What is Energy?

A laboratory experiment from
the Little Shop of Physics
at Colorado State University

Overview

We often think about energy in personal terms. People comment on the energy young children seem to possess. Others mention that they don't feel they have enough energy to make it through the day. We've heard that the world is running out of certain types of energy.

In spite of all of our everyday use of the word *energy*, it remains an abstract concept, and students may have developed quite a few misconceptions about it.

So, just what *is* energy?

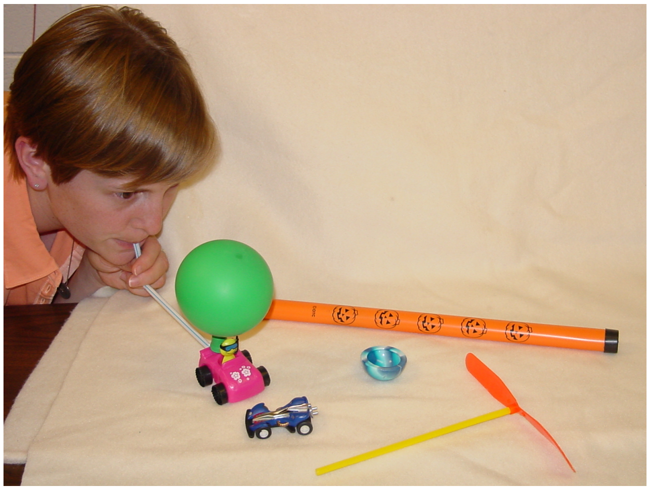
Necessary materials:

- 1 balloon car
- 1 pull-back race car
- 1 popper
- 1 groan tube
- 1 physics flyer

These toys are a great way to start your students' exploration of different energy forms and energy conversions. You can certainly use other toys or examples from the classroom or home as well. All the toys for these activities can be found at the following website: www.orientaltrading.com

Theory

Rather than *define* energy, it's easier to talk about *examples* of energy. When you walk up a set of stairs, you are using energy. When you turn on a light bulb, it is using energy. When you heat up a pot of water on the stove, you are using energy. Basically, *energy is something that lets us do things.*



Using simple toys to explore changes in energy.

Whenever you move or talk, you use energy. Any device or appliance in your house that does something uses energy too; lamps use energy, so does your television, so does your washing machine.

The weather on Earth is driven by the transfer of energy and the conversion of energy from one form to another, but this will be a difficult concept for students if they don't truly understand energy—its different forms, how it can be converted from one form into another, and the fact that it can't be created or destroyed. We believe the best way to teach students about energy is to simply let them do a variety of experiments with energy, and let them figure out what it is by themselves. In fact, all of the basic energy concepts are perhaps best discovered by exploration. The concepts are abstract, but relate nicely to commonsense notions of how the world works.

Doing the Experiment

This activity is meant to be an exploratory activity where students experiment, observe, and determine how various toys change energy from one form of to another. If this is your students' first time discussing energy, you may want to discuss types of energy, and model with other toys or materials prior to this activity.

You may introduce the toys in any order you prefer. The lesson plan is the same for each toy:

- Allow students to work with the toy.
- Have the students discuss with their neighbors what the toy does and what energy changes it illustrates.
- They should determine what form the energy starts out in, what energy changes occur while using the toy, including what form it is in when the toy stops. (Note: there are a lot of energy changes for each toy, so this can be somewhat open-ended. For instance, for the balloon car shown above, the energy starts as chemical energy in your body, which turns into motion energy of your body, which is stored as potential energy in the balloon. . .)
- It is important to follow this activity with a class discussion, to help students finalize and formalize their findings.

Guide for Specific Toys

Toy: Pull-back Race Car

1. What does the toy do? (You can nudge it forward by hitting it with your finger or you can push down on it and pull it backwards. When you let go, it races forward and you can hear a little mechanical sound.)
2. What energy change/s happen as this toy operates? (As you push down on the car and pull it backwards, you are applying a force to the car and putting some of your energy into elastic potential energy in the car, as a spring is tightly wound during this process. As you release the car, the spring extends, and the potential energy is converted into kinetic energy of the moving car. During this process, friction is at work, and some of the kinetic energy is converted to heat and sound energy.)
3. What form does the energy start out in? (After you've pulled it back, before releasing it,you've given it elastic potential energy, by winding the spring.)
4. What form does the energy turn into? (Kinetic energy of the moving car, plus some sound energy.)
5. What form is the energy in when it stops? (Heat energy. Ultimately, friction between the moving parts turns the kinetic energy into heat.)

Toy: Groan Tube

1. What does the toy do? (When you turn it upside down, a noisemaker inside the tube travels down to the bottom of the tube making a noise as it descends.)
2. What energy change/s happen as this toy operates? (When you flip the tube over in the air, you raise the noisemaker to the top of the tube. When the noisemaker is at the top of the tube, it has gravitational potential energy. As the noisemaker responds to gravity pulling it down, the potential energy is converted to kinetic (moving) energy causing air to move through the noisemaker converting some of the kinetic energy into sound energy. The noisemaker doesn't speed up as it falls, as the lost potential energy turns into sound energy. When it hits the bottom, the remaining kinetic energy is turned into heat in the collision.)
3. What form does the energy start out in? (Gravitational potential energy)
4. What form does the energy turn into? (Kinetic energy and sound energy)
5. What form is the energy in when it stops? (Heat energy)
6. Why do you think one end is open and one end is closed? (There are two reasons for this. The noisemaker makes noise via a reed in the center when there is a pressure difference across it. One side of the tube is open, the other is closed. When the noisemaker falls, air in one side is compressed —and so air is forced through the reed. If both ends of the tube were open, there would be no

compression. If both ends of the tube were closed, you would get a pressure difference—but the tube needs one side to be open so the vibrations inside the tube can be coupled with the air and our ears can perceive them as sound. When both ends are closed (try this with a piece of tape) you can barely hear a sound as the noisemaker falls. When both ends are open (replace the closed end with an open end from another tube), the air doesn't compress, vibrations are not created, so there is no sound.

Toy: Popper

1. What does the toy do? (When you turn the popper inside out and place it on a flat surface, it pops-up in a second or two and falls to the ground.)
2. What energy change/s happen as this toy operates? (You are putting some of your energy from your muscles into the toy initially. When you turn the popper inside out, you are giving the toy elastic potential energy. When the popper reverts back to its original shape the potential energy is converted into sound energy and kinetic energy. It pushes away from the surface, causing it to fly up into the air. Gravity is pulling down on the popper, causing the kinetic energy to convert to gravitational potential energy by the time it reaches its highest point. Then as it is pulled down by gravity, it converts its potential energy into kinetic energy again. When it finally hits the surface and stops, the kinetic energy has been converted into heat energy and sound energy.)
3. What form does the energy start out in? (Elastic potential energy)
4. What form does the energy turn into? (Sound energy, kinetic energy, gravitational potential energy)
5. What form is the energy in when it stops? (Heat and sound energy)

Toy: Physics Flyer

1. What does the toy do? (You hold it between your two hands and launch it by pushing your right hand past your left hand. The physics flyer starts spinning and lifting higher in the air. It keeps moving forward but starts slowing down and dropping.)
2. What energy change/s happen as this toy operates? (When you move your right hand past your left hand, you are putting energy into the Physics Flyer from your muscles. By moving your hands that way, you cause the flyer to spin in one direction (to the left) so you're giving it rotational kinetic energy. It moves forward but climbs to a higher height due to the tip of the blades on the propeller. They are tipped upward when moving to the left. Gravity is pulling down on the flyer, so some of the rotational kinetic energy is converted to gravitational potential energy, but not all of it, as it continues to spin.
3. The gravitational potential energy converts to kinetic again, but its spin starts to slow down and it eventually starts dropping to the ground, dealing with friction and buoyancy of the air. By the time it stops, its energy has converted to heat energy.)
4. What form does the energy start out in? (Rotational kinetic energy)
5. What form does the energy turn into? (Gravitational potential energy and then kinetic energy again)
6. What form is the energy in when it stops? (Heat energy)

Toy: Balloon Car

1. What does the toy do? (After you have blown up the balloon, you cover the hole where the straw was attached. When you let the car go, it moves forward and you can hear the sound of the air pushing out the back of the car and a sound of the tires spin.)
2. What energy change/s happen as this toy operates? (As you blow up the balloon, you are putting some of your energy into potential energy as you've created an area of high pressure in the balloon. As you release the car, the air under high pressure in the balloon moves to an area of lower pressure outside the balloon, thrusting the car forward. The potential energy is converted into kinetic energy of the moving car. During this process, friction is at work, and some of the kinetic energy is converted to heat and sound energy.)
3. What form does the energy start out in? (You've given elastic potential energy, by increasing the pressure in the balloon.)
4. What form does the energy turn into? (Kinetic energy of the moving car, plus some sound energy.)

5. What form is the energy in when it stops? (Heat energy. Ultimately, friction between the moving parts turns the kinetic energy into heat energy.)

Summing Up

This suite of activities on energy changes is largely qualitative, but it can be adapted to make it more quantitative as well. Doing this science lab with toys also encourages students to think *outside the walls;* to think of science as something that applies to the world beyond the classroom.

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

6.

Can energy be created or destroyed?

A laboratory experiment from the
Little Shop of Physics at
Colorado State University

Overview

Energy is the single most important science concept your students will Understanding conservation of energy is vital as students study the earth's energy budget and make informed decisions for the future.

Theory

Conservation of energy is another concept that is difficult to explain but easy to grasp through experimentation. We say that *energy is conserved*: you can convert energy from one form to another, but it cannot be created or destroyed. In this set of activities, students can make quantitative comparisons which work quite well. They can explore the rate at which energy is used: a one-minute charge of the battery via solar cell will run a flashlight for several seconds but will run a clock for quite a bit longer.

Necessary materials:

- 1 solar cell night light device, with battery
- time-keeping device (clock or stop watch)
- 1 one-battery flashlight
- 1 one-battery clock
- 1 one-battery toy car

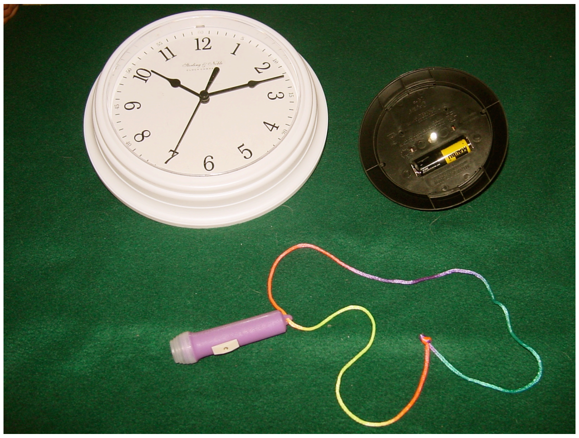
The solar cells are part of solar garden lights available at hardware and variety stores. The batter, in the top of the unit, is a NiCd battery that can be charged and discharged repeatedly. It's a standard AA battery that can run many different things.

When you put the battery in a toy or a clock or a light, you see how long the stored energy will last.

Doing the Experiment: *Part 1: First Steps*

This activity requires sunlight to charge the battery using the solar cells. You can use the sun coming in a window, or have the students take their solar cells outside for charging. We prefer the latter. When students take their solar cells outside for charging and then bring them in, it helps them see that they are bringing the energy of the sun indoors!

Now close the curtains in your classroom and turn out the lights. The lights in the solar cell night light units will come on! If the lights don't come on, it may be because there is still light hitting the top of the unit. Cover this with your finger, and the white light will come on. Have students see how long the lights will stay lit. Have them discuss: where did the energy come from to make the units light?



The battery from the solar night light can run other things as well.

Part II: Concepts

As preparation, you will need to be sure that the batteries from the solar cell night light devices are totally discharged. A good way to do this is to put the batteries in the flashlights and let them run down. You can also let the night lights run overnight. Now, proceed as follows:

•Have the students put the batteries in the solar cell units and put the cell in bright sunlight for 2 minutes then bring the solar cell unit indoors and remove the battery. This is easily done if you turn the units over so that the battery is visible.

•Have the students put the battery from the solar cell unit in the flashlight. Have them turn the flashlight on

and measure how long the energy in the battery can run the flashlight. (This is a good time to have the students think about their experimental methods. As time goes on, the flashlight gets dimmer and dimmer. How do you determine the point at which the flashlight goes out? The main thing is to have a measurement that can be made consistently!)
- Next, have students discuss why the flashlight goes out. They will likely mention energy, that the battery has run out of energy. This is correct, and it leads to consideration of the next segment of the activity, in which students will take quantitative data.

Part III: Data

This section of the activity is a chance for your students to collect data and note a trend. The data isn't perfect, but the trends are clear. This is how real science is often done, with imperfect data from which general correlations are discovered. Have the students proceed as follows:

- Set the solar cell in the sun for 1 minute to charge the battery.
- Measure the time the battery can run the flashlight.
- Set the solar cell in the sun for 2 minutes to charge the battery.
- Measure the time the battery can run the flashlight.
- Set the solar cell in the sun for increasing amounts of time: 3 minutes, 4 minutes...
- In each case, after charging, measure the time that the battery can run the flashlight.
- Finally, have students make a graph or chart of their data, to show the trend. Have them think about what deductions they can make from their data. It will be quite clear that the longer the solar cell charges the battery, the longer the battery can run the flashlight. But given uncertainties in the process, the data won't necessarily show that charging the battery for twice as long will allow it to run the flashlight for twice as much time. (A few things that make a difference: the flashlight draws more energy from the battery at the very start, and then tapers off. Also: the more charge in the battery, the faster the draw. So the time that the battery can run the bulb won't be exactly proportional to the energy in the battery. The battery may have a bit of a "rebound" effect as well, as many batteries do. If you take the flashlight and let it run the battery down and then turn the flashlight off and turn it on again after a short wait, you may find that the flashlight lights again! This rebound effect will complicate the data.)
- Have the students give an overall conclusion for this experiment. What does the data show? Have them phrase their conclusion in terms of *energy* and *energy conservation*.

Part IV: Differences

The final part of the experiment is designed to show that different devices use energy at different rates. When you charge the battery up with the solar cell for one minute, this puts a certain amount of energy in the battery. If this energy is drawn out slowly, it can last for a long time; if it is drawn out quickly, it won't last very long.

Have your students proceed as follows:

- Set the solar cell in the sun for 1 minute to charge the battery.
- With this much of a charge in the battery, see how long the battery will power the flashlight.
- After the battery is discharged, use the solar cell to recharge it for one minute; this should put the same amount of energy in the battery as before.
- Now, see how long this amount of energy will allow the battery to power the clock. You will likely find that the time is much greater; the clock uses energy at a much slower rate.
- Next, have your students see how long a one-minute solar charge will allow the battery to power the toy car. (A question: which is the best measure of how much energy is in the battery: the time that the car will run, or the distance it will travel?) You might have your students think about this.)
- Finally, have your students discuss what they have observed. Have them phrase their observations in terms of *energy* and *energy conservation*.

Summing Up

This is a wonderful activity for putting a quantitative face on the idea of energy conservation and energy changes.

For More Information

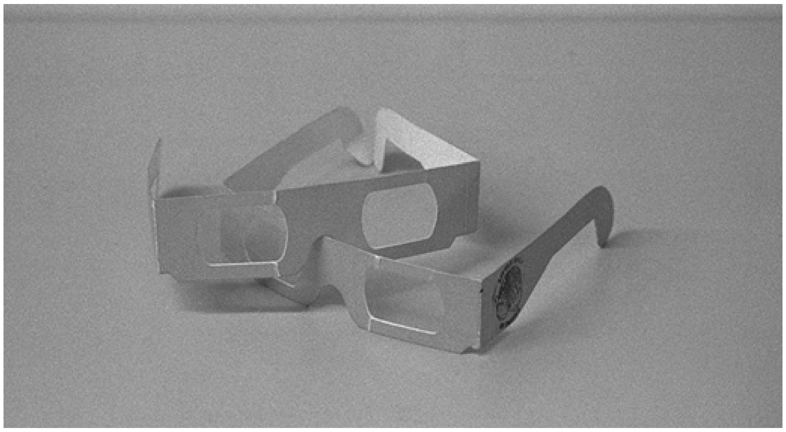
CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

Rainbow Glasses

Seeing Spectra

Introduction



The rainbow glasses are pairs of bright-colored spectacles that students can wear. When you put on a pair of Rainbow Glasses, and look at a light source, you see just what you would expect: rainbows!

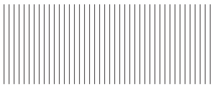
If you look carefully at the rainbows, you see that what you are observing is the spectrum of the light source. Since the dark room in the Little Shop area has a variety of different light sources, you can see a number of different effects. For instance: the phosphors on the screen of the Televised Chaos display appear yellow, but the spectrum as seen in the rainbow glasses show that they emit red light and green light—but no yellow! So red plus green makes yellow, one of the key results of the Color Mixing display!

Physics Principles

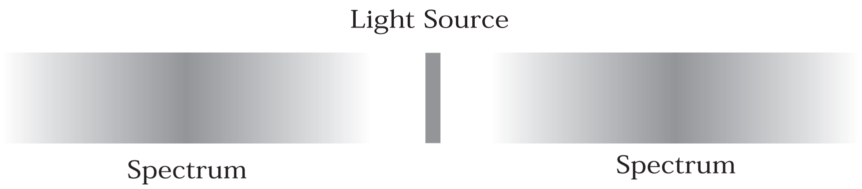
When light hits a shiny metal surface, or another smooth surface such as the surface of a pond, the light is *reflected*. When light travels from air into some transparent medium that is more dense than air, the light rays are bent; we say that the light is *refracted*. Now, when light hits obstructions that are very small, something else can happen: the light can be *diffracted*. If light passes through a very narrow slit, the light will spread out as it goes through.

The rainbow glasses have for their lenses plastic sheets that have a set of very small lines inscribed on them. The lines are far too small to see, but they will have an effect on the light that passes through them: they will diffract it. Now, since the lines are evenly spaced, there will be another effect: the diffracted light will make an *interference pattern*. We know that light can be thought of as a wave, and so it will interfere, as do other waves, making a pattern of light and dark bands. A full treatment of this is beyond the scope of this book; please consult any basic physics textbook for a full explanation.

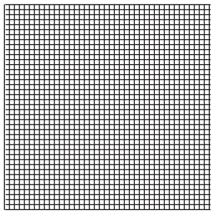
Now, if the lenses in the glasses had a single set of lines spaced like this:



there would be a simple spectrum of the light source. Actually, you would get two spectra, one on each side of the light source:



The glasses actually have a grid of lines on them:



and so you will see the usual pair of spectra, from the vertical lines, plus a set of vertical spectra, from the horizontal lines, and two "cross" spectra, from the interaction of the two!

So, you will see several spectra. This is more complicated than what you would get with a simple diffraction grating, but it is also prettier—which is why the glasses are made this way. They are sold not as science equipment, but as "Fireworks Glasses" or "3D" glasses. The goal is to make the prettiest rainbow effect, and the grid pattern does this in spades.

Construction and Use

Materials Required

Material	Cost	Source	Part Number
Rainbow Glasses	$40 for 100	American Paper Optics	
	$6.95 for 6	Edmund Scientific	T42,319

Putting it Together

There is no construction on this one: just have someone put the glasses on!

Safety Concerns

We do not expect any problems on this one. Sometimes people get so caught up over how cool things look through the glasses they bump into things, but this is not a big problem!

Experiments

Field Use

Usually, students put the glasses on for about five seconds, say “cool” or “fresh” or something like that, and walk on. Often, though, students will take these easily portable glasses around and use them to check out all the different exhibits—which is why we always set out several pairs!

Other Possibilities

We go back and forth as to whether to put the glasses in the dark area or the light area. Generally, when we are dealing with young children, we tend to put them in the light area. This way, it is very easy for them to see an effect, quickly. And the light sources tend to be continuous, so they get to see the usual ROYGBIV (well, there is no “I”, but that is another story...) rainbow that they know and love.

With older students, though, we tend to put them in the dark area. This means that they can look at all the spectra around. And there are a lot of different spectra to consider: sodium (Sodium Light Box), argon (Plasma Ball), neon (laser tube that is in plastic case for Lightbulb Guts), mercury (room lights that can be seen through the door), laser light (Laser Bongo and Laser Spirograph), and various phosphors on computer monitors and televisions. And then there are the continuous light sources! There are also LEDs (Static Sensor) and the IR LEDs from the Infrared Images display, which can be projected through on of the lenses. So placing the glasses in the dark area means that there is a lot of interesting physics to be considered.

Final Comments

The Rainbow Glasses are a perennial favorite with the people who set up the experiments (easy, safe, cheap) and with students (fun, visually stimulating, and educational). We can always find room to set out a few pairs.

I often wear the Rainbow Glasses as I walk around the dark area of the Little Shop. There are dozens of different light sources there, and I always learn something. Looking at the spectrum of the Sodium Light Box, for instance, clearly shows how monochromatic it is. The best thing we might say for a new set of glasses, if we can use a popular metaphor, is that they show you how to look at the world differently. The Rainbow Glasses definitely do this!

25.7 The Photon Model of Electromagnetic Waves

Figure 25.33 shows three photographs made with a camera in which the film has been replaced by a special high-sensitivity detector. A correct exposure, at the bottom, shows a perfectly normal photograph of a woman. But with very faint illumination (top), the picture is *not* just a dim version of the properly exposed photo. Instead, it is a collection of dots. A few points on the detector have registered the presence of light, but most have not. As the illumination increases, the density of these dots increases until the dots form a full picture.

This is not what we might expect. If light is a wave, reducing its intensity should cause the picture to grow dimmer and dimmer until disappearing, but the entire picture would remain present. It should be like turning down the volume on your stereo until you can no longer hear the sound. Instead, the left photograph in Figure 25.33 looks as if someone randomly threw "pieces" of light at the detector, causing full exposure at some points but no exposure at others.


The photo at very low light levels shows individual points, as if particles are arriving at the detector.

The particle-like behavior is not noticeable at higher light levels.

FIGURE 25.33 Photographs made with an increasing level of light intensity.

If we did not know that light is a wave, we would interpret the results of this experiment as evidence that light is a stream of some type of particle-like object. If these particles arrive frequently enough, they overwhelm the detector and it senses a steady "river" instead of the individual particles in the stream. Only at very low intensities do we become aware of the individual particles.

As we will see in Chapter 28, many experiments convincingly lead to the surprising result that **electromagnetic waves, although they are waves, have a particle-like nature.** These particle-like components of electromagnetic waves are called **photons.**

The **photon model** of electromagnetic waves consists of three basic postulates:

1. Electromagnetic waves consist of discrete, massless units called photons. A photon travels in vacuum at the speed of light, 3.00×10^8 m/s.
2. Each photon has energy

$$E_{\text{photon}} = hf \qquad (25.20)$$

   where f is the frequency of the wave and h is a *universal constant* called **Planck's constant.** The value of Planck's constant is

$$h = 6.63 \times 10^{-34}\ \text{J} \cdot \text{s}$$

   In other words, the electromagnetic waves come in discrete "chunks" of energy hf.
3. The superposition of a sufficiently large number of photons has the characteristics of a continuous electromagnetic wave.

EXAMPLE 25.8 Finding the energy of a photon of visible light

550 nm is the average wavelength of visible light.

a. What is the energy of a photon with a wavelength of 550 nm?
b. A 40 W incandescent light bulb emits about 1 J of visible light energy every second. Estimate the number of visible light photons emitted per second.

SOLVE a. The frequency of the photon is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8\ \text{m/s}}{550 \times 10^{-9}\ \text{m}} = 5.45 \times 10^{14}\ \text{Hz}$$

Equation 25.20 gives us the energy of this photon:

$$E_{\text{photon}} = hf = (6.63 \times 10^{-34}\ \text{J} \cdot \text{s})(5.45 \times 10^{14}\ \text{Hz}) = 3.61 \times 10^{-19}\ \text{J}$$

This is an extremely small energy! In fact, photon energies are so small that they are usually measured in electron volts (eV) rather than joules. Recall that $1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$. With this, we find that the photon energy is

$$E_{\text{photon}} = 3.61 \times 10^{-19}\ \text{J} \times \frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \text{J}} = 2.26\ \text{eV}$$

b. The photons emitted by a light bulb span a range of energies, because the light spans a range of wavelengths, but the *average* photon energy corresponds to a wavelength near 550 nm. Thus we can estimate the number of photons in 1 J of light as

$$N \approx \frac{1\ \text{J}}{3.61 \times 10^{-19}\ \text{J/photon}} \approx 3 \times 10^{18}\ \text{photons}$$

A typical light bulb emits about 3×10^{18} photons every second.

ASSESS The number of photons emitted per second is staggeringly large. It's not surprising that in our everyday life we would sense only the river and not the individual particles within the flow.

As we saw, a single photon of light at a wavelength of 550 nm has an energy of 2.26 eV. It is worthwhile to see just what 2.26 eV "buys" in interactions with atoms and molecules. Table 25.1 shows some energies required for typical atomic and molecular processes. These values show that 2.26 eV is a significant amount of energy on an atomic scale. It is certainly enough to cause a molecular transformation, and photons with just slightly more energy (shorter wavelength) can break a covalent bond. The photon model of light will be essential as we explore the interaction of electromagnetic waves with matter in coming chapters.

TABLE 25.1 Energies of some atomic and molecular processes

Process	Energy
Breaking a hydrogen bond between two water molecules	0.24 eV
Energy released in metabolizing one molecule of ATP	0.32 eV
Breaking the bond between atoms in a water molecule	4.7 eV
Ionizing a hydrogen atom	13.6 eV

STOP TO THINK 25.5 Two FM radio stations emit radio waves at frequencies of 90.5 MHz and 107.9 MHz. Each station emits the same total power. If you think of the radio waves as photons, which station emits the largest number of photons per second?

A. The 90.5 MHz station. B. The 107.9 MHz station.
C. Both stations emit the same number of photons per second.

25.8 The Electromagnetic Spectrum

We have now seen two very different ways to look at electromagnetic waves: as oscillating waves of the electric and magnetic field, and as particle-like units of the electromagnetic field called photons. This dual nature of electromagnetic waves is something we will discuss at length in Chapter 28. For now, we will note that each view is appropriate in certain circumstances. For example, we speak of radio *waves* but of x *rays*. The "ray" terminology tells us that x rays are generally better described as photons than as waves.

Figure 25.34 shows the *electromagnetic spectrum* with photon energy (in eV) and wavelength (in m) scales. As you can see, electromagnetic waves span an extraordinarily wide range of wavelengths and energies. Radio waves have wavelengths of many meters but very low photon energies—only a few billionths of an eV. Because the photon energies are so small, radio waves are well described by Maxwell's theory of electromagnetic waves, as we noted above. At the other end of the spectrum, x rays and gamma rays have very short wavelengths and very high photon energies—large enough to ionize atoms and break molecular bonds. Consequently, x rays and gamma rays, although they do have wave-like characteristics, are best described as photons. Visible light is in the middle. As we will see in Chapter 28, we must consider *both* views to fully understand the nature of visible light.

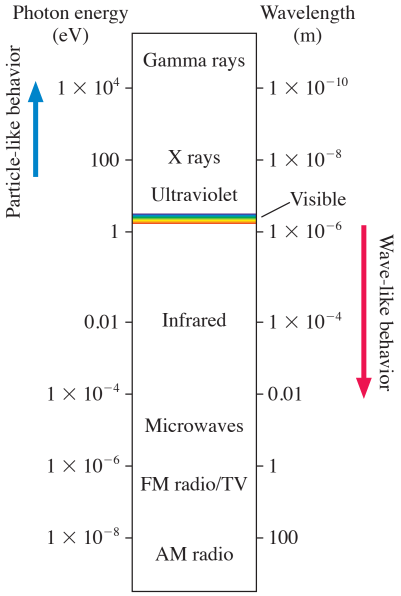


FIGURE 25.34 The electromagnetic spectrum.

Radio Waves and Microwaves

An electromagnetic wave is self-sustaining, independent of charges or currents. However, charges and currents are needed at the *source* of an electromagnetic wave. Radio waves and microwaves are generally produced by the motion of charged particles in an antenna.

Figure 25.35 reminds you what the electric field of an electric dipole looks like. If the dipole is vertical, the electric field $\vec{E}$ at points along a horizontal line is also vertical. Reversing the dipole, by switching the charges, reverses $\vec{E}$. If the charges were to *oscillate* back and forth, switching position at frequency f, then $\vec{E}$ would oscillate in a vertical plane. The changing $\vec{E}$ would then create an induced magnetic field $\vec{B}$, which could then create an $\vec{E}$, which could then create a $\vec{B}$, . . . and a vertically polarized electromagnetic wave at frequency f would radiate out into space.

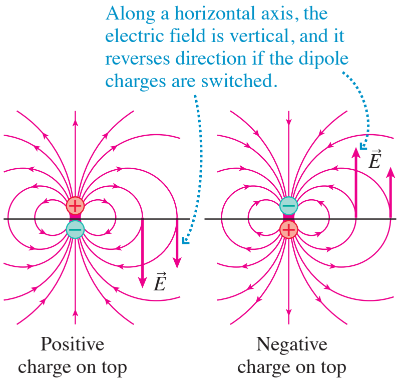


FIGURE 25.35 The electric field of an oscillating dipole.

This is exactly what an **antenna** does. Figure 25.36 shows two metal wires attached to the terminals of an oscillating voltage source. The figure shows an instant when the top wire is negative and the bottom is positive, but these will reverse in half a cycle. The wire is basically an oscillating dipole, and it creates an oscillating electric field. The oscillating $\vec{E}$ induces an oscillating $\vec{B}$, and they take off as an electromagnetic wave at speed $v_{\text{em}} = c$. The wave does need oscillating charges as a *wave source,* but once created it is self-sustaining and independent of the source.

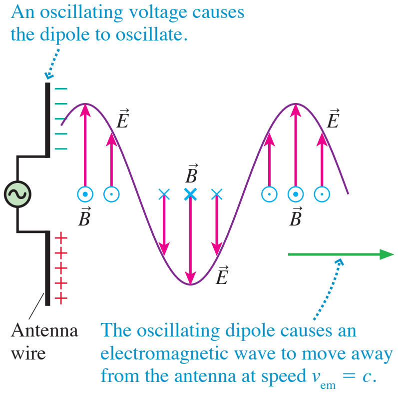


FIGURE 25.36 An antenna generates a self-sustaining electromagnetic wave.

Radio waves are *detected* by antennas as well. The electric field of a vertically polarized radio wave drives a current up and down a vertical conductor, producing a potential difference that can be amplified. For best reception, the antenna length should be about $\frac{1}{4}$ of a wavelength. A typical cell phone works at 1.9 GHz, with wavelength $\lambda = c/f = 16\text{ cm}$. Thus a cell phone antenna should be about 4 cm long, or about $1\frac{1}{2}$ inches. The antenna on your cell phone may seem quite short, but it is the right length to do its job.

AM radio has a lower frequency and thus a longer wavelength—typically 300 m. Having an antenna that is $\frac{1}{4}$ of a wavelength—75 m long!—is simply not practical. Instead, the antenna in an AM radio consists of a coil of wire wrapped around a core of magnetic material. This antenna detects the *magnetic* field of the radio wave. The changing flux of the wave's magnetic field induces an emf in the coil that is detected and amplified by the receiver.

CONCEPTUAL EXAMPLE 25.1 Orienting a coil antenna

A vertically polarized AM radio wave is traveling to the right. How should you orient a coil antenna to detect the oscillating magnetic field component of the wave?

REASON You want the oscillating magnetic field of the wave to produce the maximum possible induced emf in the coil, which requires the maximum changing flux. The flux is maximum when the coil is perpendicular to the magnetic field of the electromagnetic wave, as in Figure 25.37. Thus the plane of the coil should match the wave's plane of polarization.

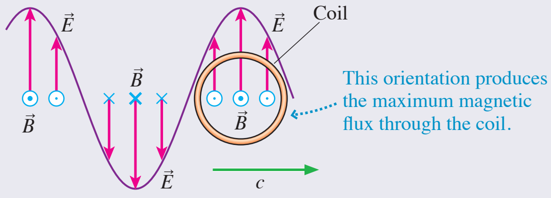
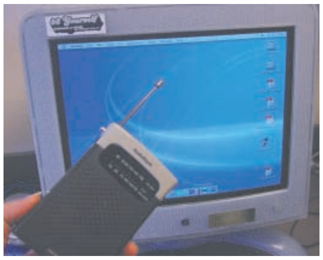


FIGURE 25.37 A coil antenna.

ASSESS Coil antennas are highly directional. If you turn an AM radio—and thus the antenna—in certain directions, you will no longer have the correct orientation of the magnetic field and the coil, and reception will be quite poor.

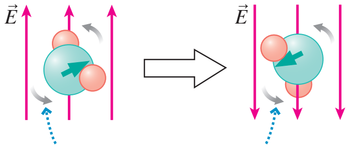
TRY IT YOURSELF



Unwanted transmissions During takeoff and landing, airplane passengers are asked to turn off electronic devices. A simple experiment shows why. Set a radio to the AM band and hold it near a computer. Adjust the radio's tuning while opening a file; you can easily find a radio signal emitted by the hard drive when it is operating, because electromagnetic waves are produced by the rapid switching of electric currents in the drive. All portable electronic devices emit radio waves whether they are designed for communicating or not, and they may cause dangerous interference with airplane systems.

The electric fields of radio waves and microwaves interact with matter by exerting a torque on molecules, such as water, that have a permanent electric dipole moment, as shown in 25.38. The molecules acquire kinetic energy from the wave, then their collisions with other molecules transform that energy into thermal energy, increasing the temperature.

This is how a microwave oven heats food. A typical home oven uses microwaves of a frequency of 2.45 GHz and a wavelength of 12.2 cm. Water molecules, with their large dipole moment, rotate in response to the electric field of the microwaves, then transfer this energy to the food via molecular collisions. Physical therapists may use electromagnetic waves for deep heating of tissue. The wavelength is generally longer than that in a microwave oven because the longer wavelengths have greater penetration.



The oscillating electric field of the wave rotates the water molecule by exerting an oscillating torque on its electric dipole moment.

FIGURE 25.38 A radio wave interacts with matter.

Infrared, Visible Light, and Ultraviolet

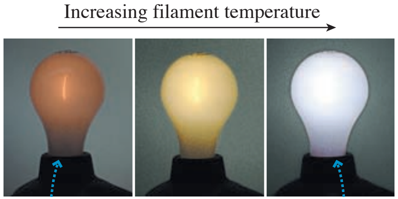
Radio waves can be produced by oscillating charges in an antenna. At the higher frequencies of infrared, visible light, and ultraviolet, the "antennas" are individual atoms. This portion of the electromagnetic spectrum is *atomic radiation*.

Nearly all the atomic radiation in our environment is *thermal radiation* due to the thermal motion of the atoms in an object. As we saw in Chapter 12, thermal radiation—a form of heat transfer—is described by Stefan's law: If heat energy Q is radiated in a time interval Δt by an object with surface area A and absolute temperature T, the *rate* of heat transfer $Q/\Delta t$ (joules per second) is

$$\frac{Q}{\Delta t} = e\sigma AT^4 \tag{25.21}$$

The constant e in this equation is the object's emissivity, a measure of its effectiveness at emitting electromagnetic waves, and σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/(m^2 \cdot K^4)}$.

In Chapter 12 we considered the amount of energy radiated and its dependence on temperature. The filament of an incandescent bulb glows simply because it is hot. If you increase the current through a lightbulb, the temperature increases and so does the total energy emitted by the bulb, in accordance with Stefan's law. The three pictures in Figure 25.39 show a glowing lightbulb with the filament at successively higher temperatures. We can clearly see an increase in brightness in the sequence of three photographs.



At lower filament temperatures, the bulb is dim, and the light is noticeably reddish.

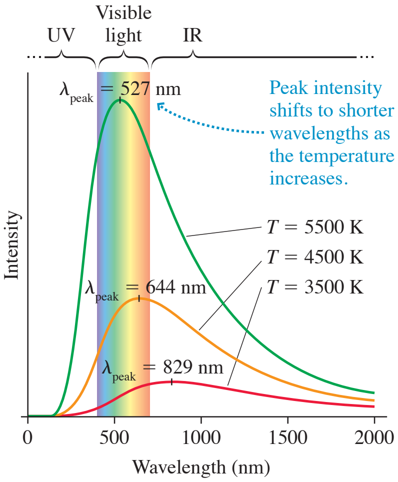
When the filament is hotter, the bulb is brighter and the light is whiter.

FIGURE 25.39 The brightness of the bulb varies with the temperature of the filament.

But it's not just the brightness that varies. The *color* of the emitted radiation changes as well. At low temperatures, the light from the bulb is quite red. (A dim bulb doesn't look this red to your eye because your brain, knowing that the light "should" be white, compensates. But the camera doesn't lie.) Looking at the change in color as the temperature of the bulb rises in Figure 25.39, we see that **the spectrum of thermal radiation changes with temperature.** It's this variation in the spectrum that we want to consider in this chapter.

If we measured the intensity of thermal radiation as a function of wavelength for an object at three temperatures, 3500 K, 4500 K, and 5500 K, the data would appear as in Figure 25.40. Notice two important features of the data:

- Increasing the temperature increases the intensity at all wavelengths. **Making the object hotter causes it to emit more radiation across the entire spectrum.**
- Increasing the temperature causes the peak intensity to shift to a shorter wavelength. **The higher the temperature, the shorter the wavelength of the peak of the spectrum.**



Peak intensity shifts to shorter wavelengths as the temperature increases.

FIGURE 25.40 A thermal emission spectrum depends on the temperature.

The wavelength corresponding to the peak of the intensity graph is given by

$$\lambda_{\text{peak}}(\text{in nm}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{T} \tag{25.22}$$

Wien's law for the peak wavelength of a thermal emission spectrum

INVERSE
p. 118

where the temperature *must* be in kelvin. The spectrum of a hotter object is a taller graph (more energy radiated) with its peak at a shorter wavelength.

EXAMPLE 25.9 Finding peak wavelengths

What are the wavelengths of peak intensity and the corresponding spectral regions for radiating objects at (a) normal human body temperature of 37°C, (b) the temperature of the filament in an incandescent lamp, 1500°C, and (c) the temperature of the surface of the sun, 5800 K?

PREPARE All of the objects emit thermal radiation.

SOLVE First, we convert temperatures to kelvin. The temperature of the human body is $T = 37 + 273 = 310$ K and the filament temperature is $T = 1500 + 273 = 1773$ K. Equation 25.22 then gives the wavelengths of peak intensity as

$$\text{a. } \lambda_{\text{peak}}(\text{body}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{310\ \text{K}} = 9.4 \times 10^3\ \text{nm} = 9.4\ \mu\text{m}$$

$$\text{b. } \lambda_{\text{peak}}(\text{filament}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{1773\ \text{K}} = 1600\ \text{nm}$$

$$\text{c. } \lambda_{\text{peak}}(\text{sun}) = \frac{2.9 \times 10^6\ \text{nm} \cdot \text{K}}{5800\ \text{K}} = 500\ \text{nm}$$

ASSESS The peak of the emission curve at body temperature is far into the infrared region of the spectrum, well below the range of sensitivity of human vision. The sun's emission peaks right in the middle of the visible spectrum, which seems reasonable. Interestingly, most of the energy radiated by an incandescent bulb is *not* visible light. The tail of the emission curve extends into the visible region, but the peak of the emission curve—and most of the emitted energy—is in the infrared region of the spectrum. A 100 W bulb emits only a few watts of visible light.

◀ **It's the pits** . . . BIO Rattlesnakes can hunt in total darkness. Prey animals are warm, and warm objects emit thermal radiation—which the snakes can sense. Rattlesnakes are in a group of snakes know as *pit vipers*. The name comes from a second set of vision organs that are simply pits with sensitive tissue at the bottom. In the photo, the pits appear as dark spots in front of the eyes. The pits are sensitive to infrared wavelengths of $\approx 10\ \mu\text{m}$, near the wavelength of peak emission at mammalian body temperatures. Pit vipers sense the electromagnetic waves *emitted* by warm-blooded animals. They need no light to "see" you. You emit a "glow" they can detect.

Infrared radiation, with its relatively long wavelength and low photon energy, produces effects in tissue similar to those of microwaves—heating—but the penetration is much less than for microwaves. Infrared is absorbed mostly by the top layer of your skin and simply warms you up, as you know from sitting in the sun or under a heat lamp. The wave picture is generally most appropriate for infrared.

In contrast, ultraviolet photons have enough energy to interact with molecules in entirely different ways, ionizing molecules and breaking molecular bonds. The cells in skin are altered by ultraviolet radiation, causing sun tanning and sun burning. DNA molecules can be permanently damaged by ultraviolet radiation. There is a reasonably sharp threshold for such damage at 290 nm (corresponding to 4.3 eV photon energy). At longer wavelengths, damage to cells is slight; at shorter wavelengths, it is extensive. Ultraviolet lamps are very effective at sterilizing surfaces because they disrupt the genetic material of bacteria sufficiently to kill them. These interactions of ultraviolet radiation with matter are best understood from the photon perspective, with the absorption of each photon being associated with a particular molecular event.

Visible light is at a transition point in the electromagnetic spectrum. Your studies of wave optics in Chapter 17 showed you that light has a wave nature. At the same time, the energy of photons of visible light is large enough to cause molecular transitions—which is how your eye detects light. The bending of light by the lens of the eye requires us to think of light as a wave, but the detection of light by the cells in the retina requires us to think of light as photons. When we work with visible light, we will often move back and forth between the wave and photon models.

EXAMPLE 25.10 Finding the photon energy for ultraviolet light

Ultraviolet radiation with a wavelength of 254 nm is used in germicidal lamps. What is the photon energy in eV for such a lamp?

SOLVE The photon energy is $E = hf$:

$$E = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34}\ \mathrm{J \cdot s})(3.00 \times 10^{8}\ \mathrm{m/s})}{254 \times 10^{-9}\ \mathrm{m}}$$

$$= 7.83 \times 10^{-19}\ \mathrm{J}$$

In eV, this is

$$E = 7.83 \times 10^{-19}\ \mathrm{J} \times \frac{1\ \mathrm{eV}}{1.60 \times 10^{-19}\ \mathrm{J}} = 4.89\ \mathrm{eV}$$

ASSESS Table 25.1 shows that this energy is sufficient to break the bonds in a water molecule. It will be enough energy to break other bonds as well, leading to damage on a cellular level.

Color Vision

The cones, the color-sensitive cells in the retina of the eye, each contain one of three slightly different forms of a light-sensitive photopigment. A single photon of light can trigger a reaction in a photopigment molecule, which ultimately leads to a signal being produced by a cell in the retina. The energy of the photon must be matched to the energy of a molecular transition for absorption of the photon energy to take place. Each photopigment has a range of photon energies to which it is sensitive. Our color vision is a result of the differential response of the three types of cones containing these three different pigments, shown in Figure 25.41.

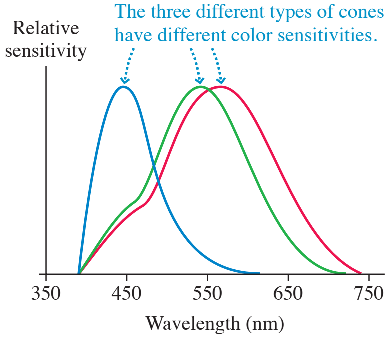


FIGURE 25.41 The sensitivity of different cones in the human eye.

CONCEPTUAL EXAMPLE 25.2 Creating the impression of a color

Computer monitors and color TVs can create millions of different colors by combining light from pixels of only three colors: red, green, and blue. These are called RGB displays. How do they do it?

REASON We've seen that there are three different types of cones in the eye. By using differing amounts of three pure colors, we can independently stimulate each of the cone types and thus mimic the response of the eye to light of almost any color.

ASSESS The fact that there are three primary colors of light—red, green, and blue—is a function of our physiology, not basic physics.

Humans have three color photopigments, mice have two, and chickens four—giving them keener color vision than you. The three color photopigments that bees possess give them excellent color vision, but a bee's color sense is different from a human's. The peak sensitivities of a bee's photopigments are in the yellow, blue, and ultraviolet regions of the spectrum. A bee can't see the red of a rose, but it is quite sensitive to ultraviolet wavelengths well beyond the range of human vision. The flowers in the photo at the start of the chapter look pretty to us, but their coloration is really intended for other eyes. The ring of ultraviolet-absorbing pigments near the center of the flower, which is invisible to humans, helps bees zero in on the pollen.

X Rays and Gamma Rays

At the highest energies of the electromagnetic spectrum we find x rays and gamma rays. There is no sharp dividing line between these two regions of the spectrum; the difference is the source of radiation. High-energy photons emitted by electrons are called x rays. If the source is a nuclear process, we call them gamma rays.

We will look at the emission of x rays in atomic processes and gamma rays in nuclear processes in Part VII. For now, we will focus on the "artificial" production of x rays in an x-ray tube, such as the one shown in Figure 25.42.

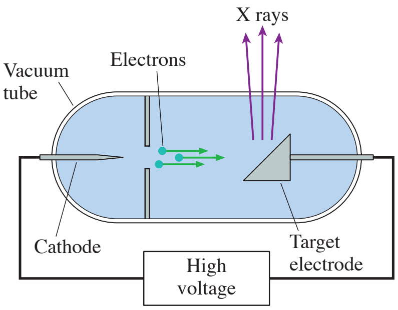


FIGURE 25.42 A simple x-ray tube.

Electrons are emitted from a cathode and accelerated to a kinetic energy of several thousand eV by the electric field between two electrodes connected to a high-voltage power supply. The electrons make a sudden stop when they hit a metal target electrode. The rapid deceleration of an electron can cause the emission of a single photon with a significant fraction of the electron's kinetic energy. These photons, with energies well in excess of 1000 eV, are x rays. The x rays pass through a window in the tube and then may be used to produce an image or to treat a disease.

EXAMPLE 25.11 Determining x-ray energies

An x-ray tube used for medical work has an accelerating voltage of 30 kV. What is the maximum energy of an x-ray photon that can be produced in this tube? What is the wavelength of this x ray?

SOLVE An electron accelerated through a potential difference of 30 kV acquires a kinetic energy of 30 keV. When this electron hits the metal target and stops, energy may be converted to an x ray. The maximum energy that could be converted is 30 keV, so this is the maximum possible energy of an x-ray photon from the tube. In joules, this energy is

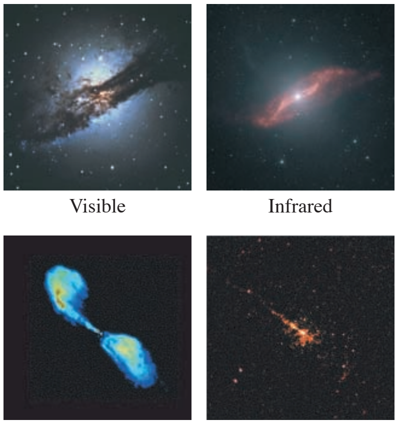
$$E = 30 \times 10^3 \text{ eV} \times \frac{1.60 \times 10^{-19}\text{ J}}{1 \text{ eV}} = 4.8 \times 10^{-15}\text{ J}$$

For electromagnetic waves, $c = f\lambda$, so we can calculate

$$\lambda = \frac{c}{f} = \frac{c}{E/h} = \frac{hc}{E} = \frac{(6.63 \times 10^{-34}\text{ J}\cdot\text{s})(3.00 \times 10^{8}\text{ m/s})}{4.8 \times 10^{-15}\text{ J}}$$
$$= 4.1 \times 10^{-11}\text{ m} = 0.041 \text{ nm}$$

ASSESS This is a very short wavelength, comparable to the spacing between atoms in a solid.

X rays and gamma rays (and the short-wavelength part of the ultraviolet spectrum) are **ionizing radiation;** the individual photons have sufficient energy to ionize atoms. When such radiation strikes tissue, the resulting ionization can produce cellular damage. When people speak of "radiation" they often mean "ionizing radiation." Ionizing radiation can be harmful to cells, but, as we will see in Chapter 30, it can also be put to good use in radiation therapy to treat cancer. Rapidly dividing cells—such as those in a tumor—are especially sensitive to the damage from ionizing radiation.



Visible

Infrared

Seeing the universe in a different light These four images of the Centaurus A galaxy have the same magnification and orientation, but they are records of different types of electromagnetic waves. (All but the visible light image are false-color images.) The visible light images shows a dark dust lane cutting across the galaxy. In the infrared, this dust lane glows quite brightly—telling us that the dust particles are hot. The radio and x ray images show jets of matter streaming out of the galaxy's center, hinting at the presence of a massive black hole. Views of the cosmos beyond the visible range are important tools of modern astronomy.

X rays and gamma rays are very penetrating, but the absorption of these high-energy photons is greater in materials made of atoms with more electrons. This is why x rays are used in medical and dental imaging. The calcium in bones has many more electrons and thus is much more absorbing than the hydrogen, carbon, and oxygen that make up most of our soft tissue, so we can use x rays to image bones and teeth.

At several points in this chapter we have hinted at places where a full understanding of the phenomena requires some new physics. We have used the photon model of electromagnetic waves, and we have mentioned that nuclear processes can give rise to gamma rays. There are other questions that we did not raise, such as why the electromagnetic spectrum of a hot object has the shape that it does. These puzzles began to arise in the late 1800s and early 1900s, and it soon became clear that the physics of Newton and Maxwell was not sufficient to fully describe the nature of matter and energy. Some new rules, some new models, were needed. After the next chapter, in which we look at AC circuits, we will return to these puzzles as we begin to explore the exciting notions of quantum physics in Part VII.

STOP TO THINK 25.6 A group of four stars, all the same size, have the four different surface temperatures given below. What is the temperature of the star that emits the most red light?

A. 3000 K B. 4000 K C. 5000 K D. 6000 K

What’s beyond the rainbow?

A laboratory experiment from the
Little Shop of Physics at
Colorado State University

Overview

Light is a form of electromagnetic radiation. The rainbow of colors from red to violet is the spread of different wavelengths that makes up visible light.

Of course, there is more to the story...

Theory

All forms of electromagnetic radiation (radio waves, microwaves, infrared, visible light, ultraviolet, x rays) are really the same basic physical phenomenon: They are waves of electric and magnetic fields.

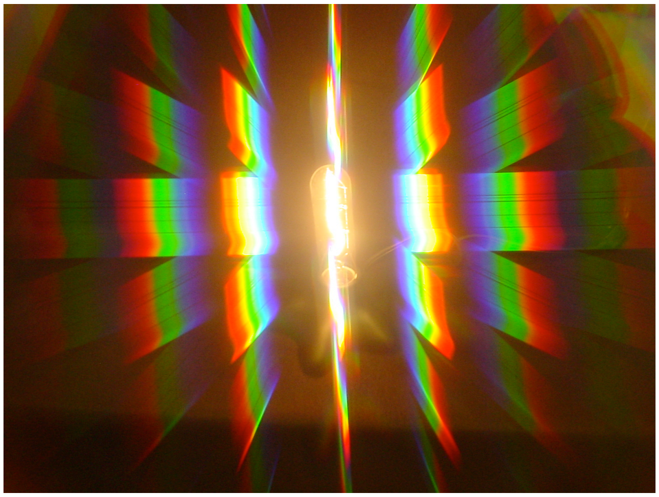
But they behave very differently. There are two big differences between different parts of the spectrum: Wavelength and energy.

Necessary materials:

- Rainbow glasses
- IR goggles
- Ceramic heat lamp
- Ultraviolet light (blacklight)
- Thermal imaging camera (optional)

This is an open-ended exploration that can be done in many different ways which would use different equipment. The thermal imaging camera, in particular, is hard to find. If you can find one, it’s great, but if you can’t, you can make the same point by feeling emitted thermal radiation.

The red end of the rainbow corresponds to long wavelength and low energy; the violet end of the spectrum, short wavelength and high energy. And the electromagnetic spectrum beyond the rainbow is even more extreme.



Here is a photo of trees, water and sky through the infrared goggles. Note the odd patterns of what is dark and what is light.

Beyond the violet is the range of very high energy. The photons of ultraviolet light are so energetic that they can damage cells. X rays are even worse, of course; that’s why you need to limit exposure.

Beyond the red is a much mellower place. The photons of infrared are so wimpy that they can only warm you up. Radio waves are so weak that they can actually go right through you.

In these experiments, we’ll get a chance to “see” the electromagnetic waves that exist beyond the rainbow...

Doing the Experiment

This is an open-ended exploration that can take many forms.

> **SAFETY NOTE I: The only real safety note is this: Students will often be walking around wearing special glasses or goggles, making it hard to see where they are walking. You need to be certain that they have a wide-open area where they are free to move around without bumping into anything!**
>
> **SAFETY NOTE II: When wearing the infrared goggles, be certain that NO ONE SHOULD LOOK AT THE SUN!!! Though the goggles reduce the radiation that comes into your eyes, the sun gives off a good deal of infrared, enough to cause irritation.**
>
> **SAFETY NOTE III: DON'T LOOK AT THE SUN!!! Have we mentioned this?**

Here are some things you can do:

- Have your students wear the rainbow glasses to explore the spectrum of visible light. Talk about the different parts of the rainbow.
- Use the infrared goggles to see beyond the rainbow... Your eyes are actually weakly sensitive to the infrared. Go outside and look around. What you are seeing is how the world looks in infrared. How does it look? Plants are light; they reflect infrared. The sky is dark; not much infrared is scattered to light the sky. Clouds are light. How about clothing? Some things that are dark in visible light are dark in the infrared; some things that are light in visible light are dark in the infrared. And some things are actually transparent to the infrared...
- Use the thermal imaging camera in a room in total darkness. You can still see, because the camera picks up the radiation that objects emit. Hot things are bright, cool things are dim. Heat something up, and notice the radiation that it emits. That's how it cools off!
- Turn on the ultraviolet light and see its effects: Objects in the room will fluoresce due to the ultraviolet radiation. It's clearly real, but you can't see it directly.

Summing Up

This is an important experiment to give your students some experience with the spectrum of electromagnetic waves. Students know about visible light, but they don't really know about the other forms. It's important that you give them a chance to explore these other parts of the spectrum before you talk about them, otherwise your discussion will be too abstract for your students to be able to comprehend.

Besides, it's cool. Seeing beyond the rainbow is a lot of fun.

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

Can you see beyond the rainbow?

A laboratory experiment from the
Little Shop of Physics at
Colorado State University

Overview

We all know about the rainbow, the spectrum of electromagnetic radiation that your eyes can see. But what lies beyond the rainbow, in the range of wavelengths that we don't normally see?

Theory

Electromagnetic radiation spans a very wide spectrum of wavelengths, from AM radio waves that are longer than a football field to gamma rays which are smaller than an atom.

But the most important "slice" of the spectrum is the segment from about 400 to 700 nm (nanometers, or billionths of a meter) which is visible light. This band is the familiar rainbow of colors that the eye can sense. The blue end of the rainbow is 400 nm; beyond this is the ultraviolet. The red end of the spectrum is about 700 nm; beyond this is the infrared.

Necessary materials:

- IR goggles
- Colorful question page
- Infrared ink
- Cyan, magenta, and yellow gel filters

You can't just buy these IR goggles; you need to create them. We purchased inexpensive welding goggles and modified them by sliding off the front of the goggles and replacing the lens with plastic that transmits only infrared, not visible light. The IR-transmitting plastic is ACRYLITE GP, Color # 1146-0. It transmits light of wavelengths greater than 750nm. The plastic can be obtained from a plastic supplier; check your local directory.

Welding goggles can be had from http://store.weldingdepot.com

Gel filters can be found at Stage Spot: www.stagespot.com

This photo was taken on a sunny day through a pair of IR goggles. Notice how the trees appear light and the sky appears dark.

There are two types of infrared: Near infrared, just beyond the range that your eyes can see, and far infrared, which is also called thermal radiation. Night vision scopes use near infrared; the thermal images you may have seen that show the temperature of objects are showing far infrared.

These goggles let through near infrared. This isn't thermal radiation; it's just a slice of the spectrum that's a lot like light, just a bit beyond the end of the rainbow. This is also a part of the spectrum that you can see, if the pesky visible light is removed. Take this away, and your eyes can sense wavelengths out to at least 800 nm—beyond the rainbow!

Doing the Experiment

The view beyond the rainbow is very eerie; familiar objects look very different. Everything looks red, because it is the red color sensors in your eyes that pick up the infrared. But notice the brightness; which things appear bright, which appear dim?

This is an open-ended exploration, and it takes time to get used to the infrared world. Before you begin, let students know about these safety precautions:

> **SAFETY NOTE 1: As students explore with the IR goggles, warn them to never look at the sun! The sun gives off a good deal of IR, but the eyes are only weakly sensitive to it, meaning there is a lot of energy present with no blink reflex to tell you to shut or avert your eyes. Unless you have special glasses designed for solar viewing, which these are not, DO NOT LOOK AT THE SUN!!!**
>
> **SAFETY NOTE 2: When you are wearing the IR goggles, it may be hard to see where you are walking, making it easy to stumble or fall. Do this activity in a wide-open area where students are free to move around without bumping into anything. Use the goggles outside during daylight, or if you work inside where there is less illumination, have students work with a partner without goggles who can serve as a guide.**

Here are some things you can explore:

- Take a look at the colored sheet accompanying this exercise. What colors can you see with the goggles on? What colors have disappeared? Is there a secret message you didn't notice in visible light, but you can read in infrared?
- Now, look around you as you are outside. This is how the world looks in infrared! Plants are light; they reflect infrared. Clouds are also light, as is snow. The sky is dark; very little infrared is scattered. (This makes sense; it's the short wavelengths at the blue end of the spectrum that are scattered the most. That's why the sky is blue!)
- Look at the people around you and check out their clothing. Do the patterns become more pronounced or disappear on any items? Some fabrics that are dark in visible light are light in the infrared; some materials that are light in visible light are dark in the infrared. And some items are actually transparent to the infrared. . .
- Take off your goggles, while others are wearing them and try to see their eyes. Now, put on your goggles and look again. Why can you see their eyes when you too, are wearing goggles?
- Stack a cyan, magenta, and yellow gel filter on top of each other. Take off your goggles and try to look through all three filters. Now, put on your goggles and look through all three filters again. Why do you think you can see through them with the goggles on?

Summing Up

This is an important experiment to give your students more experience with the spectrum of electromagnetic waves. Students are familiar with visible light, but they don't really know about the other forms they cannot see. It's important that you give them a chance to explore these other parts of the spectrum before you talk about them, otherwise your discussion will be too abstract for your students to be able to comprehend.

Besides, it's cool. Seeing beyond the rainbow is a lot of fun.

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

Would you get a sunburn on Mars?

A laboratory experiment from the
Little Shop of Physics at
Colorado State University

Overview

This question leads to a couple of related questions that you can explore with your students:

- What causes sunburn?
- Why can you get a sunburn more readily during the middle of the day than in the morning or evening?
- Can you get a sunburn underwater?

These are all things to discuss and explore with these beads, which change color in sunlight.

Necessary materials:

- Ultraviolet-detecting beads—“Sunburn beads”

These beads are the key item for this experiment. They change color when exposed to ultraviolet light, then return to being white or clear.

These beads are available in small quantities from Educational Innovations (www.teachersource.com). For large quantities (like 50,000 or more!) we can suggest wholesale suppliers.

Theory

White light can be broken up into a **spectrum**, the colors of the rainbow that vary from red to violet. What distinguishes the different colors? Light is an electromagnetic wave, a wave of electric and magnetic fields. The different colors of light correspond to different wavelengths; red light has a long wavelength, violet light a short wavelength. Of course, there’s more to the spectrum than this; beyond the red is the longer-wavelength infrared, and beyond the violet is the even shorter wavelength **ultraviolet**.

And there’s also more to the story. Investigators at the end of the 1800s discovered a remarkable thing about light. If light of the correct wavelength shone on a polished metal surface in a vacuum, it would cause electrons to be emitted from the surface. Weak violet light could do this, but intense red light could not. The red light was brighter, and clearly had more energy, but something about it was lacking.

Exposure to ultraviolet changes the color of the beads quite dramatically. They will change back after some time.

It was Albert Einstein who came up with the theoretical explanation: Light, though a wave, also has a particle nature. We can think of it as being made up of particles called **photons**. Photons each have a certain amount of energy that depends on the wavelength of the light they comprise. The shorter the wavelength, the more energetic the individual photons.

Here’s a way to think about it: Suppose you have $20, and your friend has $20. You both have the same amount of money. But suppose your $20 is in quarters, and your friend's money is in dimes. Your have the same amount of money, but yours comes in larger “chunks.” Hungry for a snack, you find a vending machine, but it won’t take any coin smaller than a quarter. You can put in coins and make transactions, but your friend is out of luck. She’s got $20, but no coin large enough to work the machine.

It's like that with red and ultraviolet light. In energy terms, if red light is a dime, ultraviolet is a quarter—it's got about 2½ times as much energy. Red light is made of photons that don't have enough energy to break chemical bonds. But ultraviolet light is made of photons with enough energy, and ultraviolet photons will do so. The irritation from this damage is what causes sunburn. That’s why the beads change color in the sun—photons of ultraviolet have enough energy to cause a (reversible) chemical change in the beads that makes them change color. More ultraviolet means a stronger reaction, and a darker color.

The ultraviolet spectrum is broken into three bands, with UV-A having the longest wavelength (and lowest energy photons) and UV-C the shortest wavelength (and highest energy photons.) The photons of UV-C have enough energy to be very damaging to life; UV-C is used in sterilizers, as it will kill microorganisms. (It's also pretty tough on mammals, especially our eyes.) Fortunately, the ozone in the upper atmosphere absorbs virtually all of the incoming UV-C. UV-A and UV-B do make it through, but they are significantly attenuated by the atmosphere. If the sun is lower, the photons have to go through a much greater thickness of air—and chances are they won't. Most are absorbed. So you won't get a sunburn at sunrise, but you will get one at midday.

Can you get a sunburn underwater? You can, up to a certain depth. Can you get a sunburn from the light through a window? Maybe. It depends on the type of glass. All window glass transmits visible light (that's the point!) but some don't transmit ultraviolet. These are all things that your students could test...

Doing the Experiment

This is a great inquiry experiment. Students can string beads and then use them to test for the presence of ultraviolet—higher intensity ultraviolet produces a darker bead color. You can ask them to suggest questions to test. Some things your students could explore, in addition to the bits noted above:

- How does ultraviolet vary with time of day? With cloud cover? (Cloud cover blocks ultraviolet too.)
- Can you get sunburned in the shade? (You can—ultraviolet is strongly scattered. Half the ultraviolet exposure you get comes directly from the sun, half from scattered ultraviolet that comes from all directions.)
- Are there lights that emit ultraviolet? (Many do, especially “full spectrum” bulbs and “black” lights.)
- How effective are different types of sunscreen?
- Can fabrics transmit ultraviolet? (Indeed they can! Just because you are covered up, that doesn't mean you won't get a sunburn. Some fabrics are pretty good at blocking ultraviolet, but others aren't.)

Summing Up

So, would you get a sunburn on Mars? Indeed. If you were out long enough, you’d get a deadly one. The light from the sun is weaker at Mars’ greater distance, but Mars’ thin atmosphere doesn’t block as much ultraviolet, and it doesn’t completely block the damaging UV-C. A day in the sunlight on the surface of Mars would be no day at the beach! Our atmosphere may look clear, but it’s not. It stops the most damaging parts of light from the sun, allowing life to flourish on our blue-green ball.

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

What is the difference between red light and blue light?

A laboratory experiment from the
Little Shop of Physics at
Colorado State University

Overview

This is an exciting experiment that demonstrates an energy change from one type of light to another. It also reinforces the idea that different colors of light are not the same, but vary in wavelength and energy.

Theory

Einstein received a Nobel prize for his explanation of the photoelectric effect. Einstein's contribution was the realization that light had a particle nature as well as a wave nature.

Light is made of individual particles or packets of energy called *photons*. Different colors of light have photons of different energies. Photons of red light have lower energy; photons of blue light have higher energy.

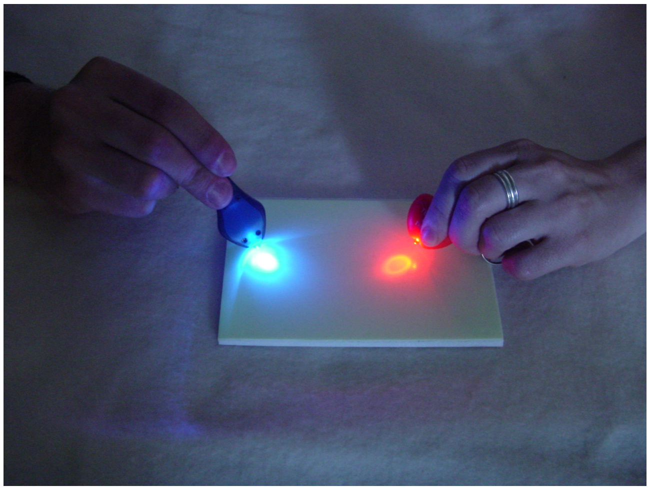
Necessary materials:

- One sheet of phosphorescent paper
- One red LED light
- One blue LED light

The most crucial piece of this experiment is the phosphorescent paper. Not all phosphorescent papers are created equal! Some hold on to the effect of light so long that students lose interest. We've had good results with paper from Educational Innovations: www.teachersource.com

You'll need a fairly dark room for this to work well.

Suppose you need to get a gallon of milk. You could get two half-gallon bottles, or you could get four quart bottles. The total amount of milk is the same—but it comes in different sized "chunks." If you have blue light, it is like getting your light in half-gallon bottles; with red light, it is like getting your light in quart bottles.



Red and blue light have very different effects, as you can show in this experiment.

When you charge up the phosphorescent surface, the individual atoms can only absorb one photon at a time. The red photons just don't have enough energy to do the job, but the photons of blue light do.

At the far end of the spectrum, ultraviolet photons have a lot of energy–they are quite zesty. That's why they can give you a sunburn!

Doing the Experiment

As soon as you dim the lights in your classroom and make it as dark as you can, students should notice an eerie green glow coming from the phosphorescent (glow in the dark) paper. Discuss why they think it is glowing. Where did the energy come from to produce the glow?

Tell them that you are going to give them a special tool to write and draw on the paper. Pass out the blue flashlight and let them experiment with drawing and writing messages on the paper. Have the students notice how the brightness of their messages changes with time.

After students have experimented with the blue flashlights, have them predict what would happen if they used a red flashlight on the phosphorescent paper. Have them try this, and discuss.

Summing Up

This activity is a nice way to transition into energy conservation. The amount of energy that comes out as light can't be more than the energy that was put in. If you shine your blue light on the surface for a long time, it will charge it up more; the image will persist for a longer time.

Another interesting thing: if you shine the red light on a bright spot on the paper, you may find that the spot actually gets dimmer. What is happening is this: if the paper is warm, it glows more brightly. This means the energy is used up faster. Shining the red light on the paper can warm it up right where the red light hits; this will make the surface discharge faster, leaving a dark spot.

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

Can you "see" thermal radiation?

A laboratory experiment from the Little Shop of Physics at Colorado State University

Overview

A normal incandescent bulb works like this: The filament inside the bulb gets hot. Hot objects emit electromagnetic radiation. And so the bulb glows.

Anything which is warm or hot gives off electromagnetic radiation. Really hot objects emit visible light. Cooler objects emit infrared; we call this "thermal radiation" because it is an important mechanism for transferring thermal energy.

Thermal radiation is much like visible light, but there's one big difference: You can't see it.

Or can you???

Necessary materials:

- Ceramic reptile heater
- Metal lamp stand
- Blindfold (optional)

You can do this experiment with a "heat lamp" which is really just a spotlight with a cooler than usual filament. But the ceramic heater is much nicer, because it has no visible glow at all. It gives off no visible light, but it gives off lots of thermal radiation!

Theory

Here's one vocabulary word that is really important: Radiation. Physicists use this term for whatever is given off by something that glows. The radiation spreads out from a source.

You can clearly see a pit in front of the snake's eye. At the bottom is a patch of tissue that is sensitive to temperature changes, allowing the snake to detect thermal radiation.

Visible light is radiation. So are x rays. Some radiation is dangerous, but most isn't; in fact, electromagnetic radiation is responsible for all life on earth!

Visible light and infrared are both kinds of electromagnetic radiation, but they have very different wavelengths. Visible light has very short wavelength, about 0.0005 mm! A typical infrared source emits electromagnetic waves with a wavelength of 0.010 mm, 20 times longer.

The other big difference is in the energy of the photons. A visible light photon has enough energy to cause a molecular transition, as it does when it strikes the retina of you eye. An infrared photon doesn't; a typical thermal radiation photon can only wiggle molecules, it can't cause a transition. So infrared can only warm things up.

But you can still "see" it...

Doing the Experiment

This is a nice experiment to do when you are just beginning your discussion of radiation. Infrared and thermal radiation can seem very abstract; in this experiment, getting a chance to "see" it will help students get a handle on just how real it is!

> **SAFETY NOTE I: The ceramic radiant heaters get very hot! Don't let your students touch them.**
>
> **SAFETY NOTE II: You may choose to have the students do this experiment wearing blindfolds. If you do, please be certain to have your students use caution, so that they don't trip or fall or touch the hot bulb!**

The experiment goes like this:

- Have your students cover their eyes or wear blindfolds, and then hold their hands out in front of them.
- Move the ceramic heater (turned on!) near your students.
- Have them move their hands to see if they can tell where the heater is. It's pretty simple to do if they are close, a bit trickier if they are far away.

Students will quickly figure out how to move their hands to sense the infrared. They detect it by measuring the heating of their palms when the infrared strikes their skin.

This is just how certain snakes can "see" thermal radiation. Pit vipers, such as rattlesnakes, have a second set of "eyes" that contain sensitive tissue that can detect the thermal radiation emitted by warm prey animals. Such snakes can easily detect a warm mammal on the cool sand of the desert even in total darkness! They detect the thermal radiation that their prey emits.

Summing Up

This is a good introduction to thermal radiation. The story of energy transfer within the earth system is dominated by radiation, so it's important that students know that this form of energy is quite real!

For More Information

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