Newton's cradle" in action. The moving ball on the left has just hit the second ball from the left, making it start to move. The other three balls are (at this moment) stationary.

If something has momentum it is hard to stop or make it change course. We use the term in every day English, such as "Jenny's business has gained so much momentum this year that it is certain to succeed." We also use it in terms of a moving object, such as, "John ran into a player from the other team, but John had enough momentum to carry the two of them over the goal line!"

In physics, momentum is related to two things: the mass of an object and its speed. Look at the steel balls in Figure 1.9. The balls themselves are all identical, but the ball on the left has more momentum than the others. That is because it is moving faster than the others. We can draw "momentum blocks" to represent the amount of momentum that each of the balls has. We start by drawing a horizontal line (this will be the width of the block) for each ball. The balls are all the same, so we will draw the lines all the same as well:

Figure 1.10 Starting a "momentum block" diagram

Then we need to add some height to each of the lines, with the height representing the speed of the object:

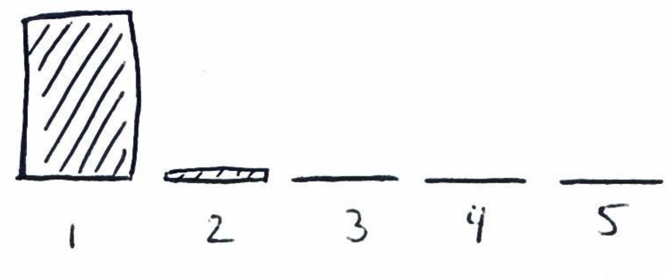

Figure 1.11 Momentum block diagram for the Newton's cradle in Figure 1.9. The numbers 1 – 5 correspond to which position the ball is in, counting from the left. The width of each block corresponds to the mass of each ball, and the height of each block corresponds to its speed. In the photo, you can see that the second ball has just barely started to move.

An instant after the photo in Figure 1.9 was taken, as you will know if you have ever played with a Newton's cradle, the ball on the left stops completely, and the ball on the right starts moving with the same speed that the ball on the left had initially. At that instant, the momentum block diagram would look like this:

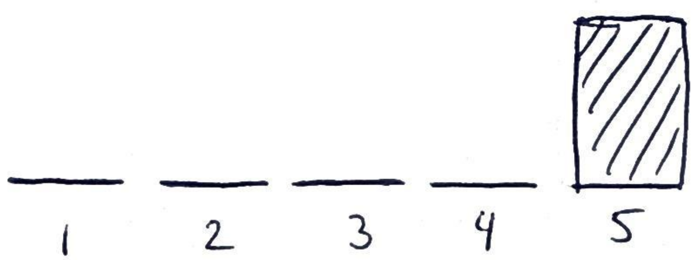

Figure 1.12 Momentum block diagram an instant after the photo in Figure 1.9 was taken

If I have drawn everything correctly, the total size of all of the blocks in Figure 1.11 and Figure 1.12 will be the same, because all of the speed that Ball 1 had just before hitting Ball 2 ends up in Ball 5, with everything else at rest. This demonstrates the physical principle called **Conservation of Momentum: the total momentum of an isolated system does not change**.

Let's break that physical principle up a little bit. "***Total momentum***" means add up the momenta of everything. What does "everything" mean? All of the parts of the "system." A "***system***" can be anything. In our example, the system is all five of the balls, because they hit each other with little effect from anything else. If you are playing tug-of-war, the system would likely include the rope and all of the members of both teams. It might even include the ground you are standing on! Often the way to decide what system you should continue is wrapped up in that word "***isolated***." An isolated system is not affected by anything outside of itself. If you are in a car crash on an icy road, a good system to choose would be the two vehicles. If the road is dry, you might have to include the road as well, which probably means including the whole earth as well! If you are hitting a baseball, at the time of impact it may be enough to include just the bat and the ball in the system. It will take practice learning to choose your system well!

What if we took that Newton's cradle we have been playing with and put a small drop of superglue at each spot where the balls touch, so that all of the balls stick together as soon as the first ball hits them? Then we would start with five balls that all have equal mass, with just one moving, and end up with one big stuck-together line of balls that has a mass five times bigger than an individual ball. What would the momentum block look like for the five balls stuck together? Something like this:

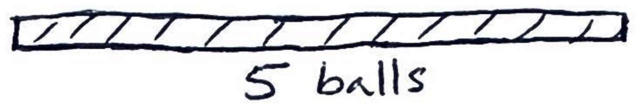

Figure 1.13 Momentum block for five balls all stuck together

I have made one wide block, about five times as wide as I made for the single balls before. And to keep the size of the block the same, I made it about 1/5 as high as the block for Ball 5 in Figure 1.12. So that means the speed of the five superglued-together blocks should be 1/5 as fast as the speed of the one ball that was initially moving.

Exercise 1.3 Draw labeled momentum blocks for each of the following:

a. **A walking adult**
b. **A running adult**
c. **An adult who is standing still**
d. **A child who is standing still**
e. **A running child**
f. **A walking child**

Exercise 1.4 Using the momentum blocks you drew for Exercise 1.3, put the following in order, from most momentum to least momentum. Ties are allowed where needed.

a. **A walking adult**
b. **A running adult**
c. **An adult who is standing still**
d. **A child who is standing still**
e. **A running child**
f. **A walking child**

Exercise 1.5 Consider a collision between a small car and a large truck on an icy road (so the system is just the two vehicles), where the vehicles stick together after the collision. Draw labeled momentum blocks for each of the following:

a. **The car moving at high speed just before the accident**
b. **The truck moving in the same direction at low speed just before the accident**
c. **The stuck-together car/truck system just after the accident**

Section 1.4 **Force**

Figure 1.14 "The Force" means something different in Hollywood than it does in physics class. (credit: GPS from San Francisco [CC BY-SA 2.0])

We have just learned about conservation of momentum, that momentum is always constant. But in fact momentum can change. Have you ever seen a small child learn about momentum? They might reach out and try to stop an adult on a swing. The adult on the swing does lose momentum, but the child is surprised to find that they are knocked over in the process. The adult's momentum changes, and so does the child's. If you consider the "system" to be just the child (as naturally any child would), the momentum of the system was affected by something outside of the system.

That thing that is outside of the system affects the system through a ***force***. A force, quite simply, is a "push" or a "pull." Forces are always interactions with other objects. Sometimes it is easy to identify the other object. In the example above, the child is interacting with the adult. Sometimes it is more difficult to identify the other object. If you hold your cell phone in the air and let go, its momentum begins to change as it falls. That force is the force of gravity between the phone and the earth, so the other object is the earth.

We will consider just a few types of forces in this class:

1. ***Gravity*** – the force of gravity is attractive. It always points toward the object that is affecting the system. In our everyday life, the gravity we feel is from the earth. And the earth is below us. So it points down.
2. ***Tension*** – if you pull on a rope (or a string, or anything else that acts like a rope) you create tension in the rope. Tension points along the length of the rope.

3. ***Normal*** – in physics class "normal" doesn't mean "regular." It means perpendicular to a surface. In the example of dropping a cell phone, when the cell phone hits the ground it stops moving downward. That is because of the normal force from the ground, which points up. Normal force always points directly out of a surface.
4. ***Friction*** – this we will cover later. It's complicated!
5. ***Applied*** – this type of force is a sort of "catch-all." It is not specified where the force comes from, but problems often ask something like "how much force must be applied to…so that…." Or else it will say that a certain force is applied and ask what happens as a result. This "applied" force could come from anything and point in any direction.

Forces have size and direction, so we represent forces with labeled arrows, like this:

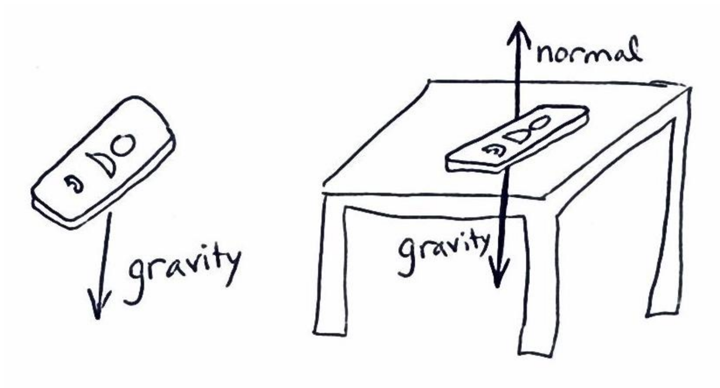

Figure 1.15 Forces on a cell phone. On the left, the phone is affected only by the force of gravity. On the right, the phone is affected by both the force of gravity and the normal force from the table.

The cell phone on the left side of Figure 1.15 is falling under the influence of the force of gravity. On the right, the phone is still affected by gravity pulling it down, but it is also affected by the normal force of the table pushing it up. We will worry later about how to combine forces to figure out what the net effect is from multiple forces acting on an object or system of objects. For now, we will work only on identifying the forces that are affecting an object. Here are some more examples:

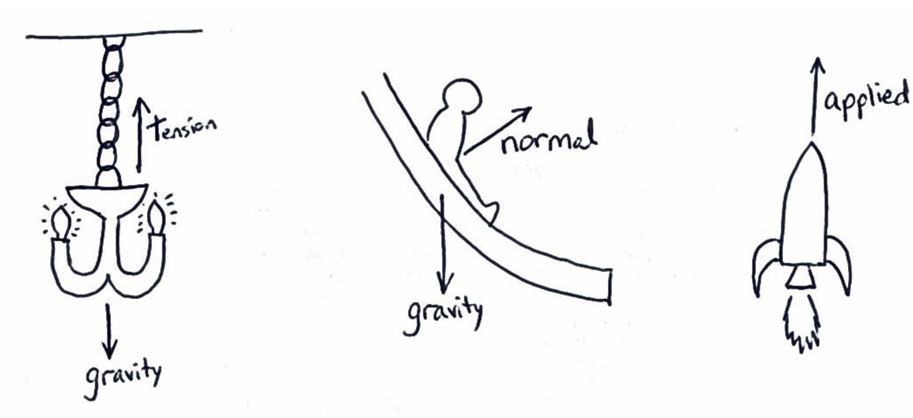

Figure 1.16 More examples of forces acting on objects: a chandelier, a child on a slide, and a rocket in space.

The chandelier on the left side of Figure 1.16 is being pulled down by gravity and held up by the tension in the chain that is connected to the ceiling. The child on a slide in the center of Figure 1.16 is being pulled down by gravity and held up by the normal force from the slide. Notice that the normal force points out at an angle. That is because the slide is angled; the normal force points directly away from the surface of the slide. The rocket on the right side of Figure 1.16 is assumed to be so far out in space that it is not affected by gravity from the earth, the sun, or anything else. When it fires its rockets, it "feels" a force from the rocket engines. This force doesn't fit neatly into any of the other categories we have for forces: gravity, tension, normal, or friction, so we will call it an "applied" force from the rocket engines.[ii]

These types of sketches are usually called ***free body diagrams***.

Exercise 1.6 **Draw free body diagrams of each elephant described below. If there are no forces, just write "no forces" under the sketch.**

a. **An elephant standing in a savannah**
b. **An elephant in mid-air after it jumped up to reach some leaves**
c. **An elephant out in space far away from the effects of gravity**
d. **An elephant sitting on a tire swing**
e. **An elephant standing on the side of a hill**
f. **A mouse head-butting an elephant that is standing in a savannah**

Exercise 1.7 **Draw a free body diagram or a series of free body diagrams showing the forces that affect a softball from the time it is thrown by the pitcher to the time a fly ball is caught in the outfield. Include the forces acting on the ball at each of the following times:**

a. **While it is in the pitchers hand and she is in the process of throwing it**
b. **While it is in the air on the way to the plate**
c. **While it is being hit by the bat**
d. **While it is in the air on the way to the outfield**
e. **While it is being caught**

[ii] This force is often called "thrust." We will focus on being able to recognize the existence of forces and figuring out how they affect objects rather than being too concerned about remembering a lot of different names for the forces. Just knowing gravity, tension, normal, friction, and applied are enough.

Section 1.5 Energy transformation

Figure 1.17 How many forms of energy can you identify in this photograph of a wind farm in Iowa? Can you identify an energy transformation from one form of energy to another? (credit: Jürgen from Sandesneben, Germany, Wikimedia Commons)

Energy is a useful concept because, like momentum, energy is conserved: the total amount of energy in an isolated system is constant. Energy can be thought of as the ability to do some sort of work. For example, it takes some work to break the shell of an egg so we can get to the interesting part inside it.

There are several ways we might consider for getting through an eggshell to get to the tasty parts inside. For example, we could…

- …tap it against the side of a bowl, using ***kinetic energy*** (energy of motion).
- …soak it in vinegar, using ***chemical potential energy*** (energy that can be released in chemical reactions, including digestion, burning, and reactions inside of batteries).
- …drop it onto the floor, using ***gravitational potential energy***.
- …use a slingshot to fire it at a brick wall, using ***elastic potential energy*** (commonly associated with springs).
- …put it into a microwave until it explodes, using ***light energy*** (energy associated with electromagnetic waves, including visible light, infrared, x-rays, microwaves, radio waves…).
- …slice it open with a cutting torch, using ***thermal energy*** (heat energy).
- …hold it high in the air during a thunderstorm until it is struck by lightning, using ***electrical energy***.
- …hit it with an atomic bomb, using ***nuclear energy***.

As you can see, there are many types of energy. And energy has the ability to transform from one type to another.

In the third example above of dropping the egg onto the floor, we give the egg gravitational potential energy by holding it high above the floor. But when we let go, the gravitational potential energy transforms into kinetic energy. When it hits the floor, the egg shell starts to deform, transforming kinetic energy into elastic potential energy, until it reaches the breaking point. Then the shell shatters, and all of the remaining elastic potential energy and kinetic energy transform into thermal energy which is lost to the environment around the egg.

The transformation of energy from one form into another is happening all the time. The chemical energy in food is converted into kinetic energy and thermal energy through metabolism; light energy is converted into the chemical energy of sugar through photosynthesis in plants. The chemical energy contained in coal is converted into thermal energy as it burns to turn water into steam in a boiler. This thermal energy in the steam in turn is converted to mechanical energy as the expanding steam spins a turbine (and cools in the process), which is connected to a generator, converting the kinetic energy to electrical energy.

Figure 1.18 Solar energy is converted into electrical energy by solar cells, which is used to run motors in this solar-power aircraft. (credit: NASA)

Another example of energy transformation occurs in a solar cell. Sunlight impinging on a solar cell (Figure 1.18) produces electricity, which in turn can be used to run an electric motor. Energy is converted from the primary source of light energy into electrical energy and then into mechanical energy. Because energy is conserved, all of the light energy absorbed by a solar cell is equal to the sum of the electrical energy produced and some thermal energy that warms up the solar panel.

Exercise 1.8 In a city, a generator powered by gasoline charges a battery. At night, the charged battery is moved to a nearby village without electricity to provide lighting.

a. Starting with the chemical potential energy of the gasoline, follow the energy transformations that result in lighting.
b. What are the energy transformations that gave rise to the gasoline? Starting with prehistoric sunlight, where did the gasoline get its chemical potential energy?

Exercise 1.9 Consider in the above scenario, there is often more than one kind of energy produced from each transformation. In particular, thermal energy is often produced along with another energy form. Thus, the energy conversion is not considered 100% efficient because some of the energy is "lost" from the system through heat to thermal energy.

a. In the scenario represented above, all of the prehistoric sunlight didn't turn into light in the rural community. Identify the many places where energy was "lost" as thermal energy along the way, rendering much less radiant energy in the rural village than the original prehistoric radiant energy that fell upon the prehistoric plants.

b. If all the lost thermal energy from the energy transformations accumulated, the earth would get hotter very quickly. Where does all this energy eventually go?

Exercise 1.10 Consider two identical solar panels next to each other in the sun. One is hooked to a motor that is doing work, while the other is not hooked to anything. Which solar panel is warmer? How do you know?

Exercise 1.11 Suppose that you eat an "energy bar" and then ride your bike very fast up a hill. From the top of the hill, you turn around and coast downward, speeding up. You stop at the bottom using your brakes.

a. Starting with the chemical potential energy in the energy bar, identify the energy conversions in this process.

b. Finishing with the chemical potential energy in energy bar you ate, identify the energy transformations that gave rise to that energy bar.