## 25.7 The Photon Model of Electromagnetic Waves
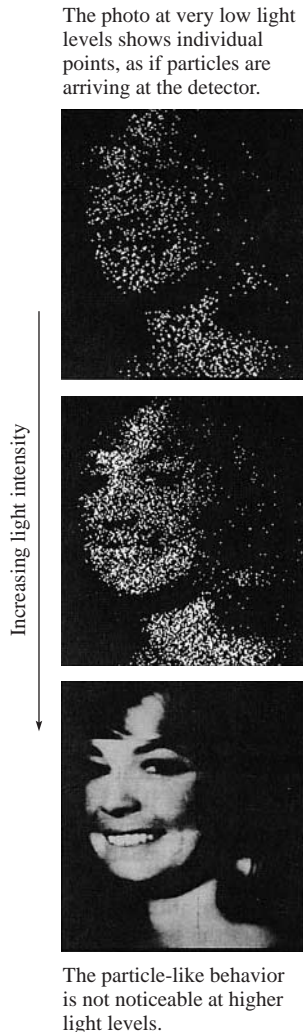
The photo at very low light levels shows individual points, as if particles are arriving at the detector.



Increasing light intensity

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

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

Figure 25.33 shows three photographs made with a camera in which the film has been replaced by a special high-sensitivity detector.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.

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, $3.00 \times 10^8$ m/s.
2. Each photon has energy

$$E_{photon} = hf \tag{25.20}$$

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:

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

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 $1 \text{ eV} = 1.60 \times 10^{-19}$ J. With this, we find that the photon energy is

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

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 $3 \times 10^{18}$ 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.
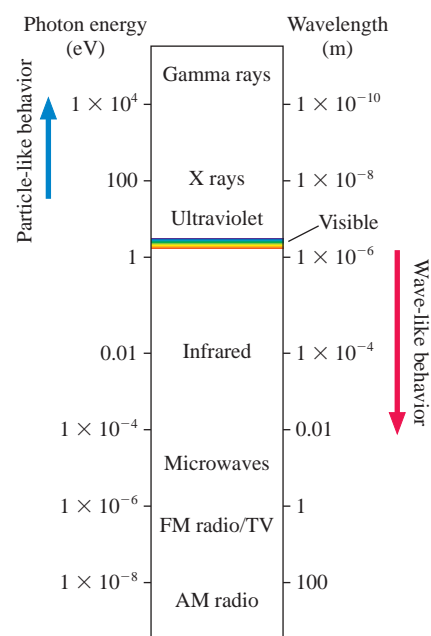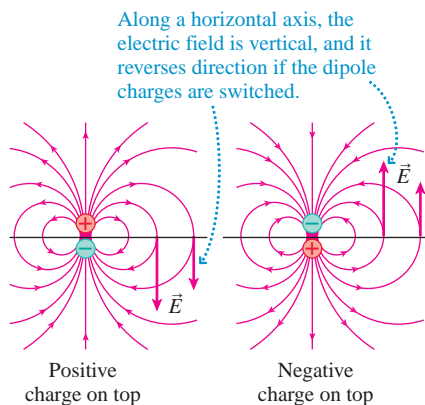


**FIGURE 25.34** The electromagnetic spectrum.

Along a horizontal axis, the electric field is vertical, and it reverses direction if the dipole charges are switched.



Positive charge on top

Negative charge on top

**FIGURE 25.35** The electric field of an oscillating dipole.

An oscillating voltage causes the dipole to oscillate.



Antenna wire

The oscillating dipole causes an electromagnetic wave to move away from the antenna at speed $v_{em} = c$.
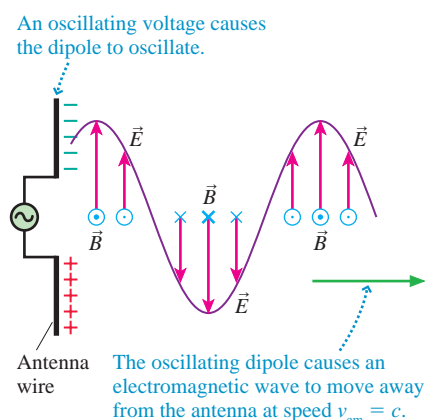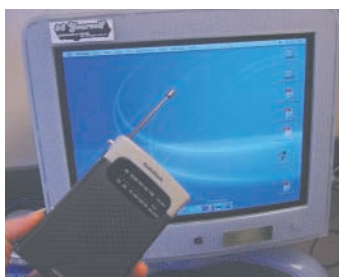
**FIGURE 25.36** An antenna generates a self-sustaining electromagnetic wave.

## 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.

## 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.

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 $v_{em} = c$. The wave does need oscillating charges as a *wave source,* but once created it is self-sustaining and independent of the source.

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 $\lambda = c/f = 16$ 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.
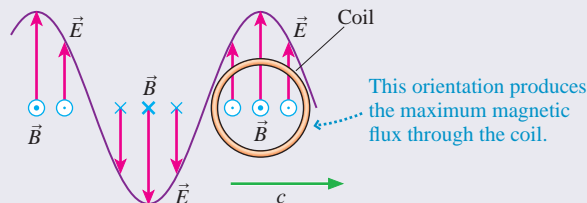


Coil

This orientation produces the maximum magnetic flux through the coil.

**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.

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.
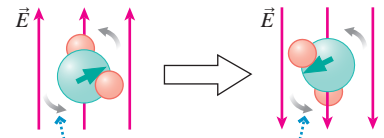


The oscillating electric field of the wave rotates the water molecule by exerting an oscillating torque on its electric dipole moment.

**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 $\Delta t$ by an object with surface area $A$ and absolute temperature $T$, the *rate* of heat transfer $Q/\Delta t$ (joules per second) is

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

The constant $e$ in this equation is the object's emissivity, a measure of its effectiveness at emitting electromagnetic waves, and $\sigma$ is the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/(m² · K⁴).

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.

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.**



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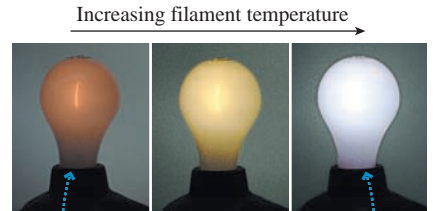
At lower filament temperatures, the bulb is dim, and the light is noticeably reddish.

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.



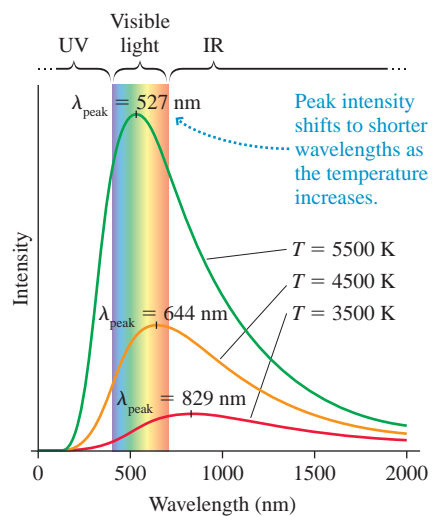Peak intensity shifts to shorter wavelengths as the temperature increases.

**FIGURE 25.40** A thermal emission spectrum depends on the temperature.

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

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

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

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

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

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

**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 ≈10 $\mu$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 $E = hf$:

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

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

In eV, this is

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

**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.

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**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.
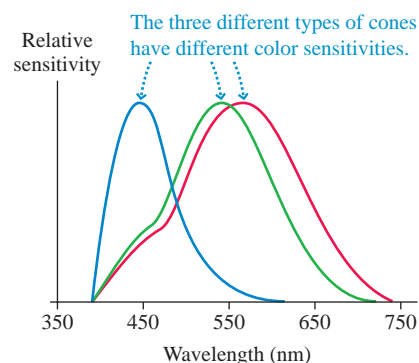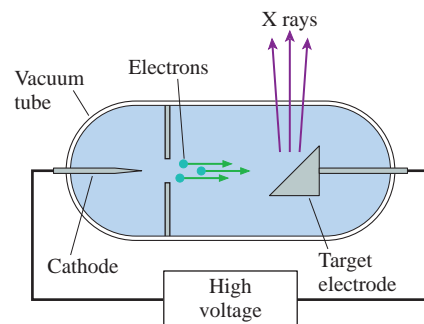


**FIGURE 25.42**  A simple x-ray tube.

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.
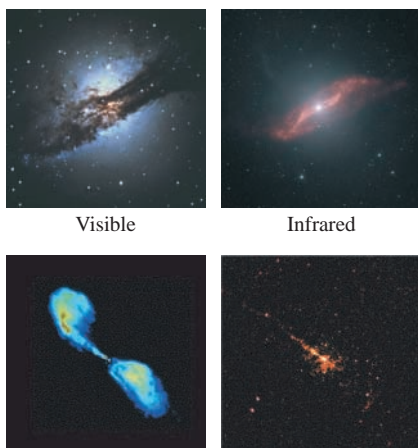
X rays and gamma rays are very penetrating, but the absorption of these high-energy photons is greater in materials made of atoms with more electrons. This is why x rays are used in medical and dental imaging. The calcium in bones has many more electrons and thus is much more absorbing than the hydrogen, 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.



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.

**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

# 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!
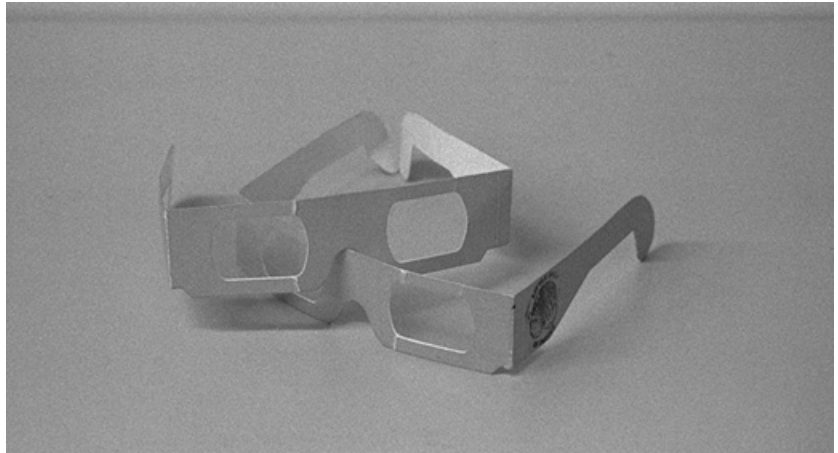
If you look carefully at the rainbows, you see that what you are observing is the spectrum of the light source. Since the dark room in the Little Shop area has a variety of different light sources, you can see a number of different effects. For instance: the phosphors on the screen of the Televised Chaos 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.
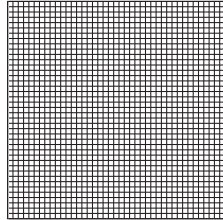
Now, if the lenses in the glasses had a single set of lines spaced like this:
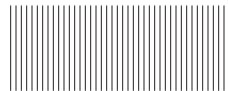
there would be a simple spectrum of the light source. Actually, you would get two spectra, one on each side of the light source:

Light Source

Spectrum                    Spectrum
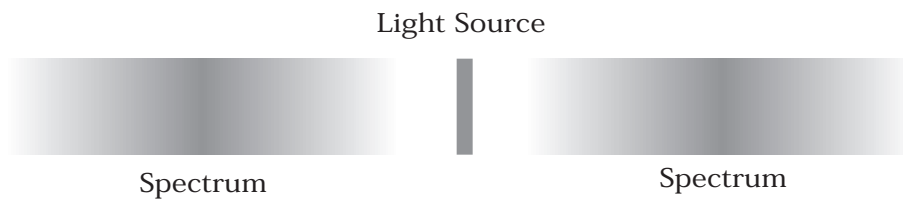
The glasses actually have a grid of lines on them:

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!

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!

# Why does the sun look yellow?

## Overview

Children's drawings often contain a lively scene topped by a bright yellow sun. To those of us here on Earth, the sun does appear yellow, but it's really white! Why then, do we see it as yellow?

## Theory

The simple answer: The sun is yellow because it's not blue...

The filters that you have, cyan, magenta and yellow, are each "complementary" or "secondary" colors. The cyan filter absorbs red light and lets the other colors pass; the magenta absorbs green, and the yellow filter absorbs blue.

Blue light is strongly scattered by the atmosphere, and when you take white light and take away the blue, what you get is... yellow! So the sun is yellow because the white light from the sun has lost its blue, leaving yellow!

### Necessary materials:

- Rainbow glasses
- Gel filters in cyan, magenta, and yellow
- A long filament light bulb
- A light bulb base

The rainbow glasses we use are called diffraction or fireworks glasses. We purchase them from companies such as American Paper Optics or Rainbow Symphony.

www.americanpaperoptics.com/

www.rainbowsymphony.com

The gel filters were purchased from
www.stageshop.com



*Additive primary color mixing shows secondary colors of light.*

## Doing the Experiment

The rainbow glasses are great for looking at many things, but they are particularly nice for showing absorption—which this experiment is about.

- Have your students put on their Rainbow Glasses and look at the light given off by the long filament light bulb, noting what colors they see.
- Now have them put the cyan filter in front of their rainbow glasses and look at the light. What color do they notice is absent from the visible spectrum? (Red) This means that red is being absorbed by the cyan filter!

- Now have them just try the magenta filter in front of their rainbow glasses. The green is absent and is absorbed by the magenta filter.
- Continue the same procedure with the yellow filter. The blue is absent this time, and thus is being absorbed by the yellow filter. From their exploration, have them discuss what they discovered that helps them answer the question: Why does the sun look yellow?
- Now have students stack all their filters together and have them put them in front of the rainbow glasses. Do they see any colors that haven't been absorbed?

## Summing Up

There are many other things you can do with these filters, as we will see...

## 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

# Why is the sky purple?

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

CMMAP

*Reach for the sky.*

## Overview

Of course, you expect the question to be "why is the sky blue?" That's the classic version.

And here's the classic answer: scattering. We'll talk about what this word means and how it leads to sky color, but we will also see that the light from the sky actually contains a bit more violet than it does blue! So why do we see glorious blue skies rather than a purple firmament when we gaze up into Earth's atmosphere?

## Theory

The first person to correctly work out the details of the process that gives rise to the color of the sky was the English physicist, Lord John Rayleigh, working in the late 1800's. Rayleigh correctly surmised that the blue color of the sky was a result of scattering. As light enters our atmosphere on its journey from the sun, it interacts with air molecules and is redirected. This redirection is more pronounced for shorter wavelengths toward the blue, or violet, end of the spectrum.

### Necessary materials:

- 1 "sunset egg"
- A white light flashlight

The most crucial piece for this experiment is the "sunset egg." The small-scale structure of these glass "eggs" works well to demonstrate the differential scattering that leads to the color of the sky and the color of the sunset.

You can find them at rock and nature shops, or you can purchase them in bulk from Pelham Grayson (www.pelhamgrayson.com) under the title "magic eggs."
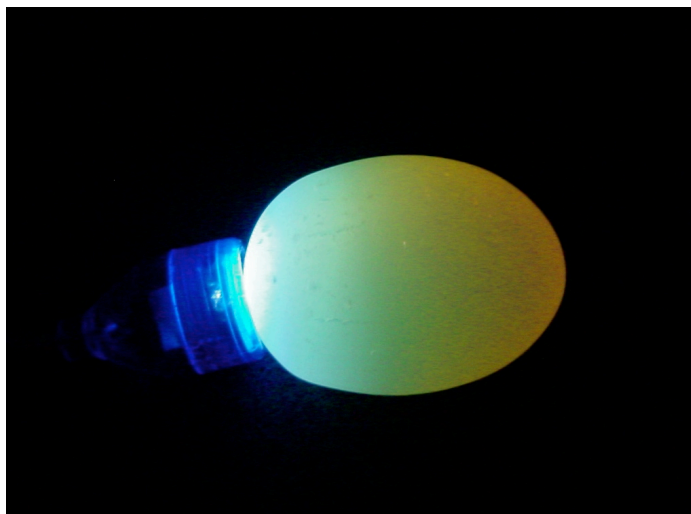


*The shorter wavelengths of visible light scatter near the beam of light, leaving only the longer wavelengths to create a sunset effect.*

Isaac Newton's experiments with prisms had shown, two hundred years before, that white light is composed of the individual colors of the visible light spectrum–red, orange, yellow, green, blue, and violet. We now know that light is an electromagnetic wave, and the spectrum comes from the continuum of wavelengths and frequencies going from red (long wavelength, low frequency, low energy) to violet (short wavelength, high frequency, high energy). Electromagnetic waves are waves of electric and magnetic fields. These fields interact with the electrons in the molecules of the air. Because the air molecules are much smaller than the wavelength of light, this interaction is much stronger for shorter wavelengths. The shorter wave-

length and the higher the frequency the more interactions with air molecules.

As the light passes through the atmosphere, the atoms actually absorb and reemit the light. This doesn't change the *intensity* of the light, but it does change the *direction*. This change in direction—which we call scattering— is ten times more pronounced for violet light than for red. This particular type of scattering is called **selective scattering** or **Rayleigh scattering**.

Blue light has a short wavelength and a high frequency, so it is strongly scattered. When you look up at the sky, any light that you see has been redirected toward your eyes—it has been scattered. Because you are seeing only scattered light, the sky appears blue. But violet light has an even shorter wavelength and a higher frequency than blue light, so by all accounts the sky light should be violet! It appears there is more to the story!

If we judge by the most prominent color, the sky *is* violet. But the sky *appears* blue due to the limitations of our eyes. Our sensitivity to light decreases as we reach the shortest wavelengths of the visible spectrum. The violet is there, but our eyes detect it only weakly. What we see is blue—present in large quantities and easily detected by our eyes.

## Doing the Experiment

This straightforward experiment shows the blue color resulting from scattering, and also explains the red color of sunrises and sunsets. At sunrise or sunset, sunlight passes through a thickness of atmosphere 12 times that at midday, so light passes through 12 times more atmosphere at sunrise and sunset. When we greet the day or say goodnight, we see beautiful sights in the yellow, orange, and red part of the spectrum, for the shorter wavelengths have been scattered away.

The experiment goes like this:

- Place a white light at one end of the sunset egg. Look at the light that comes out the side of the egg. This is the scattered light; notice its color. This blue is the blue of the sky.
- Next, look at the light that goes through the egg. This is the transmitted light—all of the light that isn't scattered. What's left when you remove the short wavelengths? Reddish light!
- Try the light on the other end of the egg, or on the egg's side. What do you notice now?
- Ask your students how they would use this experiment to explain blue skies and red sunsets.
- Try different white light sources. Depending on the tint and the intensity of the light, you'll get some interesting variations.

## Summing Up

The scattering from the crystals in the egg is selective scattering, just like that in the atmosphere, so you can use it to demonstrate the color of the sky and the color of the sunset. You can get similar selective scattering from other things; unflavored gelatin works well, as does a weak solution of milk in water. But these eggs don't spill and don't spoil!

## 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**

CMMAP
*Reach for the sky.*

## 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 wavelenghts 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**

CMMAP

*Reach for the sky.*

## 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.

## 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**
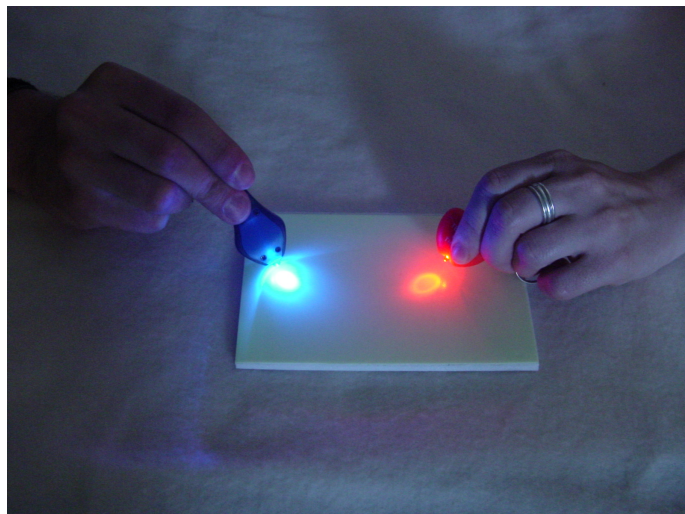
**CMMAP**

*Reach for the sky.*

## 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.

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.

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



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

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

# In an Alaskan summer, the sun is up 24 hours a day. Why isn't it hotter?

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

**CMMAP**

*Reach for the sky.*

## Overview

Alaska, known as the land of the midnight sun, attracts tourists and adventurers alike at all times of the year. If you happen to be planning a summer getaway there, however, you might want to consider packing more jackets than sun tan lotion. In the city of Barrow, which is at 71° North, the sun does not set between the middle of May and the beginning of August but their average high temperature is only 45° F (7.2° C)! How can an area of the world that experiences 24 hours a day of sunshine still be so brisk?

## Theory

Our planet is warmed by the sun, but not every part of the planet is warmed equally. The amount of energy transferred depends on the angle that the sun's rays make with the surface. If you hold a flashlight above a table top and shine it straight down you see a circle of light. If you tilt the flashlight, however, the light will stretch out to form an oval, covering a larger area of the table. The amount of light is the same, but it's spread out over a larger area; we say that the **intensity** is less.

Due to the tilt of the earth and the precession of the planet, the far North and South don't experience day and night as we do in the middle latitudes. During the summer in Barrow, the earth is tilted toward the sun. As it rotates the sun never sinks below the horizon—but the sun is always at a very low angle in the sky. The intensity is never very great.
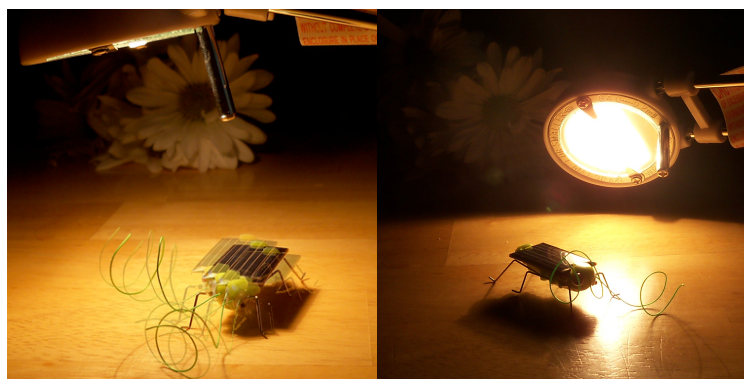


*The solar cell generates electricity that depends on the intensity of the light. So it generates more electricity when the lamp is directly overhead than when it is at an angle.*

## Doing the Experiment

Each group should set their lamp so that the light shines directly down on the solar powered grasshopper. This will be the highest intensity possible. The grasshopper will hop and shimmy as the solar cell runs the motor, a vibrating motor from a cell phone.

Now, using the lamp's base as a pivot point, tilt it slowly back and fourth in an arc so that the light falls on the solar cell from directly horizontal on one side to the other side. Ask your students to note how the intensity changes given the

1

change in behavior of the solar grasshopper. They should have observed a greatly reduced activity level of their insect when the light was coming in from a low angle across the "horizon" of the solar cell.

## Summing Up

Equatorial areas do experience the sun directly overhead but the further north or south you are from the equator, the lower the sun sits in the sky. In Barrow, the sun never gets higher than approximately 30˚ above the horizon. There might be 24 hours a day of sunshine in the summer but they never the intense sunlight you'd experience at the equator.

A low intensity for 24 hours still does lead to a significant amount of incoming energy. In fact, the total energy from the summer sun in Barrow right at the summer solstice is more than that at the equator. But there are other climate factors at work. The cooling during the long winter night takes a long time to offset, particularly for a coastal city.

This experiment is a good way to introduce seasonal variability as well as reinforce the concept of intensity.



*Most of us would associate a scene like this with dawn or dusk. This photograph, however, was taken at 10 am on a summer day in Barrow, Alaska*

## For More Information

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

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

# Why is it tropical in the tropics?

CMMAP

*Reach for the sky.*

## Overview

We have all seen the proverbial "wish you were here..." postcard featuring white sand beaches and palm trees bordering sapphire blue water that stretches as far as the eye can see. Why is it that there are certain regions of the world that never seem to experience winter? Why do some areas of the world have dramatic seasonal variations in temperature and others tend to stay within a smaller range?

This activity will allow students to explore the relationship between angle of incidence, intensity of solar radiation, and how it relates to seasons as well as the general climate of different regions of our planet.

### Necessary materials:

Per group of 3 or 4:

- One basketball
- A solar cell
- Rubber bands to secure cell to ball
- Multimeter
- Alligator clip leads

These days, solar cells aren't too difficult to find if you know what you're looking for. We often extract these from solar powered garden or driveway lights that can be purchased from any general store or mega mart.

## Theory

Our planet is warmed by the sun, but not every part of the planet is warmed equally. The amount of energy transferred depends on the angle that the sun's rays make with the surface. If you hold a flashlight above a table top and shine it straight down you see a circle of light. If you tilt the flashlight, however, the light will stretch out to form an oval, covering a larger area of the table. The amount of light is the same, but it's spread out over a larger area; we say that the **intensity** is less.

The Earth's spin axis is tipped 23° from the plane of its orbit around the sun. For folks in southern Florida, during the middle of the northern hemisphere summer, the noonday sun is nearly overhead, so the sunlight is quite intense. But 6 months later, the sun is never higher than a bit more than 40° above the horizon, so even at noon the intensity of sunlight never reaches the peak it does in the summer.

For locations on or near the equator, the intensity of sunlight experiences a much smaller seasonal variation. Equatorial locations are always warm, but they are also always about the same temperature. There's no winter in

*As the basketball is tipped in relation to the sun, the solar cell will generate more or less current which can be measured by the multimeter.*

Mombasa, only a wet season and a dry season, both quite toasty.

## Doing the Experiment

Your students will use the basketball as a model for the earth. The solar cell will help to determine the intensity of the sun's radiation at a given point on the surface. Most students are familiar with the fact that solar cells use the sun's light to create electricity, but this is a good point to reiterate. The current that the cell produces is, more or less, directly proportional to the captured energy.

Your students should use the clip leads to attach the multimeter to the solar cell, and set the meter to measure current. They should adjust the range so that the maximum current stays on scale. Have your students attach their solar cell to the basketball with the rubber bands. We typically place the solar cell above the "equator" of the basketball because we are at about 40° North here in Fort Collins, Colorado. You could adjust the placement to make this more relevant to your students based on where you live.

Now, it's time to go outside, and put the solar cell in the sun. Your students should orient the basketball as if it is our planet, tilted about 23°, and slowly spin it while watching the reading. Think about how to tip the ball to represent northern hemisphere winter and summer; this takes some thought.

Look at the variation in current (and thus received power) over the course of one rotation (representing a day) for the northern hemisphere winter and summer. Now move the solar cell so that it is centered on the equator and repeat the experiment. The key is to measure the seasonal variation. How much do things change between winter and summer. For latitudes of 40° N, a good deal. For the equator... Not so much.

## Summing Up

When the solar cell is at the equator, the angle between it and the sun isn't greatly affected by the precession of the planet and so students should see values that vary over a small range compared to the data from the higher latitude position. For the latter, students should be getting higher values when the solar cell is tilted towards the sun and lower values when it is tilted away. This is not due to the fact that the cell is closer or further from the sun, as per the common misconception, but due to the changing angle and therefore changing intensity of the solar radiation. This yields the vast seasonal variation experienced at the higher latitudes. The solar intensity at the equator stays high and relatively stable throughout the year making it a rather postcard-worthy region of the world.

## For More Information

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

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