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.

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Figure 25.33 shows three photographs made with a camera in which the film has been replaced by a special high-sensitivity detector.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, 3.00×10^8 m/s.
2. Each photon has energy

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

   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:

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

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.

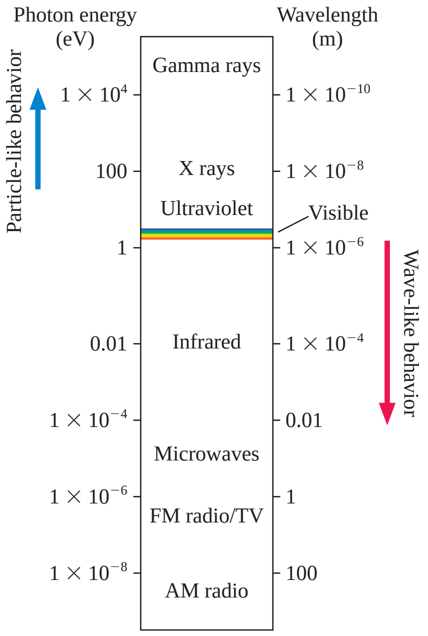
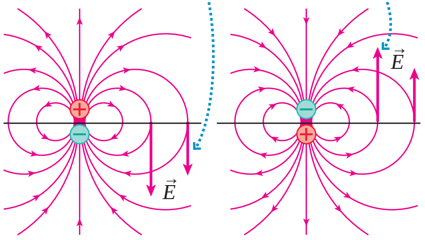


FIGURE 25.34 The electromagnetic spectrum.

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

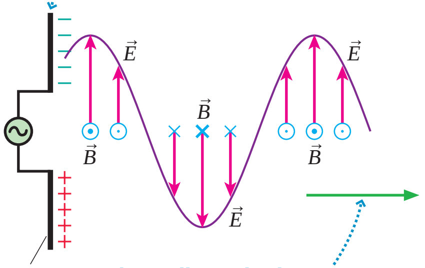


Positive charge on top

Negative charge on top

FIGURE 25.35 The electric field of an oscillating dipole.

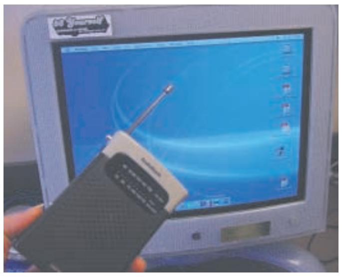
An oscillating voltage causes the dipole to oscillate.



The oscillating dipole causes an electromagnetic wave to move away from the antenna at speed $v_{\text{em}} = c$.

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

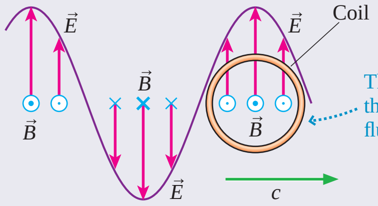
Radio waves are *detected* by antennas as well. The electric field of a vertically polarized radio wave drives a current up and down a vertical conductor, producing a potential difference that can be amplified. For best reception, the antenna length should be about $\frac{1}{4}$ of a wavelength. A typical 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.



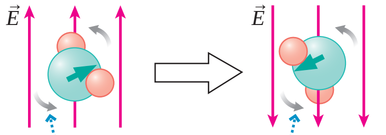
This orientation produces the maximum magnetic flux through the coil.

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 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, $\sigma = 5.67 \times 10^{-8}\ \text{W}/(\text{m}^2 \cdot \text{K}^4)$.

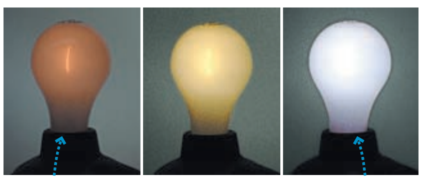
In Chapter 12 we considered the amount of energy radiated and its dependence on temperature. The filament of an incandescent bulb glows simply because it is hot. If you increase the current through a lightbulb, the temperature increases and so does the total energy emitted by the bulb, in accordance 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.

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.**

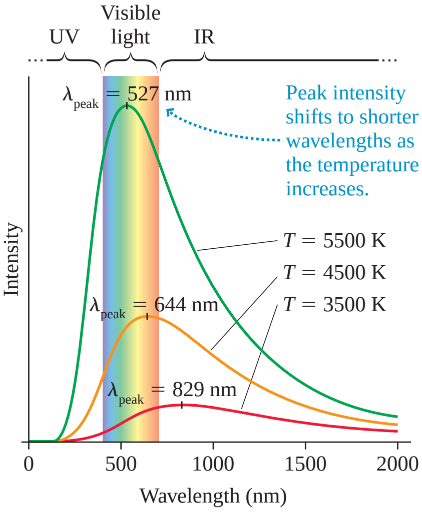
Increasing filament temperature



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

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

INVERSE p. 118

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

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 $E = hf$:

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

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

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.

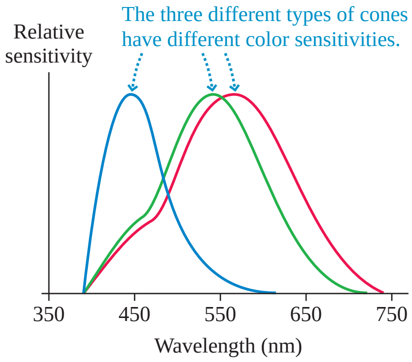


FIGURE 25.41 The sensitivity of different cones in the human eye.

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.

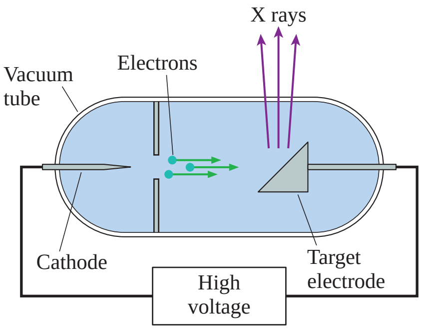


FIGURE 25.42 A simple x-ray tube.

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

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

$$= 4.1 \times 10^{-11}\ \text{m} = 0.041\ \text{nm}$$

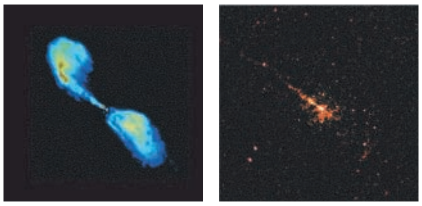
ASSESS This is a very short wavelength, comparable to the spacing between atoms in a solid.

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.

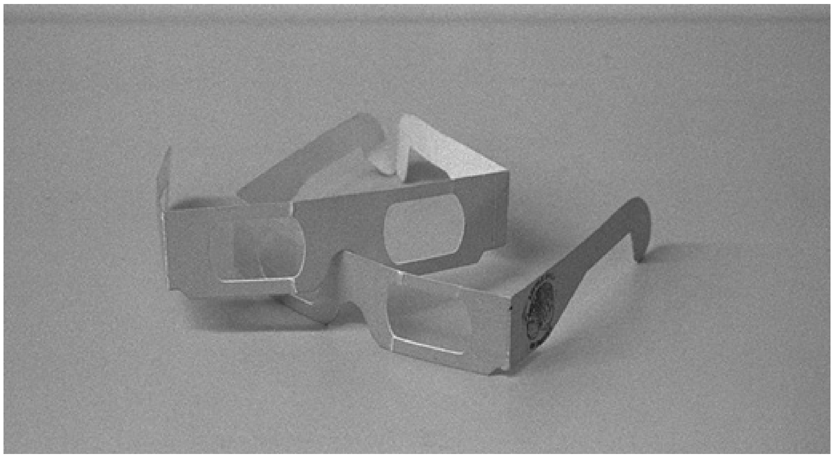
STOP TO THINK 25.6 A group of four stars, all the same size, have the four different surface temperatures given below. What is the temperature of the star that emits the most red light?

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!

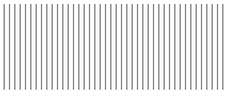
If you look carefully at the rainbows, you see that what you are observing is the spectrum of the light source. Since the dark room in the Little Shop area has a variety of different light sources, you can see a number of different effects. For instance: the phosphors on the screen of the Televised Chaos 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

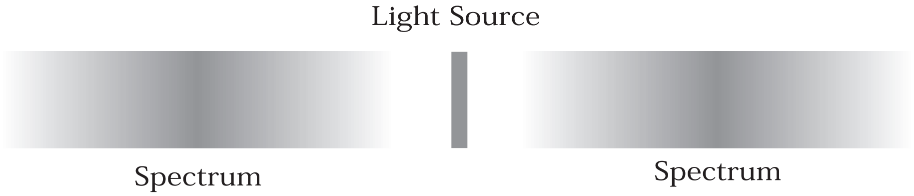
When light hits a shiny metal surface, or another smooth surface such as the surface of a pond, the light is *reflected*. When light travels from air into some transparent medium that is more dense than air, the light rays are bent; we say that the light is *refracted*. Now, when light hits obstructions 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.

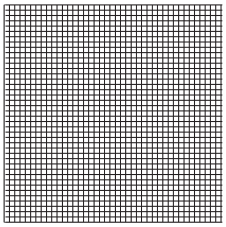
Now, if the lenses in the glasses had a single set of lines spaced like this:



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



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!

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.

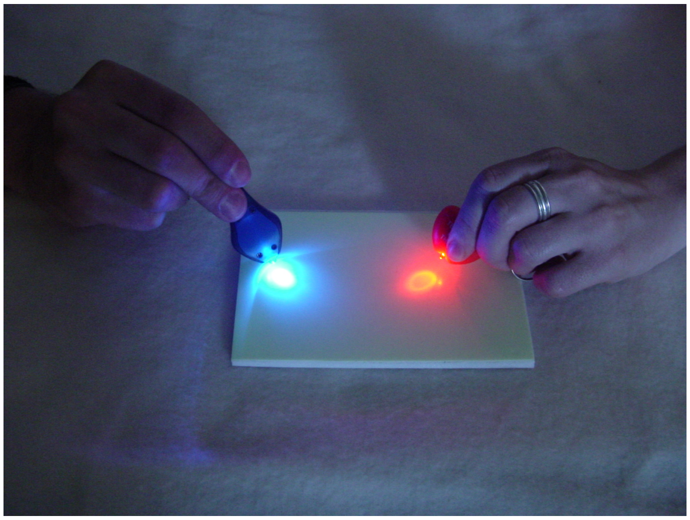
Necessary materials:

- 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

Why does the sun look yellow?

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

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

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?

Necessary materials:

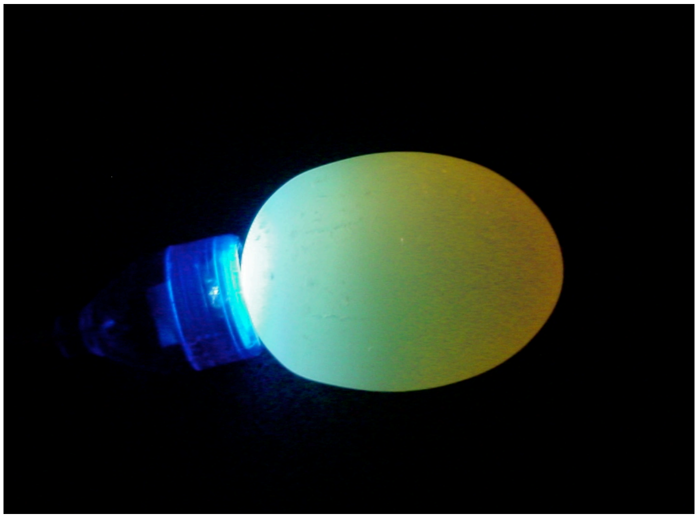
- 1 "sunset egg"
- A white light flashlight

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 "Magic Feng Shui Eggs".

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.



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 wavelength 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

Why are clouds white?

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

Overview

Clouds are made from air (which is transparent) and droplets of water (also transparent.) So clouds are made of things which are clear. Why can't we see through them? Why are clouds white, and not clear?

We let students ponder this question by having them consider a related question: Can you make a colorful cloud with colored water?

Necessary materials:

Activity 1

- Clear container of water
- One ultrasonic mister (provided)
- Paper towels
- Food coloring

The ultrasonic mister is the crucial piece for this experiment. It's necessary to break the water up into droplets to create the "cloud" above the water. You can find ultrasonic misters at http://www.mainlandmart.com/foggers.html.

If your cloud isn't appearing, make sure there is the right amount of water above the little metal speaker. Too little water means it won't work; too much means that the cloud that forms will be

Theory

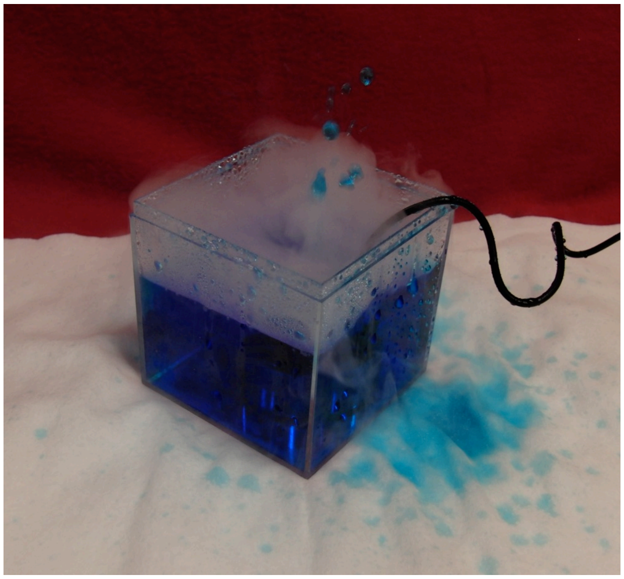
Isaac Newton performed a classic series of experiments over 300 years ago to demonstrate that the white light from the sun is composed of all the colors of the rainbow. Light is a wave (an electromagnetic wave) and these colors are each characterized by their **wavelengths**. The wavelengths of light are quite small. Red light has a wavelength of 0.0000007 meters, just 0.7 microns. One micron is 1 millionth of a meter, so that's pretty small—and that's the longest wavelength your eyes can see. Blue light has a wavelength of about 0.4 microns.

How can clouds be white when they are made of millions of tiny cloud droplets—which are clear?

Clouds are composed of millions of tiny water droplets (**cloud droplets**) or ice crystals. The average size of cloud droplets is about 10 microns. This is pretty tiny, but these cloud droplets are much bigger than the wavelengths of visible light. Since a cloud droplet is much bigger than any wavelength of light, all the different colors of light behave the same when they hit a droplet—they **scatter**. Scattering means that light is redirected in random directions. All of the colors are scattered equally, so the light is diffuse and made up of all colors...and the net result–clouds appear white!

Doing the Experiment - Activity 1

This is a demonstration activity to do with the whole class, centered around a discussion.



The larger water droplets splatter the blue color on the paper towel, but the cloud remains white!

Pose the question to your students: Why are clouds white? Gather their ideas and then explain that you have an activity that will help them ponder the answer to this question.

Put down a white paper towel on your table and then put a clear container with water in it.

Submerge the ultrasonic mister in the water and plug it in. As students observe the white cloud forming, explain: *A cloud is made up of small droplets of water in air. Air is clear and so is water.* Then ask: *So why does the cloud appear white?*

Now, ask the class: Could we make a cloud that is another color using food coloring?

Collect predictions and then have a student add food coloring to the container.

In a very short time, students should see a white cloud appearing over the colorful water. If droplets of water escape from the container however, they may leave little food coloring spots behind!

Have a discussion with your class about what they think is happening and why.

Doing the Experiment - Activity 2

This is a quick activity that students can easily try for themselves.

Have students put on the safety goggles.

Have them place a clear ice cube on the black felt square. Fold the material over the ice cube so it is covered.

Carefully crush the felt covered ice cube with the hammer and then open up the material. The smashed ice pieces should look white!

Review that this is another case of scattering and that the ice looks white because all the wavelengths of light are scattered equally.

Necessary materials:

Activity 2

- Clear ice cubes
- Black felt squares
- Safety goggles
- Hammers

If you use clear ice cubes, the results will be more dramatic for your students. We boil water, let it cool, and then freeze it in ice cube trays to get the clearest cubes.

Doing the Experiment - Activity 3

This is a great activity to pose a mystery to your students. It is also a great demonstration that helps explain why some clouds look gray or dark.

1. Assemble your mystery blocks before class begins. Take two rectangles of the paraffin wax and sandwich a piece of aluminum foil between them. The aluminum foil should be slightly smaller than the rectangles of wax. Melt the wax together by using the trigger lighter..
2. When your class arrives, tell them that you have a mystery for them to solve. Using a bright desk lamp, overhead light, or sunlight, hold the wax block horizontally so the top layer is very white, but the bottom layer is gray. Now dazzle your students by flipping the block over, so now the gray block has turned white and the white block has turned gray!
3. Ask them what they think could be happening. (The paraffin scatters light just like the cloud droplets. When light enters the wax block, the different wavelengths are scattered equally in random directions and the block appears white. But the aluminum foil blocks most of the light from reaching the lower block. The lower block still scatters all colors of light equally, and so it doesn't have a color, but because it scatters less light than the top block it appears gray. The gray and the white are really the same color—that is, no color at all—but they differ in intensity.)
4. Ask your students: Why do clouds sometimes appear white and sometimes gray? (All clouds are the same color, no color at all. When we see light scattered off the front of a cloud, it sends a lot of light our way; the cloud appears white. But if the sun is behind a thick cloud, not much light makes it to the bottom, so the cloud appears gray.)

Necessary materials:

- Paraffin Wax rectangles
- Aluminum foil
- Heat source such as a long lighter for candles or barbeque grills
- Heat source such as a long lighter for candles or barbeque grills

The wax we use is used for canning and candle making. You can find it at a grocery or hardware store.

Your students will be stunned when you flip this wax block over!

Summing Up

Clouds appear white because of scattering. The droplets in clouds are big compared to the wavelength of light, so all wavelengths scatter the same. It's a different story for the scattering of light from molecules of air in the atmosphere. These are much tinier than the wavelength of light, so blue light scatters much more than red. So the sky is blue and sunsets are red.

But clouds are white; they have no color at all, even if the water making them up has color. Clouds can appear white or gray. In fact, the same cloud can appear white to one person and gray to another. This has to do with where you are with respect to the cloud. People flying in an airplane may pass over a cloud that looks quite bright as it scatters the abundant sunlight from above, but an observer on the ground may see the same cloud as gray, because little sunlight penetrates to the lowest level.

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 does color have to do with cooling?

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

Overview

A lot, as it turns out.

You know that something black will warm up more than something white when placed in the sun. That’s because a black surface will absorb more radiant energy than a white surface.

But radiation also lets things cool off. All warm objects radiate energy, but different colors will radiate different amounts. And that’s why color can affect cooling.

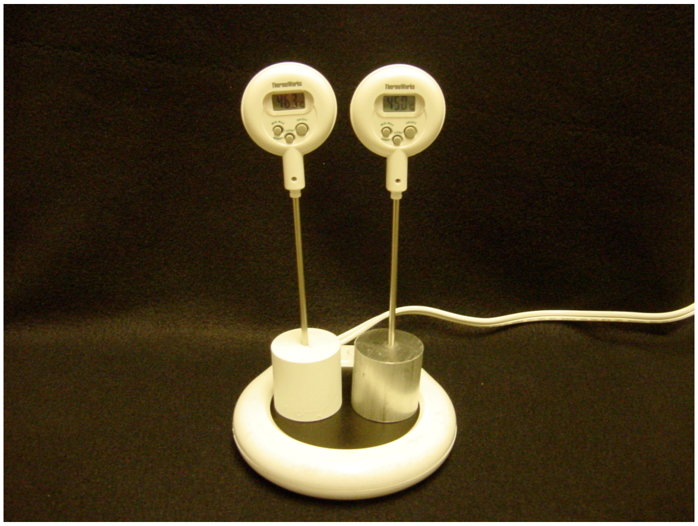
Necessary materials:

- 2 digital thermometers
- 2 aluminum cylinders with holes for the thermometers
- Mug warmer

The aluminum cylinders are the crucial part of this experiment. We used a 1 inch diameter rod from a metal supply company, cut to 1.5” lengths to make two cylinders of identical size. (You don’t need to use cylinders; you may prefer cubes.) W drilled a hole halfway down in both pieces so the thermometers would fit nicely. We left one cylinder bare metal and painted the other one white.

Theory

All warm objects emit electromagnetic radiation. Hotter objects emit more radiation, and hotter objects emit shorter wavelengths, but anything warm will “glow.” You’ve no doubt seen red and blue pictures of objects taken with thermal cameras; the hot spots appear bright, the cool spots dim.



Two cylinders on the hot plate. After they are warmed, they will be set aside to cool. Which will cool fastest—the white or the silver?

The radiation that objects emit is a very important part of the energy balance. Objects that emit a lot will quickly cool; objects that don’t emit as much will stay warm longer.

Now, let’s think about color in this context. You know that the color of an object will affect how much energy it absorbs; black will absorb more than white; shiny objects will reflect energy and not absorb it; a shiny object heat up in the sun much at all.

Color also affect emission. For objects near room temperature, which emit radiation in the far infrared part of the spectrum, most things are very black—that is, they are good absorbers and good emitters. For instance, human skin, regardless of color, is a very good absorber and emitter of far infrared. No matter what color you skin, you are black in the infrared! The same is true of fabrics and of painted surfaces. All colors of clothes and all colors of paint are black in the infrared; they absorb and emit quite nicely.

But silvery metals don't work like this. They reflect visible light and they reflect infrared too. They don't absorb it—and, more importantly, they don't emit it! So, in this experiment, the two cylinders will cool at different rates. The bare aluminum cylinder radiates less and cools rapidly; the white cylinder (and the color doesn't matter—it could be any color at all!) will radiate more and so it will cool off more quickly.

This is a very surprising result that drives home the point about the importance of radiation—emission of thermal radiation—in cooling.

Doing the Experiment

This experiment/demo involves some waiting time. You may want to set up this first part of the demo while your class is engaged in another activity of discussion, and then proceed when ready.

This is a great activity for predictions. You should certainly have students vote: Which cylinder do they think will cool off more quickly? Which will cool off less quickly? Most students will guess that the bare cylinder will cool off more quickly. The painted one seems insulated somehow.... In fact, it is! Painting will provide some insulation, limiting conduction. But the increase in radiation far outweighs this effect.

Run this as an activity or a demo as follows:

- Turn on your mug warmer.
- Place the white and aluminum finished cylinders on the mug warmer with the holes facing up.
- Turn on the two digital thermometer and insert one into each cylinder.
- Wait for about 15 minutes for the cylinders to warm up. They probably won't warm to the same temperature, your first hint that something is up...

When both aluminum cylinders have been warmed, continue the experiment:

- Tell your students that you will be removing the cylinders from the heat source. Have them each predict which cylinder will cool the fastest and why.
- Record the temperature on the thermometers and then set the cylinders on the table or a hot pad.
- Take temperatures at 1 minute intervals and ask: How do the two temperatures vary?
- You can stop taking data in a short time, once it becomes clear that the white cylinder is cooling more quickly. Now it's time to talk about why...

Discuss the results. Some questions you could ask:

- Why did the white cylinder cool more quickly?
- Why are "space blankets" that are used for emergencies made of silvery plastic?
- Why is the inside of a thermos silvery as well?

Summing Up

How does this apply to the earth system? It turns out that there's an important connection. The earth can't exchange energy with its surroundings; it can only lose heat by radiation. As we change the composition of the atmosphere, we make this emission less efficient. When the earth cools less efficiently, it stays warmer. And that's just what we see happening.

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

How does the atmosphere keep the earth warmer?

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

Overview

The earth cools by radiation. That's the only way that the earth can exchange energy with space. But the atmosphere is not transparent to the far infrared that the earth emits, and so the earth is warmer than it would otherwise be.

Theory

We can simulate the energy exchange of the earth and the atmosphere with space by using a stack of glass plates for this simple reason: Glass is transparent to the visible light and the near infrared emitted by the sun (and the lamp!), but opaque to the far infrared, the thermal radiation, emitted by the earth. So energy gets in but can't get out—at least not so easily.

Necessary materials:

- Four identical pieces of glass (You can use glass from the same size picture frames.)
- We use 4 clear rubber feet on the bottom of each piece of glass as spacers.
- Spray one side of one glass plate with flat black paint.
- Infrared thermometer
- Desk lamp with an incandescent or halogen bulb

IR thermometers can be found at www.harborfreight.com under "non-contact pocket thermometer".

We purchased our frames at a dollar store, which made them quite reasonable!

Doing the Experiment

We'll start with a simple experiment that shows how the atmosphere keeps the earth warmer. This can be done as a demo, but is more effective when small cooperative groups work to collect data and then compare with others. Once you set the experiment up, you'll need to let the lamp shine on the stack of plates for 20 minutes.

> **SAFETY NOTE I: The desk lamp with the incandescent or halogen bulb can get very hot. Be sure students are careful when working around the lamp**
>
> **SAFETY NOTE II: The glass plates have sharp edges, so students need to be especially careful when moving and lifting the plates. You may want to keep the picture frames on each glass plate and put the rubber feet on the frames instead.**

- Have your students make a stack with the 4 glass plates. They should put the black painted glass plate at the bottom of the stack. Place the desk lamp over the stack of glass plates and discuss how close you want the light bulb to be to the top of the stack.Turn the desk lamp on and let it shine on the stack of plates for approximately 20 minutes.
- While you are waiting for the experiment to be ready, model for your class, what they will be doing once they begin. Explain to your students that they are setting up a model of layers of the atmosphere. Show them how they will have to work as a group to conduct this experiment. There will be four jobs per group. One student will turn off the desk lamp and turn it away so that it doesn't keep

warming the plates with infrared radiation. The second student uses an infrared thermometer immediately to measure the temperature of the top plate, while the third student records that temperature, while the fourth student pulls the top plate off. The process is repeated by students 2, 3, and 4 until they have measured the temperature of all the plates in the stack. We recommend that you have a group of students practice this, so they all realize how quickly they have to do this. The plates start cooling immediately, so the quicker they are, the better.

- While you are still waiting for the experiment to be ready, have students predict what they think will happen with the temperatures. Which plate do they think will be the warmest? The coolest? etc.
- Conduct the experiment and have students report and compare their data. Discuss what they think is happening. They will probably find that the bottom plate is the warmest, the one above a little cooler, and the one above that cooler yet. How about the very top plate? This will depend on the light source. Why might this be?
- This will be a great place to explain how the glass plates are like layers of the atmosphere. The visible and near infrared radiation from the lamp (sun) can pass through the layers, but once this energy is absorbed by the earth (the black plate) the radiation emitted is thermal radiation and is a longer wavelength. It cannot pass through the layers as easily, so the earth gets warmer.

Activity Variation 1

- Put two glass plates painted black on a table. Put a desk lamp over them.
- Turn on the desk lamp and leave it on for at least 5 minutes.
- As soon as you turn off the desk lamp, use the infrared thermometer to take a temperature of both black plates and record.
- Immediately place a clear glass plate over one of the black plates.
- Wait one minute, remove the extra frame, and then take the temperature of both black plates again and record.
- Quickly put the extra frame back on the black felt frame and repeat the procedure again.

Activity Variation 2

- Have one student hold up his/her hand and take the temperature of the hand and record.
- Have another student hold a glass plate in front of the student's hand. Use the infrared thermometer to take the temperature again and record. The temperature reading of the hand with the glass plate in front should be much cooler.
- Discuss what they think is happening.

Summing Up

This is a good simulation that can show how the layers of the atmosphere keep the earth warmer than it would otherwise be.

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