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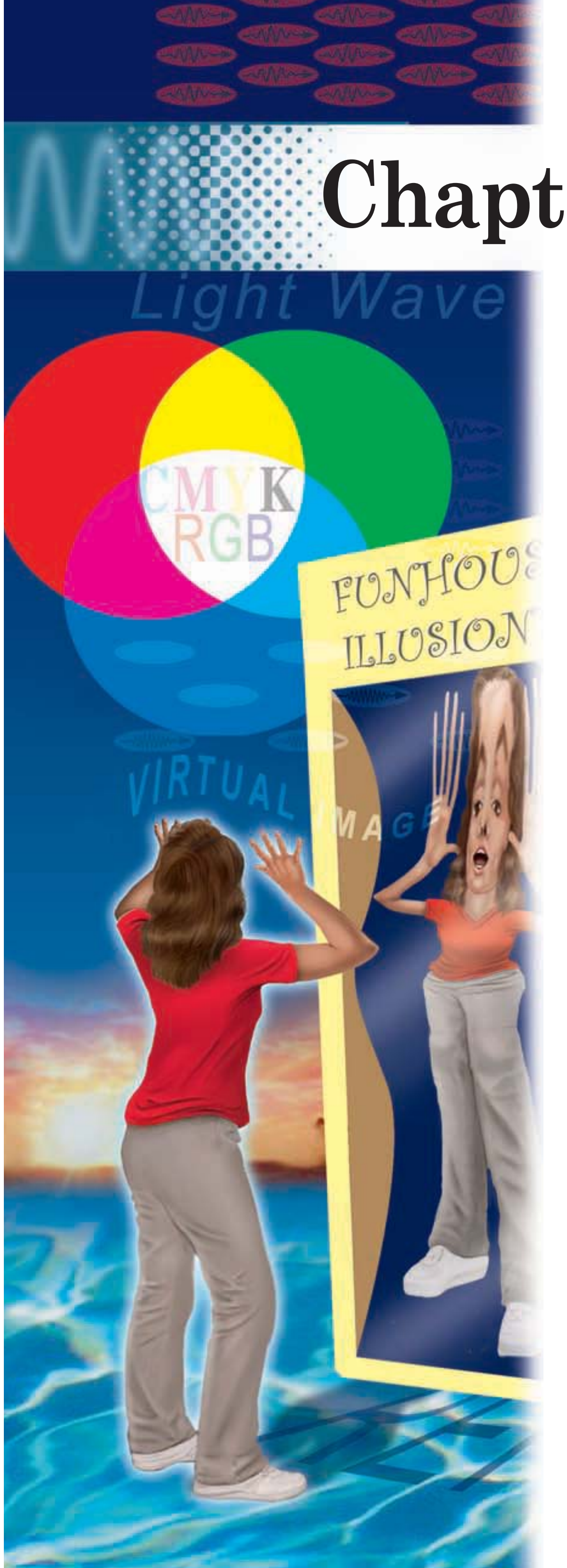
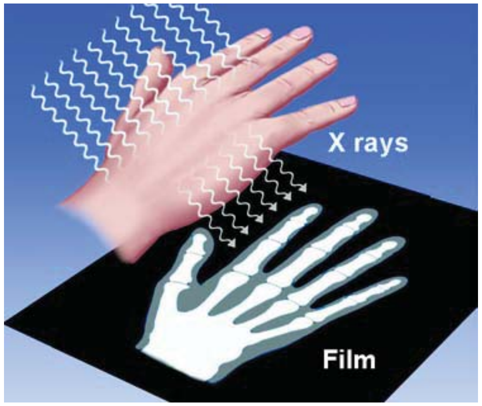


Chapter 24

The Physical Nature of Light

How is a radio like a flashlight? How can microwaves act like rays of light? While these may seem like strange questions, they are not. Radio, microwaves, and light are all three forms of the same kind of wave. They just have different frequencies — like chocolate, vanilla, and strawberry are different flavors of ice cream. The same processes of reflection and refraction work with microwaves as with ordinary light. That is why cell phone towers have funny-shaped dishes on them. The dishes act like mirrors and lenses for microwaves that carry cell phone transmissions. Human technology has found uses for almost every frequency of "light" including frequencies we cannot see.

Light is a form of energy, and in this chapter, you will learn about the electromagnetic spectrum and how electromagnetic radiation, including visible light, behaves. Microwave ovens, laptop computer screens, sunglasses, and lasers are all different types of technology that take advantage of the unique properties of the electromagnetic spectrum.



Key Questions

- ✓ What does the acronym "ROY-G-BV" refer to?
- ✓ Why do radio broadcast towers have to be so tall?
- ✓ How does glow-in-the-dark plastic work?

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24.1 The Electromagnetic Spectrum

Common objects can range in size. For example, a rock can be bigger than your fingernail but smaller than a truck. While harder to imagine, the whole range of rock sizes actually includes objects as big as the moon and smaller than a grain of sand. Wavelengths of light also come in a range of sizes. We see the range of wavelengths from red to violet (ROY-G-BV), but this visible light is just a small part of a much larger range of light waves called the electromagnetic spectrum. This section explores the whole spectrum, most of which is used by humans in one way or another.

Vocabulary

electromagnetic wave, electromagnetic spectrum, radio wave, microwave, infrared light, visible light, ultraviolet light, X rays, gamma rays

Objectives

- ✓ Learn the relationship among the frequency, energy, and wavelength of light.
- ✓ Learn how the speed of light changes in different materials.
- ✓ Identify the different kinds of electromagnetic waves.

Light is an electromagnetic wave

What is an electromagnetic wave?

Light is a wave, like sound and the ripples on a pond. What is oscillating in a light wave? Imagine you have two magnets. One hangs from a string and the other is in your hand. If you wave the magnet in your hand back and forth, you can make the magnet on the string sway back and forth. How does the oscillation of one magnet get to the other one? In Chapter 18 you learned that magnets create an invisible magnetic field around them. When you move a magnet up and down, you make a wave in the magnetic field. The wave in the magnetic field makes the other magnet move.

The frequency of the wave

However, the wave in the magnetic field also keeps travelling outward at the speed of light as an **electromagnetic wave**. If you could shake your magnet up and down 100 million times per second (100 MHz) you would make an FM radio wave. If you could shake the magnet up and down 450 trillion times per second, you would make waves of red light (Figure 24.1). Light, and radio waves are waves of electromagnetism.

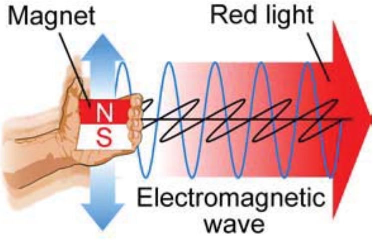

Figure 24.1: *If you could shake a magnet up and down 450 trillion times per second, you could make an electromagnetic wave that you would see as red light.*

Oscillations of electricity or magnetism create electromagnetic waves

Anything that creates an oscillation of electricity or magnetism also creates electromagnetic waves. If you switch electricity on and off repeatedly in a wire, the oscillating electricity makes an electromagnetic wave. This is exactly how radio towers make radio waves. Electric currents oscillate up and down the metal towers and create electromagnetic waves of the right frequency to carry radio signals. Tapping a stick up and down in a puddle makes ripples that spread out from where you tap. Oscillating electric current in a radio tower makes ripples of electricity and magnetism that spread out from the tower at the speed of light as electromagnetic waves.

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The electromagnetic spectrum

Properties of electromagnetic waves

Like all waves, electromagnetic waves (like light) have frequency, wavelength, amplitude, and speed. Also like other waves, electromagnetic waves carry energy in proportion to their frequency. Shaking a magnet one million times per second (1 MHz) takes more energy than shaking it once per second (1 Hz). That is why a 1 MHz electromagnetic wave has a million times more energy than a 1 Hz electromagnetic wave of the same amplitude.

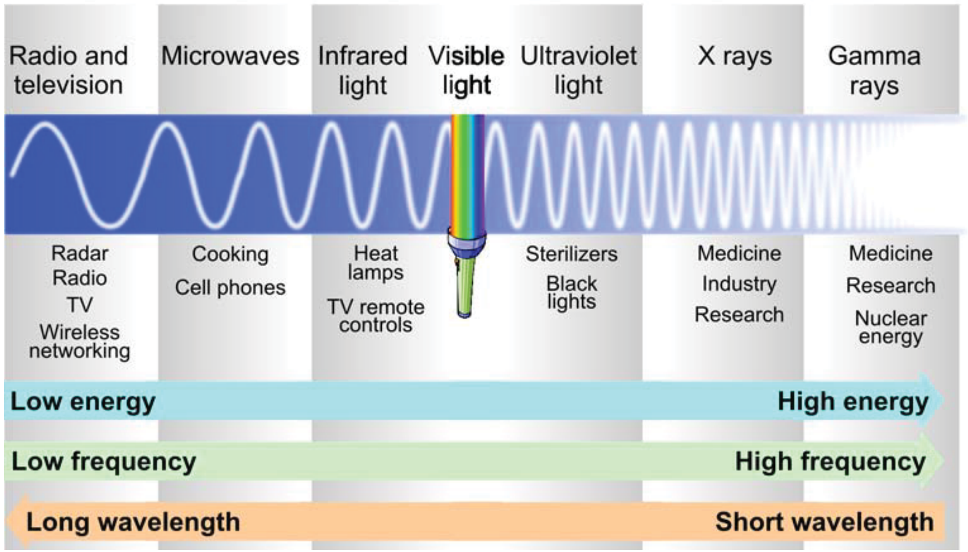
Why visible light is different

Almost all electromagnetic waves are invisible for the same reason you cannot see the magnetic field between two magnets. The exception is visible light. Visible light includes only the electromagnetic waves with the range of energy that can be detected by the human eye.

The electromagnetic spectrum

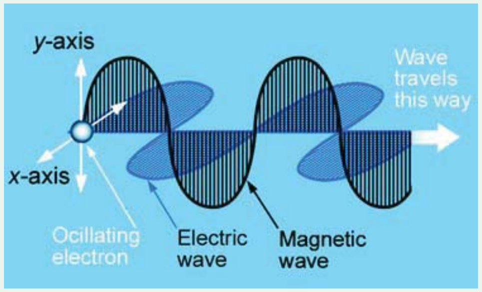
The entire range of electromagnetic waves, including all possible frequencies, is called the **electromagnetic spectrum**. The electromagnetic spectrum includes radio waves, microwaves, infrared light, ultraviolet light, X rays, and gamma rays. Visible light is a small part of the spectrum in between infrared and ultraviolet light.

The electromagnetic spectrum



How does an electromagnetic wave spread?

Electromagnetic waves have both magnetic and electrical qualities. The two qualities exchange energy back and forth like a pendulum exchanges potential and kinetic energy back and forth. In chapter 17 you learned about induction; a changing magnetic field induces an electric field and vice versa. Induction is how electromagnetic waves propagate and spread. Each cycle of the electric part of the wave creates a magnetic wave as it changes. Each cycle of the magnetic wave in turn creates a new cycle of the electric wave. The electric and magnetic parts of the wave keep regenerating each other as the wave propagates.



The wavelength and frequency of visible light

Wavelength of light

The wavelength of visible light is very small. For example, waves of orange light have a length of only 0.0000006 meter (6×10^{-7} m). Because wavelengths of light are so small, wavelengths are given in nanometers. One nanometer (nm) is one billionth of a meter (10^{-9} m). Figure 24.2 shows the size of a light wave relative to other small things. Thousands of wavelengths of red light would fit in the width of a single hair on your head!

Frequency of light

The frequency of light waves is very high. For example, red light has a frequency of 460 trillion, or 460,000,000,000,000 cycles per second. To manage these large numbers, units of terahertz (THz) are used to measure light waves. One THz is a trillion hertz (10^{12} Hz), or a million megahertz.

Wavelength and frequency are inversely related

Wavelength and frequency are inversely related to each other. As frequency increases, wavelength decreases. Red light has a lower frequency and longer wavelength than blue light. Blue light has a higher frequency and shorter wavelength than red light.

Energy and color of light

The energy of waves is proportional to frequency. Higher-frequency waves have more energy than lower-frequency waves. The same is true of light. The higher the frequency of the light, the higher the energy. Since color is related to energy, there is a direct relation between color, frequency, and wavelength. Table 24.1 shows the color, frequency, and wavelength of visible light.

Table 24.1: ***Frequencies and wavelengths of light***

Energy	Color	Wavelength (nanometers)	Frequency (THz)
Low	Red	650	462
↕	Orange	600	500
	Yellow	580	517
	Green	530	566
	Blue	470	638
High	Violet	400	750

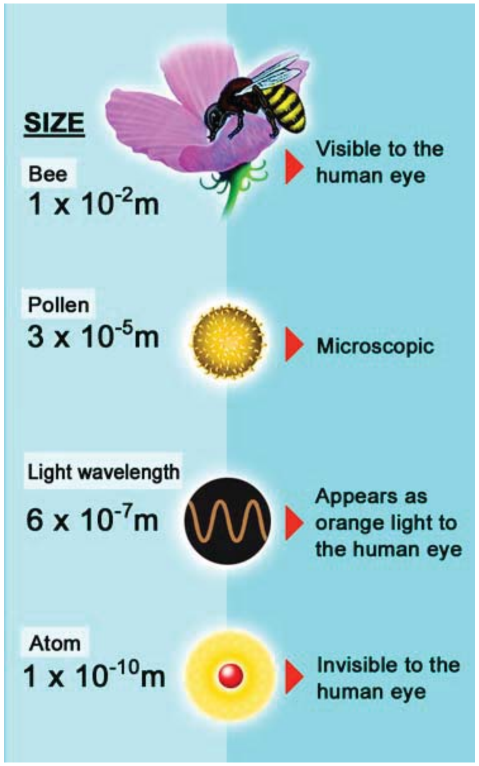


Figure 24.2: *The length of a bee is about 1×10^{-2}m; a grain of pollen is about 3×10^{-5} m wide; the wavelength of orange light is 6×10^{-7} m; and an atom is about 1×10^{-10} m in diameter.*

The speed of light waves

The speed of light

All electromagnetic waves travel at the same speed in a vacuum, the speed of light — 3×10^8 m/sec. As with other waves, the speed of light is the frequency multiplied by the wavelength.

THE SPEED OF LIGHT
(relationship between frequency and wavelength)

Wavelength (m)
Speed of light (3 x 10^8 m/sec) → $c = f\lambda$
Frequency (Hz)

Light travels slower through materials where *n* >1

When passing through a material, light is continuously absorbed and re-emitted by the atoms that make up the material (Figure 24.3). Light moves at 3×10^8 m/sec *between* the atoms. However, the process of absorption and emission by the atoms causes a delay that makes the light take longer to move through the material. The speed of light in a material is equal to the speed of light in a vacuum divided by the refractive index (n) of the material. For example, the speed of light in water ($n = 1.33$) is 2.3×10^8 m/sec (3×10^8 m/sec ÷ 1.33). The refractive index of a material is the speed of light in a vacuum divided by the speed of light in the material (see sidebar at right).

Wavelengths are shorter in refractive materials

When moving through a material, the frequency of light stays the same. Because the frequency stays the same, the wavelength of light is reduced in proportion to how the speed changes. That means the wavelength of red light is shorter in water than in air.

Finding the wavelength of light

You can find the wavelength of light from the frequency and speed. For example, the frequency of red light is 4.6×10^{14} hertz (Hz). If you used the speed of light in a vacuum, 3×10^8 m/sec, then wavelength is 6.5×10^{-7} m (3×10^8 m/sec ÷ 4.6×10^{14} Hz). Use this calculation to find the wavelength of blue-green light in a vacuum. The frequency of blue-green light is 6.0×10^{14} hertz. The answer is that blue-green light has a wavelength of 5×10^{-7} meter.

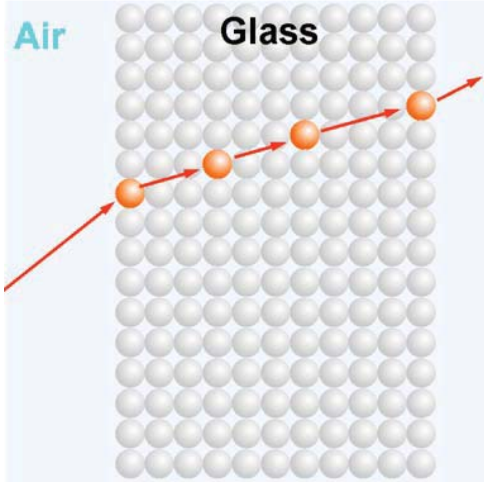


Figure 24.3: *It takes light more time to pass through a material because the light must continuously be absorbed and re-emitted by each atom in turn.*

Index of refraction

The index of refraction (n) for a material is the ratio of the speed of light in a vacuum to the speed of light in that material.

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the material}}$$

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Low-energy electromagnetic waves

What does “low-energy” mean?

We classify the energy of electromagnetic waves by comparing it to the energy it takes to remove an electron from an atom. Energy great enough to remove an electron can break the chemical bonds that hold molecules together. Low energy waves (like visible light) do not have enough energy to break most chemical bonds.

Radio waves

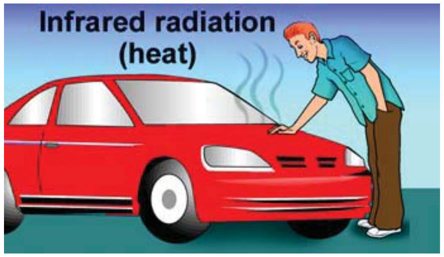
Radio waves are the lowest-frequency waves. They have wavelengths that range from kilometers down to tens of centimeters (Figure 24.4). Radio broadcast towers are tall because they need to be one-quarter of a wavelength high to efficiently create the large wavelengths of radio waves.

Microwaves

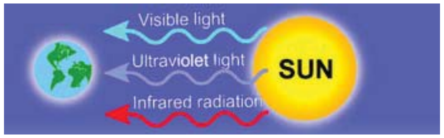
Microwaves range in length from approximately 30 cm (about 12 inches) to about 1 mm (the thickness of a pencil lead). Cell phones and microwave ovens use microwaves (Figure 24.5). The waves in a microwave oven are tuned to the natural frequency of liquid water molecules. The high intensity of microwaves inside an oven rapidly transfers energy to water molecules in food. Microwaves heat up and cook food by heating water molecules.

Infrared waves

Infrared light includes wavelengths from 1 millimeter to about 700 nanometers. Infrared waves are often referred to as radiant heat. Although we cannot see infrared waves, we can feel them with our skin. Heat from the sun comes from infrared waves in sunlight.



Visible light



Visible light has wavelengths between 700 and 400 nanometers and includes all the colors of light (ROY-G-BV) we see when white light is split by a prism. The term “light” commonly refers to this part of the spectrum. However, any part of the electromagnetic spectrum from radio waves to gamma rays can be considered as “light.” Earth receives almost the whole spectrum of electromagnetic waves from the sun, including infrared, ultraviolet, and visible light.

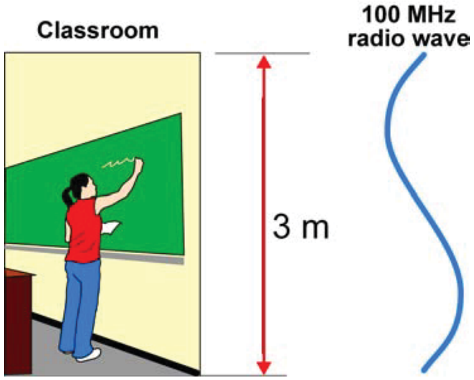


Figure 24.4: *A 100-megahertz radio wave, 100 FM on your radio dial, has a wavelength of 3 meters, about the height of a classroom.*

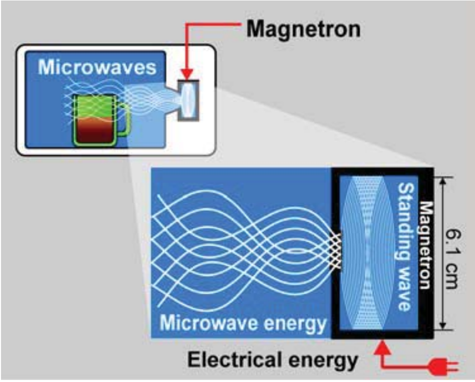
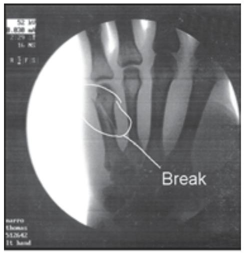


Figure 24.5: *A microwave oven uses microwaves to cook food. A device called a magnetron generates microwaves in the oven from a standing wave powered by electricity.*

High-energy electromagnetic waves

Ultraviolet light **Ultraviolet light** has a range of wavelengths from 10 to 400 nanometers. Like other forms of high energy electromagnetic waves, ultraviolet light has enough energy to remove electrons and break chemical bonds. Sunlight contains ultraviolet waves (Figure 24.6). A small amount of ultraviolet radiation is beneficial to humans, but larger amounts cause sunburn, skin cancer, and cataracts. Most ultraviolet light is blocked by ozone in Earth's upper atmosphere (Figure 24.6). A hole in the Earth's ozone layer is of concern because it allows more ultraviolet light to reach the surface of the planet, creating problems for humans, plants, and animals.

X rays **X rays** are high-frequency waves that are used extensively in medical and manufacturing applications (Figure 24.7). Their wavelength range is from about 10 nanometers to about 0.001 nm (or 10-trillionths of a meter). When you get a medical X ray, the film darkens where bones are because calcium and other elements in your bones absorb the X rays before they reach the film. X rays show the extent of an injury such as a broken bone.



x ray

Gamma rays **Gamma rays** have wavelengths of less than about ten-trillionths of a meter. Gamma rays are generated in nuclear reactions, and are used in many medical applications. Gamma rays can push even the inner electrons right out of an atom and completely disrupt chemical bonds. You do not want to be around strong gamma rays without a heavy shield.

24.1 Section Review

1. Describe an electromagnetic wave. How is one made?
2. What is the relationship between the frequency of light and its wavelength?
3. What is the speed of light in air ($n = 1.0001$)? What could you do to make light slow down?
4. Compare and contrast a radio wave and ultraviolet light.
5. Why might an infrared camera be able to "see" a person in the dark?

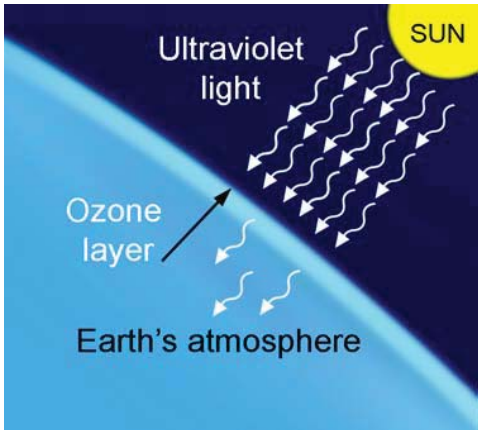


Figure 24.6: *Most of the ultraviolet light from the sun is absorbed by the Earth's ozone layer.*

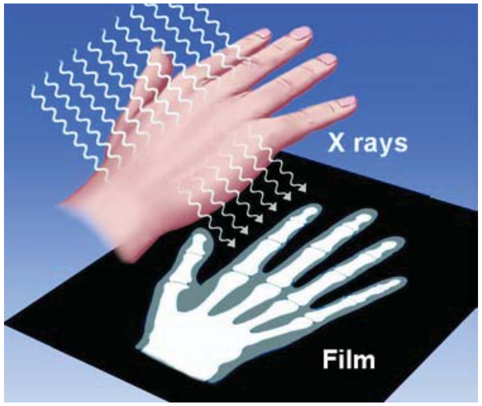


Figure 24.7: *X rays have a high enough energy to go through your soft tissue but not through your bones.*

24.2 Interference, Diffraction, and Polarization

Like sound, you cannot see the wave-like properties of light directly. In this section you will learn about experimental evidence that demonstrates how we know light is a wave. Like sound and water waves, light shows interference and diffraction. Light also has the property of polarization. Many inventions use the properties of light. Lasers use interference of light waves. We separate colors with a diffraction grating. Sunglasses and LCD screens use polarization.

Vocabulary

diffraction grating, diffraction pattern, polarizer

Objectives

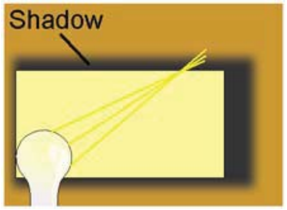
- ✓ Recognize an interference pattern and how it is created with a diffraction grating.
- ✓ Understand the difference between polarized and unpolarized light.
- ✓ Learn about applications of polarization.

Diffraction and shadows

Shadows Imagine shining a flashlight on a wall though a slot in a piece of cardboard. On the wall, you see bright light where the light rays pass through the slot. You see shadow where the cardboard blocks the light rays. If the light bulb is very small, there is a sharp edge to the shadow, showing you that light rays travel in straight lines (Figure 24.8).

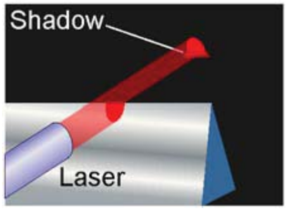
Thin slits can cause diffraction If the slot is very narrow the light on the screen looks very different. The light spreads out after passing through the opening. The spreading is caused by diffraction. Diffraction is a wave behavior. We saw the same spreading of water waves when they passed through a small opening. Diffraction occurs when a wave passes through an opening not too much wider than the wavelength of the wave. A small opening acts like the center of a new circular wave. Seeing diffraction with light is evidence that light is a wave.

The fuzzy edge of a shadow



An ordinary shadow often has a fuzzy edge for a different reason. When light comes from a light bulb, light rays from many points on the bulb cast shadows in slightly different places. The width of the fuzzy edge depends on how far away the light bulb is, how large it is, and how far the screen is.

Diffraction in a shadow



You can see diffraction in a shadow cast by a sharp edge with light from a laser. The edge of the shadow has ripples in it! The ripples are caused by diffraction. You do not see this in white light because of the mixture of wavelengths. A laser makes a pure color with a single wavelength.

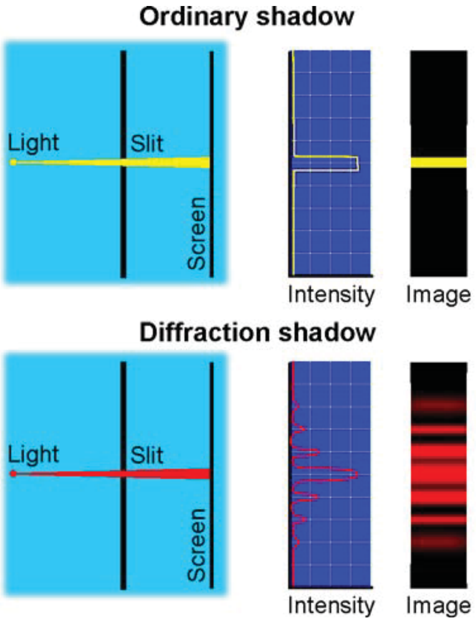


Figure 24.8: *Light and an ordinary shadow compared to diffraction.*

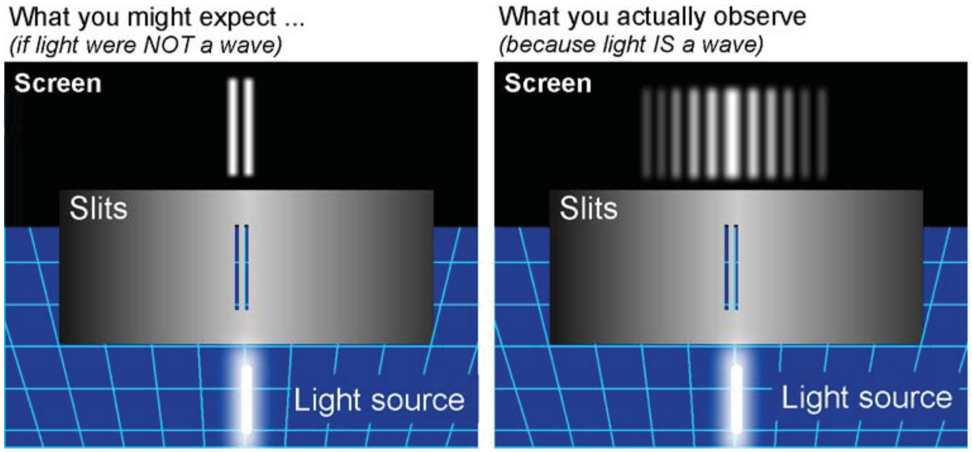
The interference of light waves

Young's double-slit experiment

Interference is a property of waves. In 1807, Thomas Young proved light was a wave when he showed that two beams of light could interfere with each other. In a famous experiment, Young let a beam of light pass through two very thin slits. After passing through the slits, the light fell on a screen.

Interpreting the experiment

If light were NOT a wave, then the pattern should look like the diagram on the left (below). The light at any point on the screen is simply the light from one slit plus the light from the other. However, when the experiment is done, the pattern looks like the diagram on the right. There are bright and dark bands across the screen caused by the interference of the two light beams



Interference of light waves

The double slit experiment is strong evidence that light is a wave because an interference pattern can only be created by the addition of waves. Think of each slit as the source of a circular wave. The waves from both slits are exactly in phase when they leave the slit, because light from both slits is from the same wave front. Straight ahead (in line with the slits), the waves reach the screen in phase and there is a bright area on the screen. Next to this bright area, the light from each slit hits the screen out of phase because one of the two waves has to go a longer distance than the other. The bright bands in an interference pattern are where the light waves from both slits are in phase at the screen (constructive interference). The dark bands appear where the light waves reach the screen out of phase (destructive interference, Figure 24.9).

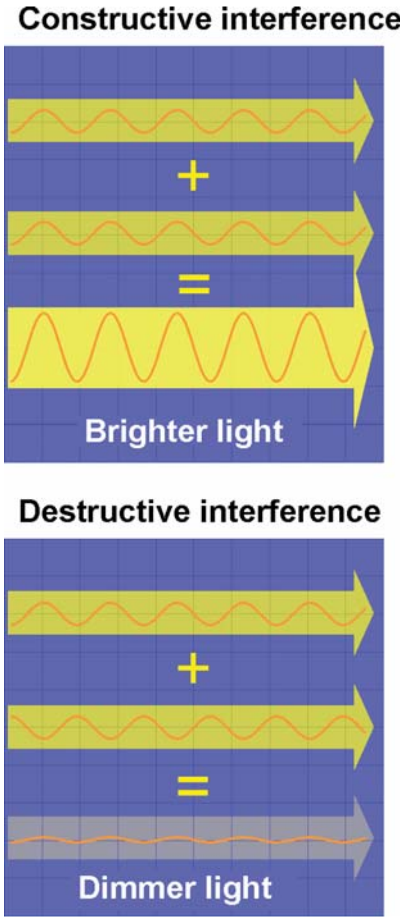


Figure 24.9: *The interference pattern (bands) comes from the interference of light as waves from each slit add up at each point on the screen. Constructive interference creates brighter light. Destructive interference creates dimmer light.*

Diffraction gratings and spectrometers

Diffraction grating

A **diffraction grating** creates an interference pattern similar to the pattern for the double slit. A grating is actually a series of thin parallel grooves on a piece of glass or plastic. When light goes through a diffraction grating, each groove scatters the light so the grating acts like many parallel slits.

The central spot

When you shine a laser beam through a diffraction grating most of the light goes straight through. A bright spot called the *central spot* appears directly in front of the grating where the light passes straight through (Figure 24.10). Some light is also scattered off many grooves. The interference of the light scattered from the grooves is what causes the additional bright bands on either side of the central bright spot.

The diffraction pattern

The **diffraction pattern** is the series of bright spots on either side of the central bright spot. The closest bright spots to the center are called the *first order*. The light waves that produce the first order are one whole wavelength different in phase from each other. The second closest set of bright spots are called second order because these are made by the constructive interference of light waves that are two wavelengths different. You can often see third order, and even fourth order spots as well.

The location of bright spots is related to wavelength

Like the double slit, a bright spot forms when the light waves from two adjacent grooves arrive in phase at the screen. The two waves travel a slightly different distance. They arrive in phase when the difference in distance between the two waves is exactly one wavelength. Because the location of the bright spots depends on wavelength, different wavelengths of light make bright spots at different distances from the central spot (Figure 24.11).

The spectrometer

When light with a mixture of wavelengths passes through a diffraction grating, each wavelength makes a bright spot at a different place on the screen. As a result the grating spreads the light out into its separate wavelengths. That is why you see a rainbow when looking at a bright white light through a diffraction grating. A spectrometer is a device that uses a diffraction grating to create a spectrum (Figure 24.12). The spectrometer has a printed scale that allows you to read different wavelengths of light directly from the pattern of light made by the grating.

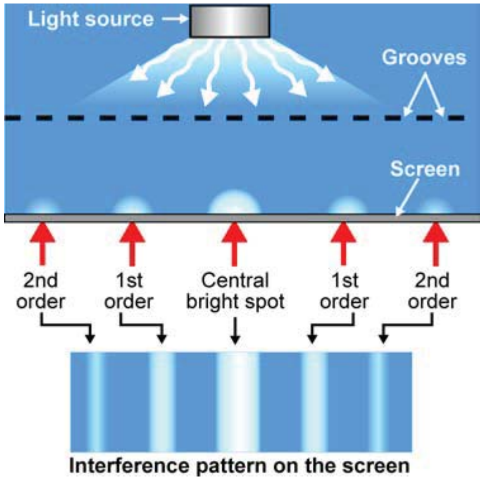


Figure 24.10: *The interference pattern from a diffraction grating.*

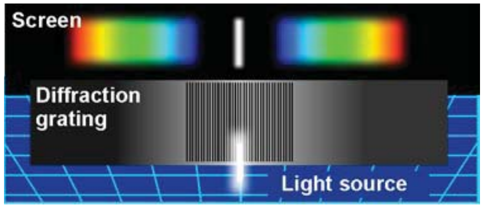


Figure 24.11: *Different wavelengths of light make bright spots at different distances from the central spot.*

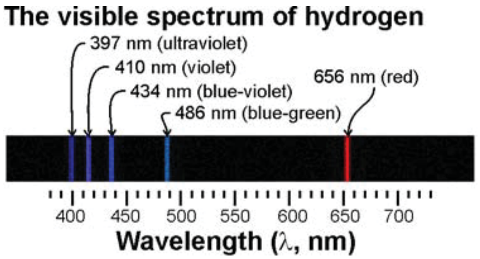
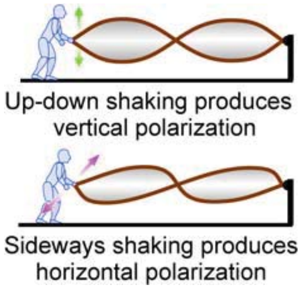


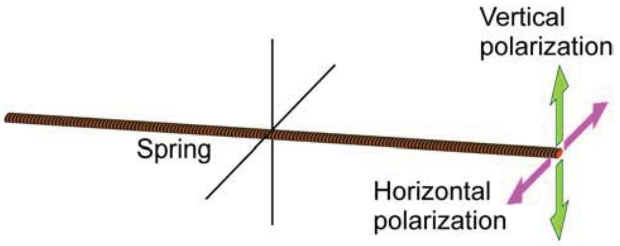
Figure 24.12: *The spectrum of light from by hydrogen gas seen in a spectrometer.*

Polarization

Polarization of a wave on a spring

An easy way to think about polarization is to think about shaking a spring back and forth. Waves move *along* the spring in its long direction. The oscillation of the *transverse* wave is perpendicular to the direction the wave travels. If the spring is shaken up and down it makes *vertical polarization*. If the spring is shaken back and forth it makes *horizontal polarization*. The polarization is the direction of the oscillation of the wave perpendicular to the direction the wave moves. Only transverse waves can have polarization. Longitudinal waves (like sound) cannot have polarization since they oscillate in only one direction, along the direction the wave moves.





Polarization of light waves

The polarization of a light wave is the direction of the electric part of the wave oscillation (Figure 24.13). Polarization is another wave property of light. The fact that light shows polarization tells us that light is a *transverse wave*. Like a spring, the polarization of a light wave may be resolved into two perpendicular directions we usually call *horizontal* and *vertical*.

Unpolarized light

Most of the light that you see is *unpolarized*. That does not mean the light has no polarization. Unpolarized light is really just an equal mixture of all polarizations. We call ordinary light unpolarized because no single polarization dominates the mixture.

Polarizers

A **polarizer** is a material that allows light of only one polarization to pass through. Light that comes through a polarizer has only one polarization — along the *transmission axis* of the polarizer. Light with a single polarization is called *polarized light*. (Figure 24.14).

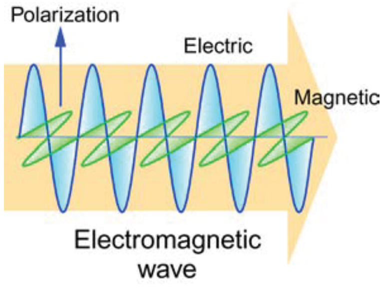


Figure 24.13: *The orientation of light is called its polarization. The polarization of light always refers to its electrical component.*

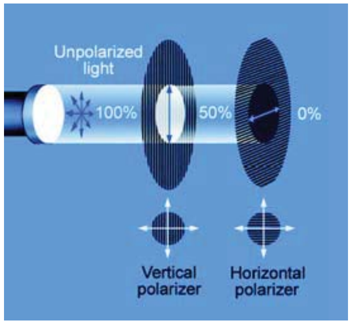


Figure 24.14: *Ordinary light is unpolarized. If this light passes through a vertical or horizontal polarizer, 50 percent of the light will pass through the polarizer. The light that passes will be horizontally or vertically polarized depending on the polarizer.*

Applications of polarization

Polarized sunglasses

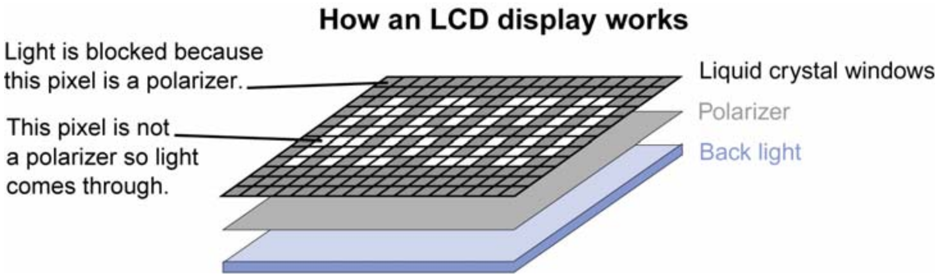
Light that reflects at low angles from horizontal surfaces is polarized mostly horizontally. Polarized sunglasses reduce glare because they selectively absorb light with horizontal polarization (Figure 24.15) while letting other light through. Using polarized sunglasses, you can still see the light reflected from other objects, but the glare off a surface such as water is blocked.

LCD computer screens

Images on a laptop computer's LCD (liquid crystal diode) screen are made using polarized light (see diagram below). Unpolarized light first comes from a lamp. This light passes through a polarizer. The resulting polarized light then passes through numerous pixels of liquid crystal that act like windows.

Dark dots are made by crossing polarizers

Each liquid crystal window can be electronically controlled to act like a polarizer, or not. When a pixel is *not* a polarizer, the light comes through and you see a bright dot. When a pixel becomes a polarizer, light is blocked and you see a dark dot. The picture is made of light and dark dots. To make a color picture there are separate polarizing windows for each red, blue, and green pixel.



24.2 Section Review

1. Why do sound waves spread out after passing through a partly open door while light waves make a beam of light that does not spread nearly as much?
2. Suppose you shine white light through a filter that absorbs a certain color of green. What will the spectrum of this light look like after passing through a diffraction grating?
3. Look at an LCD screen through polarizing sunglasses. Explain what you see when you rotate the sunglasses to change the angle of the transmission axis of the polarizing lenses.

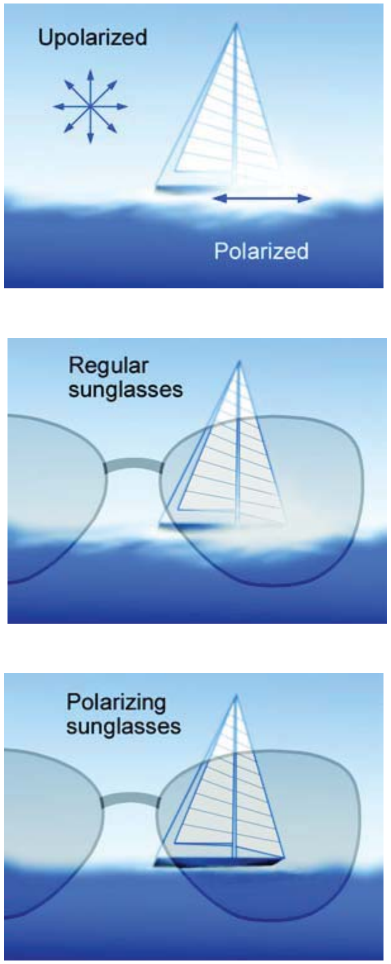


Figure 24.15: *Unpolarized light from the sun is polarized horizontally when it reflects off the water. Polarized sunglasses block out this light; regular sunglasses do not.*

24.3 Photons

Light has both wave-like and particle-like properties. By “particle-like” we mean that the energy of a light wave is divided up into little bundles called *photons*. Each atom that makes light gives off one photon at a time. Each atom that absorbs light absorbs one photon at a time. A beam of light consists of trillions of photons travelling at the speed of light.

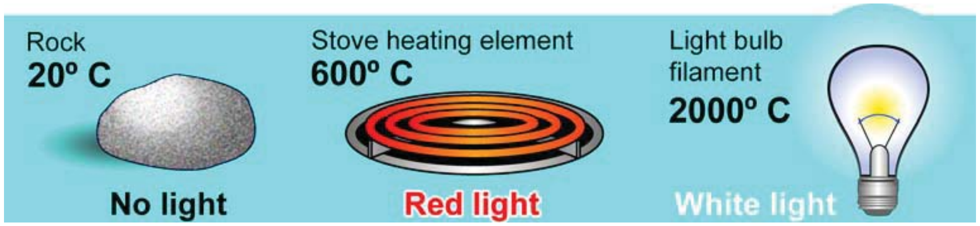
The photon theory of light

Photons The energy of a light wave is divided up in tiny bundles called *photons*. Each photon has its own color, no matter how you mix them up. Orange light is made of orange photons, red light of red photons, and so on. You can almost think of photons as colored jelly beans, except they have no mass.

Color and photons The lowest-energy photons we can see are the ones that appear red to our eyes (Figure 24.16). The highest-energy photons we can see are the color of deep violet. Low-energy atoms make low-energy photons and high-energy atoms make high-energy photons. As atoms gain energy, the color of the light they produce changes from red to yellow to blue and violet.

White light White light is a mixture of photons with a range of energy. This is because white light is created by atoms that also have a range of energy. For example, when a dimmer switch is set very low, the filament of an incandescent bulb is relatively cool (low energy) and the light is red. As you turn up the switch, the filament gets hotter and makes more green and blue light. At full power the filament is bright white—which means it is producing photons of all colors.

Temperature and energy The atoms in a material have a range of energy depending on temperature. At room temperature (20°C) a rock gives off no visible light. At 600°C, some atoms have enough energy to make red light. At 2,600°C, atoms can make all colors of light, which is why the hot filament of a light bulb appears white.



Vocabulary

photoluminescence

Objectives

- ✓ Define a photon.
- ✓ Explain how energy is related to the color of light.
- ✓ Learn that a one photon affects one electron at a time.
- ✓ Understand that seeing objects and color depends on how light is reflected and absorbed.

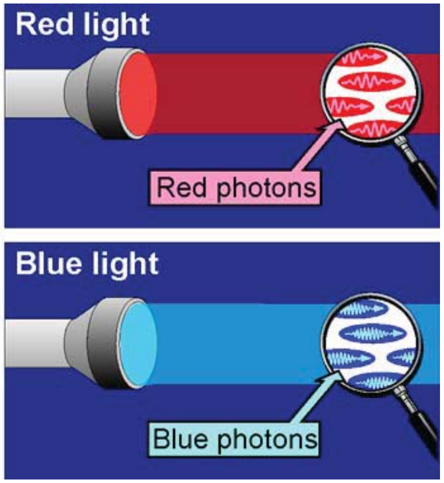


Figure 24.16: *Blue photons have a higher energy than red photons.*

The energy and intensity of light

Energy, color, and intensity

The intensity of light is a combination of both the number of photons and the energy per photon. There are two ways to make light of high intensity. One way is to have high-energy photons. A second way is to have a lot of photons even if they are low-energy (Figure 24.17). In practical terms, to make a red light with an intensity of 100 watts per meter squared (W/m^2) takes a lot more photons then it does to make the same intensity with blue light.

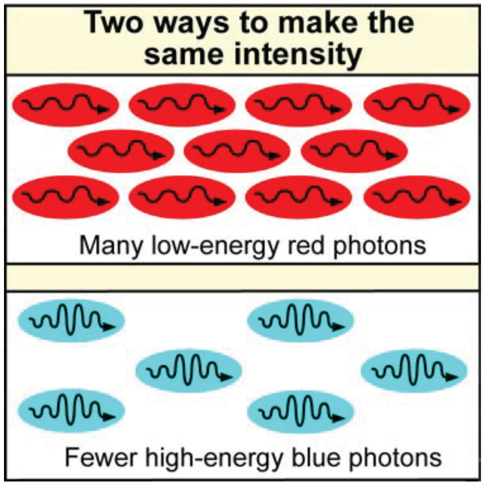


Figure 24.17: *The number and energy of photons determine the intensity of the light.*

Glow-in-the-dark plastic

If glow-in-the-dark plastic is exposed to light, it stores some energy and later is able to release the energy by giving off light. The plastic can only make light if it is "charged up" by absorbing energy from other sources of light. You can test this theory by holding your hand on some "uncharged" glow-in-the-dark plastic and then exposing it to bright light. If you then bring the plastic into a dark area and remove your hand, you can see that the areas that were covered by your hand are dark while the rest of the plastic glows (Figure 24.18).

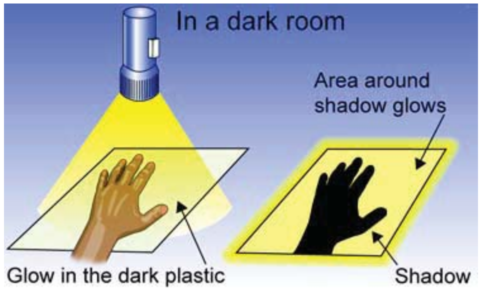


Figure 24.18: *The light from the flashlight cannot energize the phosphorus atoms that your hand blocks. These atoms will not glow because they did not receive any energy from photons from the flashlight.*

Photo luminescence

The glow-in-the-dark effect comes from phosphorus atoms that are in the plastic. When photons of light collide with phosphorus atoms, the energy from the photons is stored in the atoms. Slowly, the stored energy is released as pale green light. The process of releasing stored light energy is called **photoluminescence**.

An experiment with photon energy

Glow-in-the-dark plastic demonstrates that *a single atom only absorbs a single photon at a time*. Let's say we want a phosphorus atom to give off a green photon. To give off green light, the atom must absorb equal or greater energy. If one red photon is absorbed the atom does not get enough energy to make a green photon, and cannot glow. However, if a single atom could absorb two or more red photons it might get enough energy to emit a green photon. If you try the experiment you find that even very bright red light does not make the atoms of phosphorus glow. However, even dim blue light causes the atoms to glow. This is because one blue photon has more than enough energy to allow a phosphorus atom to release a green photon. If you try different colors, you find that only photons with more energy than those of green light will cause the glow-in-the-dark plastic to glow.

Absorbing, reflecting, and creating light

Light reflects off surfaces

Light reflected off a wall in a room started at a light source like a light bulb. Atoms in the wall first absorb and then re-emit the light energy. This process of absorbing and re-emitting light happens so fast that we may accurately describe the light as reflecting off the surfaces.

The process of how light is reflected

The atoms on the surface of this paper in the white areas absorb the light from the room and immediately emit almost all of the light back in all directions. You see a white page because the atoms on the surface of the paper absorb and re-emit light of all colors equally (Figure 24.19). The black letters are visible because light falling on black ink is almost completely absorbed and no light is re-emitted.

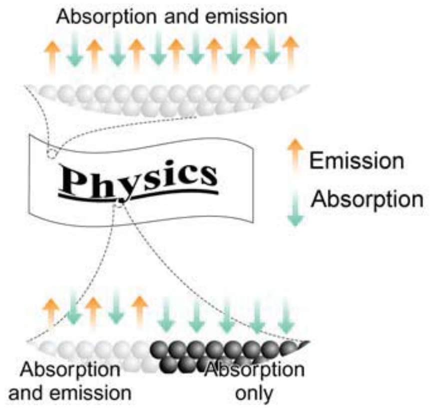


Figure 24.19: *White paper absorbs and immediately re-emits photons of all colors in all directions. Black ink absorbs photons of all colors and emits none, which is why it looks black.*

Most atoms absorb and emit light

Almost all atoms absorb and emit light. For most atoms, the absorption and emission of light happens in less than one millionth of a second. This is so fast that only the most sensitive instruments can detect the time delay. However, a phosphorus atom in glow-in-the-dark plastic is different. Phosphorus atoms have a special ability to delay the emission of a photon for a relatively long time after they have absorbed light.

Light from chemical reactions

Many chemical changes release energy. Some of the energy is absorbed within atoms and re-emitted as light. For example, the warm flickering glow from a candle comes from trillions of atoms in the wick giving up photons as they combine with oxygen atoms in the air (Figure 24.20). The light that comes from a glow stick is also made through chemical changes.

Figure 24.20: *The light from a candle flame comes from energy released by chemical changes.*

24.3 Section Review

1. Give one example where light acts like a wave and one example where light acts like a particle.
2. Is it possible for two beams of light to have the same number of photons per second yet have different amounts of power? Explain.
3. Give at least 3 differences between a photon and an atom?
4. A piece of wood does not produce light. However, a log on a fire some times glows with reddish light. Explain this observation.

The Electromagnetic Spectrum in the Sky

For thousands of years, people have looked up at the sky and wondered what the sun, moon, and planets were made of, how they were created, and what kept them going. Did you know they emit much more radiation than just visible light?

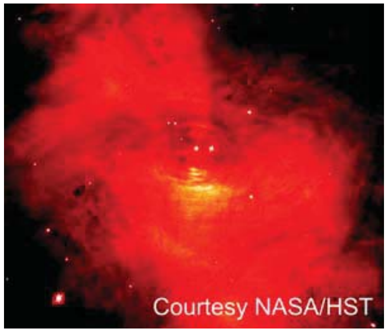
Electromagnetic radiation has helped scientists learn more about our solar system, galaxies and the universe around us. For example, astronomers confirmed the existence of black holes — very dense objects in space that have huge gravitational fields — using X-ray telescopes.

Visible light

The earliest observations were made using visible light because very little special equipment was required. The human eye makes a good observation device, and with a telescope, it's even better!

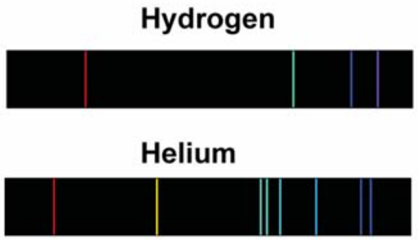
Astronomers use telescopes to do more than just magnify images. For very dim or distant objects, very little light reaches Earth. Telescopes act as "light buckets" and collect as much light from a dim source as possible. Bigger telescopes can collect more light than smaller ones and allow scientists to see objects that are farther away and dimmer.

A different approach to getting better pictures of the sky in the past 50 years is to launch telescopes mounted on satellites into orbit beyond the atmosphere. These new telescopes, like the Hubble Space Telescope, can show us crystal clear views we could never obtain on Earth.


Courtesy NASA/HST

Emissions spectra

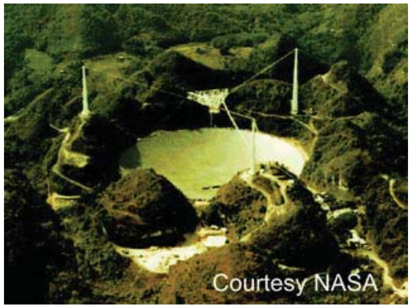
Another way in which scientists learn about celestial objects is by observing emitted light. Astronomers use spectrometers to determine which frequencies of electromagnetic radiation are present in light from stars. Patterns of spectral lines can be associated with chemical elements, so when a particular pattern appears in the spectrum of light from a star, it's a good sign that element is present in the star.



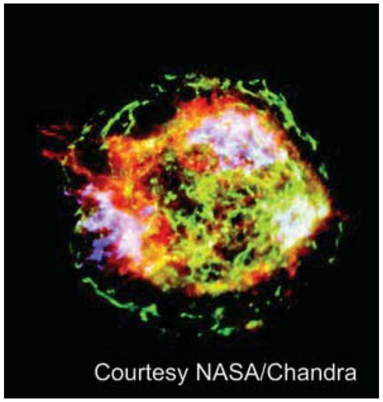
Radio telescopes

While performing a study on radio communications in the early 1900's, an engineer discovered an unknown source of interference. It turned out that the source of the radiation was located in the sky at the center of the Milky Way galaxy.

To further investigate the sources of radio waves in space, scientists built radio telescopes. Because radio waves have a much longer wavelength than visible light, equipment used to accurately detect radio waves must be much bigger. The biggest radio telescope in the world is the Arecibo Radio Telescope in Puerto Rico; it's over 300 meters across and built into a huge sinkhole in the ground! In the 1960's, new theories predicted the existence of a certain kind of pulsing star, and astronomers found them by observing radio waves.


Courtesy NASA

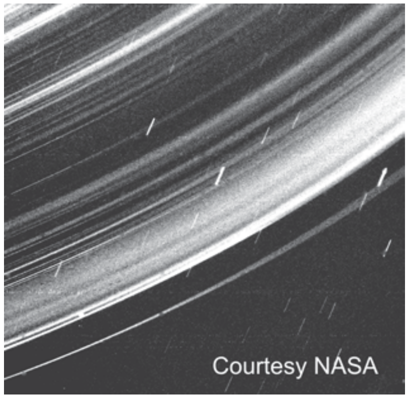
Gamma rays and X rays


Courtesy NASA/Chandra

Other objects in the sky emit high energy electromagnetic radiation, like X rays and gamma rays. Unlike most visible light and lower energy radiation, high energy electromagnetic waves do not usually pass through the atmosphere, so observations of this radiation are made from satellites. This image of the supernova remnant Cassiopeia A was taken by the NASA satellite Chandra.

Infrared telescopes

Because water vapor in the atmosphere absorbs much of the infrared radiation from space, infrared telescopes are often built high in the mountains, like the Mauna Kea Observatory in Hawaii, which is about 4,000 meters above sea level.

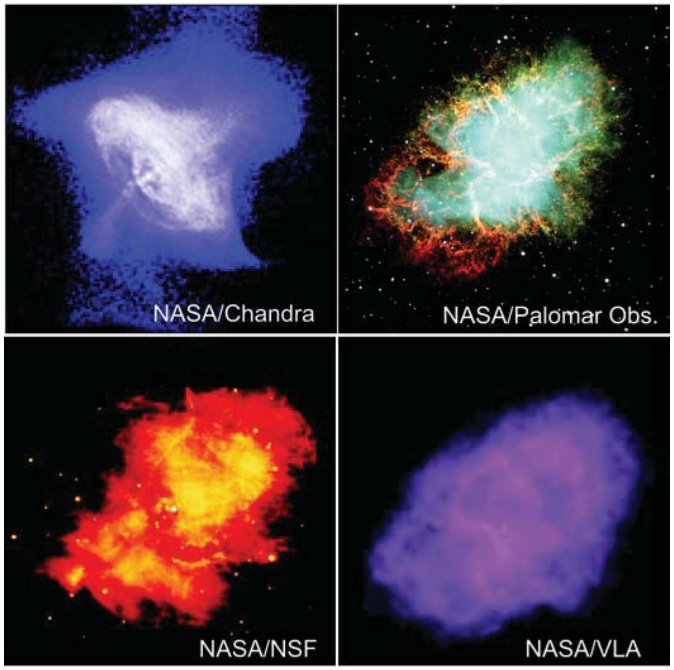

Courtesy NASA

Scientists also mount infrared sensors on an airplane and fly above 99% of the atmospheric water vapor to take more sensitive readings than on the ground. While observing a star passing behind Uranus, they saw it blinking in and out of view, and it was discovered that Uranus has rings, similar like Saturn.

Astronomers learned that the surface of the moon was covered with a fine powder years before anyone set foot there by making observations of reflected infrared light.

Electromagnetic variety show

Below are four images of the Crab Nebula: clockwise, starting in the top left, the images were taken in the X-ray region of the spectrum, the optical range, with a radio telescope, and in the infrared spectrum.


NASA/Chandra
NASA/Palomar Obs.
NASA/NSF
NASA/VLA

Questions:

1. What device could you use to help you observe objects in the night sky?
2. How much light can a "light bucket" hold?
3. What elements are likely present in our sun?
4. What conclusions could you make about the Crab Nebula, given the four different images above?

Table of Contents

Chapter 24 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

spectrometer
photons
diffraction grating
visible light
polarizer
photoluminescence
ultraviolet radiation
gamma rays
polarization
electromagnetic spectrum
infrared waves
X rays
electromagnetic waves

Section 24.1

1. Radio waves, X rays, gamma rays, and visible light are all part of the ____.
2. ____ is the type of electromagnetic wave that can cause sunburn.
3. ____ are produced by oscillations of electricity or magnetism.
4. ____ is the type of electromagnetic wave we feel as heat.
5. The part of the electromagnetic spectrum we can see with our eyes is called ____.
6. ____ are high frequency waves with a wavelength of 10 nanometers to 0.001 nanometers.
7. ____ are the highest frequency waves in the electromagnetic spectrum and are generated in nuclear reactions.

Section 24.2

8. Light passes through a ____ and comes through with only one orientation.
9. A(n) ____ measures the wavelength of light.
10. The orientation of light vibrations, either horizontal or vertical, is called a ____.
11. A(n) ____ creates interference patterns when light is passed through it.

Section 24.3

12. The process of releasing stored energy as light is known as ____.
13. Particles of light energy are known as ____.

Reviewing Concepts

Section 24.1

1. Compare red light and blue light in terms of the energy, wavelength, and frequency of both types of light.
2. The speed of light changes as it passes through different materials due to the absorption and emission of the light by atoms. As the speed changes, does its frequency, wavelength, or both change?
3. How is the index of refraction for a material dependent upon the speed of light? Is it possible for a material to have an index of refraction less than 1? Why or why not?
4. Write the equation for the speed of light that you would use in each of the following scenarios. Let c = the speed of light, f = frequency, and λ = wavelength:
   a. You know frequency and wavelength.
   b. You know the speed of light and frequency.
   c. You know the speed of light and wavelength.
5. List two different ways that microwaves are used.
6. When a beam of X rays is passed through a person's body and onto a special film, a radiograph (or X-ray photograph) is created. How do radiographs enable a doctor to "see" a broken arm?

Section 24.2

7. List *four* pieces of evidence that light is a wave.
8. How is an interference pattern of light created? In your answer, use the terms *constructive interference* and *destructive interference*.
9. Thomas Young demonstrated that light is a wave. What experiment did he use and what evidence did his experiment create?
10. What is a spectrometer used for?
11. What causes the central spot when light goes through a diffraction grating? What causes the first order bright spots?
12. Is an electromagnetic wave a transverse or longitudinal wave?
13. What does it mean to say a light wave is *polarized*?
14. Explain what a polarizer does to unpolarized light.

Section 24.3

15. How is the intensity of light related to photons?
16. How is a photon's color related to its energy?
17. What "charges up" glow-in-the-dark plastic? Does it matter what color light you use to charge up the plastic?
18. In the subtractive color process, pigments absorb some colors and reflect some colors of light. Explain the absorption and reflection of colors of an object in terms of atoms and electrons.

Solving Problems

Section 24.1

1. The following are different types of electromagnetic waves: Gamma rays, visible light, X rays, microwaves, radio waves, infrared light, ultraviolet light. Arrange these waves in order from:
   a. LOWEST energy to HIGHEST energy.
   b. SHORTEST to LONGEST wavelength.
2. For the electromagnetic waves in question (1), does it make sense to order them by their speed? Why or why not?
3. Calculate the wavelength of violet light that has a frequency of 7.5×10^{14} Hz.
4. What is the frequency of a microwave with a 30-centimeter wavelength?
5. The speed of light in a vacuum is 3×10^8 m/sec. What is the speed of light in flint glass whose index of refraction is 1.65?
6. If light travels at 1.56×10^8 m/sec through zircon. What is the index of refraction of zircon?

Section 24.2

7. A polarizer transmits 50% of a light's intensity, and the transmitted light is oriented horizontally. How much of the light intensity was absorbed, and what is the orientation of this light?
8. A red laser with a wavelength of 650 nanometers is passed through a diffraction grating. What would you expect to see?

Section 24.3

9. Photographers use a special scale called Color Temperature for comparing the colors of light sources when they take pictures. Color temperature is the temperature in Kelvins at which that color light would be emitted. Which would have the higher color temperature, a sunset or a blue flashbulb?
10. At 600°C, a heating element produces red light. Is red light also present when a light bulb filament makes white light at 2000°C?
11. A blacksmith can tell the temperature of a metal piece by looking by its color. You know that the order of colors in a rainbow is ROYGBIV. Which color would a blacksmith see first, red or white, as he heats up the metal to the highest temperature of 2600°C?

Applying Your Knowledge

Section 24.1

1. What would the world look like if your eyes could see all the different wavelengths of the electromagnetic spectrum — from radio waves to gamma waves — and not just visible light? What would your experience be like if you were able to see all kinds of electromagnetic waves? Write a short essay that answers these questions.

Section 24.2

2. Unlike humans, who sense only brightness and color, some animals in the animal kingdom use polarized vision for a variety of uses. Research an animal that uses polarized vision and, in a poster, describe how this animal uses polarized vision to its advantage. What is special about the eyes of animals with polarized vision?
3. Edwin Land (1909-1991), a physicist, invented the first filters to polarize light and held many patents in the fields of optics and photography. Research his life and inventions. Write a short paper or give a presentation that summarizes your findings about this inventor.

Section 24.3

4. The trick in building fireworks is to find materials that release light at the specific color you want to see. Research which materials are used to produce the different colors of fireworks. Make a table of the materials and the frequency and color they produce.