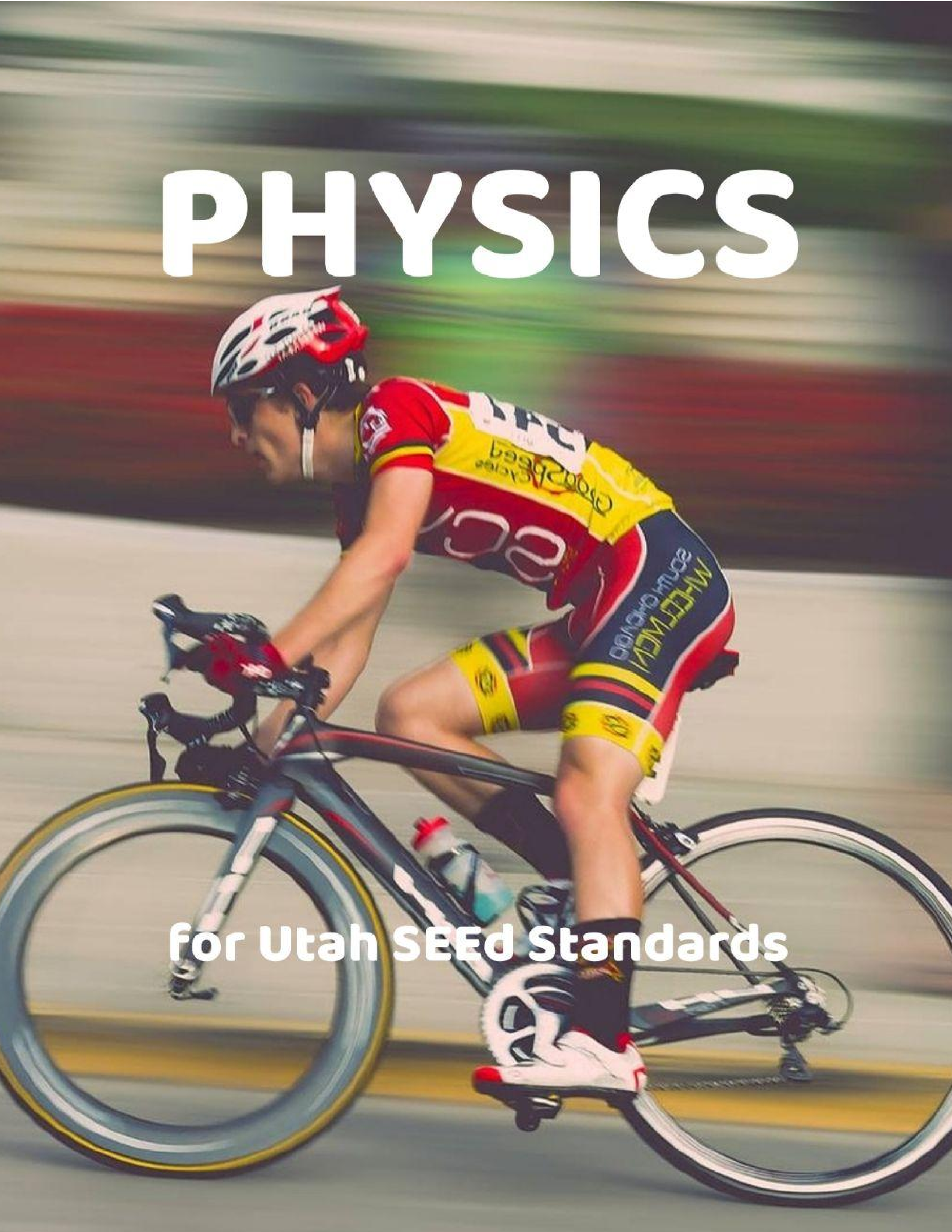
PHYSICS



for Utah SEEd Standards

Physics

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Utah State Board of Education OER

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Students as Scientists

What does science look and feel like?

If you're reading this book, either as a student or a teacher, you're going to be digging into the "practice" of science. Probably, someone, somewhere, has made you think about this before, and so you've probably already had a chance to imagine the possibilities. Who do you picture doing science? What do they look like? What are they doing?

Often when we ask people to imagine this, they draw or describe people with lab coats, people with crazy hair, beakers and flasks of weird looking liquids that are bubbling and frothing. Maybe there's even an explosion. Let's be honest: Some scientists do look like this, or they look like other stereotypes: people readied with their pocket protectors and calculators, figuring out how to launch a rocket into orbit. Or maybe what comes to mind is a list of steps that you might have to check off for your science fair project to be judged; or, maybe a graph or data table with lots of numbers comes to mind.

So let's start over. When you imagine graphs and tables, lab coats and calculators, is that what you love? If this describes you, that's great. But if it doesn't, and that's probably true for many of us, then go ahead and dump that image of science. It's useless because it isn't you. Instead, picture yourself as a maker and doer of science. The fact is, we need scientists and citizens like you, whoever you are, because we need all of the ideas, perspectives, and creative thinkers. This includes you.

Scientists wander in the woods. They dig in the dirt and chip at rocks. They peer through microscopes. They read. They play with tubes and pipes in the aisles of a hardware store to see what kinds of sounds they can make with them. They daydream and imagine. They count and measure and predict. They stare at the rock faces in the mountains and imagine how those came to be. They dance. They draw and write and write and write some more.

Scientists — and this includes all of us who do, use, apply, or think about science — don't fit a certain stereotype. What really sets us apart as humans is not just that we know and do things, but that we wonder and make sense of our world. We do this in many ways, through painting, religion, music, culture, poetry, and, most especially, science. Science isn't just a method or a collection of things we know. It's a uniquely human practice of wondering about and creating explanations for the natural world around us. This ranges from the most fundamental building blocks of all matter to the widest expanse of space that contains it all. If you've ever wondered "When did time start?", or "What is the smallest thing?", or even just "What is color?", or so many other endless questions then you're already thinking with a scientific mind. Of course you are; you're human, after all.

But here is where we really have to be clear. Science isn't just questions and explanations. Science is about a sense of wondering and the sense-making itself. We have to wonder and then really dig into the details of our surroundings. We have to get our hands dirty. Here's a good example: two young scientists under the presence of the Courthouse Towers in Arches National Park. We can be sure that they spent some amount of time in awe of the giant sandstone walls, but here in this photo they're enthralled with the sand that's just been re-washed by recent rain. There's this giant formation of sandstone looming above these kids in the desert, and they're happily playing in the sand. This is ridiculous. Or is it?

How did that sand get there? Where did it come from? Did the sand come from the rock or does the rock come from sand? And how would you know? How do you tell this story?

Look. There's a puddle. How often is there a puddle in the desert? The sand is wet and fine; and it makes swirling, layered patterns on the solid stone. There are pits and pockets in the rock, like the one that these two scientists are sitting in, and the gritty sand and the cold water accumulate there. And then you might start to wonder: Does the sand fill in the hole to form more rock, or is the hole worn away because it became sand? And then you might wonder more about the giant formation in the background: It has the same colors as the sand, so has this been built up or is it being worn down? And if it's being built up by sand, how does it all get put together; and if it's being worn away then why does it make the patterns that we see in the rock? Why? How long? What next?

Just as there is science to be found in a puddle or a pit or a simple rock formation, there's science in a soap bubble, in a worm, in the spin of a dancer and in the structure of a bridge. But this thing we call "science" is only there if you're paying attention, asking questions, and imagining possibilities. You have to make the science by being the person who gathers information and evidence, who organizes and reasons with this, and who communicates it to others. Most of all, you get to wonder. Throughout all of the rest of this book and all of the rest of the science that you will ever do, wonder should be at the heart of it all. Whether you're a student or a teacher, this wonder is what will bring the sense-making of science to life and make it your own.

Adam Johnston
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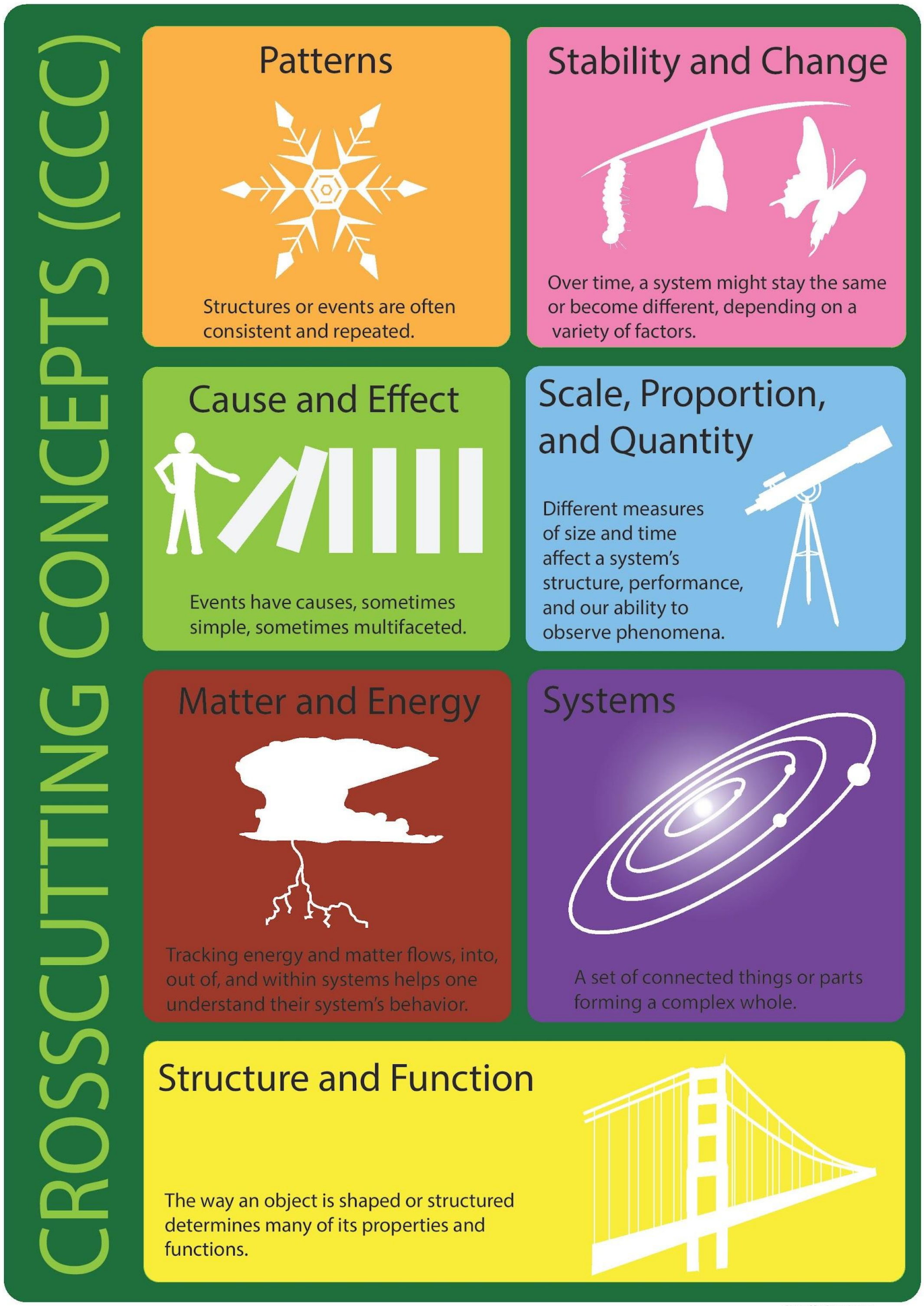
Science and Engineering Practices

Science and Engineering Practices are what scientists do to investigate and explore natural phenomena

Crosscutting Concepts

Crosscutting Concepts are the tools that scientists use to make sense of natural phenomena.



What is involved in Engineering Design?

Engineering is a creative process where each new version of a design is tested and then modified, based on what has been learned up to that point. This process includes a number of components:

1. Identifying the problem and defining criteria and constraints.
2. Generating ideas for how to solve the problem. Engineers use research, brainstorming, and collaboration with others to come up with ideas for solutions and designs.
3. Use criteria and constraints to evaluate possible design solutions to identify the one(s) that best address these parameters for the problem in context
4. Build and test the prototypes. Using data collected, the engineer analyzes how well prototypes meet the given criteria and constraints.
5. Suggest or make improvements to prototypes to optimize the design.

In the Science with Engineering Education (SEEd) Standards, specific engineering standards generally involve two types of tasks:

1. If the standard includes the idea of designing, then the design process will contain components of defining the problem (along with identifying the criteria and constraints), developing many possible solutions, and optimizing a solution (e.g., determining a best solution for the situation based on the criteria and constraints, testing the solution, refining the solution).
2. If the standard includes the idea of evaluating, then the design process will contain components of defining the problem (along with identifying the criteria and constraints) and optimizing a solution. The idea of developing many possible solutions is not included because various solutions will be provided. The idea of evaluating then means determining a best solution from the provided solutions for the situation based on meeting the criteria and constraints requirements.

Table of Contents

CHAPTER 1

Strand 1: Forces and Interactions

Chapter Outline

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Isaac Newton's Laws of Motion describe the way things move. Objects naturally maintain their state of moving or sitting still. If an object feels a greater force in a certain direction, it will accelerate, meaning its motion will change. Making graphs and data tables of position, velocity, and acceleration allows us to see the effects of forces. Measurements of motion depend on our perspective, or frame of reference. Momentum uses the mass and velocity of the objects to calculate interactions. In any system, objects can collide and exchange momentum, but the total momentum is always conserved. When two objects interact, the forces they exert on each other must be equal and in opposite directions. The length of time of a collision affects the amount of force exerted on the two objects.

1.1 Force and Motion (PHYS.1.1)

Phenomenon

Image by Keith Johnston, pixabay.com, CC0

In the photo above, a baseball player is sliding against the ground and coming to a stop.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. What is causing the baseball player to slow down?

2. How can we measure this effect?

3. What could be changed to make the baseball player slow down at a different rate?

PHYS.1.1 Force and Motion

Analyze and interpret data to determine the cause and effect relationship between the net force on an object and its change in motion as summarized by Newton's Second Law of Motion. Emphasize one-dimensional motion and macroscopic objects moving at non-relativistic speeds. Examples could include objects subject to a net unbalanced force, such as a falling object, an object sliding down a ramp, or a moving object being pulled by a constant force. (PS2.A)

In this chapter, see if you can identify the causes of an object's changes in motion.

Forces

Force can be simply defined as a push or pull between two objects. There are four fundamental forces in the universe, including the force of gravity, electromagnetic force, and weak and strong nuclear forces. Besides the force of gravity we feel towards the Earth, all forces that every-day objects experience come from the electromagnetic force between atoms and molecules. The table below describes these common forces and the symbols used to identify them.

Force Types	Description	Symbols
Weight	The force of gravity between Earth and an object at or near its surface. The direction is always towards the center of the Earth (or other planetary/celestial objects). The magnitude is directly proportional to the mass of the object.	F_g
Tension	The pulling force exerted between two objects by a string, cable, chain, or rope. The direction of tension is always parallel to the string, wire, or rope.	F_T

Spring	The force exerted between a spring or other elastic material and an object that is causing the spring to be compressed or stretched. The direction of spring force is always parallel to the spring. For an ideal spring, the magnitude is directly proportional to the amount the spring's length is changed.	F_{sp}
Normal	The pushing force exerted between two surfaces pressing against each other. The direction of the normal force is always perpendicular to the surface.	F_N
Friction	The force between two solid objects that is always parallel to their surfaces. Friction often resists, opposes, or slows down motion, but it can be used for an object to push off another surface and propel itself forward. Two Types: ● Static - when the surfaces are not sliding or slipping ● Kinetic - when the objects are sliding or slipping relative to one another	F_f f_s f_k
Drag	The force between an object and a fluid--a liquid or a gas--that is moving through. It is often known as air resistance. The object experiences this force in the opposite direction of its motion. The magnitude of the force depends on the exposed area of the object and its velocity.	F_D F_{air}
Thrust	The force between a rocket or jet and a gas that it expels at a high speed. The rocket will be thrust in the opposite direction in which the exhaust gas is expelled.	F_{thrust}
Electric Force	The force between positive and negative charges, which can be attractive or repulsive.	F_E
Magnetic Force	The force between magnetic objects, such as permanent magnets and moving charges.	F_M

All changes in motion are caused by forces. Force can cause a stationary object to start moving or a moving object to change its velocity. Because velocity includes speed and direction, changing either of these changes the velocity of an object, which is called acceleration.

Look at the child in the figure below. He pushes backward on the ground, and the force of friction between his foot and the ground propels him forward. The harder he pushes against the ground, the faster he will go.

Image by WebDonut, pixabay.com, CC0

Net Force

Force is measured in Newtons, where 1 N = 1 kg $\cdot$ m/s^2. This tells us how force is related to mass and acceleration, which we will discuss shortly.

An object may have multiple forces acting on it at the same time. The combined result of two or more forces is called the net force. Forces that are acting in the same direction will add, leading to a greater net force. Forces acting in opposite directions will subtract from each other. If two opposite forces have the same magnitude, they will have no effect. The net force is zero, because the forces are balanced. If forces in opposite directions have different magnitudes, the net force is the difference between them, and it will be in the direction of the larger force.

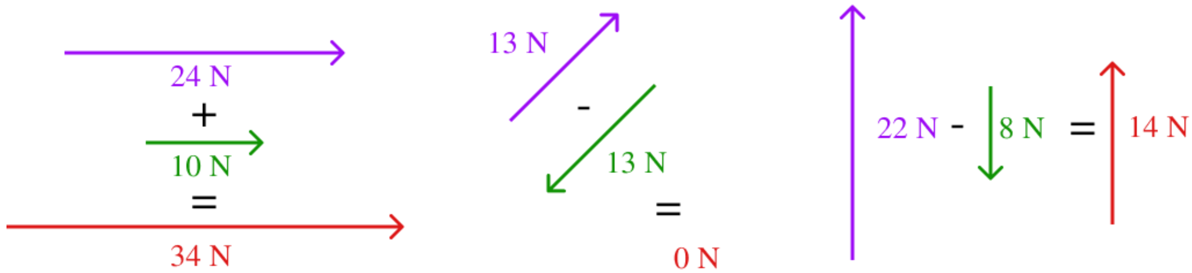


Image created by Wesley Morgan

Mass

Inertia is the property of an object that resists a change in its state of motion. An object's inertia is related to the mass of the object. The more massive an object is, the more difficult it is to start it moving or to change its speed or direction once it is moving.

Mass and weight are different things. Mass (in units of kilograms or grams) is a measure of the amount of matter in an object. Weight (in Newtons or pounds) is a measure of how much the force of gravity is pulling on an object. The small child sitting in the toy car has a low mass. This means it is easy to make him speed up or slow down. His weight is what you would measure if you placed him on a scale.

Image by ULOVInteractive, pixabay.com, CC0

Mass does not depend on location, but weight does. If an astronaut travels to a smaller moon or planet, their mass will be the same as when they were on Earth, but their weight will be less because the force of gravity has decreased.

Net Force, Mass, and Acceleration

Whenever an unbalanced force acts on an object, it will accelerate, meaning it will speed up, slow down, or change direction. Newton's Second Law of Motion describes the two factors that affect the amount of acceleration. A greater net force will cause greater acceleration, while a greater mass will cause an object to experience less acceleration. This can be represented by the equation:

$$\text{acceleration} = \frac{\text{Net Force}}{\text{mass}}$$

or

$$a = \frac{F_{Net}}{m}$$

Image by angelinawongm15, pixabay.com

This equation shows that there is a linear relationship between net force and acceleration. For example, doubling the force on the object doubles its acceleration.

The relationship between mass and acceleration is different. It is an inverse relationship, so when one variable increases, the other variable decreases by the same factor. For example, doubling the mass of an object results in only half as much acceleration for the same amount of force.

Felicia exerts a backward force against the ground, as you can see in the Figure to the right, first with one skate and then with the other. The ground pushes in the opposite direction, which pushes her forward. Although she may be experiencing air resistance, it is weaker than the force propelling her forward. Therefore, there is a forward net force on Felicia. If the net force on Felicia is 150 N, and she has a mass of 60 kg, her acceleration would be:

$a = (150\text{ N})/(60\text{ kg}) = 2.5\text{ m/s}^2$

If she were carrying a backpack that increased her mass, she would not experience as much acceleration, because the force would be divided by a larger number. Or, to maintain the same acceleration, she would need a greater net force exerted on her.

Putting It Together

Image by Keith Johnston, pixabay.com, CC0

Let us revisit this phenomenon:

Focus Questions

1) What forces are acting on the baseball player in this situation? What effects are they having?

2) What do you think would happen if the baseball player's mass was doubled? Use Newton's Second Law to justify your answer.

3) Determine what would happen if the baseball game was occuring on an ice skating rink. Use Newton's Second Law to justify your answer.

Final Task

If you had a data table of the baseball player's position at each moment in time, describe a way you could put this data into a graph in order to analyze his motion. What aspects of the graph would indicate whether a force is causing him to accelerate?

1.2 Conservation of Momentum (PHYS.1.2)

Phenomenon

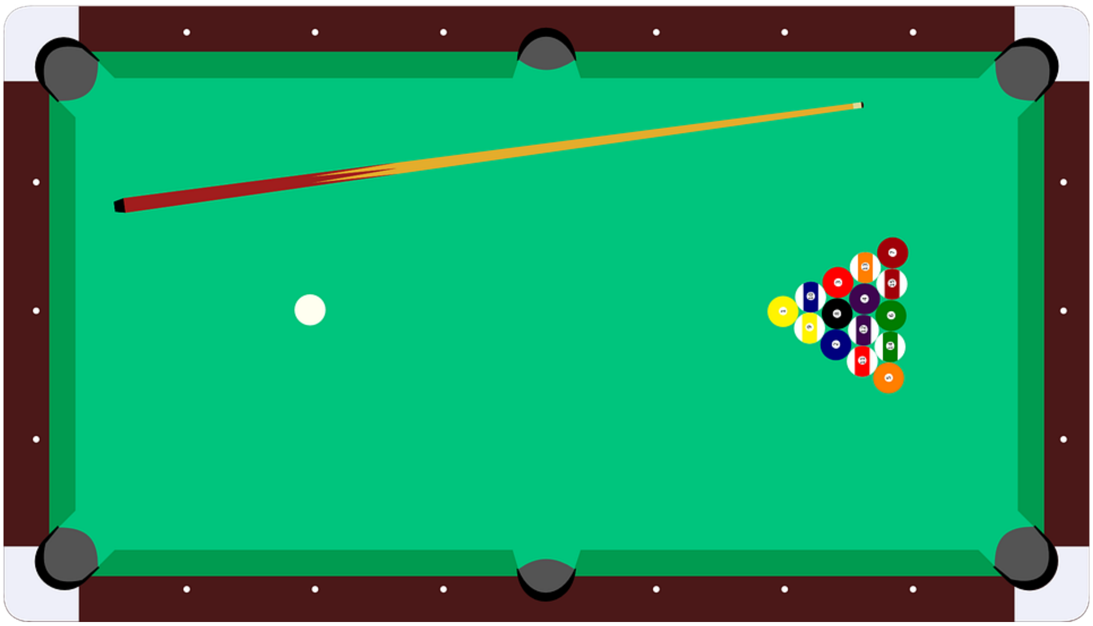


Image by Clker-Free-Vector-Images, pixabay.com, CC0

In the pool table shown above, a long stick can be used to hit the white ball towards the colored balls, which will then move in many different directions.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. What force causes the pool balls to start moving?

2. How do the pool balls affect each other when they collide?

3. Does anything affect the motion of the pool balls after they separate?

PHYS.1.2 Conservation of Momentum

Use mathematics and computational thinking to support the claim that the total momentum of a system is conserved when there is no net force acting on the system. Emphasize the quantitative conservation of momentum in interactions and the qualitative meaning of this principle. Examples could include one-dimensional elastic or inelastic collisions between objects within the system. (PS2.A)

In this chapter, you will identify how objects can transfer momentum within a system and analyze the effects of forces outside the chosen system.

What is momentum?

If a bowling ball and a ping-pong ball are each moving with a velocity of 5 mph, you intuitively understand that it will require more effort to stop the bowling ball than the ping pong ball because of the greater mass of the bowling ball. Similarly, if you have two bowling balls, one moving at 5 mph and the other moving at 10 mph, you know it will take more effort to stop the ball with the greater speed. It is clear that both the mass and the velocity of a moving object contribute to what is necessary to the momentum of the moving object.
Momentum, represented by the letter "p", is a vector that points in the direction of the velocity vector. The magnitude of momentum is the product of mass and velocity.

$$p = m \cdot v$$

The momentum of a 0.500 kg ball moving with a velocity of 15.0 m/s will be

$p = mv = (0.500 \text{ kg})(15.0 \text{ m/s}) = 7.50 \text{ kg} \cdot \text{m/s}$

You should note that the units for momentum are kg·m/s, because those are the units of the mass and the velocity that were multiplied.

A change in momentum is referred to as impulse. It is represented by the symbol Δp and calculated by finding the difference between the momentum of a single object at two different points. For example, if a 60 gram tennis ball has a velocity of -15 m/s, then it is hit by a racket, giving it a new velocity of +20 m/s, the impulse is calculated as follows:

$$\Delta p = p_2 - p_1 = (0.06\ kg)(20\ m/s) - (0.06\ kg)(-15\ m/s)$$
$$= 1.2\ kg \cdot m/s - (-0.9\ kg \cdot m/s) = 2.1\ kg \cdot m/s$$

Note that, because momentum is a vector, it is important to keep track of the direction using positive and negative signs, since the impulse will be larger when switching directions.

System

A system is a set of objects that are interacting with each other. Scientists define the boundaries of a system in order to make it easier to analyze. An isolated system is when the components within the system can affect each other, but no external forces will have any effects.

For example, the many pieces of this rocket could be considered a system. When the rocket is launched, the pieces can push off each other and even separate, but still be analyzed as a single system. However, this would be an open system, because the external force of gravity is pulling on the components of the rocket.

Image by Wikiimages, pixabay.com CC0

Conservation of Momentum

Momentum, like forces, is a useful way of looking at how objects affect each others' motion. For an isolated system, the total momentum must be conserved, meaning that if you add up the momentum of all the components before and after their interactions, the sum should be the same.

During these interactions, momentum can be transferred between objects, which is called impulse. Momentum cannot simply disappear; it has to go into another object. As far as we understand, the universe is an isolated system, therefore the total momentum of the universe is always the same. This total momentum is likely zero, since there are an equal number of objects moving in all directions, which cancel each other out.

24Hrs_2009-515l by TermV, https://flic.kr/p/6wfGx1, CC-By-NC

These skaters are racing each other at Newton's Skate Park. Skater 1 (yellow helmet) is going slow, and Skater 2 (red helmet) is going so fast that he collides with Skater 1. How does this situation illustrate conservation of momentum?

When Skater 2 runs into Skater 1, he's going faster than Skater 1 so he has more momentum. After the collision, Skater 1 will be going faster, meaning he gained momentum during the collision. However, Skater 2 will be going slower, because he will transfer some of his momentum to Skater 1. Because all of the momentum that one skater lost was gained by the other skater, the total momentum of the system should remain the same, meaning it was conserved.

Elastic and Inelastic Collisions

There are two main types of collisions that physicists analyze: elastic and inelastic. In both types of collisions, if there are no external forces, the total momentum is conserved.

Elastic collisions occur when objects bounce off of each other and no kinetic energy is lost. While it is rare to have a perfectly elastic collision, there are some examples that are very close, such as molecules in a gas bouncing off of each other.

Pendule en mouvement - Newton's Cradle by hellolapomme, https://flic.kr/p/4ugPZm, CC-BY

Newton's cradle (the device in the picture) is another example of a nearly elastic collision. If one ball swings down, exactly one ball will swing up with the same speed as the first ball. If three balls swing down, exactly three will swing back up. In these cases, all the momentum and kinetic energy of the system was conserved. One clue to identify elastic collisions is that you could imagine playing a video of the collision in reverse, and it should still appear normal, regardless of the direction you look at it.

Inelastic collisions occur when objects stick together (partially or completely) during the collision. The collisions can be easier to analyze mathematically if the objects have the same final velocity. While total momentum is conserved during inelastic collisions, some kinetic energy can be lost to other forms, such as heat, sound, or deforming the objects.

Elastic Example

A 2.0 kg toy train car moving at +2.5 m/s on a straight, level train track, towards a second train car whose mass is 3.0 kg and was moving -2.0 m/s. The train cars have repulsive magnets, so after they get very close, they bounce off in opposite directions. After this interaction, the 2.0 kg car is moving -2.9 m/s. What is the velocity of the 3.0 kg car?

There are several ways to approach this problem. One is to write out the entire conservation of momentum as a single equation, as shown below. The two objects, A and B, do not change masses, but they do change velocities, so the velocity after the collision can be represented as v_A\` or $v_B$\`. Plugging in all known numbers will allow you to solve for the missing velocity.

$$m_A v_A + m_B v_B = m_A v_A^{`} + m_B v_B^{`}$$

Additionally, we can look at the total momentum before the collision and use that to solve for the momentum of each object after.

Before: $p_A + p_B$ = (2.0 kg)(2.5 m/s)+(3.0 kg)(-2.0 m/s) = 5 kg·m/s - 6 kg·m/s = -1 kg·m/s

After: (2.0 kg)(-2.9 m/s) + p_B = -1 kg·m/s

Because the smaller train car has a momentum of -5.8 kg·m/s, the larger train car must have a momentum of +4.8 kg·m/s in order for the total momentum of the system to remain the same. We can then solve for the velocity:

v = p/m = (4.8 kg·m/s)/(3.0 kg) = 1.6 m/s.

Finally, this problem can be solved by using impulse. Using the numbers given, we can see that the first train car experienced the following impulse:

$\Delta p_A = p_A$\` - p_A = (2.0 kg)(-2.9 m/s) - (2.0 kg)(2.5 m/s) = -10.8 kg·m/s.

For the total momentum to be conserved, if object A has an impulse of -10.8 kg·m/s, then object B must have an impulse of +10.8 kg·m/s.

$\Delta p_B = p_B` - p_B = 10.8\ kg \cdot m/s = p_B` - (-6\ kg \cdot m/s)$

Once again, this shows that the final momentum of object B must be +4.8 kg·m/s, which means it has a final velocity of 1.6 m/s.

Inelastic Example

Let's take a look at a different situation where the objects stick together. A 75.0 gram arrow is moving at 32.0 m/s when it strikes an apple that has a mass of 125 grams. If the apple was not moving before, what would be the velocity of the system when the arrow and apple are stuck together?

We can write out the entire equation, just as any other collision, but here, A and B will have the same final velocity, called v_{sys} , which is the velocity of the system.

$$m_A v_A + m_B v_B = m_A v_A` + m_B v_B` = (m_A + m_B) v_{sys}`$$

Before: $p_A + p_B$ = (0.0750 kg)(32.0 m/s)+(0.125 kg)(0.0 m/s) = 2.40 kg·m/s
After: (.0750 kg + 0.125 kg)(v_{sys}) = 2.40 kg·m/s.

We can solve this equation as follows:
$v_{sys} = p_{sys}/m_{sys}$ = (2.40 kg·m/s)/(0.200 kg) = 12.0 m/s

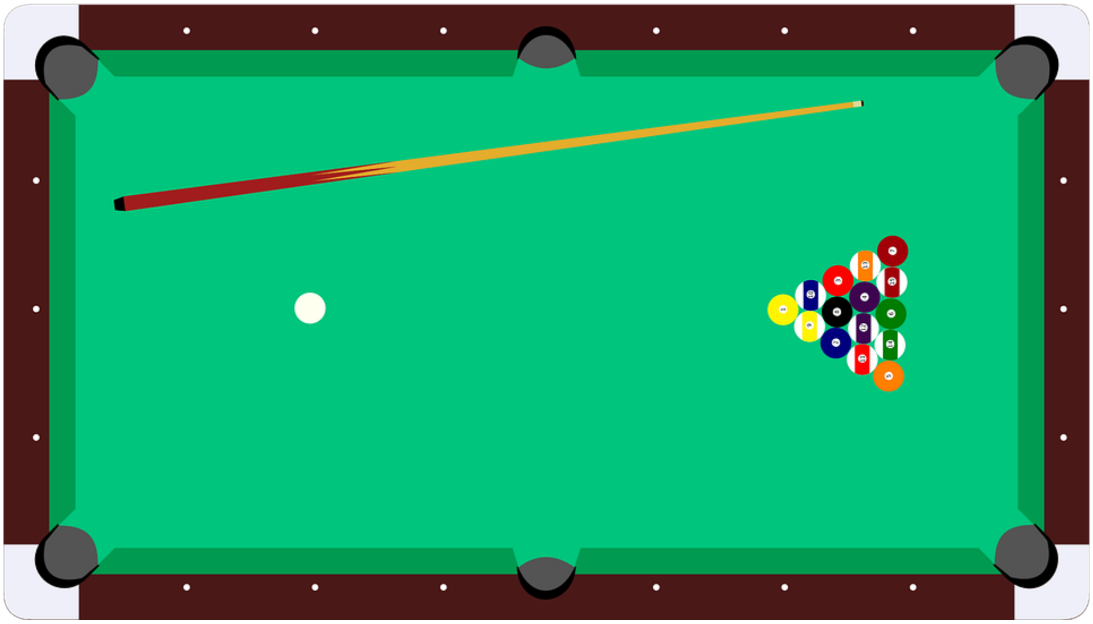
We can also check to see if momentum is conserved by calculating the impulse of each object, knowing they have the same final velocity.

Δp_{arrow} = (0.0750 kg)(12.0 m/s) - (0.075 kg)(32.0 m/s)
= 0.900 kg·m/s - 2.40 kg·m/s = -1.50 kg·m/s

Δp_{apple} = (0.125 kg)(12.0 m/s) - (0.125 kg)(0.0 m/s)
= 1.50 kg·m/s - 0.0 kg·m/s = 1.50 kg·m/s

This indicates that all of the momentum the arrow lost was gained by the apple, so the total momentum of the system was conserved.

Putting It Together



Let us revisit this phenomenon:

Focus Questions

1. If we consider our system to be only the pool balls, what external forces are adding or taking away momentum from the system?

2. Is there a way we could redefine the system boundaries so all the interactions are within the system? What additional objects would we need to include?

3. Initially, the white ball is the only pool ball with momentum. If the white ball stops moving after it strikes the others, what does that mean about the total momentum of the colored balls?

Final Task

What measurements would you need to take in order to calculate the total momentum before and after the white ball strikes the colored balls? If some of the colored balls move up, and some move down, what does that mean when we add their momentum vectors together? Do you think these collisions are close to being elastic? Why or why not?

1.3 Collisions (PHYS.1.3)

Phenomenon

Image by cfarnswroth, pixabay.com, CC0

It is state law for you to wear your seatbelt in your car. If your car is in a collision, this is meant to reduce your chances of serious injury.

Observations and Wonderings

What is the problem in this situation?

What are possible criteria (positive outcomes) to this situation?

What are constraints (limitations) with this situation?

Focus Questions

1. If your car is in a collision, what forces will act on your body? What will this do to your momentum?

2. What properties of the seat belt allow it to protect you?

3. How could the way you choose to wear a seat belt alter its effectiveness in fulfilling its function?

PHYS.1.3 Collisions

Design a solution that has the function of minimizing the impact force on an object during a collision. *Define the problem, identify criteria and constraints, develop possible solutions using models, analyze data to make improvements from iteratively testing solutions, and optimize a solution*. Emphasize problems that require application of Newton's Second Law of Motion or conservation of momentum. (PS2.A, ETS1.A, ETS1.B, ETS1.C)

In this section, we will look at how devices can be structured to minimize forces during collisions.

Engineering Design

This is an engineering standard. Refer to page 10 to read about engineering design. Which type of engineering task is utilized in this SEEd Standard?

Forces and Impulse Equation

In order to design structures that can reduce collision forces, we need to understand how forces and impulse are related. According to Newton's first law, the velocity of an object cannot change unless a force is applied. If we wish to change the momentum of a body, we must apply a force.

In section 1.1, we learned Newton's 2nd Law. Let's rewrite that in terms of force and insert the definition of acceleration: $F_{net} = ma = m\frac{\Delta v}{\Delta t}$

Impulse is a change in momentum. If the mass is constant, then the change in momentum is simply mass times the change in velocity: $\Delta p = m\Delta v$

Therefore, we can rewrite Newton's 2nd Law as follows:

$$F_{net} = \frac{\Delta p}{\Delta t} \quad \text{or} \quad \Delta p = F_{net}\Delta t$$

This tells us that the impulse, or change in momentum, of an object depends on two factors: the net force it experiences, and the amount of time the force is applied. Making a force larger or exerting it for a longer period of time will cause a greater change in momentum. This is why coaches in almost every sport tell their athletes to “follow-through” when throwing or hitting a ball. The longer they push on the ball, the faster it will go.

We can check that the units of this equation are consistent. On the left side, impulse has units of momentum: kg·m/s. On the right side, we have force multiplied by time, which would be N·s. But a Newton is just an abbreviation, where 1 N = 1 kg·m/s. Therefore 1 N·s = (1 kg·m/s^2)(s) = 1 kg·m/s.

This equation also helps us address a common misconception about forces during collisions. As we studied conservation of momentum, we saw that colliding objects experience equal and opposite impulses. Since they have the same time of contact, the impulse equation tells us that they will experience the exact same forces during that time. This is also known as Newton’s 3rd Law of motion.

Even if two objects with different masses and velocities collide, the force that one object feels is the same as the other. Their different sizes may cause them to have different accelerations and final velocities, but that does not mean the forces they experienced were different.

Calculation Practice

If you jump off a porch and land on your feet with your knees locked in the straight position, your motion will be brought to rest in a very short period of time and thus the force would need to be very large – large enough, perhaps, to damage your joints or bones.

Suppose that when you hit the ground, your velocity was 7.0 m/s and that velocity was brought to zero in 0.05 seconds. If your mass is 100. kg, what force was required to bring you to rest?

$$F = m\Delta v/\Delta t = (100.\ \text{kg})(7.0\ \text{m/s})/(0.050\ \text{s}) = 14{,}000\ \text{N}$$

If, on the other hand, when your feet first touched the ground, you allowed your knees to flex so that you increase the period of time over which your body was brought to rest, then the force on your body would be smaller and it would be less likely that you would damage your legs.

By allowing your knees to bend, you extend the stopping time to 0.50 seconds. What force would be required to bring you to rest this time?

$$F = m\Delta v/\Delta t = (100.\ \text{kg})(7.0\ \text{m/s})/(0.50\ \text{s}) = 1400\ \text{N}$$

With the longer period of time for the force to act, the necessary force is reduced to one-tenth of what was needed before. Since your momentum was the same in both cases, increasing the time of collision allowed the force to be reduced, because you had a slower rate of acceleration. We can say that, during collisions, force and time have an inverse relationship.

Extending the period of time over which a force acts in order to lessen the force is a common practice in design. Padding in shoes and seats allows the time to increase. The front of automobiles are designed to crumple in an accident; this increases the time the car takes to stop. Similarly, barrels of water or sand in front of abutments on the highway and airbags serve to slow down the stoppage time. These changes all serve to decrease the amount of force it takes to stop the momentum in a car crash, which consequently saves lives.

Additionally, when we apply a force to an object, we can apply that force to a small area or a large area. The ratio of the amount of force applied to an area is called pressure. Having a lot of force distributed across a large area may result in a small pressure, which will also reduce the likelihood of any single point experiencing a large amount of damage.

Putting It Together

Image by cfarnswroth, pixabay.com, CC0

Let us revisit this phenomenon:

Focus Questions

1. What aspects of a seat belt’s design and installation allow it to increase the time of collision?
2. If you were not wearing a seatbelt, what force might bring you to a stop? How would the time interval of this collision compare to the seatbelt?
3. How do you think seat belts are tested and redesigned to ensure their safety?

Final Task

Design your own modification to seat belts that you believe would make them safer. Explain how your design would reduce the force on the passenger. How would you account for constraints, such as making sure your design is still comfortable and does not cost too much to be practical?

CHAPTER 2

Strand 2: Energy

Chapter Outline

Image by Skeeze, pixabay.com, CC0

Energy is a number that describes the ability of a system to cause changes, through interactions such as motion, forces, and waves. Energy is like the currency of the universe. It can be transferred into different "bank accounts," but the total amount has to be conserved in isolated systems and in the universe as a whole. Uncontrolled systems always evolve toward more stable states—meaning the energy will be evenly distributed at all locations, rather than one component having excess energy. Examining the world through an energy lens allows us to model complex interactions of multiple objects within a system and address societal needs.

2.1 Conservation of Energy (PHYS.2.1)

Phenomenon

Bouncing ball strobe edit.jpg by Michael Maggs, edited by Richard Bartz, https://en.wikipedia.org/wiki/File:Bouncing_ball_strobe_edit.jpg, CC-BY-SA

A strobe light quickly flashes on and off to allow many images of a basketball to be captured. These images are all placed on the same picture in order to demonstrate motion over time.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

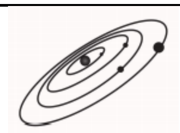
Focus Questions

1. What do you think caused the basketball to start moving?

2. How does the basketball change its motion during the time shown, and what forces may be causing this?

PHYS.2.1 Conservation of Energy

Analyze and interpret data to track and calculate the transfer of energy within a system. Emphasize the identification of the components of the system, along with their initial and final energies, and mathematical descriptions to depict energy transfer in the system. Examples of energy transfer could include the transfer of energy during a collision or heat transfer. (PS3.A, PS3.B)



In this chapter, you will identify different types of energies and how they can be transferred into, out of, or within a system of objects.

Types of Energy

Energy is a number that defines a system's capacity for causing changes in motion. Unlike momentum, energy is a scalar, not a vector, so it does not have a physical direction. It is still quantifiable, meaning that the amount of energy can go up or down and be measured. Energy can also be changed into different forms, which we will briefly list in the table below. Each energy has a different equation for calculating it, which you will learn in later chapters.

Energy Types	Description	Symbols
Kinetic	The energy of a moving object. Like momentum, this depends on your frame of reference. However, unlike momentum, the direction an object is moving does not matter, only its size and speed. Small particles or large objects can both have kinetic energy.	K E_K
Thermal or Internal	The energy from the motion of all the molecules inside a substance. If an object has a higher temperature, that means the molecules inside it are moving faster. Even very cold objects still have some thermal energy.	E_T

Radiation	The energy of a moving electromagnetic field, such as visible light, radio waves, and gamma rays.	
Wave	The energy of a wave that moves through a substance, such as sound, which varies the pressure by compressing molecules as it passes.	
Gravitational Potential	The energy from two masses pulling on each other by the force of gravity, such as you and the Earth, or Jupiter and the Sun.	U_G E_G PE_G
Spring or Elastic	The energy stored in a spring due to another object compressing or stretching it. The spring (or other elastic object) is exerting a force to try to restore itself to its original position.	U_s E_s PE_S
Electric	There are two forms of electric energy. One is the energy from charged objects pulling or pushing on each other by the electric force, such as static electricity that can cause a shock. The other is from moving electric charges, such as current in a circuit.	U_E E_E
Magnetic	The energy from two magnetic objects exerting a force on each other, or from an object moving through a magnetic field.	
Chemical	The energy stored due to the configuration of atoms and molecules in a substance, such as batteries, gasoline, and food. This is released during chemical reactions when the bonds are changed.	

Nuclear	The energy stored due to the configuration of protons and neutrons in an atom. This can be released during fission or fusion of a nucleus.	
Matter or Rest	The energy stored in the nature of particles themselves. This energy is present when particles are created, destroyed, or change forms, as described by the famous equation $E = mc^2$.	

Notice that there are two main categories of energy. One type of energy occurs when something is moving. This is called Kinetic Energy, and it is usually represented by the letter K.

The other type occurs when two or more objects are exerting a force on each other due to their positions. This is called Potential Energy, and it is usually represented by the letter U. One single object cannot have potential energy by itself, because it cannot exert a force on itself.

Conservation of Energy

Energy is conserved in a closed system, which is when no energy is transferred in or out. That is, if you add up all the forms of energy in a closed system at one time it will equal all the energy of the same objects at a later time. Mathematically, this is represented by the equation

$$\Sigma E_{intitial} = \Sigma E_{final}$$

where Σ is the Greek letter “Sigma”. It is sometimes referred to as “summation” and means the total amount or the net amount. If we use K for kinetic energy and U for potential energies, the above equation becomes:

$$K_{initial} + U_{initial} = K_{final} + U_{final}$$

Energy is never destroyed, but it can change forms within a system. Sometimes the energy changes into sound, electricity, or light. The energy can change form or type, but all energy must be accounted for so that the total amount remains the same

Let’s look at an example where energies are conserved. Our system for the following example includes a plant on a shelf, and the Earth, which is pulling it down.

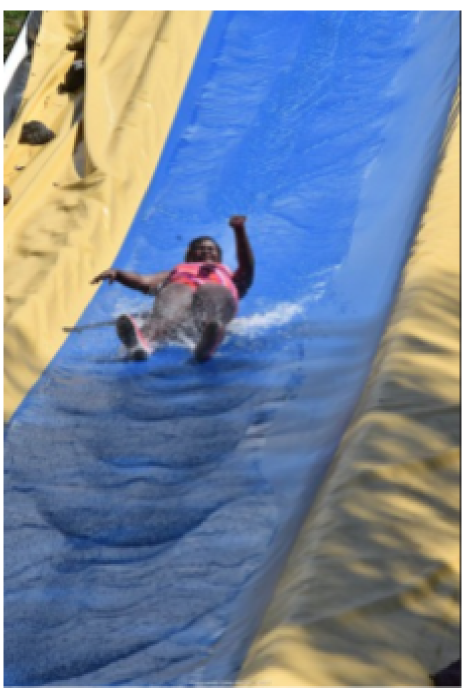
Image by Jessica Lewis (thepaintedsquare), pixabay.com, CC0

Suppose the plant has a mass of 10 kg and is sitting on a shelf that is 5 m above the ground. In this configuration, the system has a gravitational potential energy of 490 J and 0 J of kinetic energy (because the plant is not moving). The total energy of the system is 490 J. If the plant falls, the gravitational potential energy will be transferred into kinetic energy.

When the plant is halfway between the floor and the shelf (at a height of 2.5 m), the system has 245 J of gravitational potential energy. Where did the rest of the energy go? Since energy cannot be created or destroyed, it didn’t just disappear. The remaining gravitational potential energy is now kinetic energy. When the plant is half way down to the floor, it has 245 J of gravitational potential energy and 245 J of kinetic energy. It still has a total energy of 490 J.

When the plant has fallen 4 meters (so it is only 1 meter above the ground), the gravitational potential energy is only 50 J. How much kinetic energy does the plant have? It now has 440 J of kinetic energy and is moving with a speed of about 9.4 m/s.

Right before the plant hits the ground, there will be no more potential energy and it will have 490 J of kinetic energy. At any given point, the total energy must always add to 490 J.



Thursday Morning Waterslide by Camp ASCCA, https://flic.kr/p/Whxwog, CC-BY-NC

Now consider a person sliding to rest on a horizontal part of a waterslide. They start out with 500 J of kinetic energy. They come to a stop, meaning they have 0 J of kinetic energy.

Clearly the ending energy (0 J) and the beginning energy (500 J) are not the same. Where did the energy go? It did not become potential energy, because the person did not get closer or farther from Earth. Instead, it turned into thermal energy, because the person, the water, and the air will now be slightly warmer, just like when you rub your hands together.

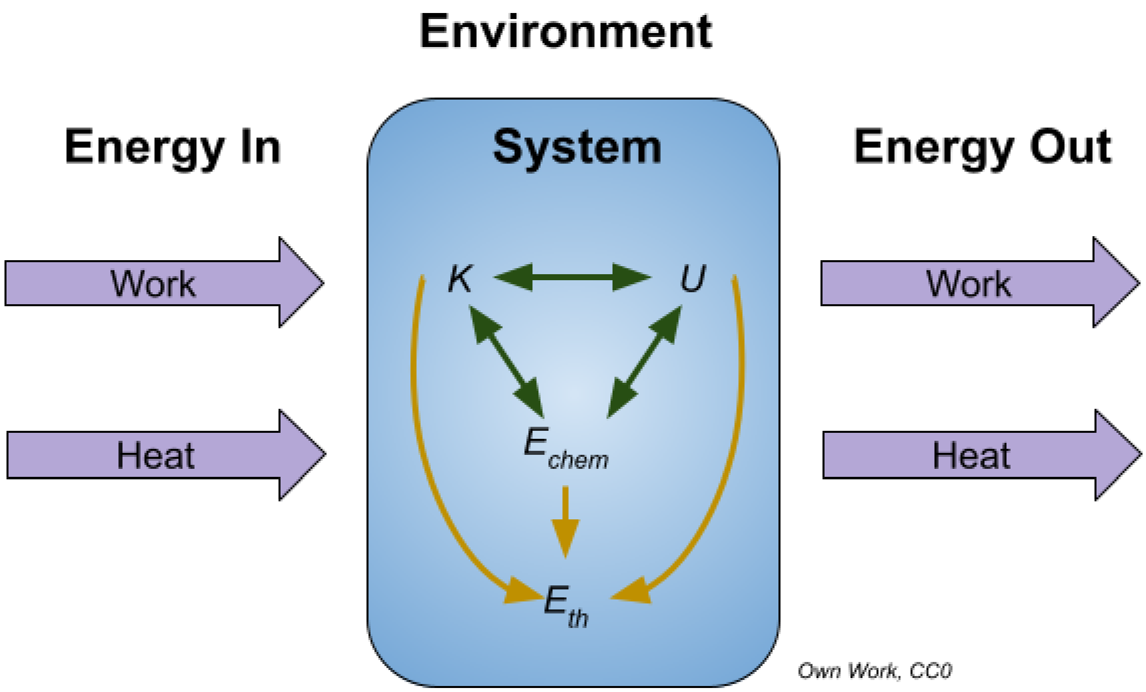
In this case the person is not a closed system, because they can lose energy to their surroundings. In real life, a system is never perfectly isolated. Energy can be transferred into or out of the system through heat or work. Heat is a transfer of thermal energy due to temperature changes, and we will learn more about this in chapter 2.2.

What is work?

The word work has both an everyday meaning and a specific scientific meaning. In the everyday use of the word, work would refer to anything which required a person to make an effort. In physics, however, work is defined as a change in energy to do a force pushing over a distance.

Let's look at a roller coaster. On the way up the first hill, the chain lift is doing work because it is exerting a force to push the cars upward. This increases the gravitational potential energy of the system. On the way down, the Earth is exerting a force on the cars, causing them to speed up. This changes the gravitational energy into kinetic energy.

Image by Paul Brennan (paulbr75), pixabay.com, CC0



In conclusion, in order to properly use the Law of Conservation of Energy, one should consider all types of energy, and account for the energies transferring into and out of a given system. The diagram above illustrates the energy transfers that could occur for a given system.

Putting It Together

Bouncing ball strobe edit.jpg by Michael Maggs, edited by Richard Bartz, https://en.wikipedia.org/wiki/File:Bouncing_ball_strobe_edit.jpg, CC-BY-SA

Let's revisit this phenomenon.

Focus Questions

1. What objects would you include in this system? Is it an open or closed system? How do you know?

2. What types of energy are present in the system? What forces are causing the energy to change forms?

3. Would you say that energy is conserved in this system? Why or why not?

Final Task

Draw a diagram for the phenomenon of the bouncing basketball. Start with a large circle, and list all the objects you included in your system. List all the energies inside the system, and use arrows to represent the forces that cause these to change forms. Also draw arrows to represent any energy entering or leaving the system.

2.2 Thermal Energy (PHYS.2.2)

Phenomenon

Image by insightzaoya, pixabay.com, CC0

In order to keep water cold we have to add ice.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. In terms of energy, how do a cold cup of water and a warm room interact?

2. What does adding an ice cube to the water do to the energy of the system? Why does this help keep the water cold?

PHYS.2.2 Thermal Energy

Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperature are combined within a closed system results in a more uniform energy distribution among the components in the system. Emphasize that uniform distribution of energy is a natural tendency. Examples could include the measurement of the reduction of temperature of a hot object or the increase in temperature of a cold object. (PS3.B)

In this section, use what you know about energy to explain why objects have a certain temperature and how that can change.

What is the difference between thermal energy, temperature and heat?

Thermal energy is the internal energy of a substance due to the motion of molecules inside it. All substances have thermal energy. Depending on the phase of matter, this could mean that molecules are vibrating, spinning, or bouncing around a container. Thermal energy is difficult to measure directly, but we know that objects that have more molecules tend to have more thermal energy.

Temperature is the average energy per molecule for a substance. Hotter objects, meaning those with higher temperatures, have molecules that are moving faster. However, this does not mean all of the molecules are always moving quickly. Because their motion is random, some molecules may be moving faster or slower. Temperature tells us about the overall state of an object as compared to other objects it may interact with.

In physics, the word heat is only used for a transfer of energy. Heating occurs when thermal energy is transferred between two or more objects of different temperatures. Heat naturally flows from hot objects to cold ones. This can happen through direct contact (conduction), through the motion of a fluid (convection), or through light (radiation)

Consider the situation in the picture. The gas in the fire is the highest temperature, since we can see heat radiating off of it as visible light. This means those molecules are, on average, moving faster than other nearby substances. As the gas moves, it heats the kettle, as well as the water inside it. The person can feel the heat when they touch the kettle, because it is warmer than their hands. However, the person has more thermal energy than the pot of water. Even though their molecules are not moving as fast as the kettle, the person is much larger, so the energy will add up to a larger number. In fact, the frozen snow, if you consider it to be one large object, has the largest amount of thermal energy in this picture, because of its large size, even though it has a low temperature.

Image by adege, pixabay.com, CC0

Heat flows from hot objects to cold ones due to the random motion of molecules. If we have two solid objects, A and B, where A has a high temperature, and we place them in contact, their vibrating molecules will collide with each other. The faster moving molecules in object A will usually give up energy to the slower molecules in object B. Eventually, the thermal energy will be spread evenly, so both objects will have the same temperature, and all molecules will have the same average speed.

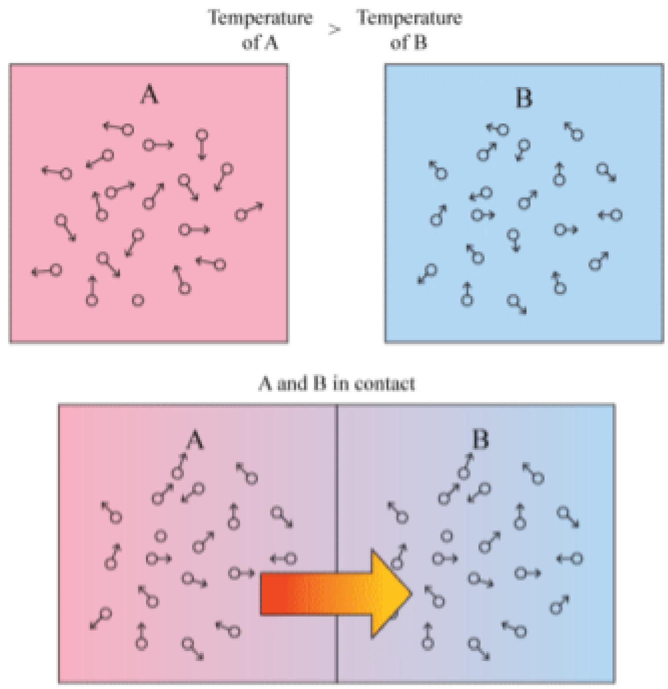


Image from ck12.org

Specific Heat Capacity

When you add the heat to different materials, the amount of temperature increase is different. Each substance has a property called specific heat capacity, which tells us how hard it is to change the material's temperature. Metals, like aluminum, have a low specific heat capacity, meaning they will change temperature fairly easily.

When heat flows into or out of an object the amount of temperature change depends on three things:

1) How much heat was added. This is represented by the letter Q, and it is measured in Joules (sometimes in Calories).
2) The mass of the object. This is represented by the letter m, and it is measured in grams (sometimes in kilograms).
3) The specific heat capacity of the object. This is represented by the letter c, and its units depend on the energy, mass, and temperature units being used.

The specific heat of aluminum is 0.903 J/g·°C. Therefore, it requires 0.903 J of energy to raise the temperature of 1.00 g of aluminum by 1.00 °C.

These relationships are described by the following equation:

$$Q = mc\Delta T$$

Here, ΔT is the change in temperature caused by the heat that is added or taken away. It is found by taking the final temperature and subtracting the initial temperature. You should note that the size of a Celsius degree and a Kelvin are exactly the same, and therefore ΔT is the same whether measured in Celsius or Kelvin.

Let's say that we have an aluminum bottle with a mass of 36.0 grams, and it is at room temperature, which is about 20.0°C. We have some cold water, which has a temperature of 10.0°C and a specific heat capacity of 4.18 J/g·°C. After we pour some water into the bottle, heat is transferred until they both have a temperature of 12.0°C. How much water did we pour in?

First, we need to determine the amount of heat the bottle lost to the cold water:

$Q = mc\Delta T = (36\ g)(0.903\ J/g\cdot°C)(12.0°C - 20.0°C) = -260.\ J$

We will assume that energy was conserved, and the water gained all that heat. This means we can rearrange the equation to solve for the mass of the water:

$m = Q/(c\Delta T) = (260.\ J)/[(4.18\ J/g\cdot°C)(12.0°C - 10.0°C)] = 31.1\ g$

Notice that even though the water and aluminum had similar masses, the aluminum had a much greater change in temperature because it had a lower specific heat capacity.

Think about some of the other factors we could change in our investigation. All of these relationships are explained by the specific heat capacity equation.
What if we added more water? This would cool down the aluminum more.
What if the water were even colder? This would also take more heat from the bottle.
What if we had a bottle of a substance with a higher specific heat capacity? This bottle would not change temperature as much.

A Change in Matter

Just like we can use thermal energy to change the temperature of matter, we can also use it to change the state of matter. For example, it takes thermal energy to melt ice into liquid water. What direction do you think the heat flows in this example into the ice or into the water? What happens to water when it boils or evaporates? Does it need to gain or lose heat?

Putting It Together

Image by insightzaoya, pixabay.com, CC0

Let's revisit this phenomenon:

Focus Questions

1. When a cold cup of water is in a warm room, what direction will heat naturally flow, and how does this occur?

2. When ice is placed into a cup of water, what does that do to the total energy of the system? What does it do to the average energy of each molecule? How will this change the way energy is transferred in the system?

Final Task

Plan an investigation that allows you to determine how much heat the water loses due to the presence of the ice. Decide what equipment you would need and list the measurements you would make. What could you vary about the setup that may change the amount of heat the water loses? List this information and predict what effects you would see in your experimental data.

2.3 Types of Mechanical Energy (PHYS.2.3)

Phenomenon

Image from MaxPixel, CC0

Jack pulls back on his new slingshot and lets the rock fly.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. What types of energy are present in this system?
2. What forces cause the energy to change forms over time?

PHYS.2.3 Types of Mechanical Energy

Develop and use models on the macroscopic scale to illustrate that energy can be accounted for as a combination of energies associated with the motion of objects and energy associated with the relative positions of objects. Emphasize relationships between components of the model to show that energy is conserved. Examples could include mechanical systems where kinetic energy is transformed to potential energy or vice versa. (PS3.A)

In this chapter, see if you can identify the different types of energy that exist for an object, based on its motion and position.

Forms of Mechanical Energy

As we saw in section 2.1, there are many forms of energy. In Physics, we tend to study Mechanical Energy, which refers to the large scale kinetic and potential energy of a system. Remember that kinetic energy is the energy of motion, while potential energy has to do with the position of two objects.

When we are discussing mechanical energy, we are ignoring the energy inside a substance, such as chemical and thermal. The energy of a closed system is constant. In order for this to occur, energy can transfer between potential and kinetic forms as the position and motion of the objects in a system change.

Common Energy Calculations

In order to properly model the different types of energy, equations have been developed to calculate and track the energy of a system. All of these are based on changes in energy relative to another object. Therefore, we will begin our equations with a mathematical definition of work, which is a change in energy caused by a force.

$$Work = Force \cdot distance$$

When you lift an object, you exert a force equal to the object's weight and the object moves due to that lifting force. If an object weighs 200. N and you lift it 1.50 meters, then your work is W=Fd=(200. N)(1.50 m)=300. J. In this case, you have added 300 J of gravitational potential energy to the system.

In the scientific definition of the word, if you push against an automobile with a force of 200 N for 3 minutes but the automobile does not move, then you have done no work. Multiplying 200 N times 0 meters yields zero work. If you are holding an object in your arms, the upward force you are exerting is equal to the object's weight. If you hold the object until your arms become very tired, you have still done no work because you did not move the object in the direction of the force.

Kinetic energy of motion, involves a mass moving at a specific velocity. You can calculate the kinetic energy of a moving object with this equation:

$$Kinetic\ Energy = \frac{1}{2}\, mass \cdot (velocity)^2$$

This equation demonstrates that an increase in velocity increases kinetic energy more than an increase in mass. If mass triples, kinetic energy triples as well, which is a linear relationship. If velocity triples, kinetic energy increases by a factor of $3^2 = 9$. This is called a quadratic relationship. We can see why this occurs with the work equation, where W = Fd. When an object is speeding up, increasing the force causes more acceleration, and going more distance will also increase the speed. So, velocity is in two factors that cause an increase in energy, which is why it is multiplied twice in the kinetic energy equation.

IMG_8455 by OkiGator, https://flic.kr/p/a5AFzf, CC-BY-NC-ND

Let's consider an example. The picture shows a boy running on the beach with his dad. The boy has a mass of 40 kg and is running at a velocity of 3 m/s. How much kinetic energy does this take?

$\frac{1}{2}\ mv^2 = \frac{1}{2}\ (40\ kg)(3\ m/s)^2 = 180\ J$

What about the dad? His mass is 80 kg, and he's running at the same velocity as the boy (3 m/s). Because his mass is twice as great as Juan's, his kinetic energy is twice as great, which is 360 J.

What if the boy runs at kinetic energy if he is now traveling 6 m/s? This would increase the original number (180 J) by a factor of $2^2 = 4$. This means running at that speed would take 720 J of energy.

Diving Board 2 by Claire Gillman, https://flic.kr/p/7BbfbV, CC-BY

Potential energy due to the position of an object above Earth's surface is called gravitational potential energy. Like the diver on the diving board, any mass that is raised up above Earth's surface has the potential to fall because of the force of gravity pulling it down and the distance it could fall.

Gravitational potential energy depends on the work required to lift an object up a certain distance (W = Fd). The minimum force is the object's weight (which is mass multiplied by gravitational acceleration) and the distance will be the height the object is raised above the ground. It can be calculated with the equation

$$\begin{aligned} Gravitational\ Potential\ Energy &= weight \cdot height \\ &= mass \cdot gravitational\ acceleration \cdot height \end{aligned}$$

A gymnast on the balance beam in the picture weighs 560 Newtons. If the balance beam is 1.2 meters above the ground, what is the gravitational potential energy of this system?

$mgh = F_g h = (560\ N)(1.2\ m) = 672\ J$

Image by Skeeze, pixabay.com, CC0

Potential energy due to an object's shape is called elastic potential energy. The force required to stretch or compress the object depends on its stiffness. For an ideal spring, this is called the spring constant, and the force is given by the equation:

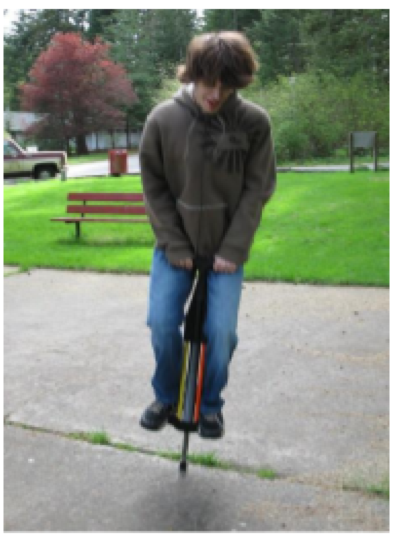
$$F_s = kx$$

In this equation "F_s" is the force required to stretch the spring, "x" is the displacement or change in length of the spring, and k is the spring constant. Based on our standard units, spring constant will be measured in Newtons/meter. A higher number means a stiffer spring. For example, a spring k = 24 N/m requires 24 Newtons to change its length by 1 meter.

Stretching or compressing an object adds energy to the system, because it has the potential to pull back to its original position. The work to add this energy is W = Fd. Here, F is the force of the spring (F_s) and d is the distance it is stretched (also called displacement in the previous equation). Combining the work and spring force equation gives the result:

$$Elastic\ Potential\ Energy = \frac{1}{2}\,(spring\ constant) \cdot (displacement)^2$$

Once again, there is a quadratic relationship due to the work equation. Lengthening the spring increases the displacement as well as the force pulling back. Therefore, this displacement is multiplied twice as energy increases.



Fwoosh! by Shavon Ni, https://flic.kr/p/6mGEFv, CC-BY-NC

Look at the pogo stick in the picture. Its spring has elastic potential energy when it is pressed down by the person's weight. When enough energy is stored, it can push the pogo stick—and the person—off the ground.

Suppose that the spring in the pogo stick has a spring constant of k = 25,000 N/m. When the person bounces on the stick they compress the spring by x = 0.4 m. How much elastic potential energy does the system have?

$\frac{1}{2} k x^2 = \frac{1}{2} (25{,}000\ N/m)(0.4\ m)^2 = 2000\ J$

What happens to the energy if the pogo is only compressed 0.2 m?

$\frac{1}{2} k x^2 = \frac{1}{2} (25{,}000\ N/m)(0.2\ m)^2 = 500\ J$

Notice that reducing the displacement by a factor of ½ changed the energy by a factor of ¼. That illustrates the quadratic relationship.

Putting It Together

Image from MaxPixel, CC0

Let us revisit this phenomenon.

Focus Questions

1. What measurements would you need to make in order to calculate the various energies in this system?

2. How could you tell if energy was conserved during this process?

Final Task

If the slingshot were fired straight up into the air, sketch a graph for the three types of energy that reflects how they would change over time. Label important points, such as when the slingshot is released and when the rock reaches its peak.

2.4 Energy Conversion (PHYS.2.4)

Authentic Situation

Adapted from image by JoshuaWoroniecki, pixabay.com, CC0

When on a multiple day camping trip, cell phones run out of battery power.

Observations and Wonderings

What is the problem in this situation?

What are possible criteria (positive outcomes) to this situation?

What are constraints (limitations) with this situation?

Focus Questions

1. What kind of energy does a cell phone need for its battery?
2. What kind of energy sources are available on a camping trip?
3. How can energy sources be transferred or converted from one form to another?

PHYS.2.4 Energy Conversion

Design a solution by constructing a device that converts one form of energy into another form of energy to solve a complex real-life problem. *Define the problem, identify criteria and constraints, develop possible solutions using models, analyze data to make improvements from iteratively testing solutions, and optimize a solution*. Examples of energy transformation could include electrical energy to mechanical energy, mechanical energy to electrical energy, or electromagnetic radiation to thermal energy. (PS3.A, PS3.B, ETS1.A, ETS1.B, ETS1.C)

In this section, use the information provided to help you construct a device that converts energy from one form to another.

Image from NASA, public domain

This giant six-limbed robot is NASA's Tri-ATHLETE. As the robot's name suggests, it is very "athletic." It was designed to do the heavy lifting in explorations of other planets and moons in the universe. The *Tri* ("three") part of its name refers to the fact that the robot can split into two separate three-limbed robots. These smaller robots can do things that the larger, six-limbed robot can't.

Engineering Design

This is an engineering standard. Refer to page 10 to read about engineering design. Which type of engineering task is utilized in this SEEd Standard?

What Is Technological Design?

The process in which tri-ATHLETE was created and perfected is called technological design. This is the process in which most new technologies are developed. Technological design is similar to scientific investigation. Both processes rely on evidence and reason, and follow a logical sequence of steps to solve problems or answer questions.

The process of designing a new technology includes much more than just coming up with a good idea. Possible limitations, or constraints, on the design must be taken into account. These might include factors such as the cost or safety of the new product or process. Making and testing a model of the design are also important. These steps ensure that the design actually works to solve the problem. This process also gives the designer a chance to find problems and modify the design if necessary. No solution is perfect, but testing and refining a design assures that the technology will provide a workable solution to the problem it is intended to solve.

Steps of the Technological Design Process

The technological design process can be broken down into a series of steps shown in the flowchart in Figure below. Typically, some of the steps have to be repeated, and the steps may not always be done in the sequence shown.

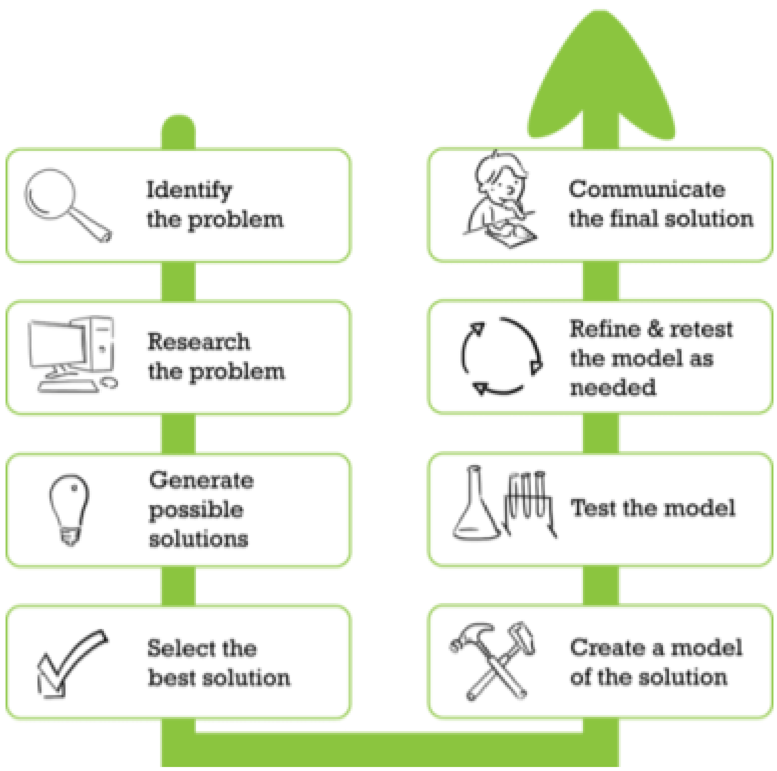


Image from ck12.org

This flowchart illustrates the steps of the technological design process.

Consider the problem of developing a solar-powered car. Many questions would have to be researched in the design process. For example, what is the best shape for gathering the sun’s rays? How will sunlight be converted to usable energy to run the car? Will a back-up energy source be needed? After researching the answers, possible designs are developed. This generally takes imagination as well as sound reasoning. Then a model must be designed and tested. This allows any problems with the design to be worked out before a final design is selected and produced.

Q: Assume you want to design a product that lets a person in a wheelchair carry around small personal items so they are easy to access. What questions might you research first?

A: You might research questions such as: What personal items are people likely to need to carry with them? What types of carriers or holders are there that might be modified for use by people in a wheelchair? Where might a carrier be attached to a wheelchair or person in a wheelchair without interfering with the operation of the chair or hindering the person?

Q: Suppose you have come up with a possible solution to the problem described in the previous question. How might you make a model of your idea? How could you test your model?

A: First, you might make a sketch of your idea. Then you could make an inexpensive model using simple materials such as cardboard, newspaper, tape, or string. You could test your model by trying to carry several personal items in it while maneuvering around a room in a wheelchair. You would also want to make sure that you could do things like open doors, turn on light switches, and get in and out of the chair without the carrier getting in the way.

Conversion of Energy

Sari and Daniel are spending a stormy Saturday afternoon with cartons of hot popcorn and a spellbinding movie. They are obviously too focused on the movie to wonder where all the energy comes from to power their weekend entertainment. They’ll give it some thought halfway through the movie when the storm causes the power to go out!

Image from ck12.org

Changing Energy

Watching movies, eating hot popcorn, and many other activities depend on electrical energy. Most electrical energy comes from the burning of fossil fuels, which contain stored chemical energy. When fossil fuels are burned, the chemical energy changes to thermal energy and the thermal energy is then used to generate electrical energy. These are all examples of energy conversion. Energy conversion is a process in which one kind of energy changes into another kind. When energy changes in this way, the energy isn't used up or lost. The same amount of energy exists after the conversion as before. Energy conversion obeys the law of conservation of energy, which states that energy cannot be created or destroyed.

How Energy Changes Form

Besides electrical, chemical, and thermal energy, some other forms of energy include mechanical and sound energy. Any of these forms of energy can change into any other form. Often, one form of energy changes into two or more different forms. For example, the popcorn machine below changes electrical energy to thermal energy. The thermal energy, in turn, changes to both mechanical energy and sound energy. You can read the Figure below how these changes happen.

Image by Jill Wellington, pixabay.com, CC0

1. The popcorn machine changes electrical energy to thermal energy, which heats the popcorn.

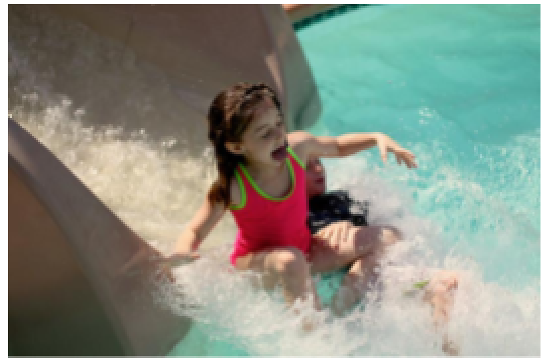
2. The heat causes the popcorn to pop. You can see that the popping corn has mechanical energy (energy of movement). It overflows the pot and falls into the pile of popcorn at the bottom of the machine.

3. The popping corn also has energy. That's why it makes popping sounds.

Kinetic-Potential Energy Changes

Mechanical energy commonly changes between kinetic and potential energy. Kinetic energy is the energy of moving objects. Potential energy is energy that is stored in objects, typically because of their position or shape. Kinetic energy can be used to change the position or shape of an object, giving it potential energy. Potential energy gives the object the potential to move. If it does, the potential energy changes back to kinetic energy.

That’s what happened to Sari. After she and Daniel left the theater, the storm cleared and they went for a swim. That’s Sari in the Figure below coming down the water slide. When she was at the top of the slide, she had potential energy. Why? She had the potential to slide into the water because of the pull of gravity. As she moved down the slide, her potential energy changed to kinetic energy. By the time she reached the water, all the potential energy changed to kinetic energy.



Whistler Water Slide Action by [illegible], https://flic.kr/p/[illegible], CC-BY-NC-ND

Q: How could Sari regain her potential energy?

A: Sari could climb up the steps to the top of the slide. It takes kinetic energy to climb the steps, and this energy would be stored in Sari as she climbed. By the time she got to the top of the slide, she would have the same amount of potential energy as before.

Q: Can you think of other fun examples of energy changing between kinetic and potential energy?

A: Playground equipment such as swings, slides, and trampolines involves these changes.

What does "NIMBY" stand for?

Not in my backyard. As much as any type of power source, wind power pits people who are concerned about the environment against, well, people who are concerned about the environment. Some people want the benefits of clean wind power but don't want the turbines in their vicinity.

Image by enriquelopezgarre, pixabay.com, CC0

Wind Energy

Energy from the Sun also creates wind, which can be used as wind power. The Sun heats different locations on Earth by different amounts. Air that becomes warm rises and then sucks cooler air into that spot. The movement of air from one spot to another along the ground creates wind. Since the wind is moving, it has kinetic energy.

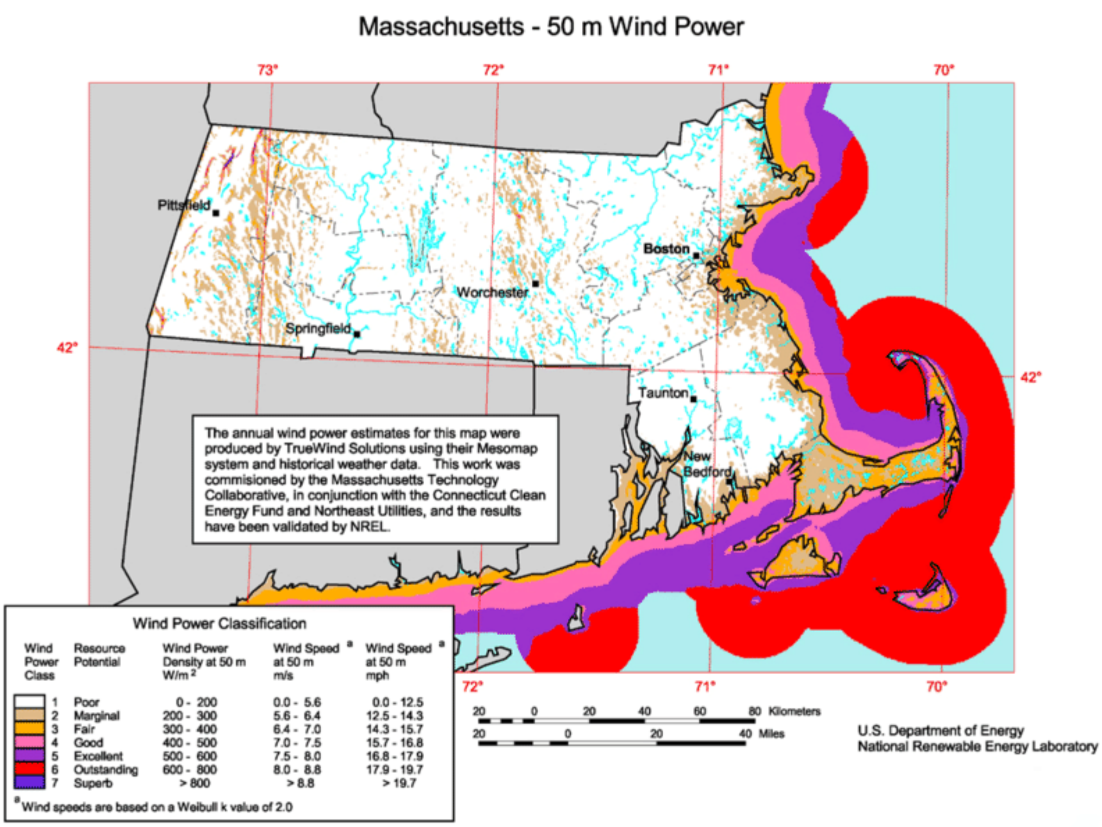
Wind power is the fastest growing renewable energy source in the world. Windmills are now seen in many locations, either individually or, more commonly, in large fields.

Wind Power Use

Wind is the source of energy for wind power. Wind has been used for power for centuries. For example, windmills were used to grind grain and pump water. Sailing ships traveled by wind power long before ships were powered by fossil fuels. Wind can be used to generate electricity, as the moving air spins a turbine to create electricity.

Consequences of Wind Power

Wind power has many advantages. It does not burn, so it does not release pollution or carbon dioxide. Also, wind is plentiful in many places. Wind, however, does not blow all of the time, even though power is needed all of the time. Just as with solar power, engineers are working on technologies that can



store wind power for later use.

Windmills are expensive and wear out quickly. A lot of windmills are needed to power a region, so nearby residents may complain about the loss of a nice view if a wind farm is built. Coastlines typically receive a lot of wind, but wind farms built near beaches may cause unhappiness for local residents and tourists.

The Cape Wind project off of Cape Cod, Massachusetts has been approved but is generating much controversy. Opponents are in favor of green power but not at that location. Proponents say that clean energy is needed and the project would supply 75% of the electricity needed for Cape Cod and nearby islands.

Putting It Together

Adapted from image by JoshuaWoroniecki, pixabay.com, CC0

Let’s revisit this situation: When on a multiple day camping trip, cell phones run out of battery power.

Focus Questions

1. What kind of energy does a cell phone need for its battery?
2. What kind of energy sources are available on a camping trip?
3. How can energy sources be transferred or converted from one form to another?

Final Task

Using the Technological Design process to design a device is able to provide a cellphone with power while camping.

a. define the problem
b. Identify criteria and constraints
c. develop possible solutions using models
d. analyze data
e. evaluate device quantitatively and qualitatively
f. optimize a solution

2.5 Renewable Energy (PHYS.2.5)

Authentic Situation

Highland under the inversion by jpstanley, https://flic.kr/p/dKcqWA, CC-BY-NC-SA

In Utah, in the winter, an inversion occurs, trapping bad polluted air in the valleys.

Observations and Wonderings

What is the problem in this situation?

What are possible criteria (positive outcomes) to this situation?

What are constraints (limitations) with this situation?

Focus Questions

1. What is the source of the air pollution?

2. What is the energy source used by what produces the air pollution?

PHYS.2.5 Renewable Energy

Design a solution to a major global problem that accounts for societal energy needs and wants. *Define the problem, identify criteria and constraints, develop possible solutions using models, analyze data to make improvements from iteratively testing solutions, and optimize a solution*. Emphasize problems that require the application of conservation of energy principles through energy transfers and transformations. Examples of devices could include one that uses renewable energy resources to perform functions currently performed by nonrenewable fuels or ones that are more energy efficient to conserve energy. (PS3.A, PS3.B, PS3.D, ETS1.A, ETS1.B, ETS1.C)

In this section, identify how we are able to produce usable energy and what are the consequences of that particular form of energy production. For each type of energy production, consider where it could be implemented. Don't just look at Utah, think globally.

Engineering Design

This is an engineering standard. Refer to page 10 to read about engineering design. Which type of engineering task is utilized in this SEEd Standard?

The Ongoing Demand

We need usable energy. As technology continues to advance and the population grows the amount of usable energy we need will continue to increase. This demand is currently being met by nonrenewable sources, such as fossil fuels. As noted in the previous section, the use of fossil fuels to power our society is not clean energy and releases tons of pollutants into our environment. What do you think will happen to the amount of pollutants in our environment if we continue this trend?

Our Part

Image by [illegible] pixabay.com CC0

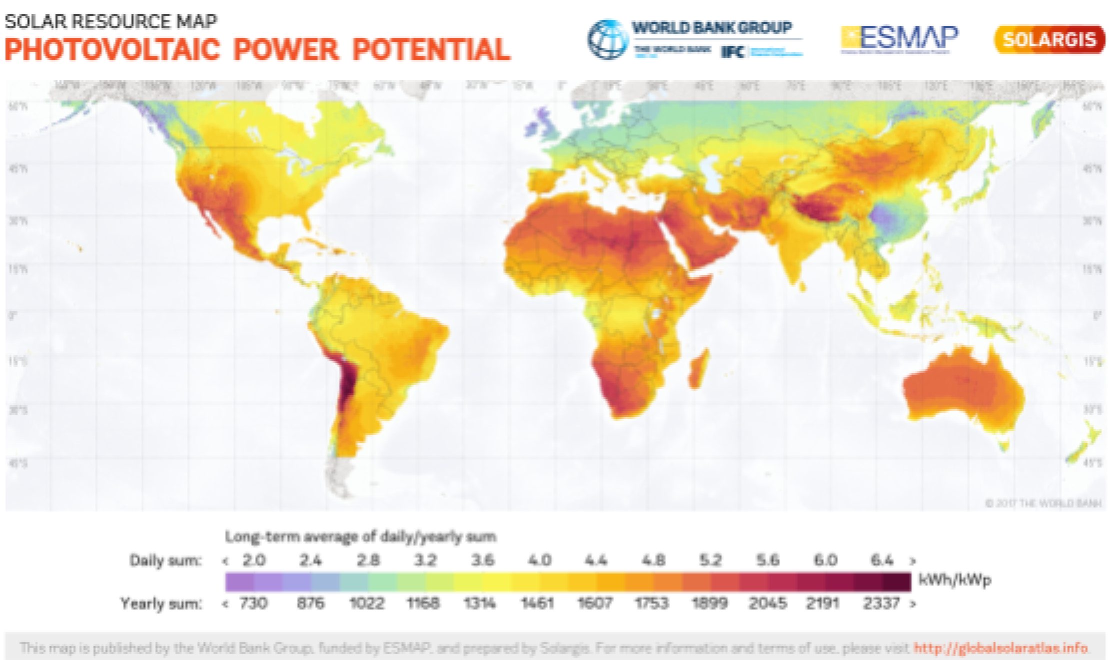
Transportation: In very recent history, we have seen enormous growth in the viability of the electric car; most notably in the form of the Tesla.

Problem solved right? If we can eliminate the estimated 1 billion combustion engine cars and replace them with clean electric cars, is that a step in the right direction? Something needs to provide the electric car with electricity and that is our current mass energy production system. Is there another way to power the vehicle?

Housing: In Utah, there has been a rise in solar panels placed on housing to meet energy demands. What are some of the issues with solar energy? Are they efficient? Are they cheap? Are they clean to produce?

Large Scale Energy Production

Thinking about large scale energy production, the one that has received arguably the most attention is solar energy. While the sun sends energy to the entire planet, some areas of the earth receive more than others. Looking at a map for the photovoltaic potential shows the estimated amount of energy that can be produced by crystalline silicon photovoltaic cells in regions across the globe.

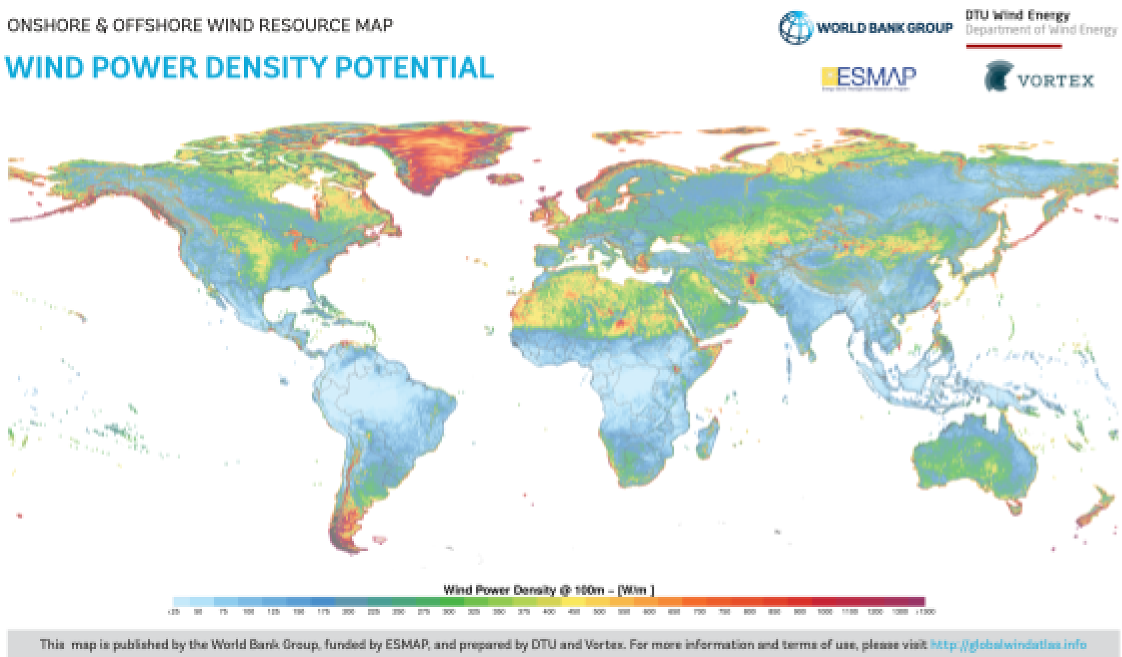


Global Map of Photovoltaic Power Potential by World Bank Group, https://globalsolaratlas.info, CC-BY

What are some patterns you notice about the potential? What are some of the factors affecting the amount of solar energy received by an area of the world? Is there an area that surprises you? Investigate

The issues that exist with small scale solar energy still exist with large scale solar energy. Is it clean to implement? Is it expensive? Is it efficient?

Wind Energy: How we convert the wind into usable energy was explained in the previous section, but it only works if there is wind. Just like solar energy, there is a wind potential that maps across the globe.



Global Map of Wind Power Density Potential by Technical University of Denmark, https://commons.wikimedia.org/wiki/File:Global_Map_of_Wind_Power_Density_Potential.png, CC-BY

What are some patterns you notice about the potential? What are some of the factors affecting the amount of wind energy received by an area of the world? Is there an area that surprises you? Investigate

There are other forms of renewable energy, such as hydroelectric power, but being clean is not enough. It must be viable to the region and affordable.

The End Goal

The goal is to produce a sufficient amount of energy to cover an ever increasing demand for that energy. We must realize that a solution for one part of the world may not work in another part of the world for various reasons.

Putting It Together

Highland under the inversion by jpstanley, https://flic.kr/p/dKcqWA, CC-BY-NC-SA

Let's revisit this phenomenon: In Utah, in the winter, an inversion occurs, trapping bad polluted air in the valleys.

Focus Questions

1. What is the cause of Utah's inversions?

2. What other kinds of energy sources are readily available to replace the energy source used by what produces the air pollution?

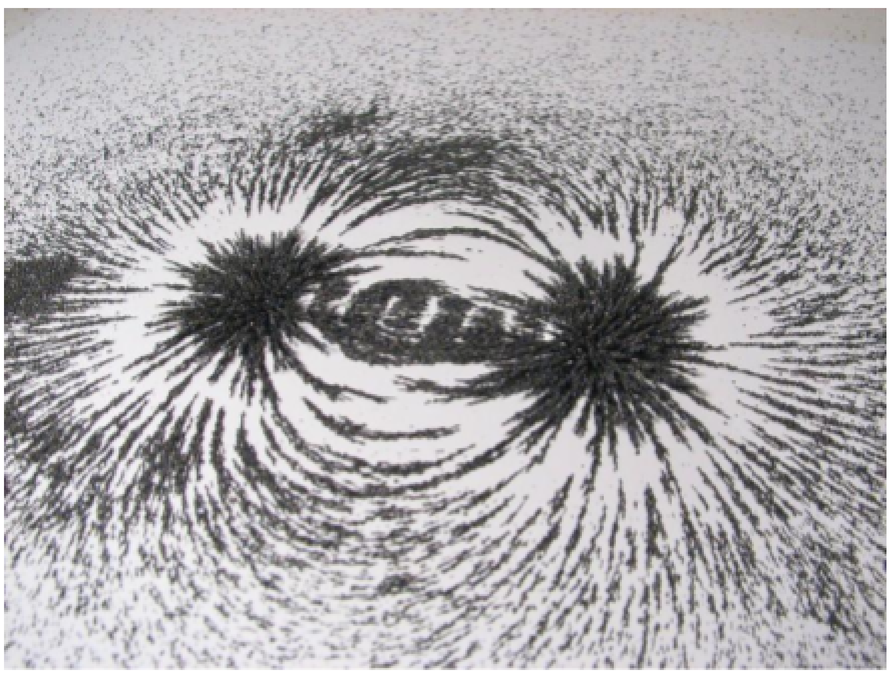
Final Task

Propose a solution to either eliminate or reduce Utah’s inversion problem.

CHAPTER 3

Strand 3: Fields

Chapter Outline



Magnetic Fields - 14 by Windell Oskay, https://flic.kr/p/7YPPbb, CC-BY

Fields describe how forces act through space and how potential energy is stored in systems. These take on different forms of electric, magnetic, or gravitational fields, but similarly provide a mechanism for how matter interacts. When two objects interacting through a field change relative position, the energy stored in the field is changed. These fields are important at a wide variety of scales, ranging from the subatomic to the astronomic.

3.1 Gravitational and Electric Fields (PHYS.3.1)

Phenomenon

Image by Milo Maughan, CC0

You are playing around with a balloon at a party and decide to hold it next to a running faucet (as depicted in the image above).

Observations & Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. What do you predict would happen if the balloon were bigger? Smaller?

2. What do you predict would happen if the balloon moved farther away from the water? Moved closer?

3. What is causing the water to bend away from the balloon?

PHYS.3.1 Gravitational and Electric Fields

Use mathematics and computational thinking to compare the scale and proportion of gravitational and electric fields using Newton's Law of Gravitation and Coulomb's Law. Emphasize the comparative strength of these two field forces, the effect of distance between interacting objects on the magnitudes of these forces, and the use of models to understand field forces. (PS2.B)

In this chapter, pay close attention to how the amount of mass/charge of each object and their distances from each other affect the forces that exist between them.

Gravitational Fields

Image by Jonny Linder, pixabay.com, CC0

Long, long ago, when the universe was still young, an incredible force caused dust and gas particles to pull together to form the objects in our solar system. From the smallest moon to our enormous sun, this force created not only our solar system, but all the solar systems in all the galaxies of the universe. The force is gravity.

Defining Gravity

Gravity has traditionally been defined as a force of attraction between things that have mass. According to this conception of gravity, anything that has mass, no matter how small, exerts gravity on other matter. Gravity can act between objects that are not even touching. In fact, gravity can act over very long distances. However, the farther two objects are from each other, the weaker is the force of gravity between them. Less massive objects also have less gravity than more massive objects. Gravity is an example where there is a force field that results when forces act on bodies, at various positions or distances in space, without touching each other (non-contact force).

Earth's Gravity

You are already very familiar with Earth's gravity. It constantly pulls you toward the center of the planet. It prevents you and everything else on Earth from floating away or being flung out into space as the planet spins on its axis. It also pulls objects that are above the surface—from meteors to skydivers—down to the surface. Gravity between Earth and the moon and between Earth and artificial satellites keeps all these objects circling around Earth. Gravity also keeps Earth and the other planets moving around the much more massive sun.

Q: There is a force of gravity between Earth and you and also between you and all the
objects around you. When you drop a paperclip, why doesn't it fall toward you instead
of toward Earth?

A: Earth is so much more massive than you that its gravitational pull on the paper clip
is immensely greater.

Image by S. Hermann & F. Richter (pixel2013), pixabay.com, CC0

You may have heard a story about Isaac Newton coming up with the idea of gravity when an apple fell out of a tree and hit him in the head. The story isn't true, but seeing how things like apples fall to Earth helped Newton form his ideas about gravity, the force of attraction between things that have mass. Of course, people had known about the effects of gravity for thousands of years before Newton came along. After all, they constantly experienced gravity in their daily lives. They observed over and over again that things always fall toward the ground. However, it wasn't until Newton developed his law of gravity in the late 1600s that people knew gravity applies to everything in the universe that has mass.

What affects the gravitational pull between two objects?

Newton is widely recognized as being the first person to suggest that gravity is universal and affects all objects in the universe. That's why Newton's law of gravity is called the law of universal gravitation. Universal gravitation means that the force that causes an apple to fall from a tree to the ground is the same force that causes the moon to keep moving around Earth. Universal gravitation also means that while Earth exerts a pull on you, you exert a pull on Earth (remember Newton's 3rd Law). In fact, there is gravity between you and every mass around you—your desk, your book, your pen. Even tiny molecules of gas are attracted to one another by the force of gravity.

Newton's law of universal gravitation had a huge impact on how people thought about the universe. A field force that acts across a distance without touching (non-contact) was unheard of while contact forces that push or pull on an object are easy to observe. Newton's law was the first scientific law that applied to the entire universe. It explains the motion of objects not only on Earth but in outer space as well.

Key Equations

$$F_G = G\frac{m_1 m_2}{d^2}$$

F is the force of gravity between an object with mass m_1 and another object of mass m_2 that has a distance between them of d. Sometimes the symbol r is used, rather than d, to show this distance. When r is used, it represents the "orbital radius", or how far the centers of the two objects are from each other.

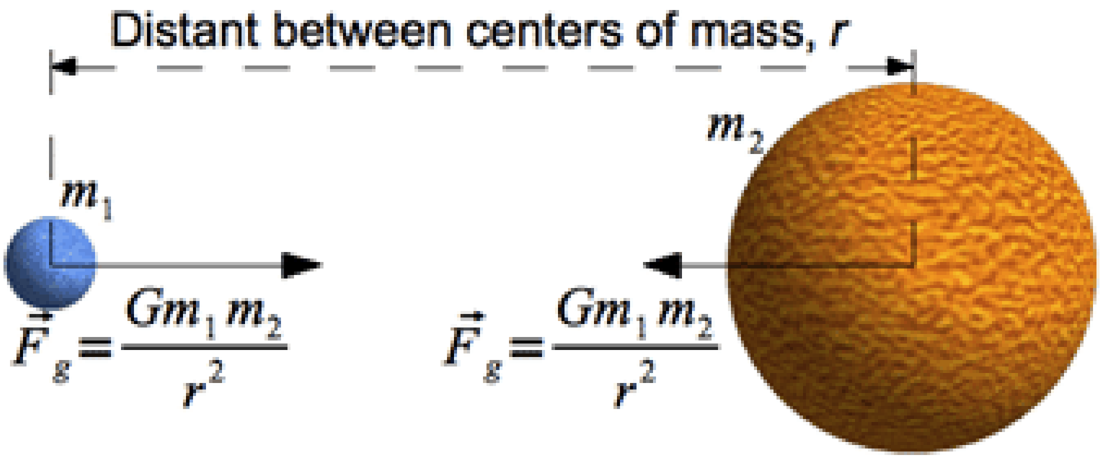
$$G = 6.67\times10^{-11}\frac{Nm^2}{kg^2}$$

This is called the universal constant of gravitation. This was determined by measuring the force between two 1.0 kg objects whose center of masses were exactly 1.0 m apart.

Look at the equation of Universal Gravitation and see what happens when you plug in masses of 1.0 kg and a distance of 1.0 m. Why would using these

quantities result in a
force that equals the gravitational constant?

Using astronomical data, Newton was able to formulate his ideas into an equation. This equation tells us the strength of the force of gravity between any two objects anywhere in the universe. Newton discovered that any two objects in the universe, with masses m_1 and m_2 with their centers of mass at a distance r apart will experience a force of mutual attraction along the line joining their centers. Here is an illustration of this law for two objects, for instance the earth and the sun:



Factors that Influence the Strength of Gravity

Newton's law also states that the strength of gravity between any two objects depends on two factors: the masses of the objects and the distance between them. According to this equation, the force of gravity is directly proportional to the masses of the two objects and inversely proportional to the square of the distance between them. This means that objects with greater mass have a stronger force of gravity between them. For example, because Earth is so massive, it attracts you and your desk more strongly than you and your desk attract each other. That's why you and the desk remain in place on the floor rather than moving toward one another. For example:

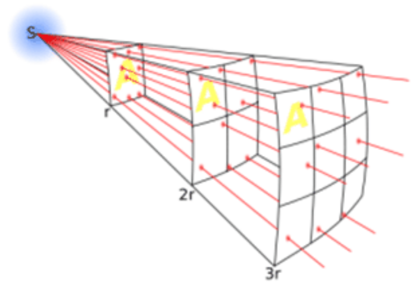
- If you double the mass of one of the objects, the force will also double.
- If you triple the mass of one of the objects, the force will triple.
- If you double the mass of one object and triple the mass of the other, the force will become six times (2×3=6) stronger.

Objects that are closer together have a stronger force of gravity between them. For example, the International Space Station is closer to Earth than it is to the more massive sun, so the force of gravity is greater between the Space Station and the Earth than between the Space Station and the Sun. That's why the

Space Station circles around Earth rather than the Sun. You can see this in the figure below.

Inverse Square Law

In physics, an inverse-square law is any physical law stating that a specified physical quantity or intensity is inversely proportional to the square of the distance from the source of that physical quantity. As an example, let's look at an image which shows how the intensity of light decreases according to the inverse square law.



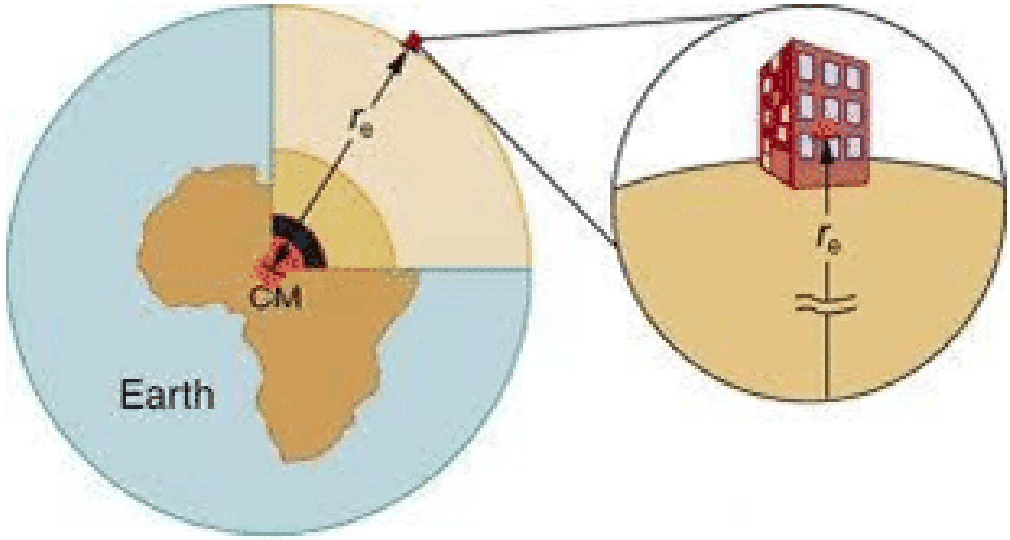
Because the light spreads out over an area, every time we double the distance, the light intensity decreases by 1/4. If we triple the distance, the light intensity will decrease by 1/9. Both the law of Universal Gravitation and Coulomb's Law (discussed in the next section) obey the inverse square law for distance. See if you can fill in the missing values in the next table.

Distance	Inverse	Inverse Square
1(D)	1/1	1(F)
2(D)	½	¼(F)
½(D)	2	4(F)
3(D)		___(F)
¼(D)		____(F)
___(D)	5/6	____(F)
___(D)	8/7	____(F)
___(D)	9/10	____(F)
___(D)		4/9(F)
___(D)		49/16(F)
___(D)		0.36(F)

Gravity on the Earth's Surface

On the surface of a planet—such as Earth—the r in the formula is very close to the radius of the planet, since a planet's center of mass is (usually) at its center. It also does not vary by much: for instance, the Earth's radius is about 6,000,000 m. Even the height of Mt. Everest is only 8,800 m, so we can say that for objects near the surface of the Earth, the r in formula is constant and equal to the Earth's radius. This allows us to say that gravity is more or less constant on the surface of the Earth. The value on (or near) the surface of Earth for the gravitational acceleration is about 9.8 m/s^2.

Here’s an illustration:



For any object near the surface of the earth, the force of gravity may be expressed as:

$$F_G = G \frac{mass_{Earth} mass_{object}}{r^2_{radius\ of\ the\ earth}}$$

In fact, an object’s weight is the magnitude of the gravitational force on it. To find the weight of an object on another planet, star, or moon, use the appropriate values in the formula for the force of gravity.

Some data needed for the problems:
• The radius of the Earth is 6.4×10^6 m.
• The mass of the Earth is about 6.0×10^{24} kg.
• The mass of the Sun is about 2.0×10^{30} kg.
• The Earth-Sun distance is about 1.5×10^{11} m.
• The Earth-Moon distance is about 3.8×10^8 m.

G= Gravitational Constant= $6.67300\times10^{-11} m^3 kg^{-1} s^{-2}$ or $G = 6.673\times10^{-11}$ N m^2 kg^{-2}

Guidance

When using the Universal Law of Gravity formula and the constant G above, make sure to use SI units of meters and kilograms. The direction of the force of gravity is in a straight line between two objects. It is always attractive. Newton relied on calculus in order to prove that for a spherical object (like Earth) one can assume all of its mass is at the center of the sphere (thus in his formula, one can use the radius of Earth for the distance between a falling rock and Earth).

Newton’s Laws apply to all forces; but when he developed them only one was known: gravity. Newton's major insight—and one of the greatest in the history of science—was that the same force that causes objects to fall when released is also responsible for keeping the planets in orbit.

Example 1
Determine the force of attraction between a 15.0 kg box and a 63.0 kg person if they
are 3.45 m apart. Assume that the distance given is the distance between the two centers of the objects.

$$F_g = \frac{Gm_1 m_2}{d^2} = \frac{(6.67\,x\,10^{-11}\,\frac{Nm^2}{kg^2})(15.0\,kg)(63.0\,kg)}{(3.45\,m)^2} = 5.30\,x\,10^{-9}N$$

Example 2
Determine the force of attraction between the sun and the Earth.

$$F_g = \frac{Gm_1 m_2}{d^2} = \frac{(6.67\,x\,10^{-11}\,\frac{Nm^2}{kg^2})(2.0x\,10^{30}\,kg)(6.0\,x\,10^{24}\,kg)}{(1.5\,x\,10^{11}\,m)^2} = 3.6\,x\,10^{22}N$$

Electric Fields


Image from sethink, pixabay.com, CC0

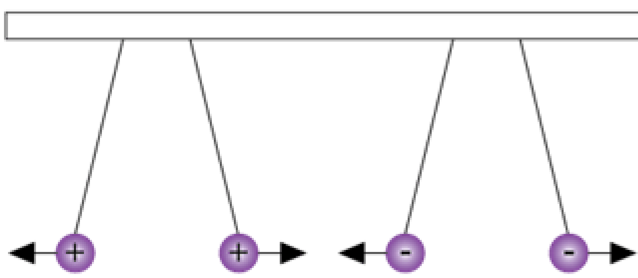
A lightning bolt is like the spark that gives you a shock when you touch a metal doorknob. Of course, the lightning bolt is on a much larger scale. But both the lightning bolt and spark are a sudden transfer of electric charge.

Introducing Electric Charge
Electric charge is a physical property of particles or objects that causes them to attract or repel each other without touching. All electric charge is based on the protons and electrons in atoms. A proton has a positive electric charge, and an

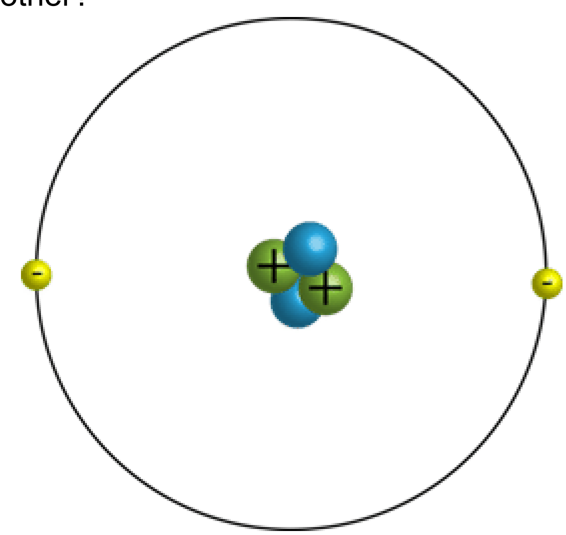
electron has a negative electric charge. In the figure below, you can see that positively charged protons (+) are located in the nucleus of the atom, while negatively charged electrons (-) move around the nucleus.

Electric Force

When it comes to electric charges, opposites attract, so positive and negative particles attract each other. You can see this in the diagram below. This attraction explains why negative electrons keep moving around the positive nucleus of the atom. Like charges, on the other hand, repel each other, so two positive or two negative charges push apart. This is also shown in the diagram. The attraction or repulsion between charged particles is called electric force. The strength of electric force depends on the amount of electric charge on the particles and the distance between them. Larger charges or shorter distances result in greater force.



Q: How do positive protons stay close together inside the nucleus of the atom if like
charges repel each other?



A: There are other stronger forces in the nucleus holding the protons together.

Key Equation

q=Ne: Any object's charge is an integer multiple of an electron's charge.

- q represents the total charge on an object, measured in units of Coulombs (which is abbreviated as C).
- N represents the number of extra or missing electrons.
- e represents the fundamental charge unit, 1.6 Å~ 10-19 C.

Opposite charges attract and like charges repel.

The charge (q) of an electron (e) and proton is 1.6Å~10-19 C. An electron has a negative charge and a proton has a positive charge. This is called the fundamental charge unit. If an object has a net negative charge, it means that the object has gained electrons. If the object has a net positive charge, it means that the object has lost electrons. One can determine the number of excess electrons (or protons if positive charge) by dividing the object's charge by the fundamental charge. Most objects are electrically neutral (equal numbers of electrons and protons). This enables gravitational force to dominate on a macro scale.

Example 1

Question:
If an object has +0.003 C of charge, how many electrons did the object lose?

Solution:
q=Ne
$0.003 \text{ C} = N(-1.6 \times 10^{-19} \text{ C})$
$N = -1.875 \times 10^{16}$ electrons

Answer:
1.875×10^{16} electrons fewer than protons.

What is Coulomb's Law?

Charles-Augustin de Coulomb (1736-1806)

All objects have positive and negative charges inside them. If the number of positive and negative charges are equal, as they most often are, then the object is neutral. Charged objects are objects with more positive charges than negative ones, or vice versa. Opposite charges attract, and similar charges repel. Electric fields are created by a net charge and point away from positive charges and towards negative charges. Many macroscopic forces can be attributed to the electrostatic forces between molecules and atoms.

Charles-Augustin de Coulomb noticed that a force existed between charged particles. He called this force electrical force. This force was different from the gravitational force between objects with mass. The force between charged particles varied directly with the magnitude of the charges and inversely squared to the distance between the particles. For example, particles with a larger charge (either more negatively charged or positively charged) would have a greater force between them. He also noticed that this force between the charges could be either attractive (between opposite charges) or repulsive (between like charges). This is different from gravitational forces, because gravitational force can only be attractive.

Similar to the gravitational force, the electrical force follows the inverse-square law with distance. As the distance between the objects increases, the electrical force between the objects decreases. The relationship between charge, distance, and force is called Coulomb's Law.

The Coulomb Force Law states that any two charged particles (q_1 and q_2) with charge
measured in units of Coulombs at a distance r (with distance measured in units of meters) from each other will experience a force of repulsion or attraction along the line
joining them equal to:

$$F_e = k\frac{q_1 q_2}{d^2}$$

This looks a lot like the Law of Universal Gravitation, which deals with the attraction between objects with mass. It depends on the product of the two charges and obeys the inverse square law for distance.

For example, if you double the charge on one of the objects, the force will also double.
If you triple the charge on one of the objects, the force will triple.

If you double the charge on one object and triple the charge on the other, the force will
become six times (2 × 3 = 6) stronger. This is because the charge and the force are
directly proportional.

If we double the distance, the force decreases by 1/4. If we triple the distance, the force will decrease by 1/9. This is because the distance and the force are inverse-squared proportional.

Coulomb's Law Summarized

There are two types of charge: positive and negative.

- Electrons have a negative charge.
- Protons have a positive charge.
- Magnitude of the charge is the same for electrons and protons: $e=1.6\times10^{-19}$

Coulomb's law is used to calculate the force between two charged particles, where k is a constant, q is the charge, and d (or r) is the distance between the charged particles.

- k has a value of approximately 8.99 Å~ 109 $N \cdot m^2 / C^2$

The force can be attractive or repulsive depending on the charges:

- Like charges (charges with the same sign) repel.
- Charges with opposite signs attract.

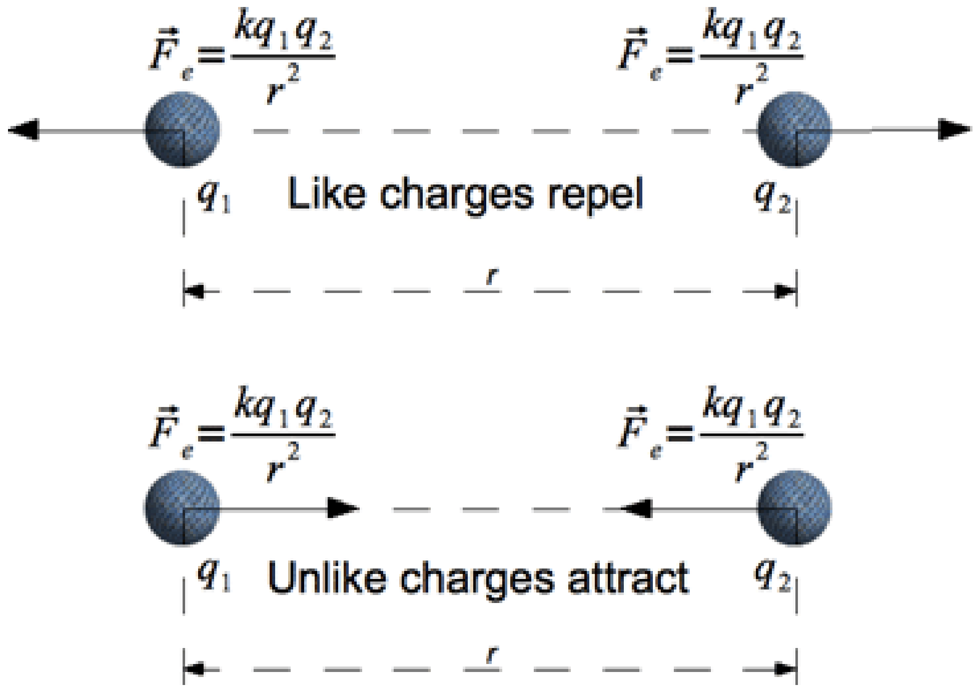
Q: What do you think would happen if the distance between the charges was cut in half?

A: The inverse of 1/2 is 2/1=2. The inverse SQUARE is 22 = 4. The force would become four times stronger.

What's the difference?

The big difference is that while any two masses experience mutual attraction, two charges can either attract or repel each other, depending on whether the signs of their charges are alike:

- The sign of the force can tell you whether the two particles attract or repel.
- If the force between two charged particles is positive, then we can say the force is repulsive.
- For example, if the two charges are both positive, say +2 C and +3 C, the product of the charges will be positive.
- If the two charges are both negative, say -2 C and -3 C, the product of the charges will also be positive.
- If the force between two charged particles is negative, then we can say the force is attractive.
- For example, if one charge is positive and the other is negative, say +2 C and -3 C, the product of the charges will be negative.

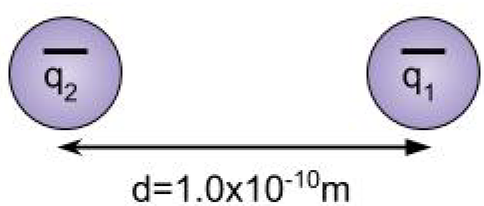


Like gravitational (and all other) forces, Coulomb forces add as vectors. Thus to find the force on a charge from an arrangement of charges, one needs to find the vector sum of the force from each charge in the arrangement.

Example 1

An electron is located 1.00Å~10^{-10} m to the right of another electron. What is the force on the first electron from the second electron, Fe_1? What is the force on the second electron from the first electron, Fe_2? What if these are protons instead?

It is useful to draw a picture just to visualize the problem. The first electron is 1.00Å~10^{-10} m to the right of the second electron, so the appropriate drawing is: We want to first find the force on q_1 from q_2.



$$F_e = k\frac{q_1q_2}{d^2}$$

To solve this problem, we need to use Coulomb's Law and merely substitute in the appropriate values. The magnitude of Coulomb's law is:

We know that k = $8.99\times10^9 \frac{Nm^2}{C^2}$ and d (or r) is given in the problem as

$1.00x10^{-10}$m.

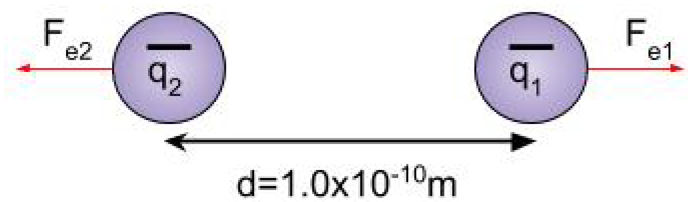
The charge of an electron is e= - $1.6x10^{-19}$ C. So, plugging these into the equation, we get:

$$F_e = k\frac{q_1q_2}{d^2}$$
$$= 8.99x10^9 \frac{Nm^2}{C^2} \frac{(1.6x10^{-19}C)(1.6x10^{-19}C)}{(1.0x10^{-10}m)^2}$$
$$= 2.31x10^{-8}\ N$$

This gives us the magnitude of the force. The sign of our answer, positive, tells us that the force is repulsive. So, the force on q_1 is directed away from q_2, or to the right.

Finally, our answer is:

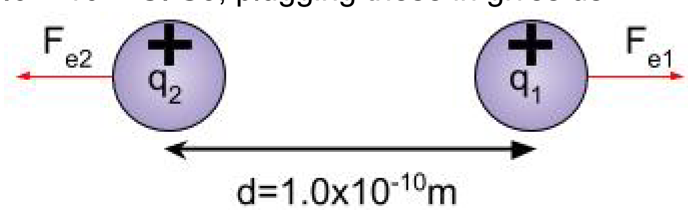
$Fe_1=2.31x10^{-8}$ N to the right



The force on q_2 is equal and opposite (remember Newton's third law?). Therefore Fe_2 = 2.31 × 10_{-8} N to the left.

Now consider the question, "What if these are protons instead?"

Most of the numbers are the same. The only difference is that the charge of a proton is p+ = 1.6 × 10^{-19} C. So, plugging these in gives us



$$F_e = k \frac{q_1 q_2}{d^2}$$

$$= 8.99 \times 10^9 \frac{Nm^2}{C^2} \frac{(1.6 \times 10^{-19} C)(1.6 \times 10^{-19} C)}{(1.0 \times 10^{-10} m)^2}$$

$$= 2.31 \times 10^{-8}\ N$$

Which is again a positive number. So the force is repulsive, and will be directed away from the other proton.

$Fe_1 = 2.31 \times 10^{-8}$ N to the right
$Fe_2 = 2.31 \times 10^{-8}$ N to the left

Notice that the answer is the same, although the charges are different. What are some examples of electrostatics in life?

The Van de Graaff Generator

Van de Graff Generator by Ricardo Mendonça Ferreira, https://flic.kr/p/4Ltz6v. CC-BY-NC-SA

What explains this shocking photo? The man in the picture is touching a device called a Van de Graaff generator. The dome on top of the device has a negative electric charge. When the man places his hand on the dome, he becomes negatively charged as well—right down to the tip of each hair!

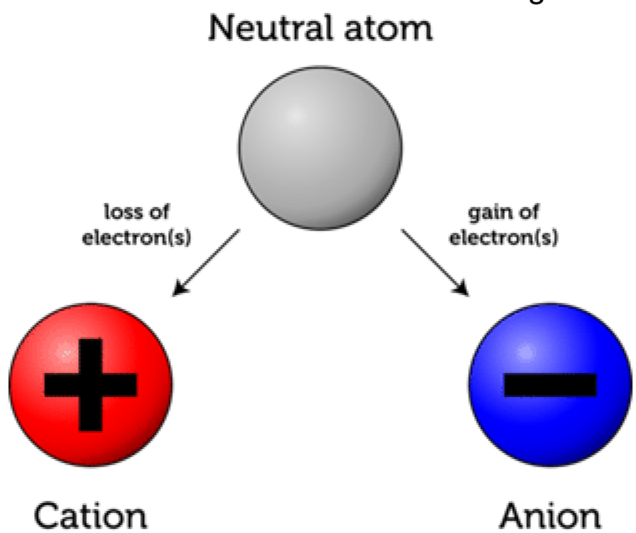
Q: Why is the man's hair standing on end?
A: All of the hairs have all become negatively charged, and like charges repel each other. Therefore, the hairs are pushing away from each other, causing them to stand on end.

Transferring Electrons

The man pictured above became negatively charged because electrons flowed from the Van de Graaff generator to him. Whenever electrons are transferred between objects, neutral matter becomes charged. This occurs even with individual atoms. Atoms are neutral in electric charge because they have the same number of negative electrons as positive protons. However, if atoms lose or gain electrons, they become charged particles called ions. You can see how this happens in the figure below. When an atom loses electrons, it becomes a positively charged ion. When an atom gains electrons, it becomes a negatively charged ion.

Conservation of Charge

Like the formation of ions, the formation of charged matter in general depends on the transfer of electrons, either between two materials or within a material. Three ways this can occur are referred to as conduction, polarization, and friction. All three ways are described below. However, regardless of how electrons are transferred, the total charge always remains the same. Electrons move, but they aren't destroyed. This is the law of conservation of charge.



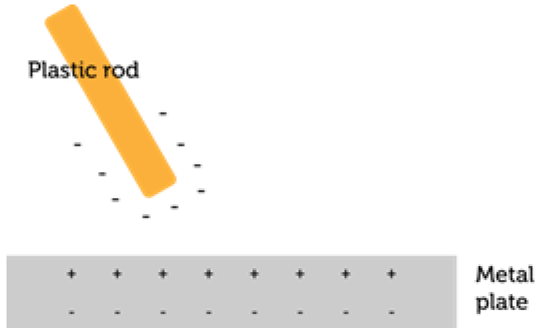
Conduction

The transfer of electrons from the Van de Graaff generator to the man is an example of conduction. Conduction occurs when there is direct contact between materials that differ in their ability to give up or accept electrons. A Van de Graaff generator produces a negative charge on its dome, so it tends to give up electrons. Human hands are positively charged, so they tend to accept electrons. Therefore, electrons flow from the dome to the man's hand when they are in contact.

You don't need a Van de Graaff generator for conduction to take place. It may occur when you walk across a wool carpet in rubber-soled shoes. Wool tends to give up electrons and rubber tends to accept them. Therefore, the carpet transfers electrons to your shoes each time you put down your foot. The transfer of electrons results in you becoming negatively charged and the carpet becoming positively charged.

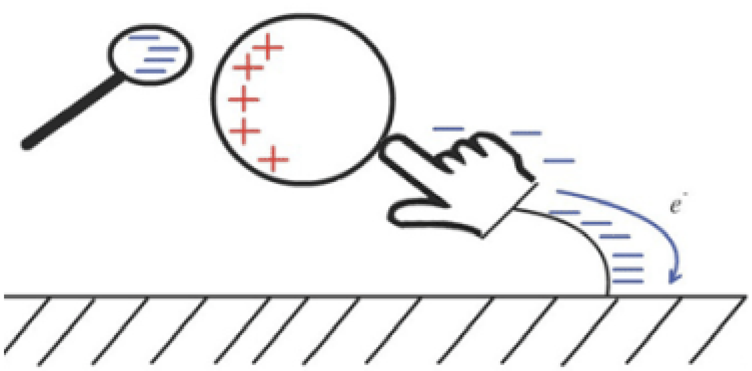
Polarization

Assume that you have walked across a wool carpet in rubber-soled shoes and become negatively charged. If you then reach out to touch a metal doorknob, electrons in the neutral metal will be repelled and move away from your hand before you even touch the knob. In this way, one end of the doorknob becomes positively charged and the other end becomes negatively charged. This is called polarization. Polarization occurs whenever electrons within a neutral object move because of the electric field of a nearby charged object. It occurs without direct contact between the two objects. The figure models how polarization occurs.



When the negatively charged plastic rod is placed close to the neutral metal plate (above), the electrons in the plate are repelled by the positive charges in the rod. The electrons move away from the rod, causing one side of the plate to become positively charged and the other side to become negatively charged. Charging by induction is when we charge an object without touching it. There are many methods for charging objects by induction, but here is one process for charging a single object by induction.

1. First touch one finger to the neutral object to ground the object.
2. Then, bring a charged object (we'll assume it's negatively charged, but it can be either) close to the neutral object. This causes negative charges in the neutral object to be repelled through your body to the ground.
3. When the finger is removed, the neutral object will be positively charged.
When charging by induction, the originally neutral object will always end up with the opposite charge.



When charge moves, electrons are always the ones that move. Protons cannot move between atoms.

Friction

Did you ever rub an inflated balloon against your hair? Friction between the balloon an hair causes electrons from the hair to “rub off” on the balloon. That’s because a balloon attracts electrons more strongly than hair does. After the transfer of electrons, the balloon becomes negatively charged and the hair becomes positively charged. The individual hairs push away from each other and stand on end because like charges repel each other. The balloon and the hair attract each other because opposite charges attract.

Electrons are transferred in this way whenever there is friction between materials that
differ in their ability to give up or accept electrons.

Q: If you rub a balloon against a wall, it may stick to the wall. Explain why.
A: Electrons are transferred from the wall to the balloon, making the balloon negatively
charged and the wall positively charged. The balloon sticks to the wall because opposite charges attract. You’re a thoughtful visitor, so you wipe your feet on the welcome mat before you reach out to touch the brass knocker on the door. Ouch! A spark suddenly jumps between your hand and the metal, and you feel an electric shock.

Image by Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

Q: Why does electric shock occur?

A: An electric shock occurs when there is a sudden discharge of static electricity.

What Is Static Electricity?

Static electricity is a buildup of electric charges on objects. Charges build up when negative electrons are transferred from one object to another. The object that gives up electrons becomes positively charged, and the object that accepts the electrons becomes negatively charged. This can happen in several ways. One way electric charges can build up is through friction between materials that differ in their ability to give up or accept electrons. When you wipe your rubber-soled shoes on the wool mat, for example, electrons rub off the mat onto your shoes. As a result of this transfer of electrons, positive charges build up on the mat and negative charges build up on you.

Once an object becomes electrically charged, it is likely to remain charged until it touches another object or at least comes very close to another object. That's because
electric charges cannot travel easily through the air, especially if the air is dry.

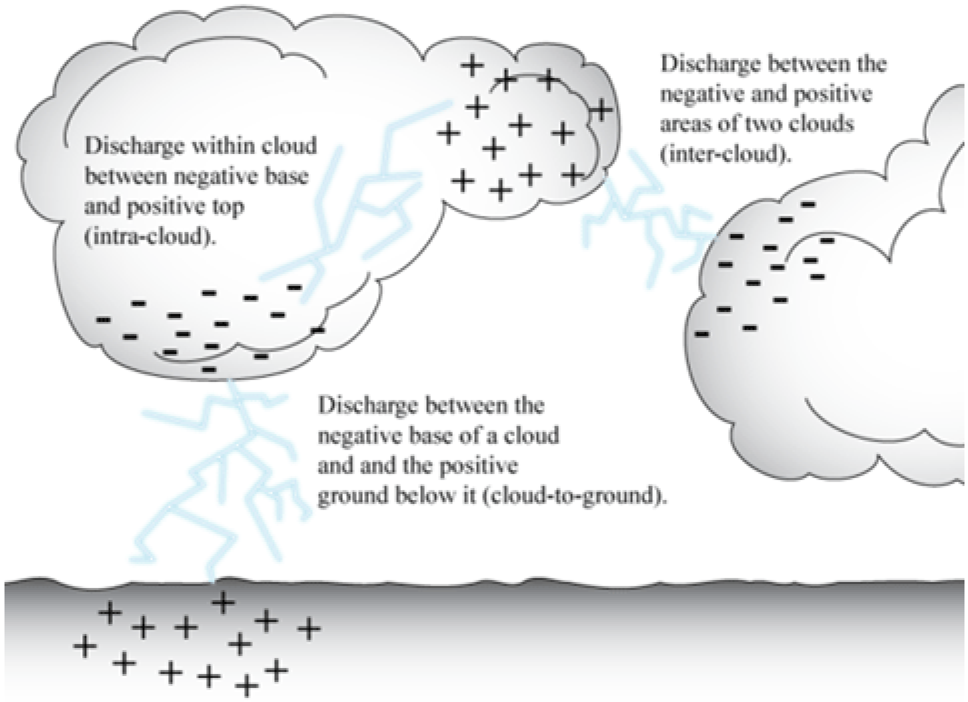
Q: You're more likely to get a shock in the winter when the air is very dry. Can you
explain why?
A: When the air is very dry, electric charges are more likely to build up objects because they cannot travel easily through the dry air. This makes a shock more likely when you touch another object.

Static Discharge
What happens when you have become negatively charged and your hand approaches
the metal door-knocker? Your negatively charged hand repels electrons in the metal, so the electrons move to the other side of the knocker. This makes the side of the knocker closest to your hand positively charged. As your negatively charged hand gets very close to the positively charged side of the metal, the air between your hand and the knocker also becomes electrically charged. This allows electrons to suddenly flow from your hand to the knocker. The sudden flow of electrons is static discharge. The discharge of electrons is the spark you see and the shock you feel.

Watch the animation "John Travoltage" at the following URL to see an example of static electricity and static discharge. • http://go.uen.org/b3D

How Lightning Occurs
Another example of static discharge, but on a much larger scale, is lightning. You can see how it occurs in the following diagram and animation as you read about it below.

During a rainstorm, clouds develop regions of positive and negative charge due to the movement of air molecules, water drops, and ice particles. The negative charges are concentrated at the base of the clouds, and the positive charges are concentrated at the top. The negative charges repel electrons on the ground beneath them, so the ground below the clouds becomes positively charged. At first, the atmosphere prevents electrons from flowing away from areas of negative charge and toward areas of positive charge. As more charges build up, however, the air between the oppositely charged areas also becomes charged. When this happens, static electricity is discharged as bolts of lightning.



Credit: Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

Glass Plasma Globe by Slimsdizz, https://commons.wikimedia.org/wiki/File:Glass_plasma_globe.jpg, CC0

A plasma globe, such as the one pictured above, is filled with a mixture of noble gases and has a high-voltage electrode at the center. The swirling lines are electric discharge lines that connect from the inner electrode to the outer glass insulator. When a hand is placed on the surface of the globe, all the electric discharge travels directly to that hand.

The Electric Field

Coulomb's Law gives us the formula to calculate the force exerted on a charge by another charge. On some occasions, however, a test charge suffers an electrical force with no apparent cause. That is, as observers, we cannot see or detect the original charge creating the electrical force. Michael Faraday dealt with this problem by developing the concept of an electric field. According to Faraday, a charge creates an electric field about it in all directions. If a second charge is placed at some point in the field, the second charge interacts with the field and experiences an electrical force. Thus, the interaction we observe is between the test charge and the field and a second particle at some distance is no longer necessary.

The strength of the electric field is determined point by point and can only be identified by the presence of test charge. When a positive test charge, *qt,* is placed in an electric field, the field exerts a force on the charge. The field strength can be measured by dividing the force by the charge of the test charge. Electric field strength is given the symbol E and its unit is Newtons/coulomb. Where E= F/q or Force per unit charge.

The test charge can be moved from location to location within the electric field until the entire electric field has been mapped in terms of electric field intensity.

Electric Field Strength

Example

A positive test charge of 2.0×10^{-5}C is placed in an electric field. The force on the test charge is 0.60 N. What is the electric field intensity at the location of the test charge?

$E=F/q= 0.60N/2.0\times10^{-5}C= 3.0 \times 10^{4}$ N/C

Putting It Together

Image by Milo Maughan, CC0

Let’s revisit this phenomena: the water is curving away from the balloon.

Focus Questions:

3. Explain what causes the water to curve towards the balloon in the image above.

4. Create, draw, or find a model to help illustrate your explanation.

Final Task:

Describe what would happen if we changed the mass of the balloon, the charge on the balloon, and the distance between the water and the balloon. Use Newton’s Universal Law of Gravitation and Coulomb's Law to justify your explaination.

3.2 Electromagnetic Induction (PHYS.3.2)

Phenomenon

Stripped Down Motor by Exploratorium, https://www.exploratorium.edu/snacks/stripped-down-motor, CC-BY-NC-SA

When the device is connected to a battery the copper ring (on the right above the cup) starts to spin.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Question

1. What happens to the wire when the battery is connected to it?

2. What causes the wire ring to spin when the battery is connected?

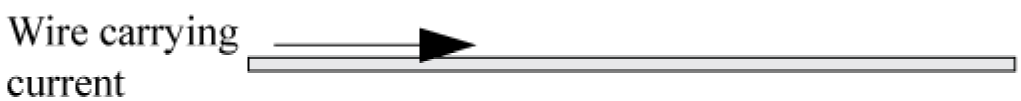
PHYS.3.2 Electromagnetic Induction

Plan and conduct an investigation to provide evidence that an electric current causes a magnetic field and that a changing magnetic field causes an electric current. Emphasize the qualitative relationship between electricity and magnetism without necessarily conducting quantitative analysis. Examples could include electromagnets or generators. (PS2.B)

In this section, see if you can identify when a magnetic field causes an electric current and when an electric current causes a magnetic field.

What Is Electromagnetism?

Electromagnetism is magnetism produced by an electric current. When electric current flows through a wire, it creates a magnetic field that surrounds the wire in circles. You can see this in the diagram below. Note that electric current is conventionally shown moving from positive to negative electric potential, as in this diagram. However, electrons in current actually flow in the opposite direction, from negative to positive potential.



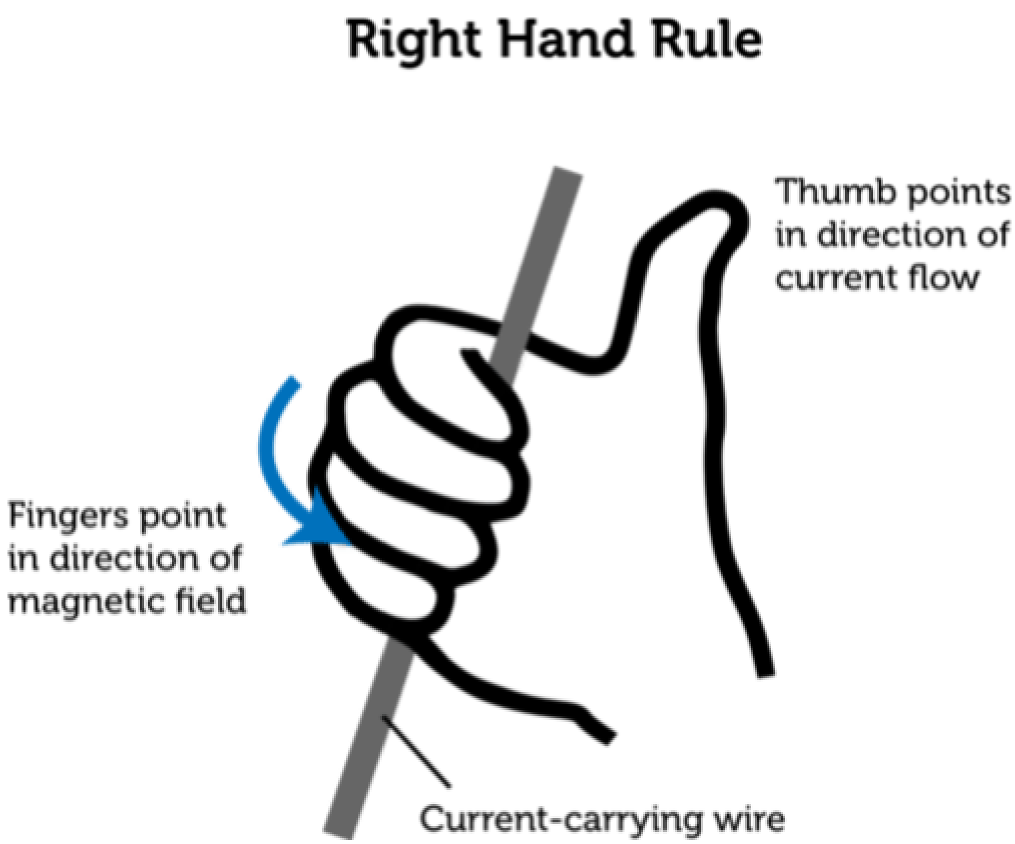
https://flexbooks.ck12.org/cbook/ck-12-middle-school-physical-science-flexbook-2.0/section/22.1/primary/lesson/electromagnetism-ms-ps/

Q: If more current flows through a wire, how might this affect the magnetic field surrounding the wire?

A: With more current, the magnetic field is stronger.

Right Hand Rule

The direction of the magnetic field created when current flows through a wire depends on the direction of the current. A simple rule, called the right hand rule, makes it easy to find the direction of the magnetic field if the direction of the current is known. The rule is illustrated in the Figure below. When the thumb of the right hand is pointing in the same direction as the current, the fingers of the right hand curl around the wire in the direction of the magnetic field.



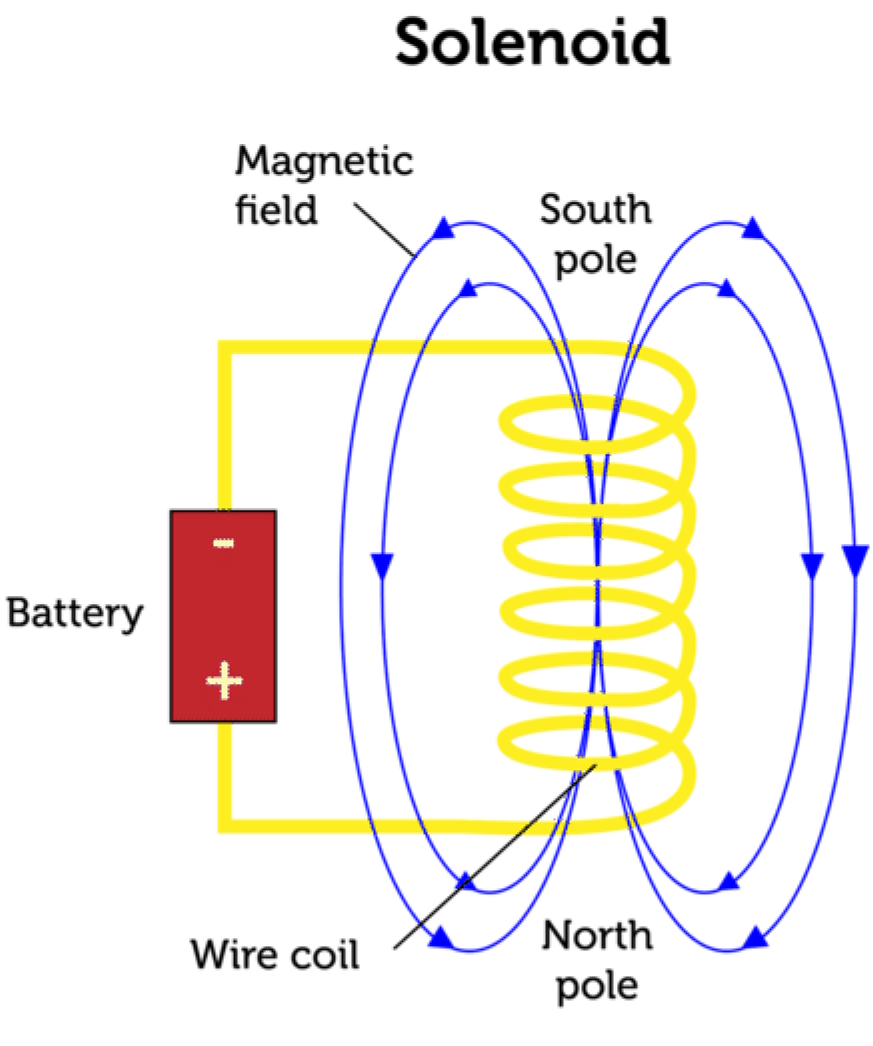
Hand by Wizard191, modified by Christopher AuYeung for CK-12 Foundation; http://commons.wikimedia.org/wiki/File:Right-hand_grip_rule.svg; CC BY-NC 3.0

Uses of Electromagnetism

Electromagnetism is used not only in doorbells but in many other electronic devices as well, such as electric motors and loudspeakers. It is also used to store information on computer disks. An important medical use of electromagnetism is magnetic resonance imaging (MRI). This is a technique for making images of the inside of the body in order to diagnose diseases or injuries. Magnetism created with electric current is so useful because it can be turned on or off simply by turning the current on or off. The strength of the magnetic field is also easy to control by changing the amount of current. You can't do either of these things with a regular magnet.

What Is a Solenoid?

A solenoid is a coil of wire with electric current flowing through it. You can see a solenoid in the Figure below. Current flowing through the coil produces a magnetic field that has north and south poles.



https://flexbooks.ck12.org/cbook/ck-12-middle-school-physical-science-flexbook-2.0/section/22.3/primary/lesson/solenoid-ms-ps/

Q: How is a solenoid like a bar magnet?

A: Like a bar magnet, a solenoid has north and south magnetic poles and is surrounded by a magnetic field.

Strength of a Solenoid

Any wire with current flowing through it has a magnetic field. However, the magnetic field around a coiled wire is stronger than the magnetic field around a straight wire. That's because each turn of the wire in the coil has its own magnetic field. Adding more turns to the coil of wire increases the strength of the field. Increasing the amount of current flowing through the coil also increases the strength of the magnetic field.

Uses of Solenoids

A solenoid is generally used to convert electromagnetic energy into motion. Solenoids are often used in devices that need a sudden burst of power to move a specific part. In addition to paintball markers, you can find solenoids in machines ranging from motor vehicles to electric dishwashers. Another device that uses solenoids is pictured in the Figure below.

Image by Will Scullin;
http://www.flickr.com/photos/93278581@N00/3588801321; CC BY 2.0

What Is Electromagnetic Induction?

Electromagnetic induction is the process of generating electric current with a magnetic field. It occurs whenever a magnetic field and an electric conductor, such as a coil of wire, move relative to one another. As long as the conductor is part of a closed circuit, current will flow through it whenever it crosses lines of force in the magnetic field. One way this can happen is illustrated in the Figure below. The sketch shows a magnet moving through a wire coil.

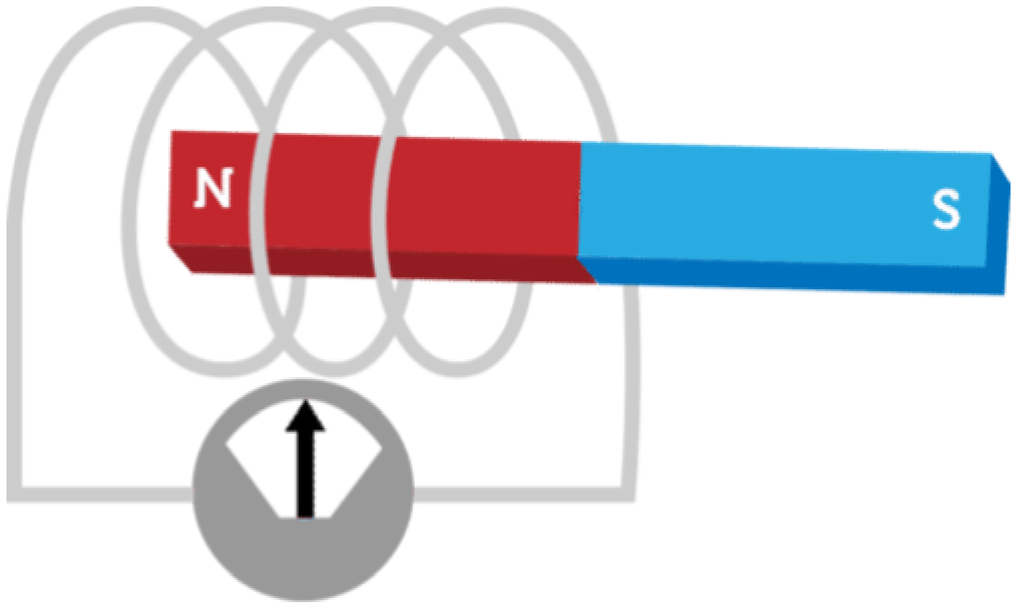


Image by Christopher AuYeung; CK-12 Foundation; CC BY-NC 3.0

Q: What is another way that a coil of wire and magnet can move relative to one another and generate an electric current?

A: The coil of wire could be moved back and forth over the magnet.

The Current Produced by a Magnet

The device with the pointer in the Figure above is an ammeter. It measures the current that flows through the wire. The faster the magnet or coil moves, the greater the amount of current that is produced. If more turns were added to the coil or a stronger magnet were used, this would produce more current as well.

The Figure below shows the direction of the current that is generated by a moving magnet. If the magnet is moved back and forth repeatedly, the current keeps changing direction. In other words, alternating current (AC) is produced. Alternating current is electric current that keeps reversing direction.

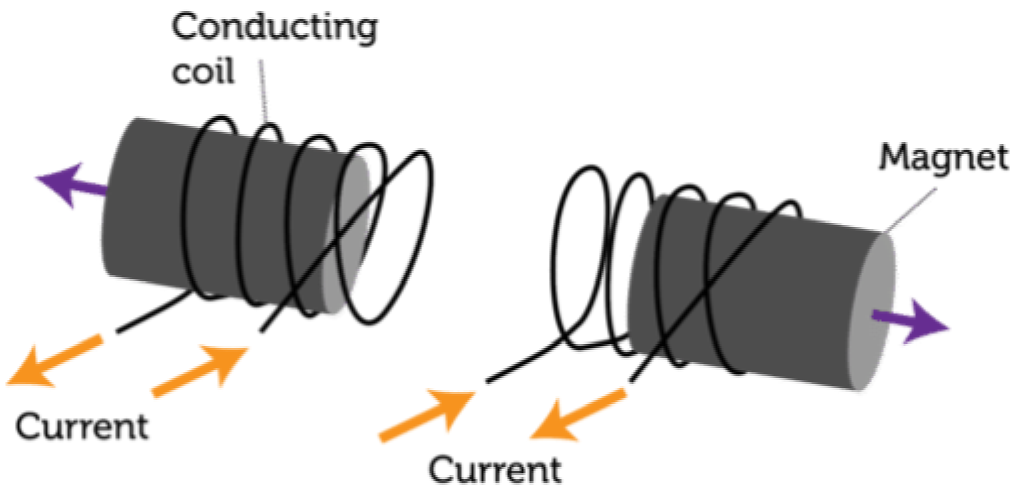


Image by Christopher AuYeung; CK-12 Foundation; CC BY-NC 3.0

How Electromagnetic Induction Is Used

Two important devices depend on electromagnetic induction: electric generators and electric transformers. Both devices play critical roles in producing and regulating the electric current we depend on in our daily lives. Electric generators use electromagnetic induction to change kinetic energy to electrical energy. They produce electricity in power plants. Electric transformers use electromagnetic induction to change the voltage of electric current. Some transformers increase voltage and others decrease voltage.

Force in a Current Carrying Wire

If we let a wire carrying a current pass through a magnetic field, a force must be experienced since we have two magnetic fields. Depending on the direction of the current, the force can either be attractive or repulsive. Since our motor has a wire ring, current flows in both directions so both attractive and repulsive forces are felt. How can you diagram these attractive and repulsive forces?

Putting It Together

Stripped Down Motor by Exploratorium,
https://www.exploratorium.edu/snacks/stripped-down-motor,
CC-BY-NC-SA

Let's revisit this phenomena: When the device is connected to a battery the copper ring (on the right above the cup) starts to spin.

Focus Questions:

1. What happens to a wire when a current flows through it?

2. What is the benefit of making a coil of wire?

3. Why does the wire ring spin when the battery is connected?

Final Task:

Construct a model which illustrates why the coil of wire spins when the wire is connected to the battery.

3.3 Interacting Objects and Fields (PHYS.3.3)

Phenomenon

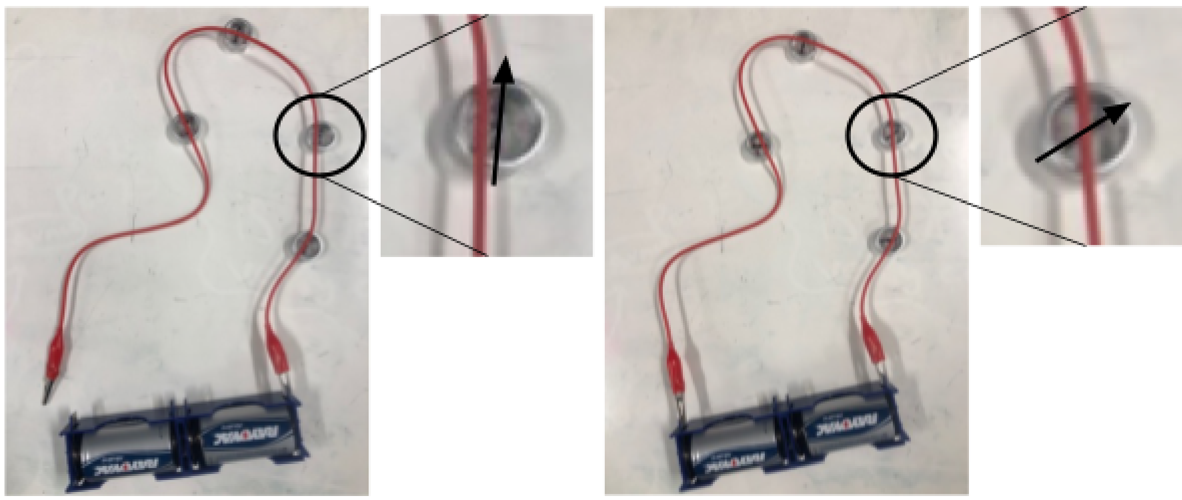


Image by Milo Maughan, CC0

When a compass is put near a wire and no current is flowing through the wire, the compass points north (picture on left). However, when a current is put through the wire, it points in a direction perpendicular to the wire (picture on right).

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. What does a current flowing through a wire cause to happen?

2. What causes a needle on a compass to point a different direction?

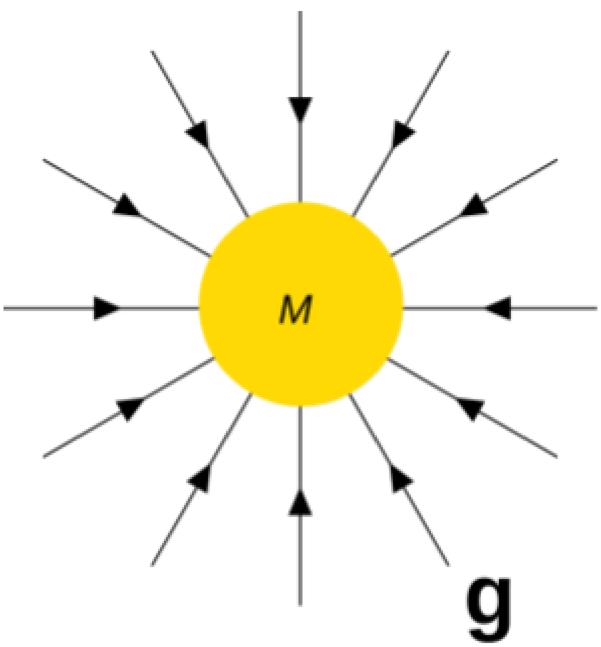
PHYS.3.3 Interacting Objects and Fields

Analyze and interpret data to compare the <u>effect</u> of changes in position of interacting objects on electric and gravitational forces and energy. Emphasize the similarities and differences between charged particles in electric fields and masses in gravitational fields. Examples could include models, simulations, or experiments that produce data or illustrate field lines between objects. (PS3.C)

In this chapter, see if you can identify how a change in an object's motion is caused by the presence of a field.

Interacting Objects and Fields

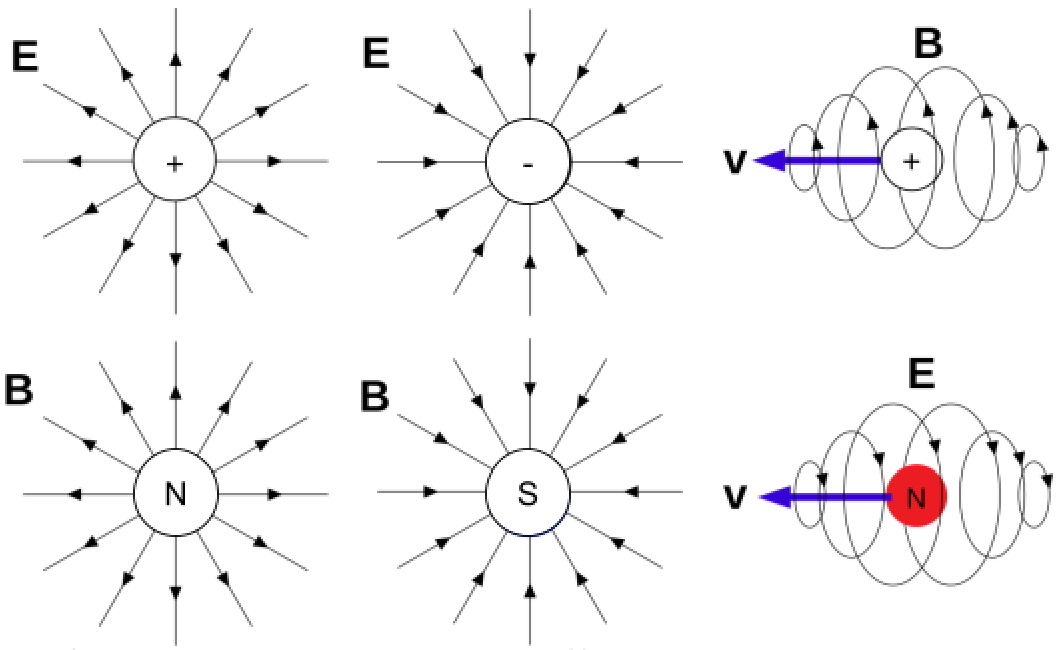
As discussed in section 3.1, two objects with mass will be attracted to each other and two objects with charge will be attracted or repelled from each other. These are interacting objects. These interactions and changes in an object's motion cause fields to emanate from an object.



Gravitation in Newton's theory by Maschen, CC0

A Field, In physics, is a region in which each point is affected by a force. Objects fall to the ground because they are affected by the force of earth's gravitational field. A paperclip placed in the magnetic field surrounding a magnet, is pulled toward the magnet, and two like magnetic poles repel each other when one is placed in the other's magnetic field. An electric field surrounds an electric charge; when another charged particle is placed in that region, it experiences an electric force which either attracts or repels it.

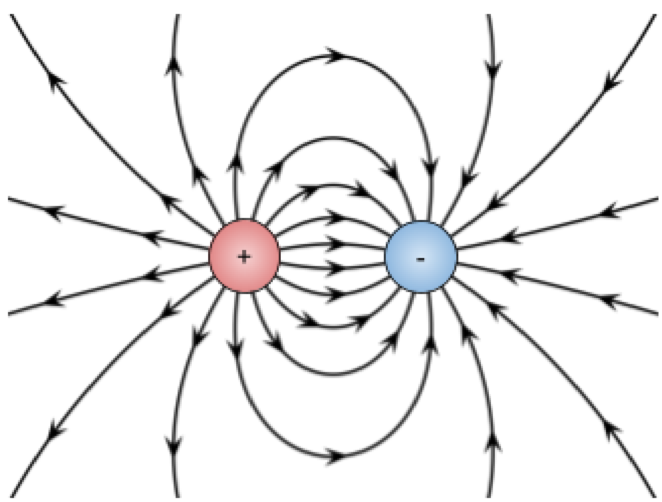
We can represent a field around an object with a series of vector lines. The diagram above represents a gravitational field around an object of mass, for example, the Earth. The strength of a field, or the forces in a particular region, can be represented by field lines; the closer the lines, the stronger the forces in that part of the field.



EM fields due to electric and magnetic monopoles by Maschen, CC0

The fields around a charged object or a magnetic object will look similar to that around an object with mass. The diagram illustrates the fields around a charged object (white/positive, black/negative) and a magnetic object (Red/North, Blue, south). However, notice that the field lines can go towards (negative, south) or away (positive, north) from our object.

Additionally, as discussed in Section 3.2, a moving charge creates a magnetic field, and a moving magnet creates an electric field. This is also illustrated on the diagram.



Adapted from "Field of a Positive and Negative Charge Point" by Geek3, https://en.wikipedia.org/wiki/Field_(physics)#/media/File:VFPt_charges_plus_minus_thumb.svg, *CC-BY-SA 3.0*

When two objects with similar fields are put in proximity to each other, the fields will interact. This interaction is illustrated in the diagram of positive and negative point charges. This interaction of fields is what produces the changes in motion. See section 3.4 for more information about field characteristics.

Putting It Together

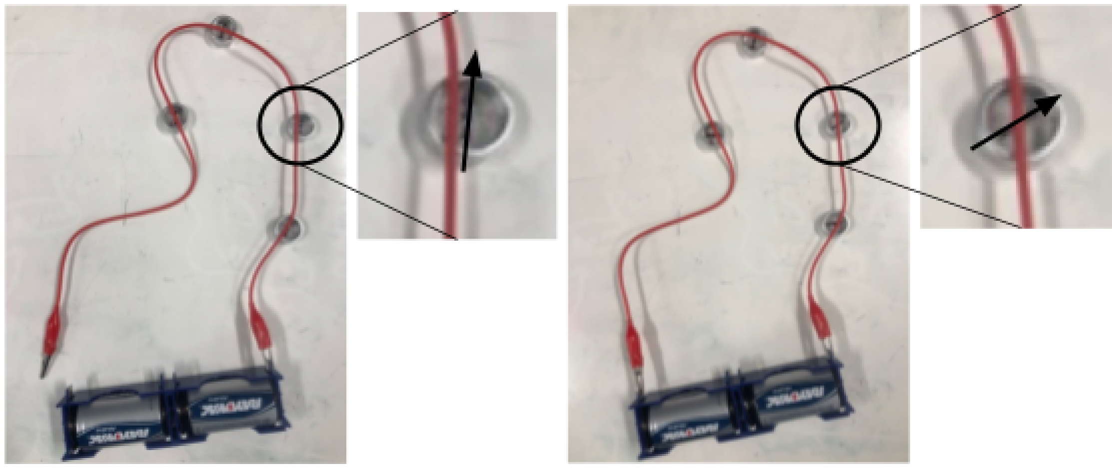


Image by Milo Maughan, CC0

Let’s revisit this phenomena: When a compass is put near a wire and no current is flowing through the wire, the compass points north (picture on left). However, when a current is put through the wire, it points in a direction perpendicular to the wire (picture on right).

Focus Questions:

1. What does a current flowing through a wire cause to happen?

2. What causes a needle on a compass to point a different direction?

3. What caused the magnetic compass to point perpendicular to the wire when a current passed through the wire?

Final Task:

Create, draw, or find a model to illustrate why the needle pointed perpendicular to the wire when a current was put through the wire.

3.4 Field Characteristics (PHYS.3.4)

Phenomenon

Static Electricity by Spencer Garness, https://flic.kr/p/79bDFN, CC-BY-NC-SA

When a charged balloon is brought near pieces of paper, pieces that are close to the balloon attract and stick to the balloon. However, pieces of paper that are farther away only slightly wiggle or don't move at all.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. What effects does a charged object have on an uncharged object?

2. What would cause an uncharged object to move towards a charged object?

3. How does distance affect how a charged object affects the area around it?

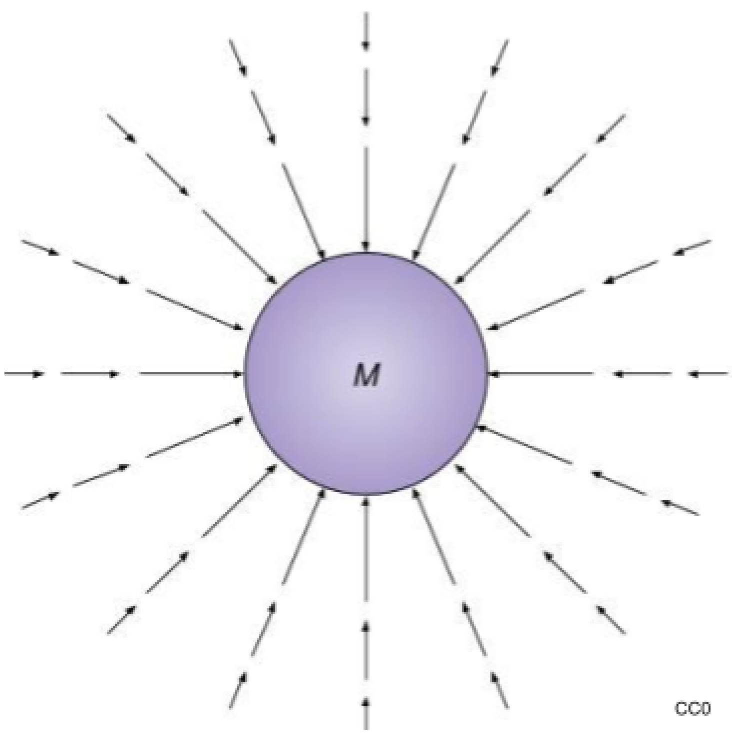
PHYS.3.4 Field Characteristics

Develop and use a model to evaluate the <u>effects</u> on a field as characteristics of its source and surrounding space are varied. Emphasize how a field changes with distance from its source. Examples of electric fields could include those resulting from point charges. Examples of magnetic fields could include those resulting from dipole magnets or current-bearing wires. (PS3.C)

In this chapter, see if you can identify the causes and effects in motion as the position inside of a field is changed.

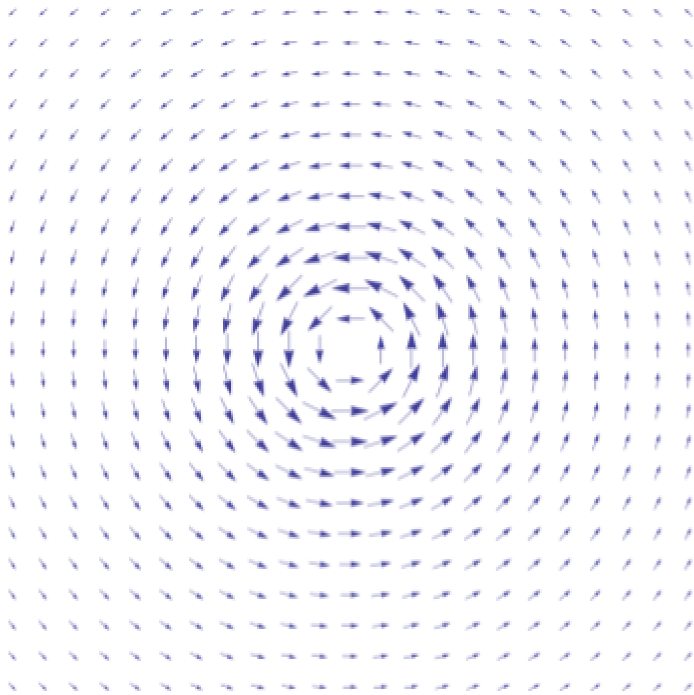
Field Characteristics

Section 3.3 introduced you to fields, this section will describe the characteristics of fields. Section 3.3 illustrated a field using continuous field lines. Alternatively, a field can be represented using a series of vectors. The diagram shows a vector field around the Earth.



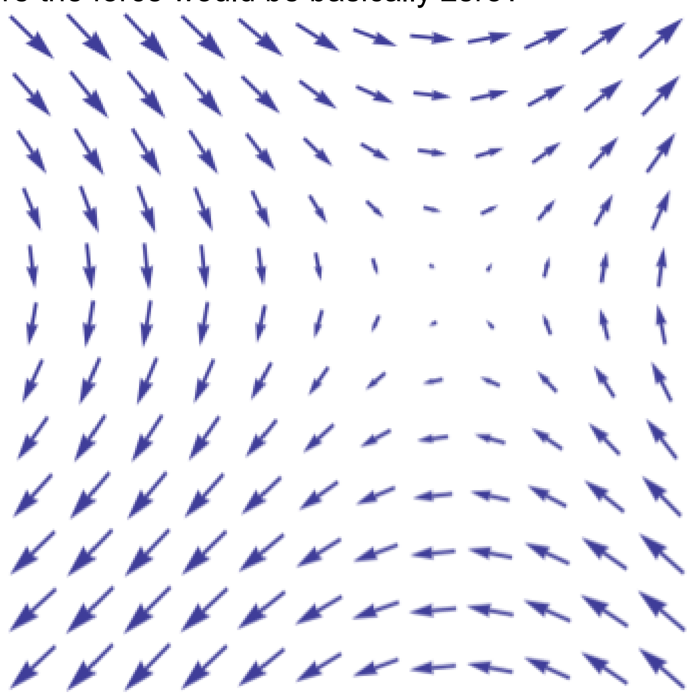
This model of a field is helpful because it shows the strength of the field at different positions. This is represented by the length of the vectors. The longer the vector, the stronger the gravitational force on the object. When looking at the diaphragm, the farther away an object is from the Earth, the weaker the gravitational force is (as indicated by shorter vectors farther away from the earth).

Any field can be represented by this type of vector diagram. The picture below illustrates a magnetic vector field around a wire carrying current.



Irrotational Field by AllenMcC,
https://en.wikipedia.org/wiki/Vector_field#/media/File:Irrotationalfield.svg, CC-BY-SA 3.0

Vector fields can also be useful to show what would happen to the force in the presence of multiple interacting fields. The next diagram illustrates this idea. Can you identify where the force would be basically zero?



Vector Fields by Jim.belk, CC0

Putting It Together

Static Electricity by Spencer Garness, https://flic.kr/p/79bDFN, CC-BY-NC-SA

Let's Revisit this phenomenon: When a charged balloon is brought near pieces of paper, pieces that are close to the balloon attract and stick to the balloon. However, pieces of paper that are farther away only slightly wiggle or don't move at all.

Focus Questions

1. What effects does a charged object have on an uncharged object?

2. What would cause an uncharged object to move towards a charged object?

3. How does distance affect how a charged object affects the area around it?

Final Task:

Draw a model showing the electric field around the balloon. Illustrate the pieces of paper and explain why some pieces of paper are attracted to the balloon while others are not.

CHAPTER 4

Strand 4: Waves

Chapter Outline

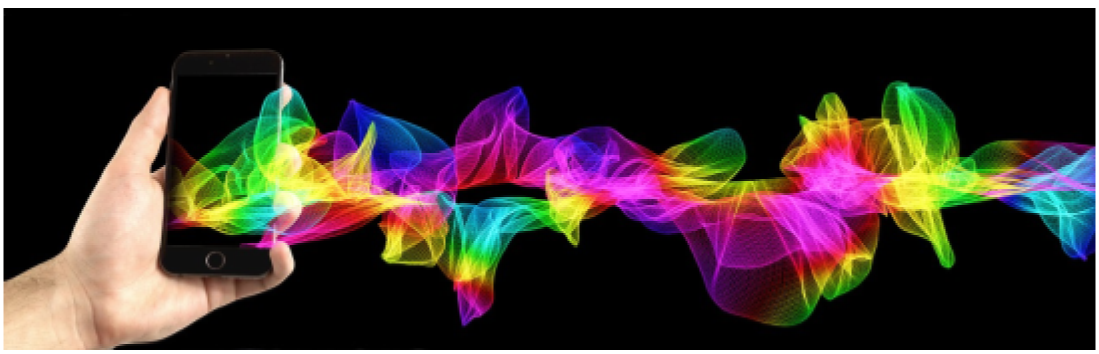


Image by Gerd Altmann (geralt), pixabay.com, CC0

Waves transfer energy through oscillations of fields or matter. The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it passes. Waves produce interference as they overlap but they emerge unaffected by each other. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. Electromagnetic radiation can be modeled as a wave of changing electric and magnetic fields or as particles called photons. When light or longer wavelength electromagnetic radiation is absorbed in matter, it is generally converted into thermal energy. Because waves depend upon the properties of fields and the predictable transformation of energy, they can be used to interpret the nature of matter and its energy. Waves are utilized to transmit information both in analog and digital forms.

4.1 Wave Speed Relationship (PHYS.4.1)

Phenomenon

Image by sethink, pixabay.com, CC0

When lightning strikes, there is time in-between when we see the lightning and when we hear the thunder.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

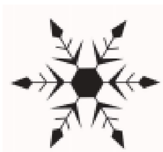
Focus Questions

1. What are the similarities and differences between light and sound waves?

2. What characteristics of light and sound would cause you to see the lightning before you hear the thunder?

PHYS.4.1 Wave Speed Relationship

Analyze and interpret data to derive both qualitative and quantitative relationships based on patterns observed in frequency, wavelength, and speed of waves traveling in various media. Emphasize mathematical relationships and qualitative descriptions. Examples of data could include electromagnetic radiation traveling in a vacuum or glass, sound waves traveling through air or water, or seismic waves traveling through Earth. (PS4.A)



Usually when looking for patterns we are looking at tangible objects and comparing and contrasting. For this section, look for patterns in the relationships of the mathematical models that are developed.

Image by Arek Socha (qimono), pixabay.com, CC0

No doubt you've seen this happen. Droplets of water fall into a body of water, and concentric circles spread out through the water around the droplets. The concentric circles are waves moving through the water.

What is a Mechanical Wave?

The waves in the picture above are examples of mechanical waves. A mechanical wave is a disturbance that transfers energy through matter. A mechanical wave starts when matter is disturbed. A source of energy is needed to disturb matter and start a mechanical wave. Where does the energy come from in the water wave pictured above?

The Medium

The energy of a mechanical wave can travel only through matter. The matter through which the wave travels is called the medium (plural, media). The medium in the water wave pictured above is water, a liquid. But the medium of a mechanical wave can be any state of matter, even a solid. How do the particles of the medium move when a wave passes through them?

Types of Mechanical Waves

There are three types of mechanical waves: transverse, longitudinal, and surface waves. They differ in how particles of the medium move. You can see this in the figure and in the animation at the following URL.

• http://go.uen.org/b4o

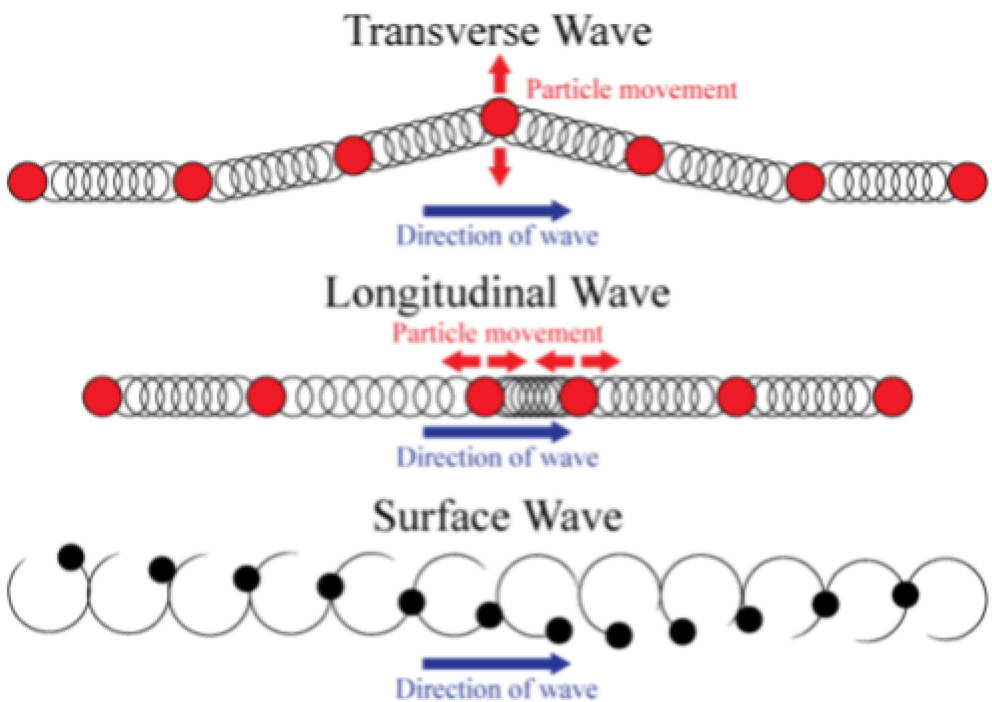


Image by CK-12 Foundation, CC-BY-NC-SA 3.0

In a transverse wave, particles of the medium vibrate up and down perpendicular to
the direction of the wave.

- In a longitudinal wave, particles of the medium vibrate back and forth parallel to the direction of the wave.
- In a surface wave, particles of the medium vibrate both up and down and back and forth, so they end up moving in a circle. Think of this as a combination of transverse and longitudinal wave

What Is a Transverse Wave?

A transverse wave is a wave in which particles of the medium move at right angles, or perpendicular, to the direction that the wave travels. Another example of a transverse wave is the wave that passes through a rope with you shake it up and down, as in the figure. The direction of the wave is down the length of the rope away from the hand. The rope itself moves up and down as the wave passes through it.

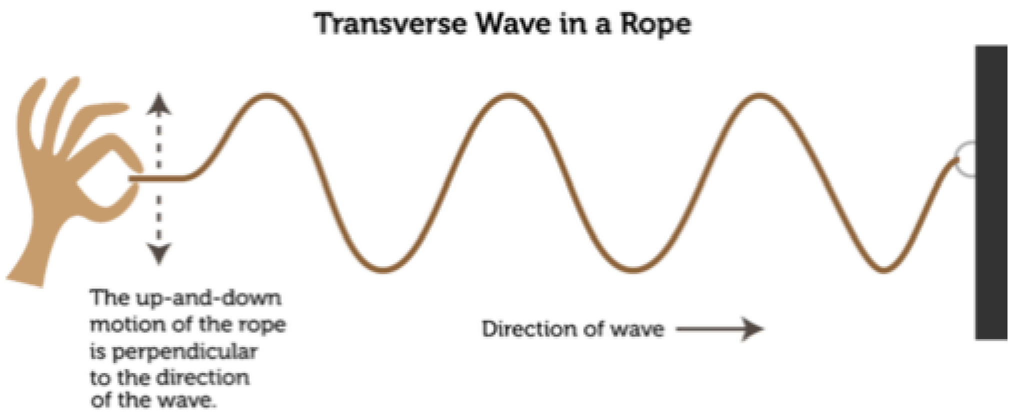


Image by Christopher Auyeung;Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

When a guitar string is plucked, in what direction does the wave travel? In what direction does the string vibrate?

Crests and Troughs

A transverse wave is characterized by the high and low points reached by particles of the medium as the wave passes through. The high points are called crests, and the low points are called troughs. You can see both in the figure.

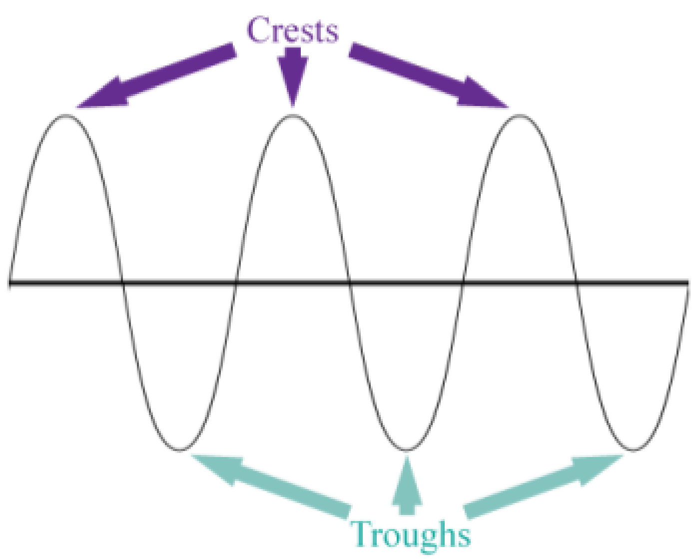


Image Image by Christopher Auyeung;Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

What Is a Longitudinal Wave?

A longitudinal wave is a type of mechanical wave. A mechanical wave is a wave that travels through matter, (referred to as a medium, such as air or water). In a longitudinal wave, particles of the medium transfer kinetic energy through collisions in a direction that is parallel to the direction that the wave travels. You can see this in the figure. The person's hand pushes and pulls on one end of the spring. The energy of this disturbance passes through the coils of the spring to the other end.

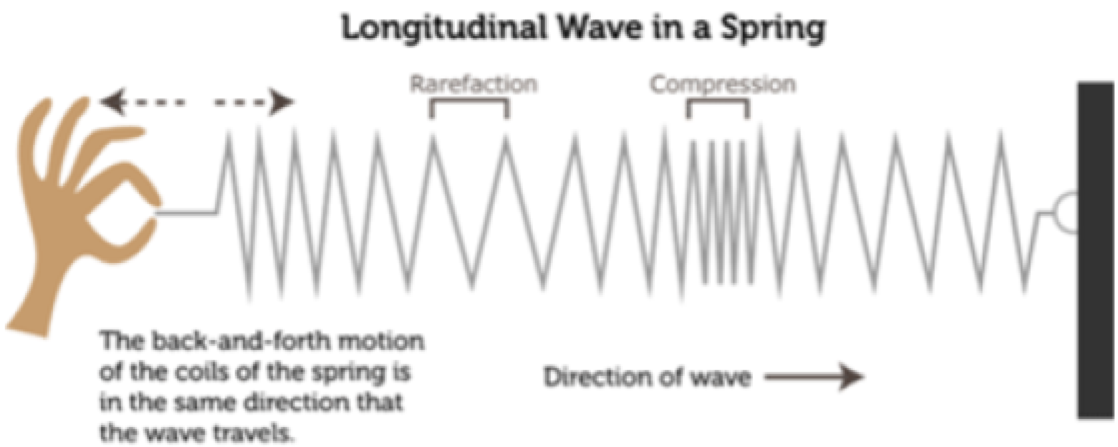


Image by Christopher Auyeung;Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

Wavelength
Wavelength is one way of measuring the size of waves. It is the distance between two corresponding points on adjacent waves, and it is usually measured in meters. How it is measured is a little different for transverse and longitudinal waves. In a transverse wave, particles of the medium move up and down at right angles to the direction that the wave travels. The wavelength of a transverse wave can be measured as the distance between two adjacent crests, or high points, as shown in the diagram.

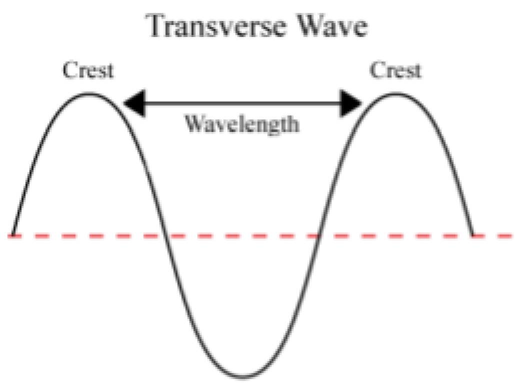


Image by Christopher Auyeung;Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

In a longitudinal wave, particles of matter move back and forth in the same direction that the wave travels. The wavelength of a longitudinal wave can be measured as the distance between two adjacent compressions, as shown in the diagram. Compressions are the places where particles of the medium crowd close together as the energy of the wave passes through.

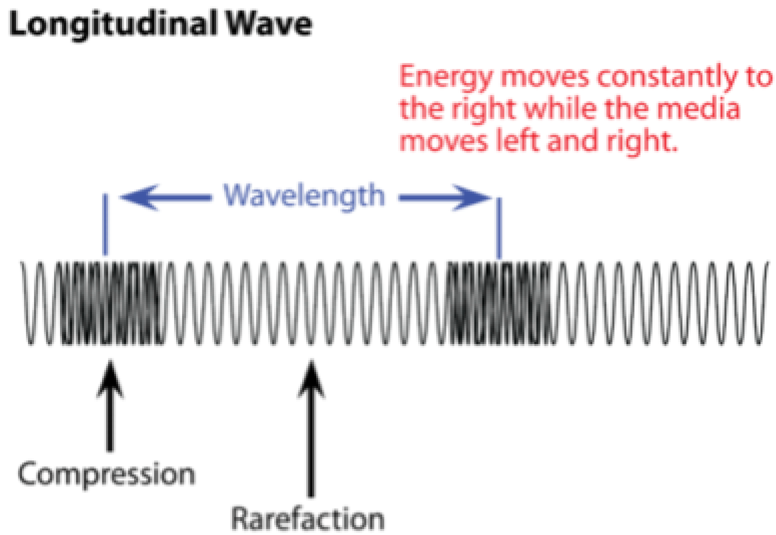


Image by Christopher Auyeung;Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

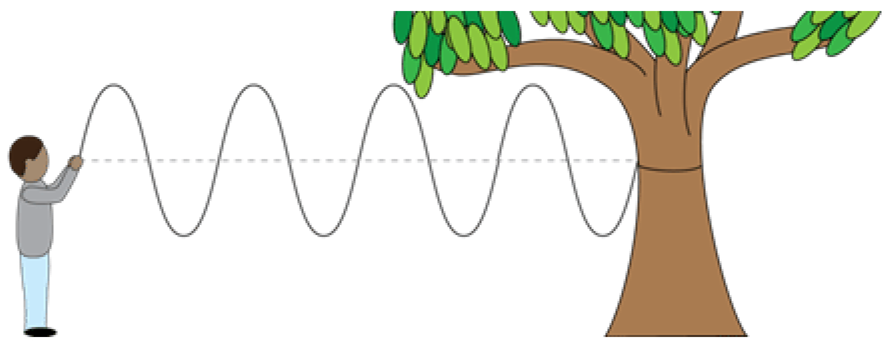


Image by Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

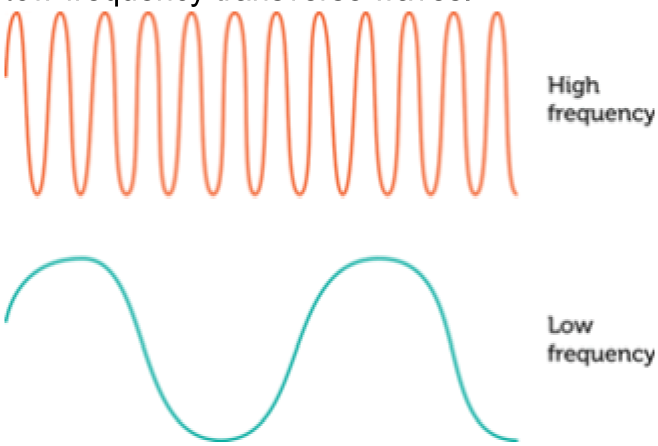
Imagine making transverse waves in a rope, like the person in the sketch above. You tie one end of the rope to a tree or other fixed point, and then you shake the other end of the rope up and down with your hand. You can move the rope up and down slowly or quickly. How quickly you move the rope determines the frequency of the waves. You can make a longitudinal wave by moving a slinky back and forth in the same direction as illustrated in the previous diagram.

Period

The period, commonly represented by the symbol T, is the amount of time for the harmonic motion to repeat itself, or for the object to go one full cycle. The period of a wave is the time it takes the object to return to its exact starting point and starting direction. The period of a wave depends on the period of oscillation of the object creating the wave.

Frequency

The number of waves that pass a fixed point in a given amount of time is wave frequency. Wave frequency can be measured by counting the number of wavelengths of waves that pass a fixed point in 1 second or some other time period. The higher the number is, the greater the frequency of the waves. The SI unit for wave frequency is the hertz (Hz), where 1 hertz equals 1 wave cycle passing a fixed point in 1 second. The figure below shows high-frequency and low-frequency transverse waves.



The higher frequency also has the shortest wavelength.

Image by Christopher AuYeung; CK-12 Foundation; CC BY-NC 3.0

How are speed, wavelength, and frequency related?

Assume that you move one end of a rope up and down just once to generate a wave in the rope. How long will it take the wave to travel down the rope to the other end? It depends on the length of the rope and the speed of the wave.

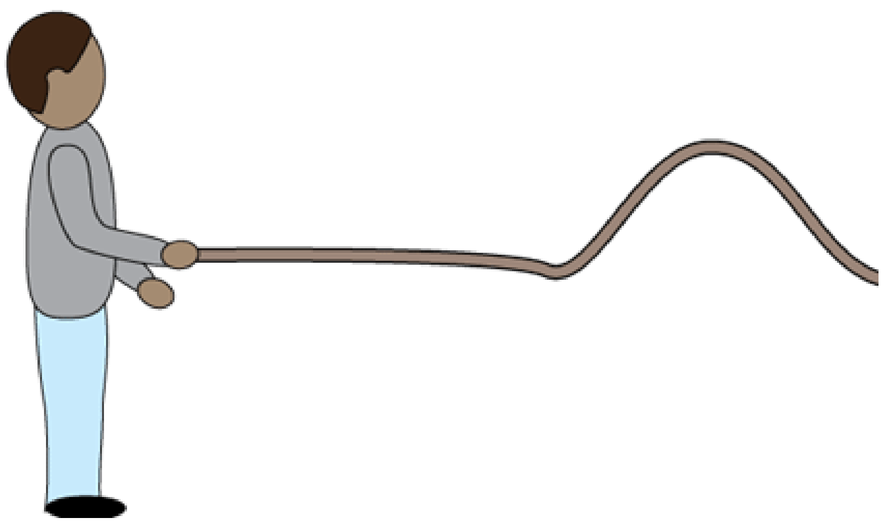


Image by Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0

The Speed of a Wave

To mathematically model the speed of a wave we make the assumption that the wave speed will remain constant. This allows us to use the simple relationship between distance traveled, speed, and time

$$v = \frac{d}{t}$$

We want to express the wave speed in terms of wave measurements, specifically wavelength and frequency.

First we should set a time limit for the motion to occur, let's allow one period of time to pass. How far will the wave travel in one period of time?

$$v = \frac{\lambda}{T}$$

where λ represents the wavelength measured in meters

By using the reciprocal relationship between period and frequency, we arrive at the wave speed equation

$$v = \lambda f$$

How are wavelength and frequency related? What would have to happen to the wavelength of a wave if it travels at the same speed, but has a decrease in frequency?

How are electromagnetic waves made?

Electromagnetic waves are waves that are created by vibrating charges in an electromagnetic field. Like other waves, electromagnetic waves transfer energy from one place to another. The transfer of energy by electromagnetic waves is called electromagnetic radiation. Electromagnetic waves can transfer energy through matter or across empty space.

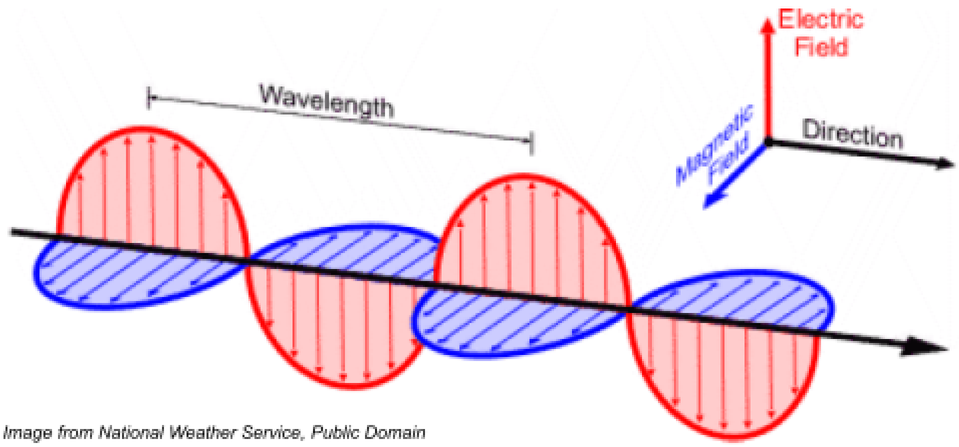


Image from National Weather Service, Public Domain

How an Electromagnetic Wave Travels

As you can see in the diagram, the electric and magnetic fields that make up an electromagnetic wave are perpendicular (at right angles) to each other. Both fields are also perpendicular to the direction that the wave travels. Therefore, an electromagnetic wave is a transverse wave. However, unlike a mechanical transverse wave, which can only travel through matter, an electromagnetic transverse wave can travel through empty space since it travels through this EM field. When waves travel through matter, they lose some energy to the matter as they pass through it. But when electromagnetic waves travel through space, no energy is lost. Therefore, electromagnetic waves don't get weaker as they travel. However, the energy is "diluted" as it travels farther from its source because it spreads
out over an ever-larger area.

How fast do EM waves travel?

The term "electromagnetic radiation" is a fancy term for light. What we know as light is only a small portion of all possible light. Birds, for example, can see in the ultraviolet region and humans glow in the infrared. Older TV remotes that have the light bulb on the end transmit information through a blinking IR bulb. You can see this through your smart phone, provided it is not Apple. Why wouldn't an Apple device show this?

Speed of Electromagnetic Waves

All electromagnetic waves travel at the same speed through empty space. That speed, called the speed of light, is about 300 million meters per second (3.0x108 m/s) and is denoted with the letter c. No matter what frame of reference you select, this is the speed you measure. It is the main idea behind the special theory of relativity. Our wave speed model can then be specified for light as $c = \lambda f$

Putting It Together

Image by sethink, pixabay.com, CC0

Let’s revisit this phenomena: When lightning strikes, there is time in-between when we see the lightning and when we hear the thunder.

Focus Questions:

1. What are the similarities between the characteristics of sound and light waves?

2. What are the differences between the characteristics of sound and light waves?

Final Task:

Construct an explanation using evidence as to why we hear thunder after seeing lightning.

4.2 Particle-Wave Duality (PHYS.4.2)

Phenomenon

Reverse Refractions by Trina Alexander; https://flic.kr/p/MkgXc; CC BY-NC-ND

Your friend has a glass ball and you observe his image while looking through the glass ball.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

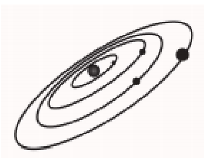
Focus Questions

1. What is the orientation of the person in the picture? How does this orientation compare to what we are seeing in the glass ball?

2. What is happening to the light in order to produce the image that we see in the glass ball?

PHYS.4.2 Particle-Wave Duality

Engage in argument based on evidence that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model better explains interactions within a system than the other. Emphasize how the experimental evidence supports the claim and how models and explanations are modified in light of new evidence. Examples could include resonance, interference, diffraction, or the photoelectric effect. (PS4.A, PS4.B)

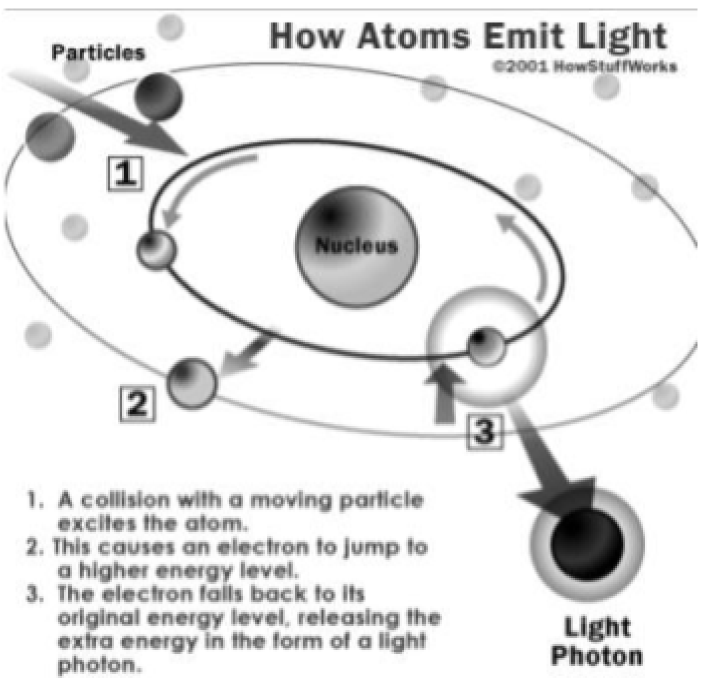


In this chapter, see if you can identify if the characteristics of light discussed supports whether the system of a light behaves like a wave or like a particle.

What is Light?

Have you ever wondered what light is? What is it made of? As mentioned in section 4.1, visible light is only a small portion of a much larger spectrum, the electromagnetic spectrum.

Electromagnetic waves are waves that consist of vibrating electric and magnetic fields. Like other waves, electromagnetic waves transfer energy from one place to another. The transfer of energy by electromagnetic waves is called electromagnetic radiation. Electromagnetic waves can transfer energy through matter or across empty space.



How an Electromagnetic Wave Begins

An electromagnetic wave begins when an electrically charged particle vibrates (see diagram). A vibrating charged particle causes the electric field surrounding it to vibrate as well. A vibrating electric field, in turn, creates a vibrating magnetic field. The two types of vibrating fields combine to create an electromagnetic wave.

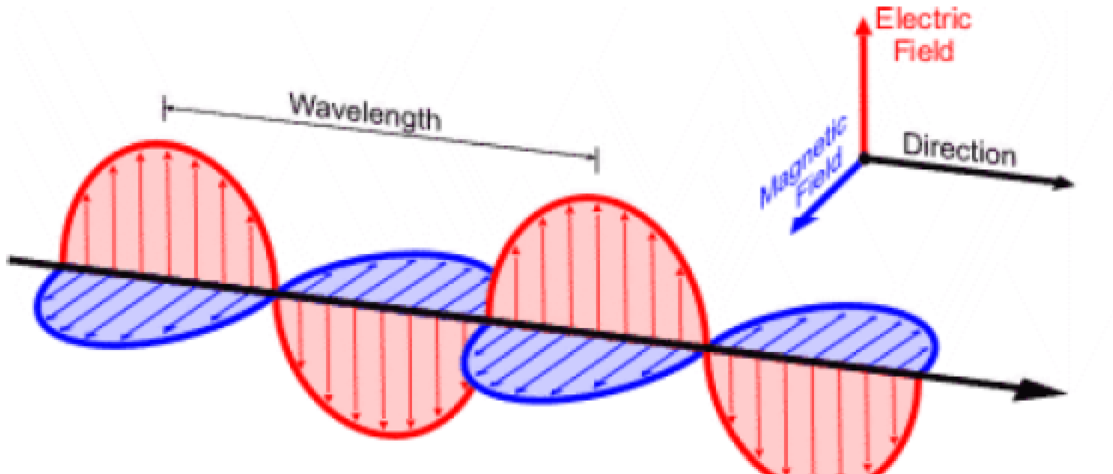


Image from National Weather Service, Public Domain

How an Electromagnetic Wave Travels

As you can see in the diagram, the electric and magnetic fields that make up an electromagnetic wave are perpendicular (at right angles) to each other. Both fields are also perpendicular to the direction that the wave travels. Therefore, an electromagnetic wave is a transverse wave. However, unlike a mechanical transverse wave, which can only travel through matter, an electromagnetic transverse wave can travel through empty space. When waves travel through matter, they lose some energy to the matter as they pass through it. But when electromagnetic waves travel through space, no energy is lost. Therefore, electromagnetic waves don't get weaker as they travel. However, the energy is "diluted" as it travels farther from its source because it spreads out over an ever-larger area.

How fast do EM waves travel?


Image by Thomas Tangelakis, pixabay.com, CC0


Image by rawpixel, pixabay.com, CC0

What do these two photos have in common?

They both represent electromagnetic waves. These are waves that consist of vibrating electric and magnetic fields. They transmit energy through matter or across space. Some electromagnetic waves are generally harmless. The light we use to see is a good example. Other electromagnetic waves can be very harmful and care must be taken to avoid too much exposure to them. X rays are a familiar example. Why do electromagnetic waves vary in these ways? It depends on their properties. Like other waves, electromagnetic waves have properties of speed, wavelength, and frequency.

Speed of Electromagnetic Waves

All electromagnetic waves travel at the same speed through empty space. That speed, called the speed of light, is about 300 million meters per second (3.0×10^8 m/s). Nothing else in the universe is known to travel this fast. The sun is about 150 million kilometers (93 million miles) from Earth, but it takes electromagnetic radiation only 8 minutes to reach Earth from the sun. If you could move that fast, you would be able to travel around Earth 7.5 times in just 1 second!

Section 4.1 discussed the wave speed equation where, $|v| = \lambda f$. Therefore, if either wavelength or frequency is known, the missing value can be calculated since we always know the speed of the wave. Consider an electromagnetic wave that has a wavelength of 3 meters. Its speed, like the speed of all electromagnetic waves, is 3.0×10^8 meters per second. Its frequency can be found by substituting these values into the frequency equation:

$$f = \frac{|v|}{\lambda}$$

$$f = \frac{3\times10^8 \text{ m/s}}{3\text{m}} = 1\times10^8 \text{ Hz}$$

Sometimes the speed of electromagnetic waves is represented by c.

$c = \lambda f$ wave equation for light

$c = 3 \times 10^8 \; m/s$ the speed of light in a vacuum

What is the EM spectrum?

Electromagnetic (EM) waves are classified by their frequency and wavelength. EM waves with a high frequency also have a short wavelength. EM waves with a low frequency have a long wavelength. Energy is directly related to the frequency of a wave. The higher the frequency, the more energy the wave has.

Radio waves have a very low frequency and therefore a low energy. Gamma rays have a high frequency and high energy.

Visible light (the part of the EM spectrum that we see) is a very small portion of the EM spectrum. Red has the lowest frequency and the longest wavelength of the light that humans can see. Violet light has the highest frequency of visible light. EM waves that have a slightly lower frequency than red are called infrared waves. EM waves with a slightly higher frequency than violet light are called ultraviolet waves.

The spectrum of electromagnetic radiation can be roughly broken into the following ranges:

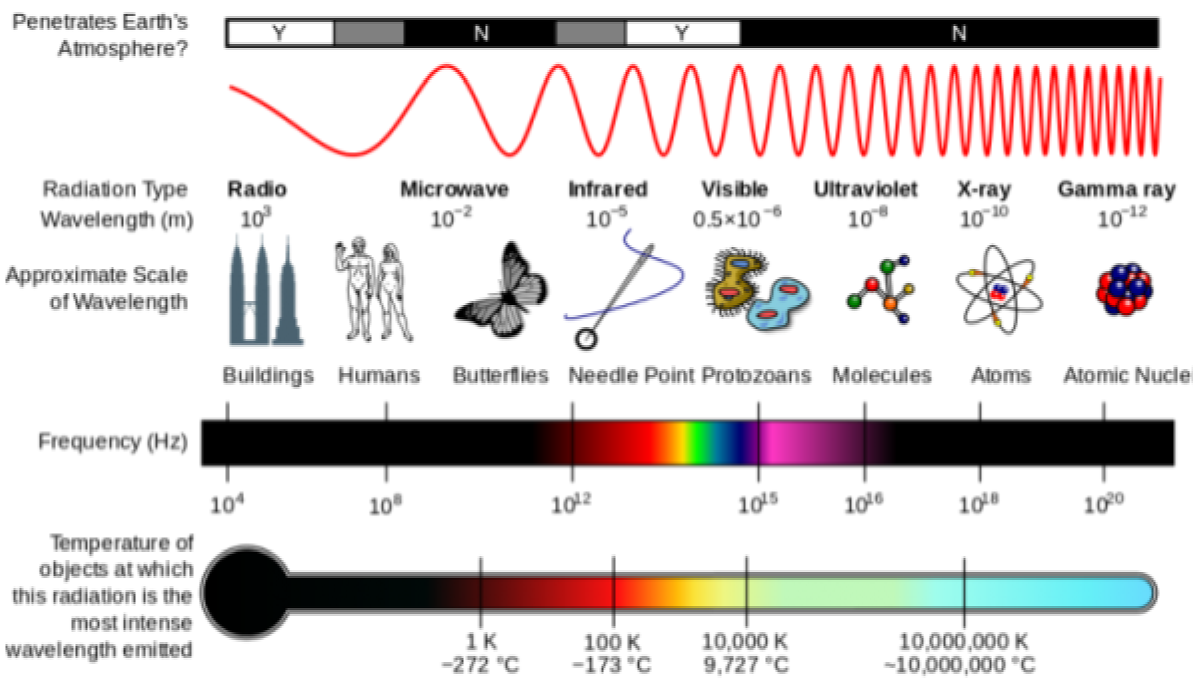


Photo: By Inductiveload, NASA – self-made, information by NASABased off of File:EM Spectrum3-new.jpg by NASAThe butterfly icon is from the P icon set, File:P biology.svgThe humans are from the Pioneer plaque, File:Human.svgThe buildings are the Petronas towers and the Empire State Buildings, both from File:Skyscrapercompare.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2974242

In the table below, the parts of the EM spectrum are classified by their wavelengths.

EM wave	Wavelength range	Comparison size
gamma-ray (γ - ray)	10^{-11} m and shorter	atomic nucleus
x – ray	10^{-11} m–10^{-8} m	hydrogen atom
ultraviolet (UV)	10^{-8} m–10^{-7} m	small molecule
violet (visible)	~4×10^{-7} m(400 nm)	typical molecule
blue (visible)	~450 nm	typical molecule
green (visible)	~500 nm	typical molecule
red (visible)	~650 nm	typical molecule
infrared (IR)	10^{-6} m – 1 mm	human hair
Microwave	1 mm – 10 cm	human finger
Radio	Larger than 10 cm	car antenna

Electromagnetic Wave Interactions

When electromagnetic waves strike matter, they may interact with it in the same ways that mechanical waves interact with matter. Electromagnetic waves may:

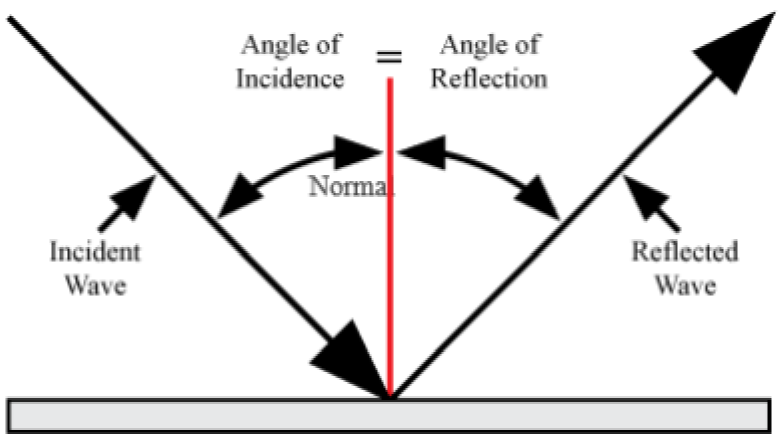
- Reflect - bounce back from a surface;
- Refract - bend when entering a new medium;
- Diffract - spread out around obstacles or through openings.

Electromagnetic waves may also be absorbed by matter and converted to other forms of energy. Microwaves are a familiar example. When microwaves strike food in a microwave oven, they are absorbed and converted to thermal energy, which heats the food.

Reflection

An echo is an example of wave reflection. Reflection occurs when waves bounce back from a boundary that separates two different mediums. Reflection can happen with any type of waves, not just sound waves. For example, light waves can also be reflected. In fact, that's how we see most objects. Light from a light source, such as the sun or a light bulb, shines on the object and some of the light is reflected. When the reflected light enters our eyes, we can see the object.

Reflected waves have the same speed and frequency as the original waves before they were reflected because they do not change the medium. However, the direction of the reflected waves is different. When waves strike an obstacle head on, the reflected waves bounce straight back in the direction they came from. When waves strike an obstacle at any other angle, they bounce back at the same angle but in a different direction. This is illustrated in the diagram. In this diagram, waves strike a wall at an angle, called the angle of incidence. The waves are reflected at the same angle, called the angle of reflection, but in a different direction. Notice that both angles are measured relative to a line that is perpendicular to the wall. This line is called the normal line.



Refraction

Refraction is another way that waves interact with matter. Refraction occurs when waves bend as they enter a new medium at an angle. You can see an example of refraction in the picture. Light bends when it passes from air to water or from water to air. The bending of the light traveling from the fish to the man's eyes causes the fish to appear to be in a different place from where it actually is.

Waves bend as they enter a new medium because they start traveling at a different speed in the new medium. For example, light travels more slowly in water than in air. This causes it to refract when it passes from air to water or from water to air.

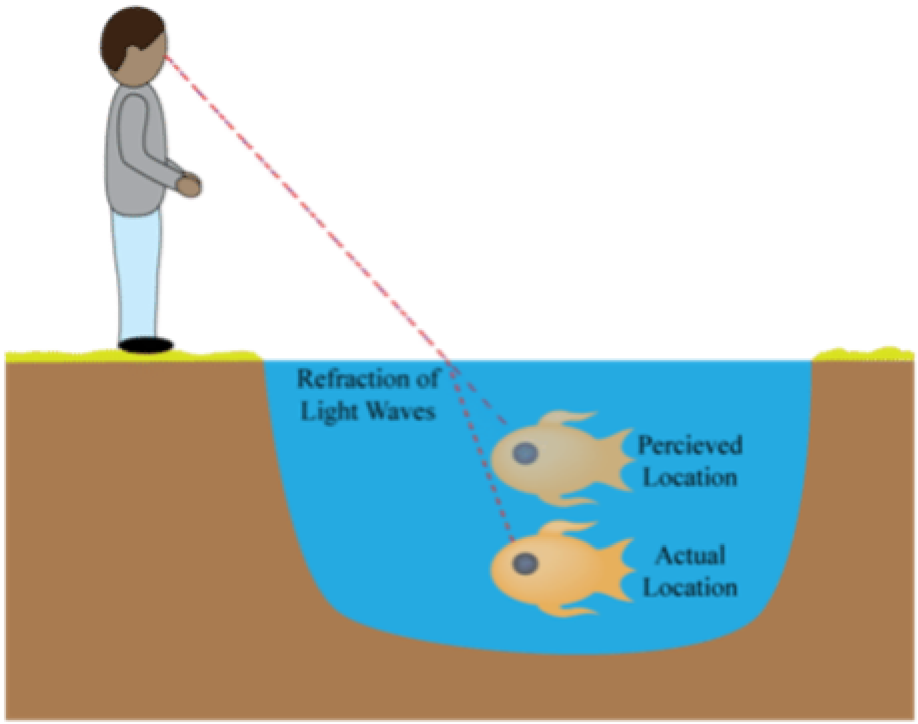


Image by CK-12 Foundation CC-BY-NC-SA 3.0

Q: Where would the fish appear to be if the man looked down at it from straight above its actual location?
A: The fish would appear to be where it actually is because refraction occurs only when waves (in this case light waves from the fish) enter a new medium at an angle other than the normal.

Diffraction
Did you ever notice that you can hear sounds around the corners of buildings even though you can't see around them? The figure shows why this happens. As you can see from the figure, sound waves spread out and travel around obstacles. This is called diffraction. It also occurs when waves pass through an opening in an obstacle. All waves may be diffracted, but it is more pronounced in some types of waves than others. For example, sound waves bend around corners much more than light does. That's why you can hear but not see around

corners.

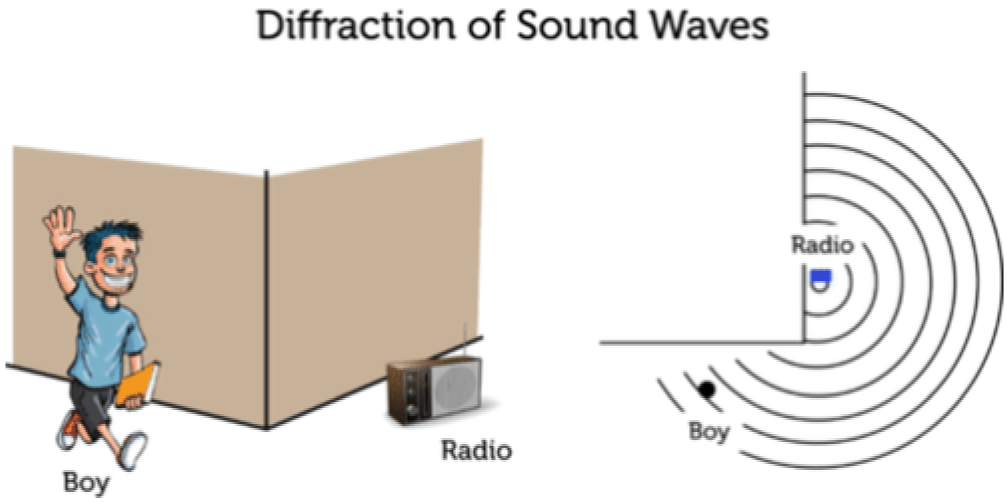
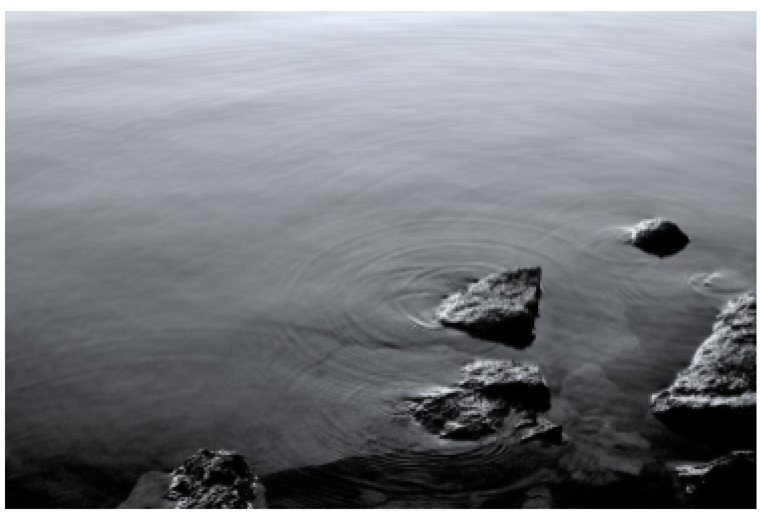


Image by ck12 Foundation, CC-BY-SA

For a given type of wave, such as sound waves, how much the waves diffract depends on the size of the obstacle (or opening in the obstacle) and the wavelength of the waves. In the figure, there is a small opening for the sound waves coming from the radio. This small opening allows a small amount of diffraction to happen and the sound can now be heard around the corner by the boy. Note that the wavelength of the wave is the distance between the vertical lines.

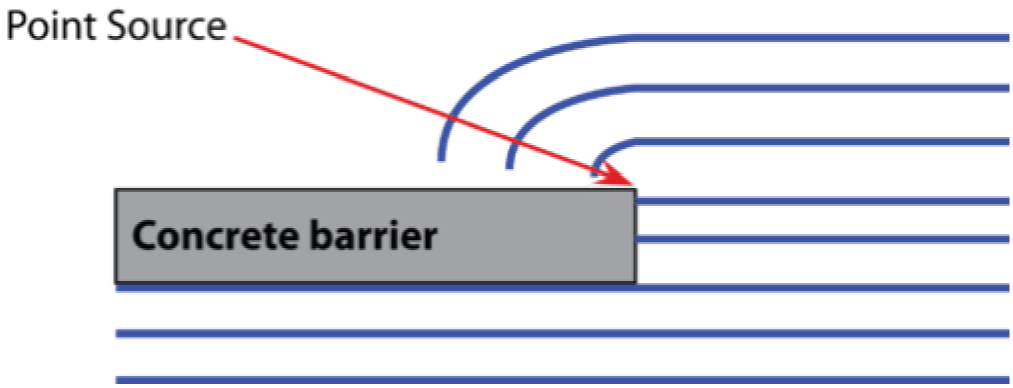
Diffraction and Interference



Zen Ripples by kansasphoto;Samantha Bacic, https://flic.kr/p/665E3r, CC-BY

When waves strike a small slit in a wall, they create circular wave patterns on the other side of the barrier. This is seen in the image above, where ocean waves create precise circular waves. The circular waves undergo constructive and destructive interference, which generates a regular interference pattern.

When a series of straight waves strike an impenetrable barrier, the waves stop at the barrier. However, the last particle of the medium at the back corner of the barrier will create circular waves from that point, called the point source. This can be seen in the image below. This phenomenon is called diffraction, and it occurs in liquid, sound, and light waves. While the waves become circular waves at the point source, they continue as straight waves where the barrier does not interfere with the waves.



Any two waves in the same medium undergo wave interference as they pass each other. At the location where the two waves collide, the result is essentially a summation of the two waves. In some places, a wave crest from one source will overlap a wave crest from the other source. Since both waves are lifting the medium, the combined wave crest will be twice as high as the original crests. Nearby, a wave trough will overlap another wave trough and the new trough will be twice as deep as the original. This is called constructive interference because the resulting wave is larger than the original waves. Within the interference pattern, the amplitude will be twice the original amplitude. Once the waves pass through each other and are alone again, their amplitudes return to their original values.

In other parts of the wave pattern, crests from one wave will overlap troughs from another wave. When the two waves have the same amplitude, this interaction causes them to cancel each other out. Instead of a crest or trough, there is nothing. When this cancellation occurs, it is called destructive interference.

Image by Kathy Shield, CK-12 Foundation, CC BY-NC-SA

It is easy to see how waves emanating from multiple sources, such as drops of rainwater in still water, create interference patterns. But a single source of waves can create interference patterns with itself as a result of diffraction.

The Double Slit Experiment

A similar situation to the raindrops above occurs when straight waves strike a barrier containing two slits. These waves are cut off everywhere except for where the waves that pass through the two slits. The medium in the slits again acts as a point source to produce circular waves on the far side of the barrier.

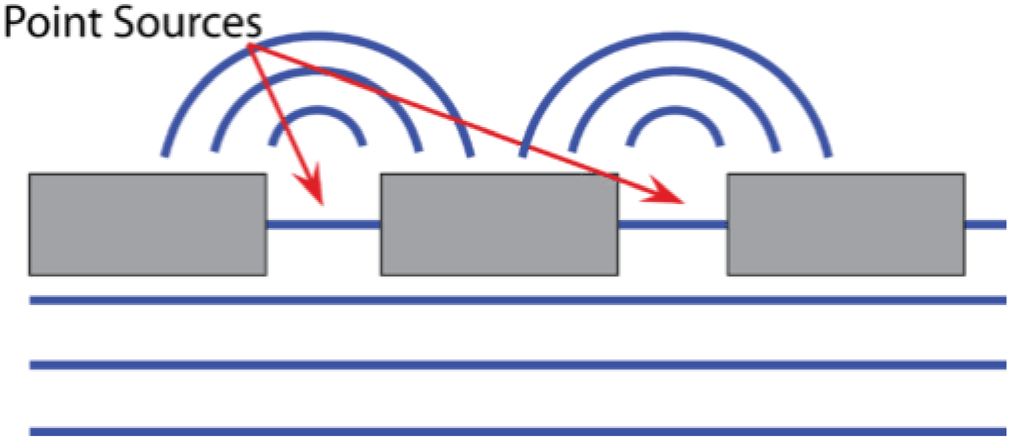


Image by CK-12 Foundation CC-BY-NC-SA 3.0

As long as these two circular waves have the same wavelength, they interfere constructively and destructively in a specific pattern. This pattern is called the wave interference pattern. The same thing is observed when using light and is characterized by light and dark bands. The light bands are a result of constructive interference, and the dark bands occur because of destructive interference.

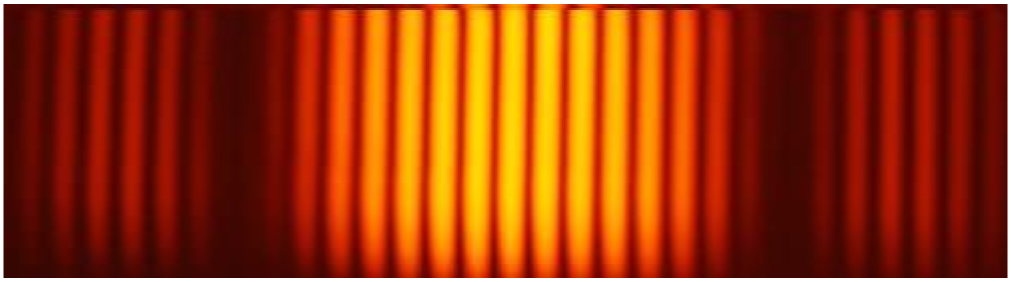


Image by Pieter Kuiper, Public Domain

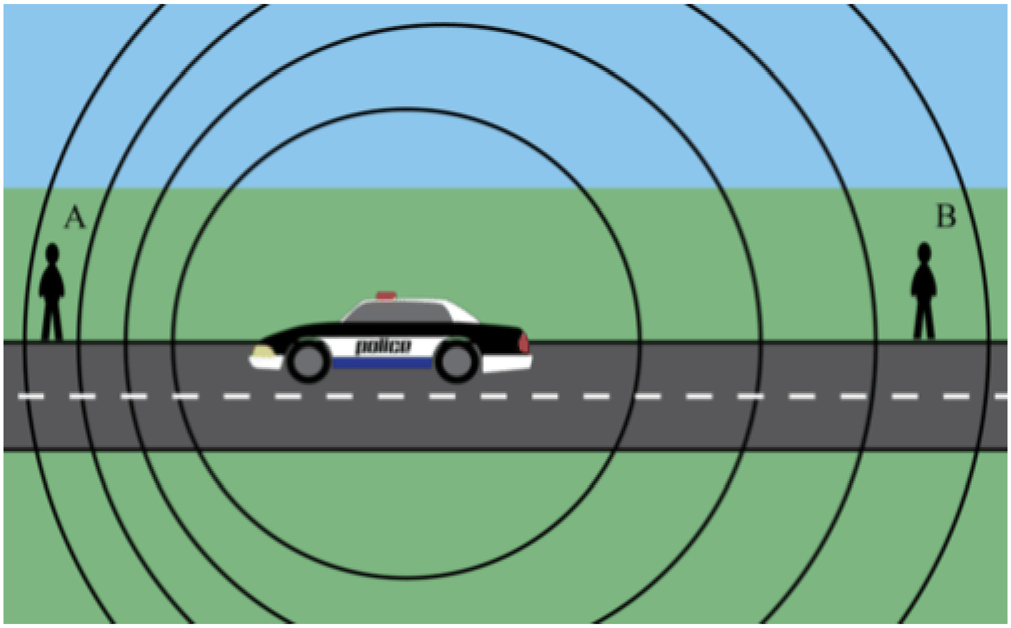
In the early 1800s, light was assumed to be a particle. There was a significant amount of evidence to point to that conclusion, and famous scientist Isaac Newton's calculations all support the particle theory. In 1803, however, Thomas Young performed his famous Double Slit Experiment to prove that light was a wave. Young shined a light onto the side of a sealed box with two slits in it, creating an interference pattern on the inside of the box opposite the slits. As seen above, interference patterns are characterized by alternating bright and dark lines. The bright lines are a result of constructive interference, while the dark lines are a result of destructive interference. By creating this interference pattern, Young proved that light is a wave and changed the course of physics.

Doppler Effect

Image by Military_Material, pixabay.com, CC0

Has this ever happened to you? You hear a siren from a few blocks away. The source is a police car that is racing in your direction. As the car approaches, zooms past you, and then speeds off into the distance, the sound of its siren keeps changing in pitch. First the siren gets higher in pitch, and then it suddenly gets lower. Do you know why this happens? The answer is the Doppler Effect.

The Doppler Effect is a change in the frequency of waves that occurs when the source of the wave is moving relative to a stationary observer. (It can also occur when the source is stationary and the observer is moving.) The diagram shows how the Doppler Effect occurs.



The sound waves from the police car siren travel outward in all directions. Because the car is racing forward (to the left), the sound waves get bunched up in front of the car and spread out behind it. As they propagate outward they retain their circular shape. Sound waves that are closer together have a higher frequency, and sound waves that are farther apart have a lower frequency. The frequency of sound waves, in turn, determines the pitch of the sound. Sound waves with a higher frequency produce sound with a higher pitch, and sound waves with a lower frequency produce sound with a lower pitch.

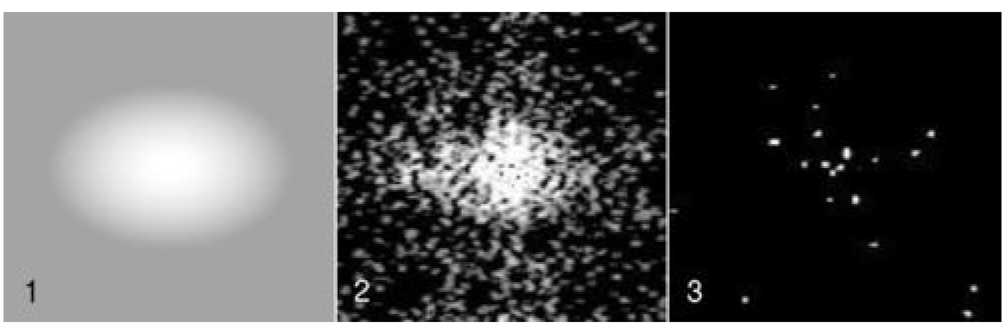
Doppler Effect and Light - Blueshift and Redshift

Blueshift and redshift is simply another way to word the Doppler Effect for EM waves. Remember that the Doppler Effect is the observed change in the frequency of a wave when objects are in relative motion. Red-shift can occur when either the Earth is moving away from a distant star (or other object) or when the star is moving away from the Earth. Using equations for the Doppler Effect, scientists can determine the relative speeds of planets, stars, galaxies, and other celestial bodies in our universe.

A blue-shift is any decrease in wavelength (increase in frequency); the opposite effect is referred to as redshift. In visible light, this shifts the color from the red end of the spectrum to the blue end. The term also applies when photons outside the visible spectrum (e.g. x-rays and radio waves) are shifted toward shorter wavelengths. In physics (especially astrophysics), red-shift happens when the original wavelength of light seen coming from an object that has a relative velocity away from us is shifted towards the red end of the spectrum.

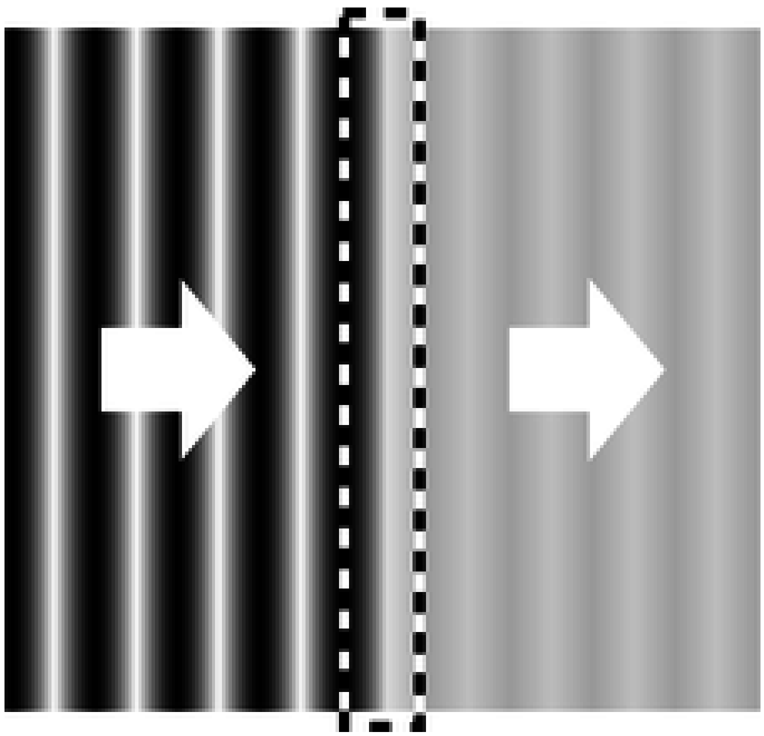
Evidence for Light as a Particle

So far in this section we have been focused on the characteristics of light as it behaves like a wave. But for a long time, physicists tried to explain away the problems with the classical theory of light as arising from an imperfect understanding of atoms and the interaction of light with individual atoms and molecules. The ozone paradox, for example, could have been attributed to the incorrect assumption that one could think of the ozone layer as a smooth, continuous substance, when in reality it was made of individual ozone molecules. It wasn't until 1905 that Albert Einstein threw down the gauntlet, proposing that the problem had nothing to do with the details of light's interaction with atoms and everything to do with the fundamental nature of light itself.

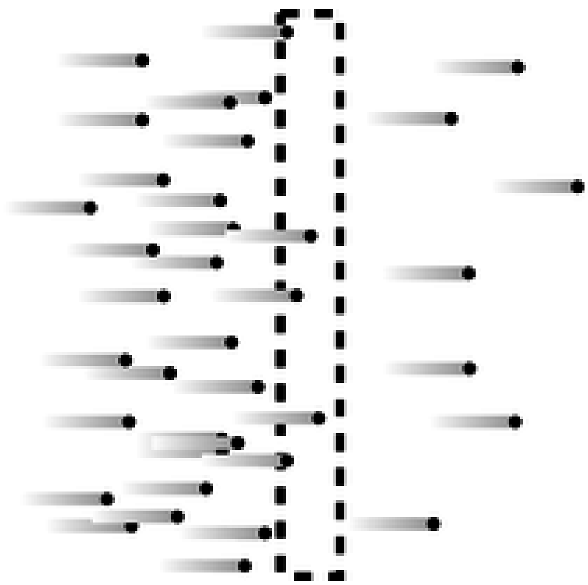


In those days the data were sketchy, the ideas vague, and the experiments difficult to interpret; it took a genius like Einstein to cut through the thicket of confusion and find a simple solution. Today, however, we can get right to the heart of the matter with a piece of ordinary consumer electronics, the digital camera. Instead of film, a digital camera has a computer chip with its surface divided up into a grid of light-sensitive squares, called “pixels.”

Compared to a grain of the silver compound used to make regular photographic film, a digital camera pixel is activated by an amount of light energy orders of magnitude smaller. In the image above Figure 1 is fake, but 2 and 3 are real digital-camera images made by Prof. Lyman Page of Princeton University as a classroom demonstration. Figure 1 is what we would see if we used the digital camera to take a picture of a fairly dim source of light. In figures 2 and 3, the intensity of the light was drastically reduced by inserting semitransparent absorbers like the tinted plastic used in sunglasses. Going from 1 to 2 to 3, more and more light energy is being thrown away by the absorbers.



The results are drastically different from what we would expect based on the wave theory of light. If light was a wave and nothing but a wave, like in the image above, then the absorbers would simply cut down the wave's amplitude across the whole wavefront. The digital camera's entire chip would be illuminated uniformly, and weakening the wave with an absorber would just mean that every pixel would take a long time to soak up enough energy to register a signal.



But figures 2 and 3 show that some pixels take strong hits while others pick up no energy at all. Instead of the wave picture, the image that is naturally evoked by the data is something more like a hail of bullets from a machine gun, as imaged above. Each “bullet” of light apparently carries only a tiny amount of energy, which is why detecting them individually requires a sensitive digital camera rather than an eye or a piece of film.

Although Einstein was interpreting different observations, this is the conclusion he reached in his 1905 paper: that the pure wave theory of light is an oversimplification, and that the energy of a beam of light comes in finite chunks rather than being spread smoothly throughout a region of space. This paper was on what we refer to as the Photoelectric effect.

Photoelectric Effect

In 1905, Albert Einstein (1879-1955) proposed that light be described as quanta of energy that behave as particles. A photon is a particle of electromagnetic radiation that has zero mass and carries a quantum of energy. The energy of photons of light is quantized according to the E=hv equation. For many years, light had been described using only wave concepts, and scientists trained in classical physics found this wave-particle duality of light to be a difficult idea to accept. A key experiment that was explained by Einstein using light’s particle nature was called the photoelectric effect.

The photoelectric effect is a phenomenon that occurs when light shines onto a metal surface and causes the ejection of electrons from that metal. It was observed that only certain frequencies of light are able to cause the ejection of electrons. If the frequency of the incident light is too low (red light, for example), then no electrons were ejected even if the intensity of the light was very high or it was shone onto the surface for a long time. If the frequency of the light was higher (green light, for example), then electrons were able to be ejected from the metal surface even if the intensity of the light was very low or it was shone for only a short time. This minimum frequency needed to cause electron ejection is referred to as the threshold frequency.

Classical physics was unable to explain the photoelectric effect. If classical physics applied to this situation, the electron in the metal could eventually collect enough energy to be ejected from the surface even if the incoming light was of low frequency. Einstein used the particle theory of light to explain the photoelectric effect as shown in Figure below.

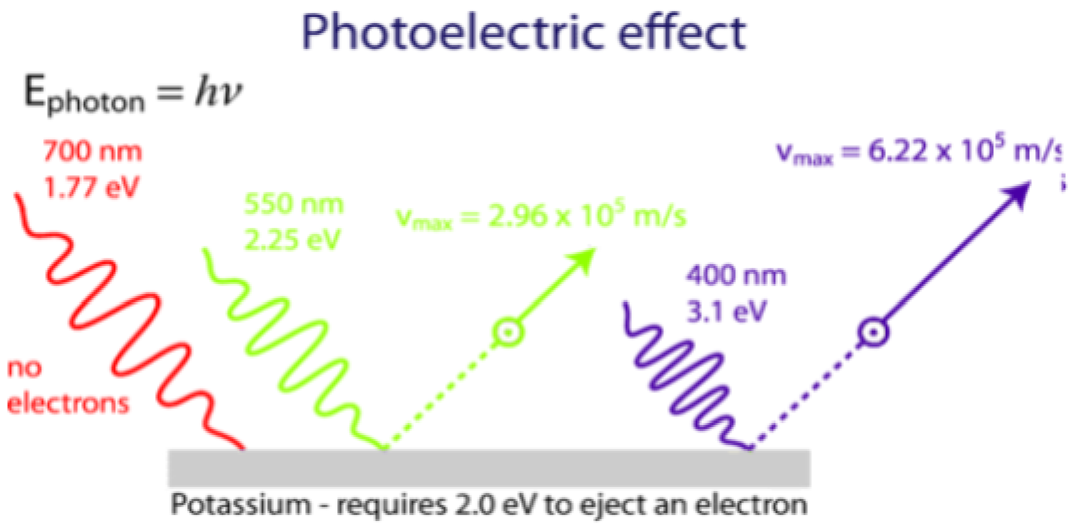


Image by CK-12 Foundation - Christopher Auyeung;Raymond Chou, CC-BY-NC-SA 3.0

Consider the E=hv equation. The E is the minimum energy that is required in order for the metal's electrons to be ejected. If the incoming light's frequency, v, is below the threshold frequency, there will never be enough energy to cause electrons to be ejected. If the frequency is equal to or higher than the threshold frequency, electrons will be ejected. As the frequency increases beyond the threshold, the ejected electrons simply move faster. An increase in the intensity of incoming light that is above the threshold frequency causes the number of electrons that are ejected to increase, but they do not travel any faster. The photoelectric effect is applied in devices called photoelectric cells, which are commonly found in everyday items such as a calculator which uses the energy of light to generate electricity.

Wave-Particle Duality Nature of Light

Light can behave as both a wave and a particle. Let's take a second to recap how this is true. First let's define a particle and a wave. A wave is a vibration which exhibits superposition and interference. While a particle is a distinct object which can only exist in whole numbers. Light has wave light characteristics: it gets refracted, it experiences interference, and exhibits the doppler effect. Light also has particle characteristics: it reflects/bounces like you would expect a ball to and its photons have distinct energy or quanta. Although these seem like very inconsistent categories, light exhibits both of these models in what we refer to as wave-particle duality.

Putting It Together

Phenomenon

Reverse Refractions by Trina Alexander; https://flic.kr/p/MkgXc; CC BY-NC-ND

Let's revisit this phenomenon: Your friend has a glass ball and you observe his image while looking through the glass ball.

Focus Questions:

1. What is the orientation of the person in the picture? How does this orientation compare to what we are seeing in the glass ball?

2. What is happening to the light in order to produce the image that we see in the glass ball?

3. In this instance, is it easier to explain this phenomena using the particle model or the wave model of light? Explain why.

Final Task:

Create, draw, or find a model which illustrates why the image in the glass ball is flipped upside down.

4.3 Biological Effects of Electromagnetic Radiation (PHYS.4.3)

Phenomenon

Image by ales_kartal; pixabay.com, CC0

When at the dentist, they treat your teeth with a UV light.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. How dangerous is UV radiation on biological tissue?

2. What are the dangers of using electromagnetic radiation in medical treatments?

PHYS.4.3 Biological Effects of Electromagnetic Radiation

Evaluate information about the effects that different frequencies of electromagnetic radiation have when absorbed by biological materials. Emphasize that the energy of electromagnetic radiation is directly proportional to frequency and that the potential damage to living tissue from electromagnetic radiation depends on the energy of the radiation. (PS4.B)

In this chapter, identify the effects that different frequencies of electromagnetic (EM) radiation have when absorbed by biological materials.

Effects of Radiation on living things

Image by De Wood, Pooley, USDA, ARS, EMU, Public Domain

That's in our food?

Bacterial contamination in our food often makes the news. There are many bacteria present on raw food, especially raw meat. Campylobacter (pictured above), salmonella, and other microorganisms can be found, even after cooking if the meat has not been sufficiently exposed to the heat. Ionizing radiation can be used to disrupt the DNA-RNA-protein synthesis cycle that allows the bacteria to reproduce. Cobalt-60 is a common radiation source, as is cesium-137. But, just to be safe, order that burger well-done.

Effects of Radiation

In order to better understand how cellular radiation damage occurs, we need to take a quick review of how the cell functions. DNA in the nucleus is responsible for protein synthesis and for regulation of many cellular functions. In the process of protein synthesis, DNA partially unfolds to produce messenger RNA (mRNA). The mRNA leaves the nucleus and interacts with ribosomes, transfer RNA, amino acids, and other cellular constituents in the cytoplasm. Through a complex series of reactions, proteins are produced to carry out a number of specialized processes within the organism. Anything that disturbs this flow of reactions can produce damage to the cell.

The Effects of Radiation on Living Things

Image by Clker-Free-Vector-Images, pixabay.com, CC0

You may have seen this sign before—maybe in a hospital. The sign means there is danger of radiation in the area. Radiation consists of particles and energy that are given off by radioactive isotopes, which have unstable nuclei. But you don't have to go to a hospital to be exposed to radiation. There is radiation in the world all around you.

Radiation in the Environment

A low level of radiation occurs naturally in the environment. This is called background radiation. One source of background radiation is rocks, which may contain small amounts of radioactive elements such as uranium. Another source is cosmic rays.

These are charged particles that arrive on Earth from outer space. Background radiation is generally considered to be safe for living things.

Dangers of Radiation

Long-term or high-dose exposure to radiation can harm both living and nonliving things.

Radiation knocks electrons out of atoms and changes them to ions. It also breaks bonds in DNA and other compounds in living things. One source of radiation that is especially dangerous to people is radon. Radon is a radioactive gas that forms in rocks underground. It can seep into basements and get trapped inside buildings. Then it may build up and become harmful to people who breathe it. Long-term exposure to radon can cause lung cancer.

Exposure to higher levels of radiation can be very dangerous, even if the exposure is short-term. A single large dose of radiation can burn the skin and cause radiation sickness. Symptoms of this illness include extreme fatigue, destruction of blood cells, and loss of hair.

Nonliving things can also be damaged by radiation. For example, high levels of radiation can weaken metals by removing electrons. This is a problem in nuclear power plants and space vehicles because they are exposed to very high levels of radiation.

Q: Can you tell when you are being exposed to radiation? For example, can you sense radon in the air?

A: Radiation can't be detected with the senses. This adds to its danger. However, there are other ways to detect it.

Using Radiation

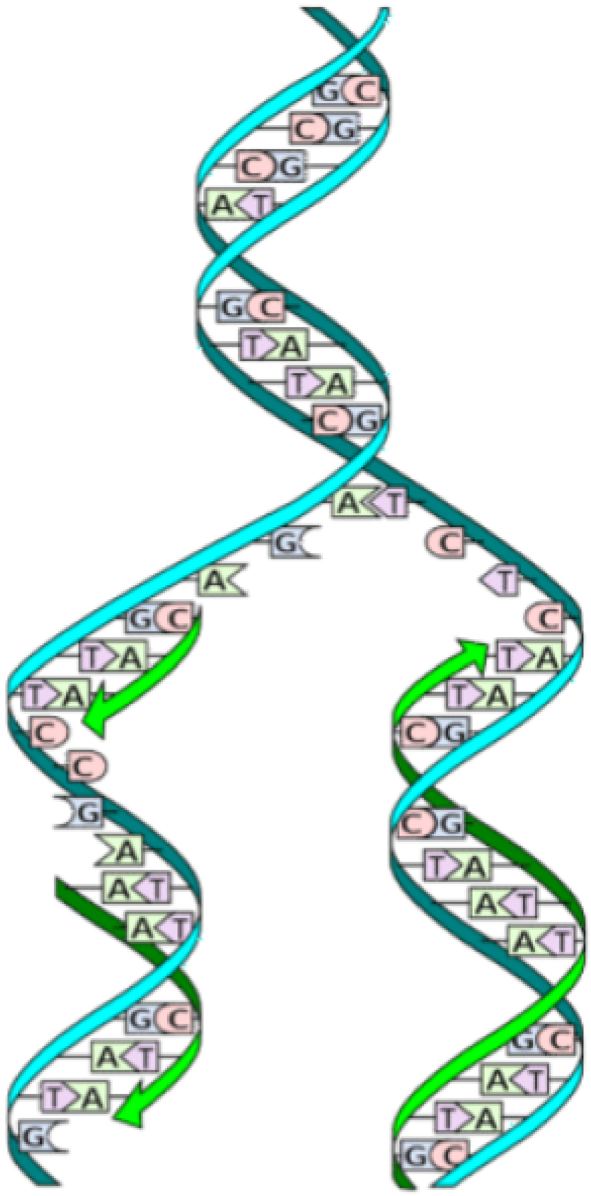
Despite its dangers, radioactivity has several uses. For example, it can be used to determine the ages of ancient rocks and fossils. It can also be used as a source of power to generate electricity. Radioactivity can even be used to diagnose and treat diseases, including cancer. Cancer cells grow rapidly and take up a lot of glucose for energy. Glucose containing radioactive elements can be given to patients. Cancer cells take up more glucose than normal cells do and give off radiation. The radiation can be detected with special machines like the one in the figure below. The radiation may also kill cancer cells. The image machine scans a patient's body and detects radiation.

MRI by Florey Institute, https://flic.kr/p/H5msHB, CC-BY-NC-ND

The major effect of ionizing radiation on the cell is the disruption of the DNA strand. With the DNA structure damaged, the cell cannot reproduce in its normal fashion. Protein synthesis is affected, as are a number of processes necessary for proper cell function. One common effect is the generation of cancer cells. These cells have an abnormal structure due to the damaged DNA. In addition, they usually grow rapidly since the normal control processes regulating cell growth have been changed by the altered composition of the DNA. Tissue damage is also common in people with severe exposure to radiation.

Effects of Radiation on Humans

We can see two general types of effects when humans are exposed to radiation. Low-level exposure can lead to the development of cancer. The regulatory processes regulating cell growth are disrupted, leading to uncontrolled growth of abnormal cells. Acute exposure can produce nausea, weakness, skin burns, and internal tissue damage. Cancer patients receiving radiation therapy experience these symptoms, but the radiation is targeted to a specific site in the body so that the damage is primarily to the cancer cells and the patient is able to recover from the exposure.



DNA Replication by Madprime, https://en.wikipedia.org/wiki/DNA_replication#/media/File:DNA_replication_split.svg, CC-BY-SA

Putting It Together

Image by ales_kartal; pixabay.com, CC0

Let us revisit this phenomenon: When at the dentist, they treat your teeth with a UV light.

Focus Questions:

1. Why is Electromagnetic Radiation used in medical treatments?
2. How dangerous are the different types of electromagnetic radiation on biological tissue?
3. What are the dangers of using electromagnetic radiation in medical treatments?

Final Task:
Construct an explanation with evidence identifying if the UV treatment your dentist uses is safe

4.4 Digital Waves (PHYS.4.4)

Phenomenon

Image by Jan Vašek , pixabay.com, CC0

Every Day, People use cell phones to communicate with each other without the use of wires.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. How is a cell phone able to transmit information securely?

2. How is a cell phone able to transmit information reliably?

3. How can information on a cell phone be stored securely and permanently?

PHYS.4.4 Digital Waves

Ask questions and construct an explanation about the stability of digital transmission and storage of information and their impacts on society. Emphasize the stability of digital signals and the discrete nature of information transmission. Examples of stability and instability could include that digital information can be stored in computer memory, is transferred easily, copied and shared rapidly, can be easily deleted, has limited fidelity based on sampling rates, or is vulnerable to security breaches and theft. (PS4.A)

In this section, think about how we are able to take a digital signal and retain the information it contains. The stability of information is crucial in the information age.

Why go Digital?

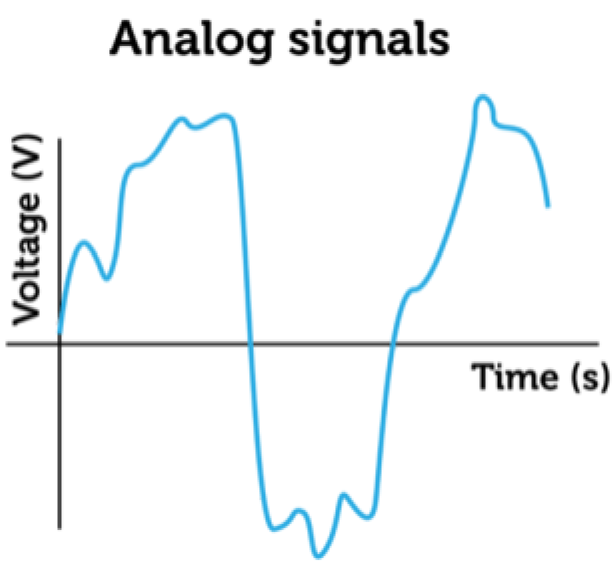


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC 3.0

Every raw signal is called an analog signal. Just like your voice can smoothly increase and decrease in volume, an analog signal can go up and down smoothly; an analog signal is curvy. While this signal completely describes the information it is, however, susceptible to distortion. Any deformation of the signal reduces the quality of the signal and the longer the signal travels, the weaker the signal becomes.

analog TV by David Beach, https://flic.kr/p/66nezz, CC-BY

A digital signal can be completely described using nothin but a binary base (1s for voltage and 0s for no voltage). With a digital signal, the only goal is to get the signal to the end point. It will weaken as it travels, but as long as it exists the information is preserved; if it's not a 0 then it is a 1.

It is also more resilient to interference since 1 that has been deformed will still be interpreted as a 1. The only way a digital signal can be disrupted if the 0s and 1s get flipped or if the signal gets shut down completely. For these reasons, information that used to be transmitted by analog has switched to digital. It is a far more reliable and stable form of information transmission. Can you think of a case where analog is still preferred to digital?

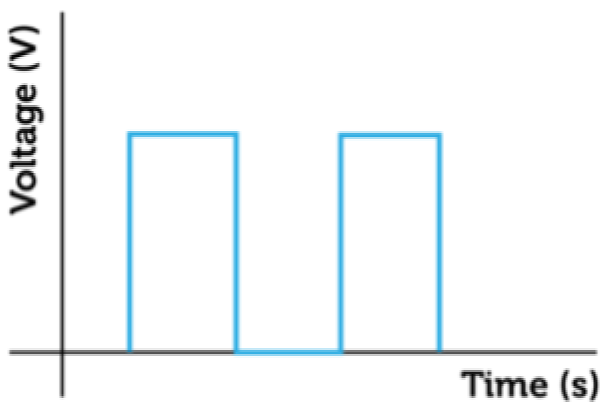
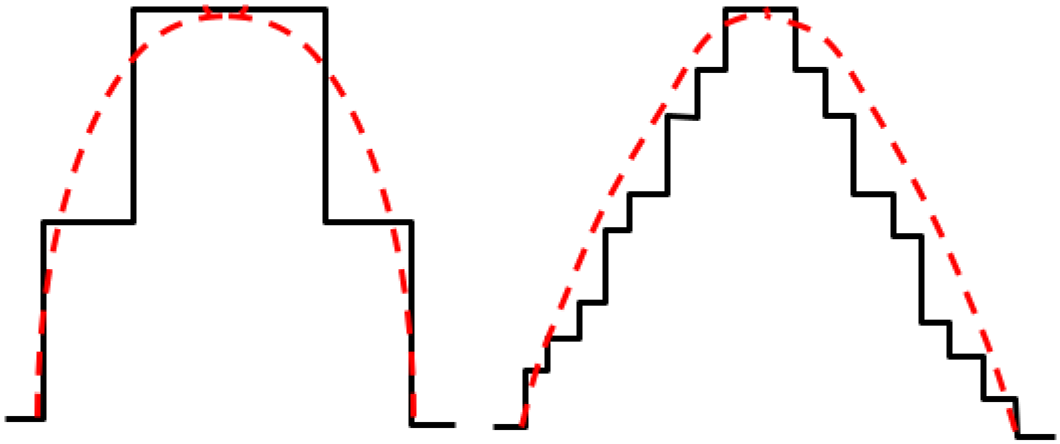


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC 3.0

How do we switch from Digital to Analog



If the bit depth is low, the signal will be inaccurately converted because it's sampled in large increments. If the bit depth is increased, you get finer increments for a more accurate representation of the signal. (Image by Author, CC0)

In order to convert an analog signal to a digital signal, we sample the signal. What you see is that the more steps we include, the closer to the true signal we get. The closer we get to this signal the higher the quality becomes. With more samples comes an increase in the number of 0s and 1s needed to describe each section. If we increase the number of 0s and 1s what property of a digital file will tend to increase as well?

Storing and Transmitting

To store this data we have developed technologies to meet ever improved quality

CD - 700 MB
DVD - 4.7 GB
Blu-Ray - 25 GB

The most recent example of this is a remake of Final Fantasy 7 which on its initial release in 1997 took 3 CDs to store its information. The remake which is scheduled to be released in 2020 will need 2 Blu-Ray discs.

Transmitting this digital information is incredibly fast over a wired connection and currently we are able to stream digital video in real time over wireless connections. Even though this is incredibly fast, it is vulnerable to interception and theft. For a YouTube video this is not an issue; it is an issue though when it comes to secure numbers such as credit cards, social security, and other sensitive information. Before a digital signal is sent, it must be encrypted. The goal is that the sender and the receiver know what the message is, but anyone in the middle will not. How can we encrypt messages before transmission? How can we protect information that is stored?

Putting It Together

Image by Jan Vašek , pixabay.com, CC0

Let's revisit the phenomena: Every Day, People use cell phones to communicate with each other without the use of wires.

Focus Questions

1. How is a cell phone able to transmit information securely?
2. How is a cell phone able to transmit information reliably?
3. How can information on a cell phone be stored securely and permanently?
4. Do we need to have the absolute highest sampling rate for our devices?

Final Task

Construct an explanation using evidence about how to securely transmit information.

4.5 Capture and Transmission of Waves (PHYS.4.5)

Phenomenon

Public Domain

Communication towers, like what is pictured above, are found throughout our cities and on mountaintops. Radio, TV stations, and cell phones use these.

Observations and Wonderings

What are you observing about this phenomenon?

What are you wondering about this phenomenon?

Focus Questions

1. What kind of energy do these towers use to communicate?

2. How does the matter in a tower like this generate a “signal”?

3. How does the matter in a tower like this receive and interpret a “signal”?

PHYS.4.5 Capture and Transmission of Waves

Obtain, evaluate, and communicate information about how devices use the principles of electromagnetic radiation and their interactions with matter to transmit and capture information and energy. Emphasize the ways in which devices leverage the wave-particle duality of electromagnetic radiation. Examples could include solar cells, medical imaging devices, or communication technologies. (PS4.A, PS4.B, PS4.C)

In this chapter, see if you can identify how matter is interacting with energy to allow communication between electronic devices.

Communication

Electromagnetic waves are a major way that communication occurs with today's technology. The process that each device uses is roughly the same, but let's learn about how a cell phone works.

Image by PhotoMIX-Company; pixabay.com; CC0

How Does A Cell Phone Work?

When you speak into your cell phone, the microphone takes the sound waves and turns it into a digital signal. This digital signal, which we learned about in the previous section, consists of zeros and ones. An antenna in your phone is then going to transmit the zeros and ones by generating an electromagnetic wave. That wave is generated by forcing an electron up and down the antenna, creating a vibration in the electromagnetic field. Electromagnetic waves are used to transmit zeros and ones by changing the wave characteristics, such as amplitude, frequency, phase, or a combination of these. For example, in the case of frequency, zeros and ones are transmitted by using low and high frequencies, as diagrammed in the image below.

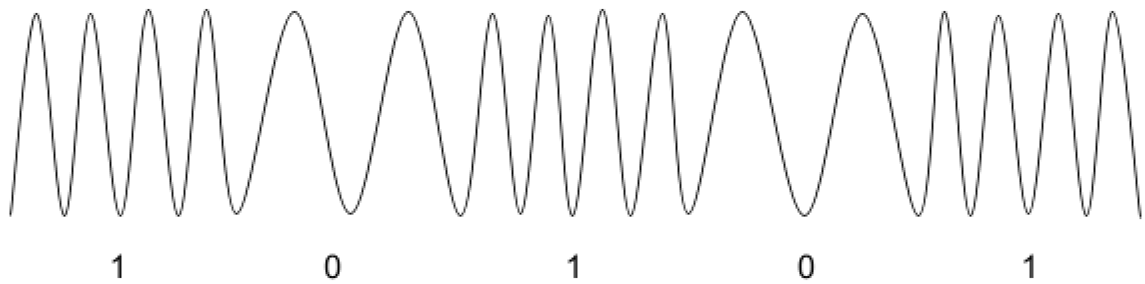


Image created by Milo Maughan; CC BY

Now, if your friend's cell phone was close then you would be able to connect and make a call, just like a walkie talkie does. However, it is difficult for the electromagnetic waves from your cell phone to travel long distances. The waves lose their strength due to the presence of physical objects, electrical equipment, and even some weather. Even without these obstructions, there would be a limit to how far the waves would travel due to the curvature of the earth. To solve the issue of distance and obstructions, cell towers and cellular technology were implemented.

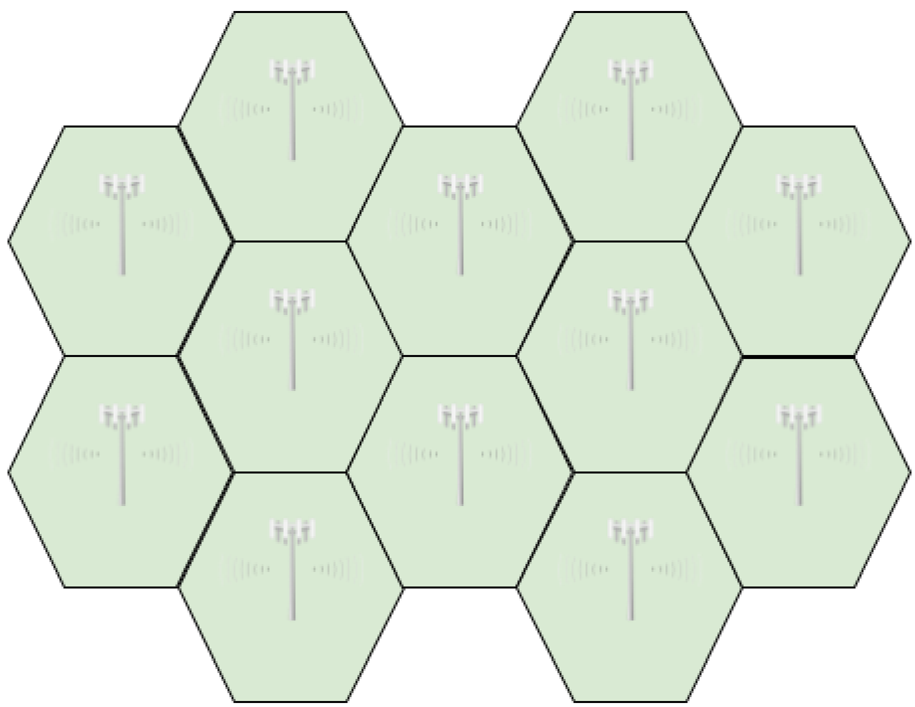


Image Created by Milo Maughan; CC BY

In the image above, a geographical region is divided into hexagonal cells with each cell having its own frequencies and towers. The electromagnetic waves made by your phone are picked up by antennas on these towers. The waves interact with electrons in the antenna which the antenna interprets into the zeros and ones generated by the phone. The tower then converts the zeros and ones into high frequency light pulses which are processed and transmitted to the destination tower through a wired fiber optic network. Once the destination tower receives the pulse, the process is now reversed, and the tower radiates the transmission outward in the form of electromagnetic waves. Your friend's phone then receives the signal, which is processed and turned into sound waves for your friend to hear. This process happens very quickly and uses both wires and wireless technology.

Electromagnetic Waves & Connectivity

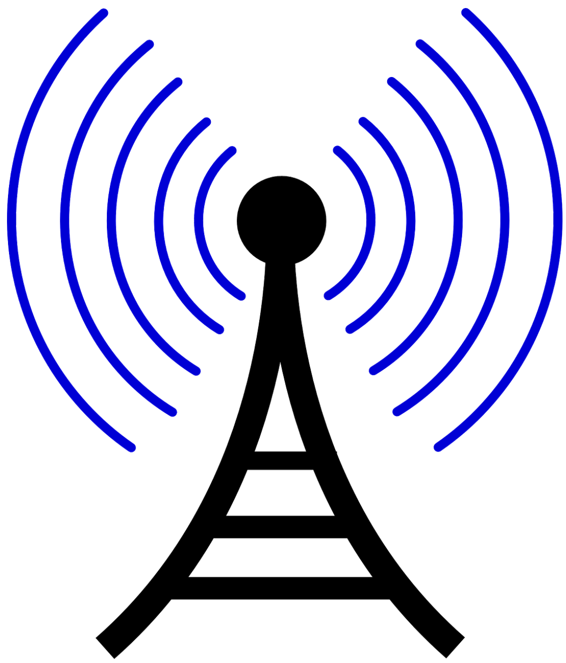


Image by Clker-Free-Vector-Images; pixabay.com; CC0

Cell phones use high frequency radio waves and/or low frequency microwaves to communicate. There are many things that can cause issues with cell phone connections. The waves from cell phones transmit in all directions. These waves can be absorbed and reflected by objects around them. The magnitude of the received signal from a cell tower is called the "signal strength", which is commonly indicated by the "bars" on your phone. The greater the number of bars, the closer the cell tower is or the fewer the number of objects that are blocking the signals. If the cell tower gets far away, or the number of impediments increases, the poor reception (fewer bars) occurs.

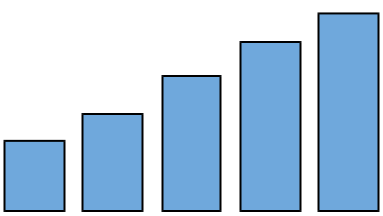


Image created by Milo Maughan; CC0

In order to conserve battery power, your cell phone will change the strength of the signal it is using to communicate with the cell tower. It will only use the minimum amount of energy required to communicate with the nearest cell tower. When you have poor reception, the cell phone increases the strength of the signal, using more energy, and draining your battery faster.

Putting It Together

Public Domain

Let's revisit this phenomena: Communication towers, like what is pictured above, are found throughout our cities and on mountaintops. Radio, TV stations, and cell phones use these.

Focus Questions:

1. What kind of energy do these towers use to communicate?
2. How does the matter in a tower like this generate a "signal"?
3. How does the matter in a tower like this receive and interpret a "signal"?

Final Task:

Create a model which illustrates how cell phones use cell towers to transmit cell phone calls.