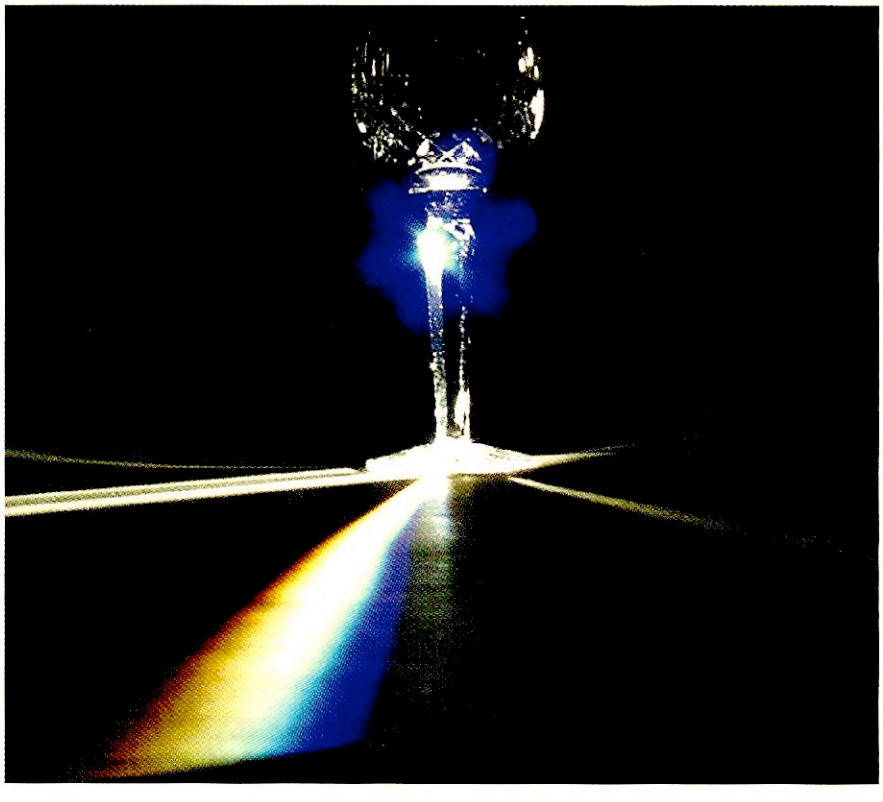
CHAPTER 14

Light

Although radio waves and microwaves are useful for communications and energy transfer, there's another portion of the electromagnetic spectrum that we find far more important: light. Light consists of very-high-frequency, very-short-wavelength electromagnetic waves. Light's frequencies are so high that normal antennas can't handle it. Instead, it's absorbed and emitted by the individual charged particles in atoms, molecules, and materials. Because of its special relationship with the charged particles in matter, light is important to physics, chemistry, and materials science. Moreover, it's one of the principal ways by which we interact with the world around us.

EXPERIMENT: Splitting the Colors of Sunlight

We see light because it stimulates cells in our eyes. This stimulation is an example of light's ability to influence chemistry. And because our eyes are able to distinguish



Courtesy Lou Bloomfield

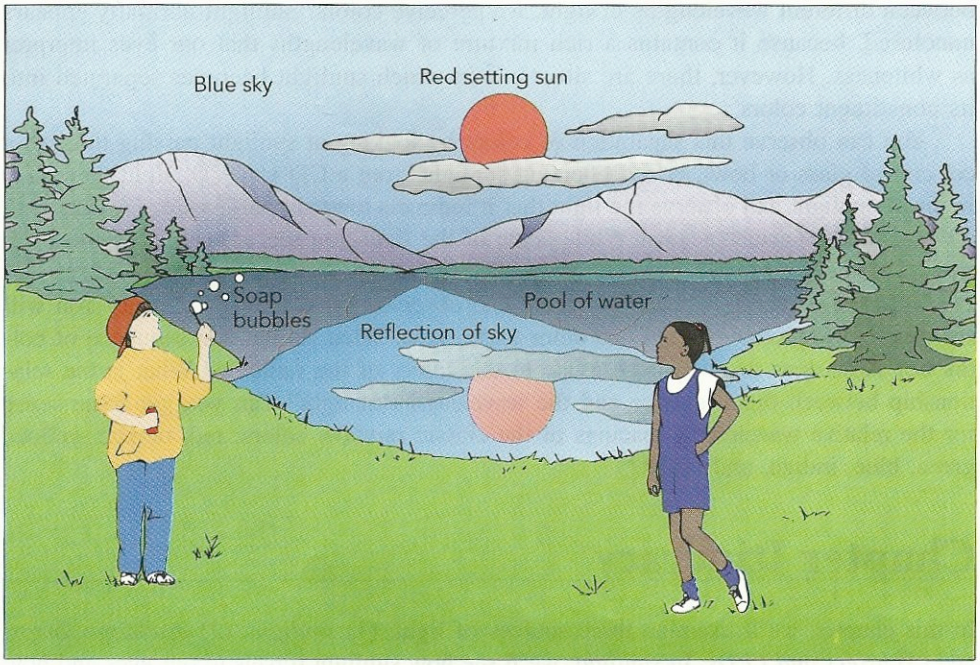
between different wavelengths of light, we perceive colors. Sunlight normally appears uncolored, because it contains a rich mixture of wavelengths that our eyes interpret as whiteness. However, there are situations in which sunlight becomes separated into its constituent colors.

You can observe this separation of colors by looking at sunlight passing through a cut crystal glass or bowl, or by reflecting sunlight from a CD or DVD. Hold the object in direct sunlight and observe the light that it redirects toward your eyes or projects onto a white sheet of paper nearby. While some of the light you see will still be white, you should see colors as well.

Turn the object slowly in your hand and observe how the colors change. You will see gradual progressions from one color to the next. What should that sequence of colors be? How does this sequence relate to the colors of the rainbow? What is the relationship between this sequence and the wavelengths of light? Can you get some sense for the relative wavelength spacings of the classic rainbow colors: red, orange, yellow, green, blue, indigo, and violet?

Chapter Itinerary

In this chapter, we'll examine three sources of light: (1) *sunlight*, (2) *discharge lamps*, and (3) *lasers and LEDs*. In *sunlight*, we'll see how sunlight travels to our eyes and how its passage through the atmosphere, raindrops, and soap bubbles can separate it into its constituent colors. In *discharge lamps*, we'll explore the ways in which atoms and molecules emit and absorb light, and how different atoms and molecules can be used to produce light of different colors. In *lasers and LEDs*, we'll look at how atoms, molecules, and solids can duplicate or amplify the light passing through them and thus produce intense beams of highly ordered light. In the process of studying these three light sources, we'll also learn about three different types of light: thermal light, atomic resonance light, and coherent light. For additional preview information, flip to the Chapter Summary at the end of the chapter.



SECTION 14.1 Sunlight

For thousands of years, people have marked the passage of time by the rising and setting of the sun over the horizon. The sun first appears as a red disk in the east every morning, rises white in the blue sky, and then sets once again as a red disk in the west. The sunlight that we see takes about 8 minutes to travel the 150,000,000 km (93,000,000 mi) from the sun to our eyes and provides most of the energy and heat that make life on earth possible. Although the light in sunlight is really just another electromagnetic wave and could be considered part of the previous chapter, it's so important to everyday life that it deserves special attention. Therefore we'll begin by looking at how sunlight interacts with our world.

Questions to Think About: *Why is the sky blue during the day? Why is the sun red at sunrise and sunset? Why do you see rainbows only when the sun is relatively low in the sky? Why do we see colors when sunlight passes through cut crystal? Or through a soap bubble? How can sunlight be used to produce electricity?*

Experiments to Do: *Sunlight is actually composed of many different electromagnetic waves. These waves differ in frequency and wavelength like the radio waves from your two favorite stations. You don't need a machine to help you distinguish between various wavelengths of light; you can use your eyes. Take a look at a soap bubble on a bright, sunny day. You see the bubble because it reflects light. In fact, the clear bubble appears colored, even though the sunlight hitting it is white. That's because the bubble separates sunlight according to wavelength and sends only certain wavelengths toward your eyes.*

Sunlight and Electromagnetic Waves

Electromagnetic waves can have any wavelength, from thousands of kilometers to a fraction of the width of an atomic nucleus. The radio waves and microwaves that we examined in Chapter 13 have wavelengths longer than 1 mm. In the present chapter, we'll turn our attention to shorter wavelength radiation. In particular, we'll study electromagnetic waves with wavelengths between 400 nm and 750 nm (recall that 1 nm or 1 nanometer is 10^{-9} m). These are the electromagnetic waves that we perceive as **visible light** and the principal components of sunlight.

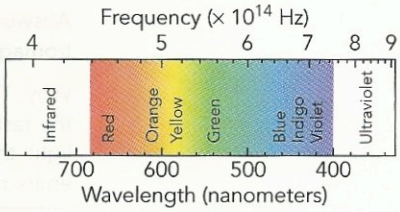


Fig. 14.1.1 The visible portion of the spectrum of sunlight. Each wavelength of visible light has a particular frequency and is associated with a particular color. At the ends of the visible spectrum are invisible infrared and ultraviolet lights.

Because the electromagnetic waves in sunlight have such short wavelengths, their frequencies lie between 10^{14} Hz and 10^{15} Hz (Fig. 14.1.1). As one of these waves of sunlight passes by, its electric field fluctuates back and forth almost 1,000,000,000,000,000 times each second. Since producing microwaves, which have much longer wavelengths and much lower frequencies, already requires specialized components and tiny antennas, what can possibly emit or absorb light waves? The answer is the individual charged particles in atoms, molecules, and materials. These tiny particles can move extremely rapidly, often vibrating about at frequencies of 10^{14} Hz, 10^{15} Hz, or even more. As these charged particles accelerate back and forth, they emit light waves. Similarly, passing light waves cause individual charged particles in atoms, molecules, and materials to accelerate back and forth, thereby absorbing the light waves as well.

Sunlight originates at the outer surface of the sun, in a region called the photosphere. There, atoms and other tiny charged systems (mostly atomic ions and electrons) jostle about at 5800 K. Since these charged particles accelerate as they bounce around, they emit electromagnetic waves.

Because the sun's surface emits light through the random, thermal motions of its charged particles, the distribution of wavelengths it emits is determined only by its temperature. It emits a blackbody spectrum, as we discussed in Section 7.3. Because the photosphere's temperature is 5800 K, the jostling motions are extremely rapid, and most of the sunlight falls in the visible portion of the electromagnetic spectrum (Fig. 14.1.2).

However, not all sunlight is visible. On the long-wavelength, low-frequency side of visible light is **infrared light**. We can't see infrared light with our eyes, but we feel it when we stand in front of a hot object. In sunlight, infrared light is produced by charges that are accelerating back and forth more slowly than average.

On the short-wavelength, high-frequency side of visible light is **ultraviolet light**. We can't see ultraviolet light either, but we're aware of its presence because it induces chemical damage in molecules. It causes sunburns and encourages skin to tan. In sunlight, ultraviolet light is produced by charges that are accelerating back and forth more rapidly than average.

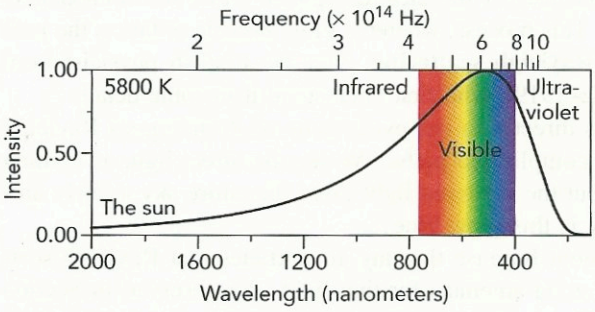


Fig. 14.1.2 Sunlight comes from the sun's photosphere, where the temperature is 5800 K. This light has a blackbody distribution of wavelengths, with much of its intensity concentrated in the visible portion of the overall electromagnetic spectrum.

Check Your Understanding #1: The Rosy Glow of Candlelight

Why does a burning candle emit reddish or yellowish light?

Answer: Charged particles in the hot flame accelerate back and forth and emit electromagnetic waves that include the low-frequency end of the visible spectrum.

Why: The accelerating charged particles in hot objects emit light. The hotter the object, the faster the charged particles move and accelerate and the higher the frequencies of light they emit. A candle isn't hot enough to emit the whitish light of the sun, so it emits mostly reddish or yellowish light.

Sunlight's Passage to the Earth

Sunlight travels from the sun to the earth at the speed of light—but what sets the speed of light? Actually, as we learned in Section 4.2, it's one of the fundamental constants of nature, with a defined value of 299,792,458 m/s in empty space. Although one could argue that the speed of light is set by the relationships between the electric and magnetic fields, that observation simply passes the buck. If you were then to ask what sets the relationships between the electric and magnetic fields, the answer would be the speed of light.

Rather than justifying why sunlight travels as fast as it does in empty space, let's look at what happens to it when it enters a region that's not empty. After all, sunlight eventually reaches the earth's atmosphere and, when it does, several interesting things happen.

First, the sunlight slows down as its electric and magnetic fields begin to interact with the electric charges in the atmosphere. Light polarizes the molecules it encounters, a process that delays its passage and reduces its speed. Since most transparent materials respond much more strongly to light's electric field than to its magnetic field, we'll concentrate on only electric effects.

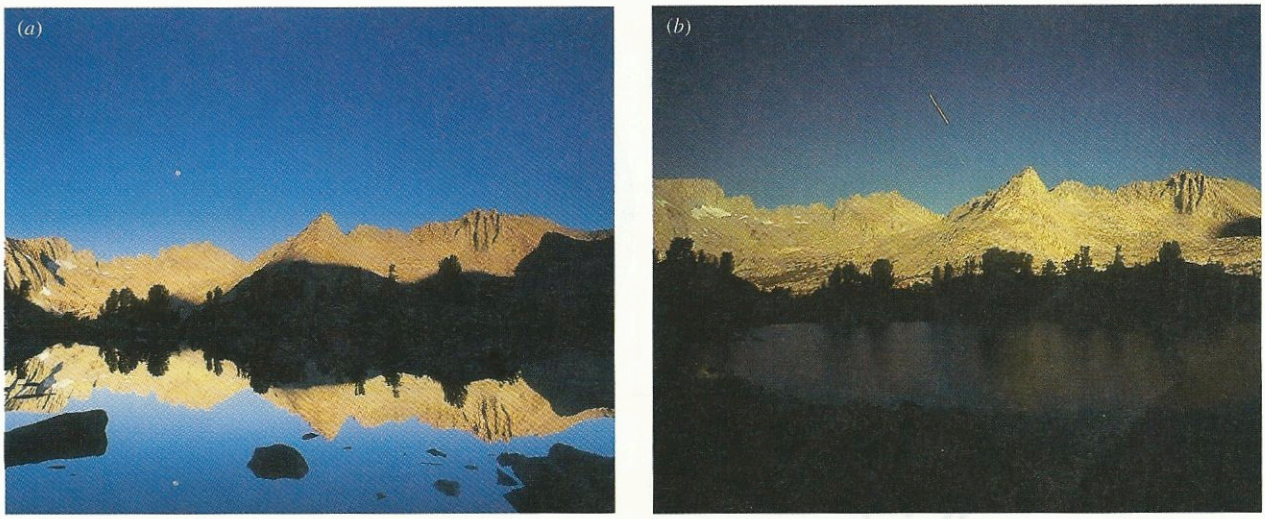
The factor by which light slows down in a material is known as the material's **index of refraction**. Light travels particularly slowly through materials that are easy to polarize, and some of them have indices of refraction of 2 or even 3. Because air near sea level is only slightly polarizable, however, its index of refraction is just 1.0003. Although this reduction in light's speed is too small to notice, we do notice the polarized air particles that cause it. These polarized air particles are what makes the sky blue (Fig. 14.1.3).

The particles in air consist of individual atoms and molecules, small collections of atoms and molecules, water droplets, and dust. As a wave of sunlight passes through one of these particles, the particle becomes polarized. Its electric charges accelerate back and forth as the sunlight's electric field pushes them around, and they reemit a new electromagnetic wave of their own.

This new wave draws its energy from the original wave. In effect, the particle acts as a tiny antenna, temporarily receiving part of the electromagnetic wave and immediately retransmitting it in a new direction. This process, whereby a tiny particle redirects the path of a passing light wave, is called **Rayleigh scattering**, after the English physicist Lord Rayleigh (John William Strutt, 1842–1919), who first understood it in some detail.

Although most sunlight travels directly to our eyes, some of it undergoes Rayleigh scattering and reaches us by more complicated paths. We see the direct light as coming from the brilliant disk of the sun, but the scattered light gives the entire sky a fairly uniform blue glow (Fig. 14.1.4). Why is this glow blue?

The sky's blue color comes about because the tiny air particles that Rayleigh-scatter sunlight are too small to make good antennas for that light. We observed in Section 13.1 that an antenna works best when it is one-quarter as long as the wavelength of its



Galen Rowell/Mountain Light Photography, Inc.

Fig. 14.1.3 (*a*) During the day, the sky above Monument Valley appears blue because the earth's atmosphere scatters mostly blue sunlight toward us. (*b*) At night, the scattered sunlight is gone, and the atmosphere is a clear window through which to observe the stars. The time-lapse photograph on the right shows these stars as nearly vertical streaks in the night sky.

electromagnetic wave. The air particles make particularly bad antennas for long-wavelength red light, so that very little red sunlight undergoes Rayleigh scattering on its way through the atmosphere. However, the air particles are not such bad antennas for short-wavelength blue light. Some of the blue sunlight does Rayleigh-scatter and reaches our eyes from all directions. We see this Rayleigh-scattered light as the blue glow of the sky.

Rayleigh scattering not only makes the sky blue; it also makes the sunrises and sunsets red. As the sun rises or sets, its light must travel long distances through the earth's atmosphere in order to reach your eyes. Its path is so long that most of the blue light Rayleigh-scatters away miles to your east or west, and all you see is the remaining red light. Sometimes the whole local sky appears reddish because there simply isn't any blue light left to scatter toward you. Sunrises and sunsets are particularly colorful when extra dust or ash is present in the atmosphere to enhance the Rayleigh scattering. Air pollution, forest fires, and volcanic eruptions tend to create unusually red sunrises and sunsets.

In contrast, clouds and fog appear white because they're composed of relatively large water droplets. These droplets are larger than the wavelengths of visible light and scatter all of sunlight's wavelengths equally well. Although this scattering is often so effective that you can't see the sun's disk through a cloud, it doesn't give the cloud any color. The cloud simply looks white.

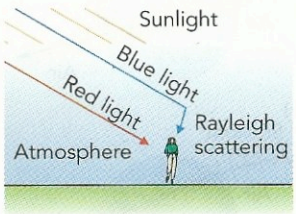


Fig. 14.1.4 As sunlight passes through the atmosphere, some of its blue light undergoes Rayleigh scattering from particles in the air. We see this redirected blue light as the diffuse blue sky. The remaining light reaches our eyes directly from the sun and tends to be reddish, particularly at sunrise and sunset.

Check Your Understanding #2: **Seeing the Blues**

The air in a dark, smoky room often looks bluish when illuminated by white light. What creates this bluish appearance?

Answer: Rayleigh scattering from the microscopic smoke particles scatters more blue light than red light and gives the air a bluish glow.

Why: When smoky air in a dark room is illuminated by a bright spotlight or another white light source, the tiny particles in the air Rayleigh-scatter some of the light. When you look at the air against a dark background you can see this glow. Since Rayleigh scattering affects blue light most strongly, the air appears bluish.

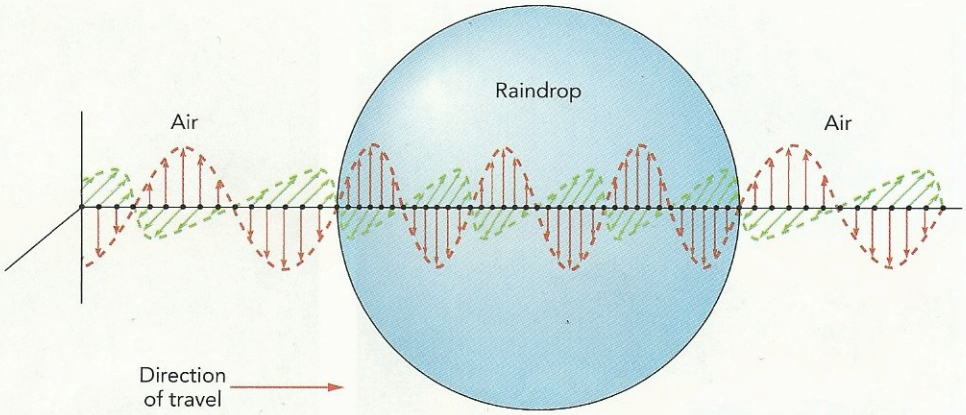


Fig. 14.1.5 As an electromagnetic wave enters a material, its speed decreases and the waves bunch up together. Its wavelength decreases.

Rainbows

Sometimes water droplets do separate the colors of sunlight. When sunlight shines on clear, round raindrops as they fall during a storm, these raindrops can create a rainbow. To understand how clear spheres of water can bend sunlight's path and separate it according to wavelength, we must understand three important optical effects: refraction, reflection, and dispersion. We encountered those same wave phenomena while studying water surface waves in Section 9.3, but now they appear in a new context: light waves!

Let's begin by looking at what happens when a wave of sunlight passes directly through a raindrop. Because water is more polarizable than air, the wave slows down inside the raindrop and its cycles bunch together (Fig. 14.1.5). Although this bunching effect reduces the light's wavelength inside the drop, the light's frequency remains unchanged. The cycles don't disappear as they go through the raindrop, they just move more slowly.

If a narrow wave of sunlight is aimed directly through the center of the raindrop, it will follow a straight path and emerge essentially unaffected from the other side (Fig. 14.1.6*a*). However, if that wave strikes the raindrop near the top, it will bend as it enters the water (Fig. 14.1.6*b*). This occurs because the lower edge of the wave will reach the water first and slow down, the upper edge will then overtake it, and the wave will bend downward. The wave will head more directly into the water.

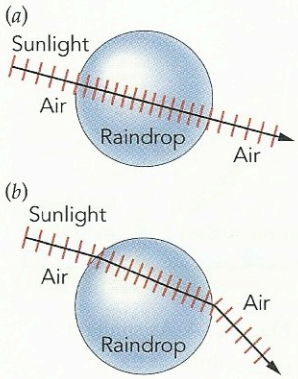


Fig. 14.1.6 A side view of two narrow waves of sunlight entering and leaving raindrops. The lines drawn across each light wave represent upward electric field maxima and are bunched together as light slows down in water.

As the wave in Fig. 14.1.6*b* leaves the raindrop, its upper edge emerges first and speeds up, while the lower edge lags behind. The wave bends downward even further and heads less directly into the air and away from the water.

This bending of sunlight at the boundaries between materials is *refraction*. It occurs whenever sunlight changes speeds as it passes through a boundary at an angle. If sunlight slows down at a boundary, it bends to head more directly into the new material. If sunlight speeds up at a boundary, it bends to head less directly into the new material. The amount of the bend increases as the speed change increases.

However, part of the sunlight striking a boundary doesn't pass through the boundary at all. Instead, it *reflects*. In Section 9.3, we attributed wave reflection specifically to changes in wave speed at a boundary. However, the more general cause of wave reflections is an **impedance mismatch**—an abrupt change in how the wave moves through its environment. In general, **impedance** is the measure of a system's opposition to the passage of a current or a wave. For an electromagnetic system, impedance measures how much voltage or electric field is needed to produce a particular current or magnetic field. In other words, electrical impedance measures how hard it is for electric activity to produce

magnetic activity. Impedance effects are common in nature (see ■) and also apply to mechanical waves and currents. When sound and water waves encounter impedance mismatches, they also partly reflect.

■ When electromagnetic waves travel through wires, they reflect from impedance mismatches. These mismatches occur whenever the relationship between electric and magnetic fields changes and must carefully be avoided in television wiring. If you don't provide an impedance-matching device when connecting an antenna wire (300 V) to a video cable input (75 V), you'll have reflections in the wires and ghost images on the screen.

The impedance of empty space is high because an electric field there has nothing to aid it in producing a magnetic field. Inside most materials, however, the electric field has help. The electric field polarizes the material, which then helps to create the magnetic field. Because of this assistance, the impedance of most materials is much less than that of empty space. Since air is almost empty space, the boundary between air and water is an impedance mismatch for light.

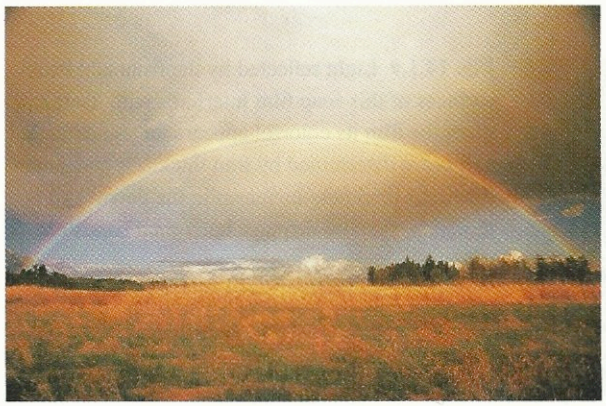
Passing through an impedance mismatch upsets the balance between a light wave's electric and magnetic fields. To compensate for this imbalance, part of the incoming wave experiences reflection off the boundary. Thus some sunlight reflects each time it enters or leaves a water droplet. The fraction of light that reflects depends on the severity of the impedance mismatch but is typically 4% between air and most transparent materials, including water (for reflection from sand, see ■). In contrast, metals polarize so easily that their impedances are essentially zero and they reflect light almost perfectly.

■ Sand appears white because it redirects sunlight in all directions. One explanation for this effect is that the sand grains act as tiny antennas that respond to and reemit light's electromagnetic waves. A second explanation is that the sand grains present the sunlight with thousands of air–sand boundaries from which to reflect. However, both explanations are descriptions of exactly the same physics—the charged particles in the sand grains are electrically polarized by the waves passing through them. These waves are randomly redirected without being absorbed, and they give the sand its white appearance.

There is one more important point about sunlight's passage through water: red light travels about 1% faster through water than violet light does. That's because higher-frequency violet light polarizes the water molecules a little more easily than lower-frequency red light, and that increased polarization slows down the violet light. This frequency dependence of light's speed in a material is *dispersion*. Dispersion affects refraction. The more light slows as it enters a raindrop, the more it bends at the boundary. Since violet light slows more than red light, violet light also bends more, and the different colors of sunlight follow somewhat different paths through the raindrop.

A rainbow is created when raindrops separate sunlight according to color (Fig. 14.1.7). To see the rainbow, you stand with the sun at your back and look up at the sky. When sunlight hits the raindrops, they redirect some of that light back toward you. Since each raindrop redirects light only in a narrow range of angles, you can't see light from every raindrop. Only the raindrops in a narrow arc of the sky redirect visible light toward you. This arc appears brightly colored because raindrops at the inner edge of the arc send violet light toward you, while raindrops at the outer edge of the arc send red light toward you. In between, you see all the colors of the rainbow.

Figure 14.1.8 shows how a raindrop redirects different colors of light in different directions. Although there are many possible paths light can take through the raindrop,



Steve Satushek/The Image Bank/Getty Images

Fig. 14.1.7 A rainbow forms when water droplets reflect sunlight back toward your eyes. Because the different wavelengths of light follow slightly different paths, we see the different colors coming from slightly different directions and observe bands of color.

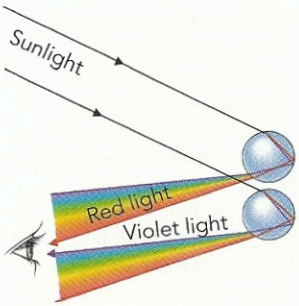


Fig. 14.1.8 As sunlight passes through spherical raindrops, its colors separate. Violet light bends more at each air/water boundary than does red light, and the two emerge from the raindrops heading in different directions. You see red light coming toward you from the upper raindrops and violet light from the lower raindrops.

this path is the one that produces rainbows. Sunlight enters near the top of the raindrop and bends inward. Violet light bends more than red light, so the sunlight begins to separate according to color. Some sunlight is also reflected from the raindrop but doesn't contribute to rainbows.

When the light inside the raindrop strikes the back surface, most of it leaves the drop and is lost. A small fraction of the light reflects from that surface, however, and continues to travel through the raindrop. When this light reaches the raindrop's front surface, most of it leaves the drop. Violet light bends more strongly than red light as they reenter the air, so the different colors of light leave the drop heading in different directions. Since violet light is redirected more upward than red light, you see violet light coming toward you from the lower raindrops. Red light is redirected more downward, so you see it coming toward you from the upper raindrops. Thus the upper arc of the rainbow is red while the lower arc is violet.

Check Your Understanding #3: The Look of Diamonds

A diamond pendant sparkles with color when you look at it in sunlight. From where do the colors come?

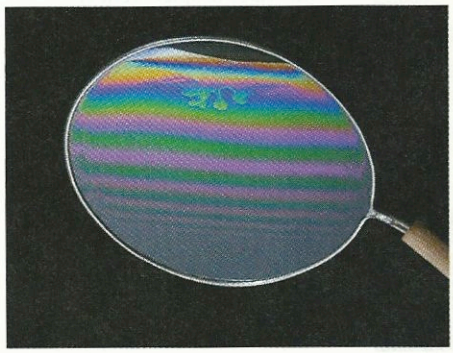
Answer: A diamond exhibits dispersion so that different frequencies of sunlight follow somewhat different paths through the diamond's polished facets. The different colors of sunlight emerge from the diamond traveling in slightly different directions, so that you can see them individually.

Why: One of the delightful aspects of a diamond is its strong dispersion. It bends violet light, much more than red light, so that sunlight is separated into its different colors as it passes through the stone. Cleverly cut facets help to isolate the individual colors.

Soap Bubbles

Soap bubbles also separate sunlight into its various colors (Fig. 14.1.9), but they use another wave phenomenon: interference. We encountered interference of mechanical waves in Section 9.3 when we studied wave beat at the seashore and interference of electromagnetic waves in Section 13.2 when we considered the unevenness of microwave cooking. Now we'll look at interference in another type of electromagnetic wave: light.

Light's interference effects stem from the summing or *superposition* of its electromagnetic waves. When several light waves overlap at a particular location, their electric



Courtesy Lou Bloomfield

Fig. 14.1.9 Light reflected by the front and back surfaces of this soap film interferes with itself and gives the film its colorful appearance. Since the colors are determined by film thickness and since the film's thickness increases in the downward direction, the film displays horizontal bands of color.

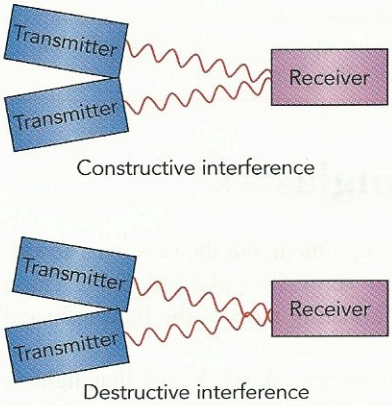


Fig. 14.1.10 (top) When waves from two separate paths arrive in phase at the receiver, constructive interference produces a particularly large effect on the receiver. (bottom) When waves arrive out of phase, destructive interference produces a particularly weak effect on the receiver.

fields sum together and so do their magnetic fields. If their individual fields all point in the same direction, the waves experience *constructive interference*—they sum together in a mutually assisting way, and the light intensity at that location is enhanced (Fig. 14.1.10*a*). However, when their individual fields point in opposing directions, the waves experience *destructive interference*—they sum together in a canceling way, and the light intensity at that location is reduced (Fig. 14.1.10*b*).

Both forms of interference occur when sunlight reflects from the outer skin of a soap bubble. As each wave of sunlight hits that thin film of soapy water, the film's front surface reflects about 4% of the wave and the film's back surface reflects another 4% (Fig. 14.1.11). Since both reflections travel in the same direction, the reflected light that you see reaches your eyes via two different paths, one from each reflection. If these two waves arrive in phase—that is, with their electric fields synchronized and assisting one another—you see the particularly bright reflection of constructive interference. If the two waves arrive out of phase—with their electric fields canceling one another—you see the particularly dim reflection of destructive interference.

Whether you see constructive or destructive interference depends on the wavelength of the sunlight. The back surface reflection has to travel twice through the soap film, so it's delayed relative to the front surface reflection. If the delay is just long enough for the wave to complete an integral number of cycles, then the two reflected waves are in phase with one another as they head toward your eye and you see a bright reflection. If the delay allows the back surface reflection to complete an extra half cycle, then the two reflected waves are out of phase with one another and you see a dim reflection.

Sunlight contains many different wavelengths of light, and these wavelengths behave differently during the reflection process. You see a colored reflection, consisting mainly of those wavelengths of light that experience constructive interference. Because the delay experienced by the back surface reflection depends on the thickness of the soap film, you can actually determine the film's thickness by studying its colors.

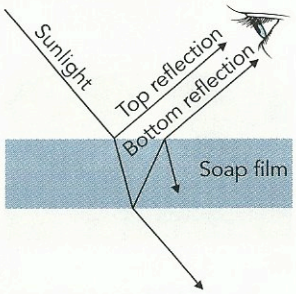


Fig. 14.1.11 Sunlight reflects from both the front and back surfaces of a soap film. The back surface reflection is delayed relative to the front surface reflection because it must pass twice through the soap film itself. If the two reflected waves arrive in phase, you see a bright reflection. If they are out of phase, you see a dim reflection.

Check Your Understanding #4: A Slick-Looking Oil Slick

A thin layer of oil or gasoline floating on water appears brightly colored in sunlight. From where do these colors come?

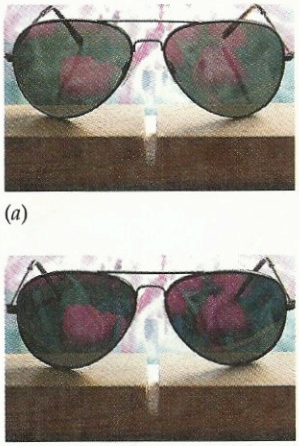
Answer: They come from interferences between light reflected by the top and bottom surfaces of the floating layer of oil.

Why: A thin film of almost anything on water will appear colored because of interference. Part of each light wave striking the film reflects from the top surface, and part

reflects from the bottom surface. These two reflected waves interfere with one another in a wavelength-dependent manner and make the layer appear brightly colored. Different colors correspond to different thicknesses of the thin films.

Sunlight and Polarizing Sunglasses

Courtesy Lou Bloomfield



(*a*)

(*b*)

Fig. 14.1.12 (*a*) Ordinary sunglasses simply darken the scene. (*b*) Polarizing sunglasses block horizontally polarized light, the main component of glare.

All sunglasses absorb some of the sunlight passing through them, but the best ones absorb horizontally polarized light much more strongly than vertically polarized light. These polarizing sunglasses dramatically reduce glare by eliminating most of the light reflected from horizontal surfaces.

When light strikes a transparent surface at right angles, about 4% of that light is reflected, regardless of its polarization. However, when light strikes a horizontal surface at a shallow angle, horizontally polarized light reflects much more strongly than vertically polarized light. That's because horizontally polarized light's horizontal electric field pushes electric charges back and forth along the surface. Charges shift relatively easily in that direction, and the surface becomes even easier to polarize as the angle becomes shallower. As a result, the surface reflects more horizontally polarized light at shallow angles than it does at steeper angles.

On the other hand, vertically polarized light's vertical electric field pushes electric charges up and down vertically. At shallow angles, this field acts to lift the charges in and out of a horizontal surface. Since the charges can't leave the surface, the surface becomes harder to polarize as the angle becomes shallower. A horizontal surface doesn't reflect much vertically polarized light, and there is even a special angle, **Brewster's angle**, at which no vertically polarized light reflects at all.

Direct sunlight is an even mixture of vertically and horizontally polarized waves. Since horizontally polarized waves reflect most strongly from horizontal surfaces, sunglasses that absorb horizontally polarized light will prevent you from seeing most of this reflected light (Fig. 14.1.12). That's why polarizing sunglasses are so effective at reducing glare.

Check Your Understanding #5: **Looking into the Reflecting Pool**

When you look into a pool of water, you see mostly a reflection of the sky. When you wear polarizing sunglasses, however, you see into the water clearly. Explain.

Answer: Most of the light that reflects from the water is horizontally polarized. The sunglasses block horizontally polarized light so that you see mostly light from within the pool of water.

Why: Sunlight reflecting from a horizontal surface is mostly horizontally polarized waves. By blocking horizontally polarized light, polarizing sunglasses virtually eliminate this reflected light, and you see mostly light from below the surface. If you turn the sunglasses sideways, they will block the wrong polarization of light and you will see mostly the reflected light. Try it.

Solar Energy

Sunlight isn't just a source of illumination; it's also an important source of renewable energy. Developing solar energy is a critical part of sustainable energy policy, particularly as the costs and consequences of burning fossil fuels increase. But beyond lighting and the

direct heating of your home on a sunny winter day, solar energy is a bit difficult to use. How can solar energy be turned into a more readily usable form—namely, electricity?

The two most common approaches are solar electric generating plants and photovoltaic cells. In a solar generating plant, most of the sunlight striking a large, open area is concentrated with mirrors and used to heat a liquid to temperatures high enough to produce pressurized steam. That steam passes through a spinning turbine, where it does work on the turbine's blades and allows the turbine to power an electric generator. It's a heat engine (Section 8.2) that uses the sun's thermal radiation (Section 7.3) to boil water for steam (Section 7.2) to power a turbine (Section 2.1) that powers an electric generator (Section 11.3). Isn't it wonderful when everything comes together so nicely?

Concentrating the sunlight is crucial, because direct sunlight can't produce pressurized steam. When the sun is directly overhead on a clear day, each square-meter of the earth's surface receives about 1000 W of solar radiation. That's enough to make a black driveway painfully hot on your bare feet and to slow-cook an egg, but it's not enough to produce pressurized steam. That's because a black surface also emits thermal radiation (Section 7.3) and, before it reaches 100 °C, it's already radiating away heat as fast as its receiving heat from the sun. To heat a surface above 100 °C and produce pressurized steam, the sunlight must be concentrated.

Lenses can concentrate sunlight nicely, but they're too expensive for large-scale solar power generation. Instead, solar plants concentrate sunlight using mirrors. Each mirror or mirror segment is carefully aligned so that its reflected sunlight overlaps with the reflected sunlight from other mirrors or segments. For example, when flat mirrors are arranged to form a parabolic curve, each mirror reflects rays of sunlight about a line perpendicular to that mirror, and all of their reflections overlap at one location (Fig. 14.1.13). The intensity of this concentrated sunlight greatly exceeds 1000 W/m^2, so it can heat a surface well above 100 °C. A liquid placed in a black container at that location will get hot enough to boil water and provide pressurized steam for electric power generation.

Scientists and engineers have been working on solar electric generating plants since at least the 1980s (Fig. 14.1.14). When built in desert areas with strong, steady sunlight, they can produce electric power at reasonable costs and with almost no pollution or fuel consumption. As the technologies improve, these plants can be expected to compete effectively with fuel-based electric generating plants.

Photovoltaic cells are essentially sun-powered batteries. A current arrives at a photovoltaic cell's negative terminal at a low voltage and leaves from its positive terminal at a high voltage. Although the cell's voltage rise is small, typically only 0.6 V, it is nonetheless providing electric power. For greater voltages, you simply connect

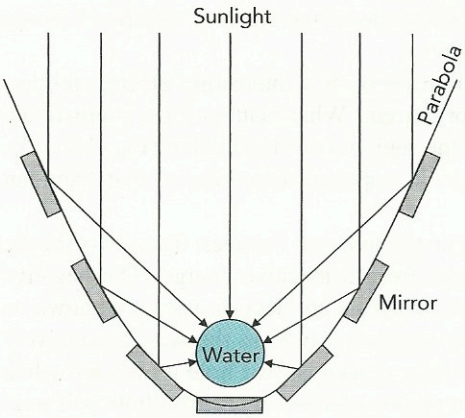
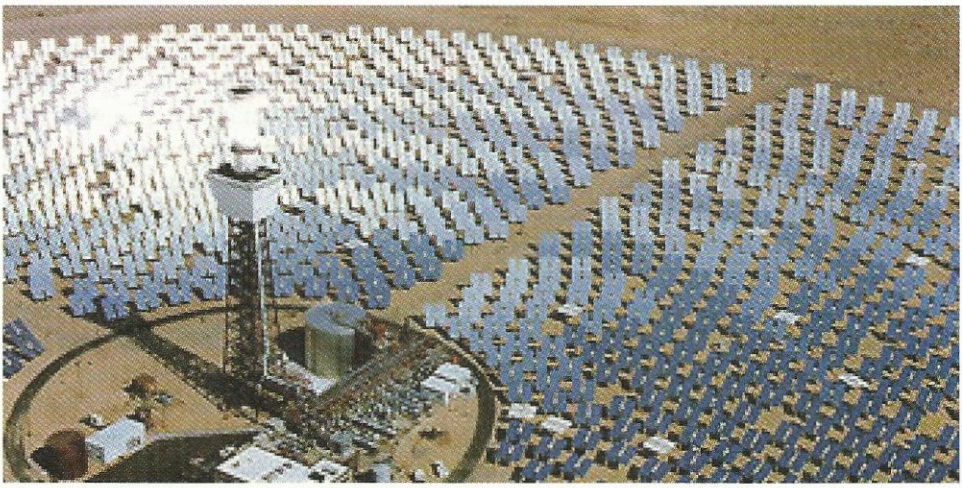


Fig. 14.1.13 When flat mirrors are arranged in a parabolic arc, they reflect the parallel rays of sunlight toward a single spot or focus. Such an array of mirrors can concentrate sunlight onto a black container of water and transform the water into pressurized steam.



Courtesy National Renewable Energy Laboratory

Fig. 14.1.14 Known as Solar Two, this experimental solar power plant operated in the Mohave Desert from 1995 to 1999. Its 1926 mirrors concentrated sunlight by a factor of 600, and it was capable of producing 10 MW of electric power.

several photovoltaic cells in series, just like the battery chains used in flashlights (Section 10.3).

Although photovoltaic technology advances almost daily, the basic concept underlying most cell designs remains unchanged. A photovoltaic cell uses the energy in a photon or quanta of sunlight to separate a positive charge from a negative charge. It collects those positive and negative charges on two different terminals so they can be used to do work in an electric circuit.

Most photovoltaic cells are structurally similar to diodes, the one-way devices for current that we examined in Section 12.1. Like diodes, photovoltaic cells have a pn-junction formed when two different semiconductor materials are joined together. However, because photovoltaic devices operate so differently from diodes, let's take a fresh look at their structures.

A classic photovoltaic cell consists of a sheet of electron-rich (n-type) semiconductor layered onto a sheet of electron-poor (p-type) semiconductor. Contact between those two sheets causes a spontaneous transfer of electrons across the junction between them. Electrons can reduce their potential energies by diffusing from the electron-rich material to the electron-poor material, but as they cross the junction, they create a charge imbalance between its two sides. That charge imbalance produces an electric field that opposes further electron transfers. As the electric field grows stronger, the electron transfers become less frequent until they eventually stop altogether.

When everything reaches equilibrium, this junction has interesting electric properties. It can act as a diode, a one-way device for current. What matters for a photovoltaic cell, however, is that it has an electric field in the region near its junction (Fig. 14.1.15). That field pushes positive and negative charges in opposite directions so that they can end up on different terminals of the device.

When a photon of sunlight is absorbed near the junction between those two sheets, that photon's energy separates a positive charge from a negative charge. The negative charge is simply an electron, while the positive charge is an electron vacancy known as a **hole**. You can think of a hole as a positively charged bubble in the sea of negatively charged electrons. Just as a bubble rises when water descends, so a hole moves left when all the electrons move right. Therefore, when a photon creates an electron-hole pair near

the junction, the junction's electric field pushes the electron toward the electron-rich material and the hole toward the electron-poor material. Those separated charges accumulate, and you can use them to provide power to an electric circuit.

Unfortunately, once enough separated charges have accumulated on the two sides of the junction, their electric field will cancel out the junction's electric field and the charge accumulation will stop. The effect limits the voltage rise of the photovoltaic cell. The voltage cannot exceed the band gap of the semiconductor used to make the cell (see Section 12.1). For an ordinary silicon photovoltaic cell, the band gap and voltage rise is about 0.6 V. Although a photovoltaic cell made from a larger band gap semiconductor can provide a larger voltage rise, it also requires more energetic photons. There is a tradeoff between the fraction of the sunlight photons a photovoltaic cell can use and the voltage rise it can provide.

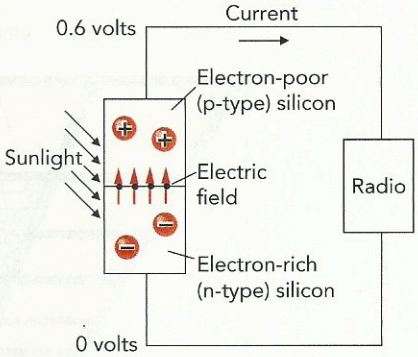


Fig. 14.1.15 A silicon photovoltaic cell is formed when layers of electron-rich (n-type) and electron-poor (p-type) silicon semiconductor are joined. A redistribution of electrons near the junction produces an electric field at the junction. When a photon of sunlight separates a positive and negative charge, that electric field pushes them in opposite directions. Those separated charges are collected and used to power an electric circuit.

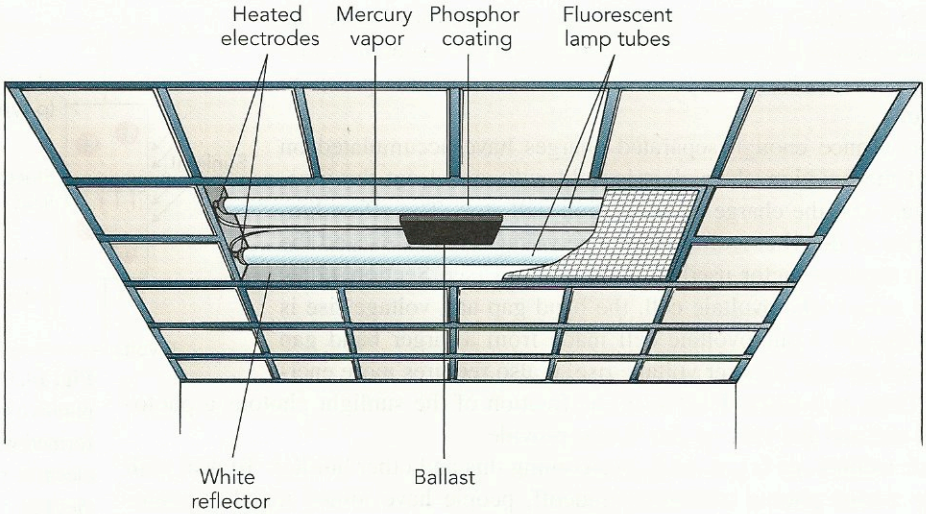
Photovoltaic technology is gradually overcoming this and other hurdles. To deal with the voltage rise versus photon utilization tradeoff, people have joined together photovoltaic cells made from different band gap materials to use nearly all the energy in all of the photon. Because simple photovoltaic cells reflect or transmit much of the sunlight that strikes them, people have developed techniques to increase the fraction of photons that enter the materials and are absorbed near the junction. Also, because the materials used in photovoltaics tend to be sophisticated and expensive, people are working to find simpler, cheaper materials. There are many challenges, but also many successes. With world-class photovoltaic cells approaching 50% sunlight-to-electric-power efficiencies and some commercial photovoltaic power plants almost cost-competitive with fossil fuel power plants, solar photovoltaic power is definitely on the rise.

Check Your Understanding #6: A Brighter Day

While a cloud is passing overhead, a photovoltaic cell sends a 1-A current through an electric circuit. When the cloud leaves, the sunlight intensity on the photovoltaic cell doubles. What current does the photovoltaic cell send through the circuit now?

Answer: It sends a 2-A current.

Why: Because the sunlight is now twice as bright, twice as many photons strike the photovoltaic cell each second, and those photons separate twice as many electrons and holes each second. The photovoltaic cell uses that doubled charge to send twice the previous current through the electric circuit.



SECTION 14.2 Discharge Lamps

Energy efficiency is crucial to modern lighting. Incandescent lamps provide pleasant, warm illumination, but most of the power they consume is wasted as invisible infrared light. Fluorescent and other gas discharge lamps produce far more visible light with the same amount of electric power and now dominate office, industrial, and street lighting. In this section we'll explore several types of discharge lamps—fluorescent, mercury vapor, sodium vapor, and metal–halide lamps—that all share a common theme: current passing through a gas.

Questions to Think About: *Why are incandescent lightbulbs being phased out? Why do different fluorescent lamps often have slightly different colors? Why is the light from a neon sign red? Why shouldn't you turn a fluorescent lamp on and off frequently? Why are streetlights so dim when they first turn on? Why are some highway lights orange?*

Experiments to Do: *Examine the discharge lamps around you, particularly the white fluorescent tube lamps. Where do their lights originate? In a fluorescent lamp, it comes from the white phosphor coating on the tube's inner surface. What about in a neon lamp or a mercury vapor streetlight? Compare the colors of various lamps, including several different fluorescent lamps. Are their lights identical?*

Both fluorescent and neon lamps start almost immediately—but watch how long it takes a streetlight to start. Fluorescent and neon lamps remain cool during operation, but the mercury, sodium, and metal–halide lamps used in street lighting get hot. Watch a streetlight warm up. Does its color change? If the streetlight loses power even for a moment, it must wait about 5 minutes before it can start again. Why must it wait?

How We See Light and Color

Before examining discharge lamps, let's look at how our eyes recognize color. It might seem that they actually measure the wavelengths of light, but that's not the case. Instead, our retinas contain three groups of light-sensing *cone cells* that respond to three different

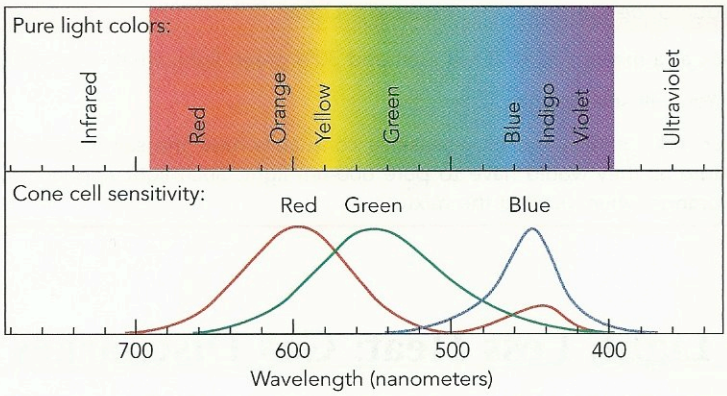


Fig. 14.2.1 The red-sensitive cells in our retina detect light near 600 nm, the green-sensitive cells near 550 nm, and the blue-sensitive cells near 450 nm. The red-sensitive cells also respond near 440 nm, so that we see violet.

ranges of wavelengths. One group of cone cells responds to light near 600 nm and lets us see red, another responds to light near 550 nm and lets us see green, and a third responds to light near 450 nm and lets us see blue (Fig. 14.2.1). These cone cells are most abundant at the center of our vision. Our retinas also contain *rod cells*, which are more light-sensitive than cone cells, but rod cells can't distinguish color. They are most abundant in our peripheral vision and provide us with night vision.

Having only three types of color-sensing cells doesn't limit us to seeing just three colors. We perceive other colors whenever two or more types of cone cells are stimulated at once. Each type of cell reports the amount of light it detects, and our brains interpret the overall response as a particular color.

Although light of a certain wavelength will stimulate all three types of cone cells simultaneously, the cells don't respond equally. If the wavelength is 680 nm, the red cone cells will respond much more strongly than the green or blue cells. Because of this strong red response, we see the light as red.

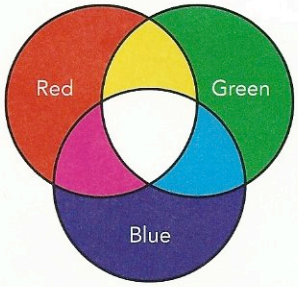
Other wavelengths of light stimulate the three types of cells somewhat more evenly. Light with a wavelength of 580 nm is in between red and green light. Both the red-sensitive and the green-sensitive cone cells respond about equally to this light, and we see it as being yellow.

We also see yellow when looking at an equal mixture of 640-nm light (red) and 525-nm light (green). The 640-nm light stimulates the red-sensitive cone cells and the 525-nm light stimulates the green-sensitive ones. Even though there is no 580-nm light entering our eyes, we see the same yellow color as before.

In fact, mixtures of red, green, and blue light can make us see virtually any color. For that reason, these three are called the **primary colors of light** or the *primary additive colors* (Fig. 14.2.2*a*). Color televisions and computer screens use tiny sources of red, green, and blue light to produce their full-color images.

Although the idea of mixing primary colors also applies to paints, inks, and pigments, the palette is different. The **primary colors of pigment** or the *primary subtractive colors* are cyan, magenta, and yellow (Fig. 14.2.2*b*). When you apply one of these primary pigments to a white surface, it absorbs or subtracts one of the primary colors of light from the surface's reflection. Cyan subtracts the reflection of red, magenta subtracts the reflection of green, and yellow subtracts the reflection of blue. Color printers, photographs, magazines, and books use tiny patches of cyan, magenta, and yellow pigments to produce their full-color images.

(*a*) Additive colors (light)



(*b*) Subtractive colors (pigment)

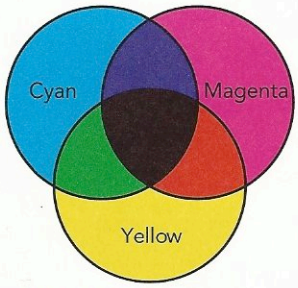


Fig. 14.2.2 (*a*) The primary colors of light or additive colors, red, green, and blue, can be combined to form any colors of light. (*b*) The primary colors of pigment or subtractive colors, cyan, magenta, and yellow, subtract red, green, and blue, respectively, from reflected or transmitted light and can be combined to form any colors of pigment.

Check Your Understanding #1: Mixed-Up Light

If you look at a mixture of 70% red light and 30% green light, what color will you see?

Answer: You will see orange.

Why: Your red-, green-, and blue-sensitive cone cells have the same response to this light mixture as they would have to pure 600-nm light. Such light appears orange, so you see orange when viewing the mixture.

More Light, Less Heat: Gas Discharges

When all three of our color-sensing cells respond about equally, we see white light. That's because our vision evolved under a single incandescent light source: the sun. Sunlight stimulates the red-, green-, and blue-sensitive cells in our eyes about evenly, so any other source of "white light" must do the same.

Most of the twentieth century's white-light illumination came from incandescent lightbulbs, but that won't be true for the twenty-first century. Although an incandescent lightbulb makes a good attempt at producing white light, it suffers from two serious drawbacks. First, because its filament can't reach the temperature of the sun's surface (5800 K), its blackbody spectrum contains too little blue light and appears redder than sunlight. Second, because most of its electromagnetic radiation is invisible infrared light, it doesn't use energy efficiently to produce visible light. It produces only about 15 lumens per watt, where the **lumen** is a standard measure of usable illumination. (For comparison, the discharge lamps that we're about to discuss can easily exceed 100 lumens per watt.)

Fortunately, modern science has given us some alternative sources of light, sources that don't use heat and thermal radiation to produce their light. Among these sources are gas discharge lamps, which emit light when electric currents pass through their gases. Some discharge lamps are colored, and others do excellent jobs of producing white light. Also, many of them are far more energy efficient at producing visible light than are incandescent lightbulbs.

To get an understanding of gas discharges and the lights they emit, let's start with one of the simplest examples: a neon sign tube. Though neon's rich red glow isn't suitable for lighting and isn't particularly energy efficient, it's great for signs and also relatively easy to understand.

A neon sign tube is a sealed glass tube that contains pure neon gas at a density less than 1% that of the atmosphere outside the tube. It has metal electrodes at each end so that electric current can enter the gas through one electrode and leave through the other. Of course, gases are normally electrical insulators and neon is no exception. To transform the tube's neon into a conductor, a large voltage difference is applied between its two electrodes. As we saw in Section 10.2, a gas breaks down when exposed to large voltage gradients; its few naturally occurring ions initiate a cascade of ionizing collisions that quickly fill the gas with charged particles and render it conducting.

Whereas ordinary air breaks down at a voltage gradient of about 30,000 V/cm, low-density neon breaks down at a much lower voltage gradient. That's because in a low-density gas, charged particles can travel farther and accumulate more kinetic energy before each collision. When about 10,000 volts is applied between the electrodes of a neon sign tube, the gas breaks down and begins to emit its familiar red glow.

The lamp is then experiencing a discharge—that is, current is flowing through the neon gas. This current consists mostly of electrons, flowing from the tube's negatively

charged electrode to its positively charged electrode (Fig. 14.2.3). Although these electrons collide frequently with neon atoms, they have so little mass that they usually just bounce off the atoms without losing much energy. Like a Ping-Pong ball rebounding from an elephant, the electron does most of the bouncing and then continues on its way.

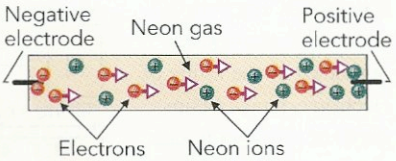


Fig. 14.2.3 A neon sign tube sends electrons through low-pressure neon gas. These electrons collide with neon atoms, transferring energy to them and causing them to emit primarily red light. Positively charged neon ions, created by particularly energetic collisions, keep the electrons from repelling one another to the walls of the tube.

Every so often, however, an electron will collide with a neon atom and something different will happen; the neon atom will rearrange internally and absorb part of the electron's kinetic energy. The electron will rebound with less energy than it had before, and the neon atom will go on to emit light, probably red light. To understand why that light is probably red, however, we'll have to look at quantum physics and the structure of the neon atom.

Check Your Understanding #2: Making Whiter Light

Some photographic lamps simulate sunlight by placing a blue filter in front of an incandescent bulb. This filter absorbs some of the red light so that the lamp appears whiter. Does this filter increase or decrease the lamp's energy efficiency?

Answer: It decreases the lamp's energy efficiency.

Why: Although the bluish filter changes the spectrum of wavelengths so that the amount of blue light leaving the lamp increases relative to the red light, it does this by absorbing some of the red light. The filter gets hot, and less electric power used by the bulb leaves as visible light.

Atoms, Light, and Quantum Physics

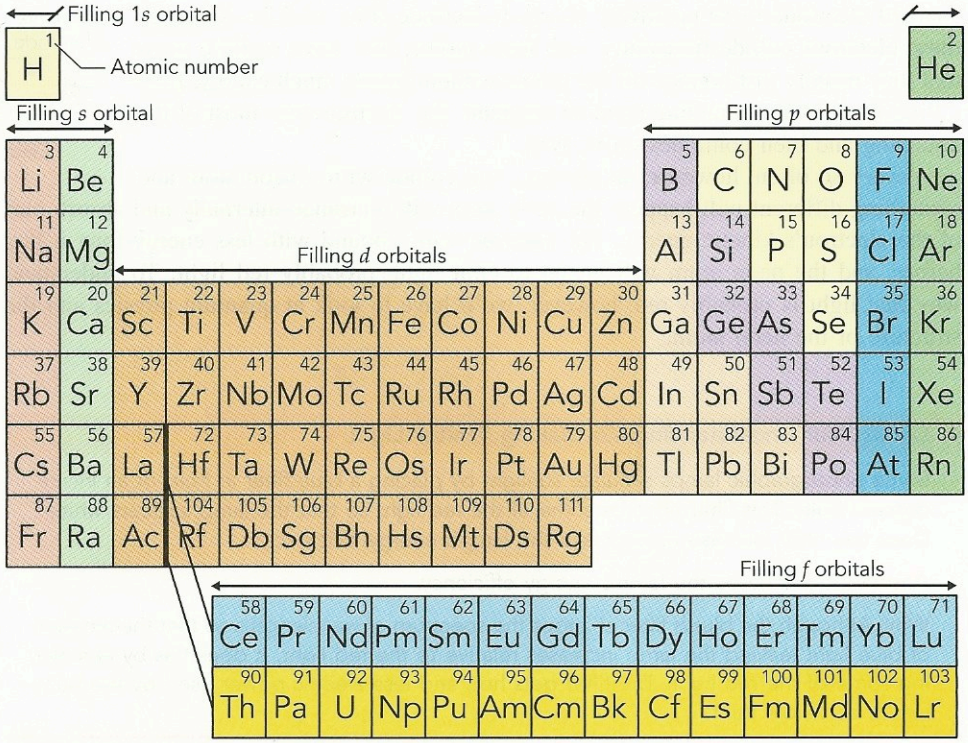
According to the wave–particle duality we encountered in Section 12.1, electrons have both particle and wave characteristics, and it is as waves that an atom's electrons are best understood. Like all objects in our universe, electrons travel as *waves* when they move from place to place, and it's only when you go looking for them that you find them as *particles* at particular locations (see ■).

■ In 1927, American physicists Clinton Joseph Davisson (1881–1958) and Lester H. Germer (1896–1972) showed that electrons travel as waves by observing interference effects when electrons were reflected from different atomic layers in a crystal of nickel metal. When the various electron waves arrived at a detector in phase, the detector found many electrons. When the waves arrived out of phase, the detector found few electrons. Their work was aided by a fortuitous accident in which air entered the experiment's glass vacuum tube. While carefully eliminating oxygen from their nickel sample after that leak, they managed to perfect its crystalline structure, making it possible to observe the interferences.

In an atom, each electron exists in a standing wave known as an **orbital**, with a specific energy and quantum frequency. Although these orbitals are three-dimensional standing waves, they resemble the two-dimensional standing waves of the drumhead shown in Fig. 9.2.9. Like the drumhead's vibrational modes, the orbitals are distinguished from one another by their patterns of nodes—surfaces along which the electron wave has no amplitude.

Like *levels* in a solid, *orbitals* in an atom can be viewed as placeholders that may or may not be occupied by electrons. From that perspective, an atom's orbitals fill with electrons from lowest energy on up. In accordance with the Pauli exclusion principle, each orbital accommodates two electrons, one spin-up and one spin-down, until all of the atom's electrons have been placed. The chemical nature of a particular atom, and its location in the periodic table of the elements (Fig. 14.2.4), is determined by how many electrons it has and how those electrons fill the available orbitals. Atoms are electrically neutral, so the number of negatively charged electrons in an atom is the same as the number of positively charged protons in its nucleus, its **atomic number**.

Just as there are patterns to levels, giving rise to the bands and band gaps that distinguish different solids, so there are patterns to orbitals, giving rise to the shells and energy



- Alkali Metals—Highly reactive, tend to donate lone *s* electron so as to empty outer shell
- Alkaline Earth Metals—Moderately reactive, tend to donate *s* electrons
- Transition Metals—Common metals with similar properties, differ only in numbers of *d* electrons
- Poor Metals—Additional metals with differing properties
- Metaloids—Intermediate between metals and nonmetals
- Nonmetals—Semiconductors and insulators
- Halogens—Highly reactive, tend to steal one *p* electron so as to complete outer shell
- Noble gases—Nonreactive gases with completed outer shells
- Lanthanides—Moderately reactive metals, differ only in numbers of 4*f* electrons
- Actinides—Moderately reactive metals, differ only in numbers of 5*f* electrons

Fig. 14.2.4 The periodic table of the elements is organized by the filling of electron orbitals. Major shells of orbitals fill with electrons from left to right. The number of electrons in a neutral atom is equal to its atomic number.

gaps that distinguish different atoms. **Shells** are groups of orbitals that have similar energies and tend to fill with electrons at about the same time. Although the orbital patterns and shells are complicated by the fact that charged electrons influence one another and distort one another's standing waves, many atomic properties are determined simply by which orbitals are occupied by an atom's electrons.

The atomic orbitals are identified primarily by an integer and a letter, both of which relate to their node patterns. The integer (1, 2, 3, …) is one more than the number of node surfaces in the orbital (0, 1, 2, …), and the letter (*s*, *p*, *d*, *f*, *g*, *h*, …) indicates how many of those node surfaces pass through the atom's center (0, 1, 2, 3, 4, 5, …). Although *s* orbitals appear one at a time, *p* orbitals appear in groups of three, *d* orbitals in groups of five, *f* orbitals in groups of seven, and so on.

A neon atom has 10 electrons, so it takes 5 orbitals to accommodate them. The first two electrons go into the 1*s* orbital, the fundamental mode with zero nodes. Filling the 1*s* orbital completes the first major shell. The next two electrons go into the 2*s* orbital, which has one node surface that doesn't pass through the atom's center. Finally, neon's last six electrons go into the three 2*p* orbitals, each of which has one node surface passing through the atom's center. Since filling the 2*s* and 2*p* orbitals completes the second major

shell, the neon atom (Ne in Fig. 14.2.4) is chemically inert. That is why neon exists as a gas of individual atoms!

An arrangement of occupied orbitals is called a **state,** and the state we have just described is neon's **ground state**—the state with the lowest possible total energy. The neon atom has other states available, but they all involve additional energy. That's where the discharge enters the picture. When a charged particle collides with a ground state neon atom, there's a chance that the collision will knock an electron out of its usual orbital into one of the empty orbitals. The neon atom will then be in an **excited state**—it will have extra energy.

Suppose, for example, that a collision has just shifted one of the neon atom's electrons from a $2p$ orbital to a $3p$ orbital. The atom will quickly undergo a series of state-to-state transitions that eventually return it to its ground state. With each transition, the atom will drop to a lower energy state and emit a photon. The photon carries away the energy released in transitioning from the higher energy state to the lower energy state. In all likelihood, one of those transitions will shift an electron from a $3p$ orbital to the $3s$ orbital and produce a photon of red light, the red of a neon sign!

As long as the electron remains in the $3p$ orbital—a particular standing wave—it can't emit an electromagnetic wave. That standing wave has a quantum oscillation; however, the oscillation is internal to the electron and neither the electron nor its charge has any overall motion. Since charge must accelerate to emit electromagnetic waves (see Chapter 13), without such overall motion there can be no emission of electromagnetic waves.

When the $3p$ electron begins its transition to the empty $3s$ orbital, its quantum wave begins to change with time. The wave moves rhythmically back and forth during the transition and its charge accelerates with it. The atom begins to emit an electromagnetic wave. By the time the transition is complete, the atom has emitted a single *particle* of light, a photon of red light. Like an electron, light travels as a *wave* but behaves as a particle when you try to locate it. While it's being emitted or absorbed by an atom, light exhibits its particle nature.

We've seen that hot objects emit light, a process called **incandescence**, but here the neon atom emits light without heat, a process called **luminescence**. That luminescence is the result of a **radiative transition**—a transition between states in which a photon of light is emitted or absorbed. In this case, the radiative transition emits a photon that carries away the energy released when the excited neon atom's $3p$ electron shifts into the empty $3s$ orbital. The difference in energy between those two states determines the photon energy, which in turn determines the frequency and color of the photon's light wave.

According to quantum physics, a photon's frequency is proportional to its energy. Specifically, the photon's energy is equal to the frequency of its electromagnetic wave times a fundamental constant of nature known as the Planck constant. This relationship between energy and frequency can be written as a word equation:

$$\text{energy} = \text{Planck constant} \cdot \text{frequency}, \tag{14.2.1}$$

in symbols:

$$E = h \cdot \upsilon,$$

and in everyday language:

Ultraviolet light and X-rays can injure your skin and tissues because each particle of high-frequency light carries a great deal of energy.

First used by German physicist Max Planck (1858–1947) in 1900 to explain the light spectrum of a hot object, the **Planck constant** has a measured value of 6.626×10^{-34} J · s. Also, although we have just encountered the Planck constant and Eq. 14.2.1 in the context of light waves, it actually applies to all quantum waves. For example, the quantum frequency of an electron is related to its energy by Eq. 14.2.1.

The Planck constant is so tiny that even a photon of 10^{15}-Hz ultraviolet light has an energy of only 6.626×10^{-19} J. A typical beam of light thus contains so many photons that you can't see that they're arriving as particles. However, the energy in a single ultraviolet photon is substantial on a molecular scale. It can damage a molecule in your skin, contributing to a sunburn and inducing your skin to tan as a defensive response. X-rays have even higher frequencies, and their energetic photons can cause more severe molecular damage.

A neon atom can only emit photons corresponding to energy differences between two of its states, a constraint that severely limits its light spectrum. Neglecting nuclear issues that we'll discuss in Chapter 16, all neon atoms are identical and emit the same characteristic spectrum of light. The visible part of that spectrum is dominated by the warm red glow of photons emitted when electrons shift from $3p$ to $3s$ orbitals, which is why a neon sign glows red.

Since atoms of different elements have different numbers of electrons and different states, each emits its own unique spectrum of light after being excited. Copper atoms emit a blue-green spectrum, strontium atoms a deep red, and sodium a bright yellow-orange. Chemists, astronomers, and manufacturers rely on those emission spectra for information and applications. As we shall soon see, so do scientists and engineers working on illumination.

Check Your Understanding #3: **Colorful Atoms**

Many fireworks involve brilliantly colored lights. How do the atoms in burning chemicals produce particular colors of light?

Answer: When fire adds energy to an atom and shifts it to an excited state, it emits photons in order to return to its ground state. Each photon's energy, frequency, and color are determined by energy differences between the atom's states.

Why: Each color in fireworks is produced by a particular type of atom. Some atoms, such as strontium and lithium, emit mostly red light as they return to their ground states. Barium atoms emit green light, copper atoms emit blue-green light, and sodium atoms emit yellow-orange light.

Check Your Figures #1: **The Particles in a Radio Wave**

How much energy is carried by a photon from a 1000-kHz AM radio station?

Answer: The photon carries 6.626×10^{-28} J.

Why: Since the Planck constant is 6.626×10^{-34} J · s and the frequency of the radio wave is 10^6 Hz or 10^6 cycles/second, the energy per photon is given by Eq. 14.2.1 as

$$\text{energy} = (6.626 \times 10^{-34}\,\text{J} \cdot \text{s}) \cdot (10^6\,\text{cycles/s}) = 6.626 \times 10^{-28}\,\text{J}.$$

This energy is so small that it's virtually impossible to observe the particulate character of radio waves.

Fluorescent Lamps

If neon tubes appeal to you for illumination, you probably march to your own drummer. Most people opt for a somewhat better simulation of sunlight in their discharge lamps. As an energy-efficient source of artificial sunlight, though, it's hard to beat fluorescent lamps.

At the heart of a fluorescent lamp is a narrow glass tube filled with argon, neon, and/or krypton gases at about 0.3% of atmospheric density and pressure. The tube also contains a few drops of liquid mercury metal, some of which evaporates to form mercury vapor. About one in every thousand gas atoms inside the tube is a mercury atom, and it's these mercury atoms that are responsible for the light.

Like a neon sign tube, a fluorescent lamp uses a discharge in its gas to produce light. Although fluorescent lamps occasionally use high voltages to initiate their discharges, most operate their discharges at household voltages and must rely on alternative techniques to render their gases conducting. These low-voltage lamps normally heat their electrodes so that thermal energy ejects electrons from their surfaces into the gas. Regardless of how the discharge is started, however, the result is current flowing through the gas and the emission of light.

The fluorescent lamp has a problem, though. While its mercury atoms emit most of the light in its discharge, that light is almost entirely ultraviolet. The final radiative transition that returns each mercury atom to its ground state ($6p \rightarrow 6s$) releases a large amount of energy and produces a photon with a wavelength of 254 nm. This light can't go through the glass walls of the tube, and you couldn't see it if it did. So the fluorescent lamp converts it into visible light with the help of phosphor powder on the inside of the glass tube.

Phosphors are solids that *luminesce*—they emit light—when something transfers energy to them. Their behavior is similar to that of an atom: an energy transfer shifts the phosphor from its ground state to an excited state, and it then undergoes a series of transitions that return it to its ground state. Some of those transitions are radiative ones and emit light.

In a fluorescent lamp, the phosphor is excited by ultraviolet light. This excitation or energy transfer is actually a radiative transition, but one in which the photon is absorbed by the phosphor; one of its electrons makes a transition from a lower energy level to a higher energy level. During this absorption, the light's electric field pushes the electron's wave back and forth rhythmically until it shifts to the new level. The photon disappears and the phosphor receives its energy.

Once the phosphor is in an excited state, its electrons begin to make transitions back to their ground state levels. Most of those transitions radiate visible light, the light that you see when you look at the lamp. However, some of the transitions radiate invisible infrared light or cause useless vibrations in the phosphor itself. Despite this wasted energy, phosphors are relatively efficient at turning ultraviolet light into visible light, a process called **fluorescence**.

The phosphors in a fluorescent lamp are carefully selected and blended to fluoresce over a broad range of visible wavelengths. That blending is necessary because, like atoms, each phosphor fluoresces with a characteristic spectrum of light that's determined by the energy differences between its levels. Several different phosphors are needed to produce the rainbow spectrum of white light. While some advertising and novelty lamps use brightly colored, unblended phosphors, fluorescent lighting tubes use phosphor mixtures that imitate white thermal radiation sources such as the sun or incandescent lightbulbs.

Because compact fluorescent lamps typically produce 60 to 100 lumens per watt, about 4 to 6 times the luminous efficiency of incandescent lightbulbs, you can save a great deal of energy by replacing incandescent lightbulbs with compact fluorescents. In

fact, incandescent lightbulbs are being phased out because of their poor energy inefficiency. To ease the acceptance of compact fluorescent lamps by a reluctant public, scientists and engineers have had to improve the quality of their light.

Early fluorescent lamps used a phosphor blend known as "daylight," which emitted far too much blue light and made everything look cold and medicinal. Daylight lamps rarely found their way into homes. The first improvement came with the developments of the "cool white" and "warm white" phosphor blends. Cool white resembled sunlight, and warm white resembled light from an incandescent lightbulb. However, even these improved lamps didn't emit true white light spectra—the blackbody spectra of the hot sun or the hot filament of an incandescent lightbulb. Objects looked a little off-color when illuminated by these lamps, so people were hesitant to use them in place of incandescent lightbulbs. Photographers and cinematographers wanting to capture true colors were particularly troubled by fluorescent lighting of that era.

However, the latest generation of fluorescent lamps uses phosphor blends that produce nearly perfect blackbody spectra. Many of those blends are even sold according to their color temperatures (see Section 7.3). For example, a 5100 K compact fluorescent lamp emits light that is almost indistinguishable from the thermal radiation emitted by a black object heated to 5100 K. That 5100 K color temperature is approximately the color temperature of sunlight averaged over a day. (Sunlight's color temperature is affected by the atmosphere and is highest at noon and lowest at dawn and dusk). If you like the color of sunlight, use 5100 K compact fluorescents.

For people who prefer the warm look of incandescent lighting, they should choose compact fluorescent lamps with a 2700 K color temperature. These lamps imitate the blackbody spectrum of a 2700 K tungsten filament almost perfectly. Because this 2700 K blackbody spectrum is richer in reds and oranges, it has a comforting, warm character to it. If you can't make up your mind between 5100 K sunlight and 2700 K incandescent light, you can choose many color temperatures in between. Even photographers and cinematographers are now using fluorescent lights, to the delight of actors and news anchors who used to sweat under the intense heat of powerful, energy-inefficient incandescent lamps.

Check Your Understanding #4: **Sorry, We Forgot the Coating**

If there were no phosphor coating on the inside of a fluorescent tube, what would you see when the lamp operated?

Answer: You would see only a dim (blue-white) glow from the lamp, because most of the light produced by the mercury discharge is invisible ultraviolet light.

Why: Without its phosphor coating, a fluorescent tube produces very little visible light. The phosphor coating is needed to convert the discharge's ultraviolet light into visible light. Even if you could see ultraviolet light, you would see very little of it leaving the tube. The tube is made of glass, which absorbs virtually all ultraviolet light with wavelengths shorter than 350 nm. Even in a normal fluorescent tube, any ultraviolet not converted to visible light by the phosphors is absorbed by the glass tube.

A Few Practical Issues

A fluorescent tube needs a substantial electric field inside it to keep its electrons moving forward. Since this electric field is proportional to the voltage drop through the tube, longer tubes need higher voltages. Power line voltages (110 V to 240 V) are appropriate

for tubes up to 3 m (10 ft) in length, but the longer and frequently colored fluorescent tubes used in artwork or advertising require much higher voltages.

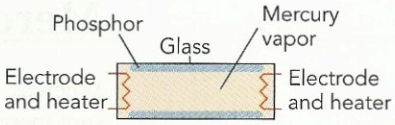


Fig. 14.2.5 In a hot-electrode fluorescent tube, the electrodes are actually filaments and are heated by running currents through them.

To keep electrons from pushing one another into its walls, a fluorescent tube must also contain positively charged mercury ions. The discharge naturally produces these ions during particularly energetic collisions. The result, a gaslike mixture of positively charged ions and negatively charged electrons, is called a **plasma**. A plasma is distinct from a gas because its charged particles exert forces on one another over considerable distances. All operating discharge lamps contain plasmas, including the neon sign that we discussed earlier.

Since a typical fluorescent lamp must heat its electrodes red-hot in order to form its plasma, it runs current through filaments at each end of its tubes (Fig. 14.2.5). Once the discharge is operating, the heating current can sometimes be turned off, because the electrodes will be kept hot by electrons that hit them from the discharge. However, some fluorescent fixtures can be dimmed, in which case electron heating alone won't sustain the plasma. Dimmable fluorescent fixtures must continue to pass heating currents through their filament/electrodes.

Each filament/electrode is coated with a material that helps it emit electrons into the gas. Unfortunately, that coating is thin and easily damaged by a process called **sputtering**, in which positive mercury ions from the plasma collide with the coating and chip away its atoms. Once enough of the coating has been removed, the lamp won't be able to sustain a discharge and it will need to be replaced. Because sputtering is particularly severe during start-up, most fluorescent lamps fail after 10,000 to 40,000 starts. Since it takes energy to construct each fluorescent lamp, turning a lamp off for only a short period, less than a few minutes, won't actually save energy in the long run. When you'll be returning to the room in a couple of minutes, leave the fluorescent lights on. Otherwise, turn them off.

Fluorescent lamps operate most efficiently and are at their brightest when their internal temperatures reach about 40 °C. Below that temperature, the vapor pressure of mercury is too low, and too much of the lamp's tiny store of mercury is liquid rather than gas. That's why most fluorescent lamps are somewhat dim when you first turn them on and they brighten as they warm up from room temperature to about 40 °C. It takes time for the mercury vapor to reach its optimum density. Though this warm-up period is objectionable to some people, it's a small price to pay for a vastly more energy-efficient lighting.

It would be great if fluorescent lamps could be based on a substance less toxic than mercury. However, mercury is uniquely well-suited to those lamps: its vapor pressure near room temperature is nearly ideal for an electric discharge, it converts electric energy into ultraviolet light with great efficiency, and it isn't damaged or consumed as the lamp operates. Much more important than eliminating mercury from fluorescent lamps is recycling those lamps after they fail. It's not hard to extract and reuse the mercury, and it should be done routinely.

Check Your Understanding #5: **Getting Red-y**

Why do the ends of some fluorescent lamps glow red during starting?

Answer: To start many lamps, their electrodes must be heated red-hot. You can often see light emitted by these hot-filament electrodes.

Why: In most fluorescent fixtures, the filaments are heated to high temperatures just before the discharge starts. Thermal energy then ejects electrons from the filament so that they can carry current through the gas.

Mercury, Metal–Halide, and Sodium Lamps

Whereas a low-pressure mercury discharge emits mostly ultraviolet light, a high-pressure mercury discharge emits more visible light than ultraviolet light. This change occurs because ultraviolet light becomes trapped in densely packed mercury atoms, and only visible light is able to escape from the discharge.

Known as **radiation trapping**, this effect occurs because mercury atoms absorb 254-nm photons just as well as they emit them. The same radiative transition that causes a mercury atom to emit a 254-nm photon ($6p \rightarrow 6s$) can also run backward to absorb that photon ($6s \rightarrow 6p$). In a dense gas of mercury, whenever one mercury atom emits a 254-nm photon, another mercury atom snaps that photon up. So while the discharge keeps pouring energy into the mercury atoms, they can't get rid of it as 254-nm photons. Instead, they emit most of their energy through radiative transitions between other excited states. Since this light is much less likely to be captured by other mercury atoms, it emerges from the lamp as bluish visible light.

When you first turn on a high-pressure mercury lamp, most of the mercury is liquid and the pressure is low. The lamp starts like a small fluorescent tube without phosphor, so you see very little visible light. However, the tube is designed to heat up during operation so that the liquid mercury evaporates to form a dense gas. As the gas pressure rises, the tube's color changes until it emits brilliant, blue-white light.

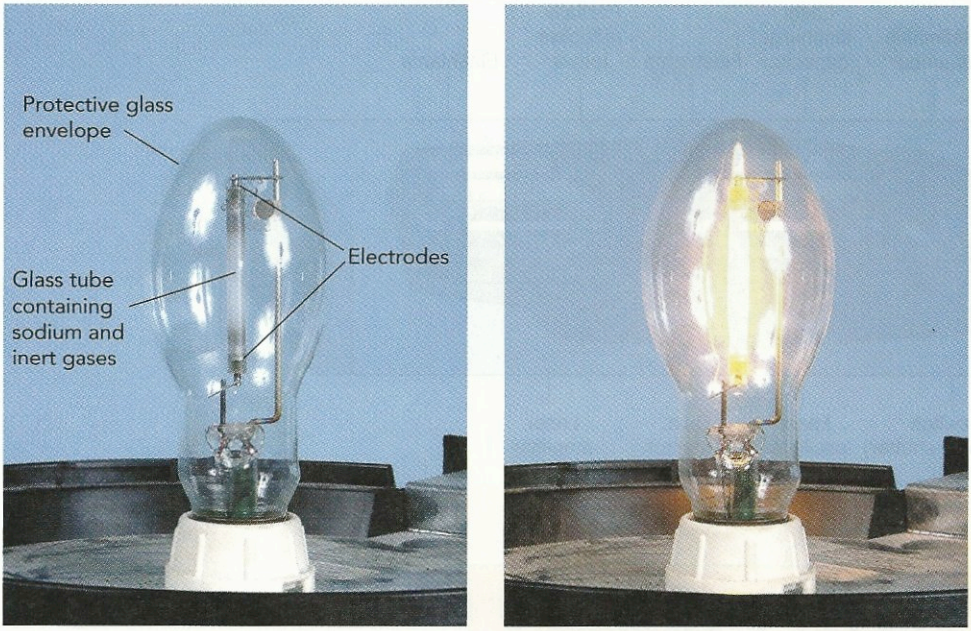
To make a lamp that's a little less bluish, some high-pressure mercury lamps contain additional metal atoms. These atoms are introduced into the lamps as metal–iodide compounds, making them metal–halide lamps. Sodium, thallium, indium, and scandium iodides all contribute their own emission spectra to the outgoing light and help to strengthen the red end of its spectrum. They give metal–halide lamps a warmer color than pure mercury lamps. Both high-pressure mercury and metal-halide lamps produce about 50 to 60 lumens per watt, making them almost as energy efficient as fluorescent lamps.

Pure sodium lamps resemble mercury lamps, except that they use sodium atoms. Sodium is a solid at room temperature, so both low- and high-pressure sodium lamps must heat up before they begin to operate properly. A low-pressure sodium lamp is extremely energy efficient because its 590-nm light comes directly from a sodium atom's strongest radiative transition. That transition is from sodium's lowest excited state to its ground state ($3p \rightarrow 3s$). Low-pressure sodium lamps produce almost 200 lumens per watt, which is why highways are frequently illuminated by their yellow-orange glow.

However, this monochromatic illumination is unpleasant and permits no color vision at all. Although it may be acceptable on a highway, you wouldn't want it near your home. That's why people buy high-pressure sodium lamps for home use (Fig. 14.2.6). For a small decrease in energy efficiency, to about 150 lumens per watt, you get a big improvement in color.

Remarkably enough, the 590-nm emission itself smears out at high pressure to cover a wide range of wavelengths, from yellow-green to orange-red. This spreading occurs because of the many collisions suffered by the densely packed sodium atoms as they try to emit 590-nm light. These collisions distort the atomic orbitals so that the photons emerge with somewhat shifted energies. Overall, a high-pressure sodium lamp emits remarkably little light exactly at 590 nm because the ground-state sodium atoms trap that light; they run the ($3p \rightarrow 3s$) transition backward and absorb the photons ($3s \rightarrow 3p$). This trapping is so effective that there is actually a hole in the lamp's spectrum right at 590 nm.

High-pressure discharge lamps suffer from a problem not found in low-pressure lamps: they're difficult to start when hot. It's much harder to initiate a discharge in a high-pressure gas than in a low-pressure gas, so they all start at low pressure and then



Courtesy Lou Bloomfield

Fig. 14.2.6 The active component of a high-pressure sodium vapor lamp is a small translucent tube. As the lamp warms up, sodium metal in the tube evaporates to form a brilliant yellow discharge. The dense vapor of sodium atoms in the tube traps the 590-nm light so that the lamp emits a richer spectrum of wavelengths and a less monochromatic glow than a low-pressure sodium lamp.

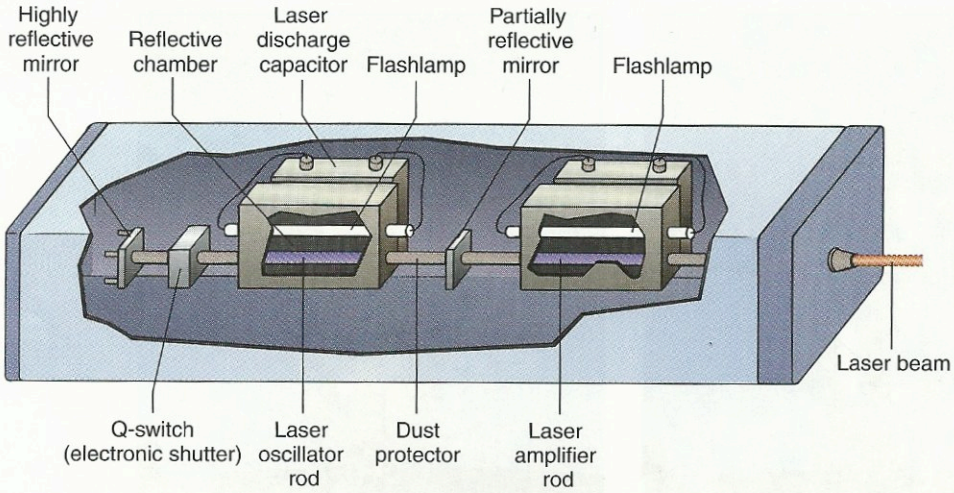
evolve to high pressure. If the discharge in a high-pressure mercury, sodium vapor, or metal–halide lamp is interrupted and loses its plasma, the lamp must cool down before it can be restarted.

Check Your Understanding #6: **Slow Glowing**

At dusk, a mercury streetlight turns on. It glows dimly at first and gradually increases in brightness. What is happening during this warm-up period?

Answer: The small high-pressure discharge tube is heating up, vaporizing more mercury.

Why: When the streetlight first turns on, the pressure of mercury atoms inside it is low and it emits very little visible light. As the discharge heats the tube, more mercury atoms evaporate until eventually all of the mercury inside the tube is gaseous.



SECTION 14.3 Lasers and LEDs

Few devices have inspired our imaginations more than lasers. Since their invention in the late 1950s, lasers have found countless uses, from cutting metal and clearing human arteries to surveying land and playing CDs and DVDs. However, lasers are more than just novel applications of old ideas. Instead, they bring together quantum and optical physics to produce a new type of light. This light is radically different from the light produced by incandescent and fluorescent lamps, and its properties make it particularly useful for many applications. In this section we'll examine the nature of this new light and the ways in which lasers produce it.

Questions to Think About: *Why is laser light usually brightly colored? Why does laser light often appear as a narrow beam? In movies, "lasers" are often shown to emit bright streaks of light that can be dodged if one jumps quickly enough; is that view realistic?*

Experiments to Do: *Although lasers are household objects, the ones in CD or DVD players and laser printers are relatively inaccessible. If you don't own a laser pointer, look at a store barcode scanner. The scanning system contains a gas or solid-state laser that emits a very narrow beam of bright red light. This system also contains a rotating mirror or holographic disk that directs the beam as a pattern of thin stripes onto anything that passes through the scanner. A light sensor inside the window watches for this moving beam of light to travel across a label. If you look down at the laser light emerging from the scanner's window or observe the spot of a laser pointer on the wall, you'll see both the purity of its color and its strange speckled character; the light appears to consist of tiny light and dark speckles. These speckles are caused by interference effects, which are extremely pronounced in the ordered laser light. This light also appears unusually bright and, as when looking at the sun, you should keep your gaze brief to avoid eye injury.*

Warning

Laser light is dangerous. Because laser light can be extremely bright and can focus so tightly, it presents a serious eye hazard. A laser beam entering your eye will focus to a tiny spot on your retina and may cause rapid and permanent injury. Although lasers up to Class III are relatively eye-safe, they rely on your natural blink reflex to protect you. You should never stare into any laser. Class IV lasers are not eye-safe, and their light should never enter your eyes at all.

Lasers and Laser Light

To understand lasers, you must understand how laser light differs from the normal light emitted by hot objects or by individual atoms in an electrical discharge. Each particle of normal light, each photon, is emitted willy-nilly without any relationship to the other light particles being emitted nearby. Because of this light's independent and unpredictable character, it's called *spontaneous light*, and its creation is called **spontaneous emission of radiation**.

Theoretical work by Albert Einstein and others in the 1920s and 1930s predicted the existence of a second type of light, *stimulated light*, that can be created when an excited atom or atomlike system duplicates a passing photon. Although this **stimulated emission of radiation** can occur only when the excited atom is capable of emitting the duplicate photon spontaneously, the copy that it produces is so perfect that the two photons are absolutely indistinguishable. Together, these two photons form a single electromagnetic wave.

To get a slightly better picture for how such stimulation occurs, think about an isolated atom in an excited state. That atom will eventually return to its ground state, but it must emit one or more photons in order for this to happen. That atom waits around in the excited state until it begins a spontaneous radiative transition. During the transition, one of the atom's electrons accelerates back and forth and the atom emits a photon.

If a similar photon passes through the atom as it's waiting in the excited state, that photon's electric field can stimulate the radiative transition process through sympathetic vibration. The field pushes and pulls on the atom's electrons and makes them accelerate back and forth. Although this effect is small, it may be enough to trigger the emission of light. If the atom does emit light, the photon it will produce will be a perfect copy of the stimulating photon.

When this stimulated emission process was first discovered, people immediately recognized that it made light amplification possible. If enough excited systems could be assembled together, a single passing photon could be duplicated exactly over and over again. Instead of a single particle of light, you would soon have thousands, or millions, or even trillions of identical light particles.

Implementing this idea had to wait until the late 1950s, however, when the technical details for how to actually achieve light amplification were worked out. In 1960, the first laser oscillators were constructed. These were devices that emitted intense beams of light, in which each particle of light was identical to every other particle of light. A single particle of light had been duplicated by the stimulation process into countless copies.

When individual excited atoms or atomlike systems emit light through spontaneous emission, the particles of light head off separately as many independent electromagnetic waves (Fig. 14.3.1*a*). Light consisting of many independent electromagnetic waves is called **incoherent light**.

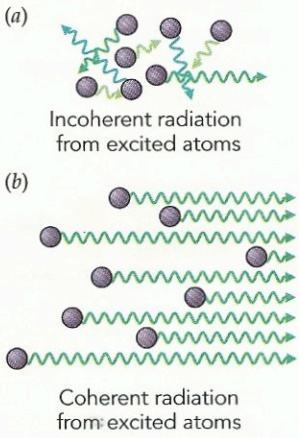


Fig. 14.3.1 (*a*) Photons of incoherent light are created independently and have somewhat different wavelengths and directions of travel. (*b*) Photons of coherent light are produced by stimulated emission and are identical to one another in every way.

However, when that same collection of excited atoms or atomlike systems emit light by stimulated emission, all of the light particles are *absolutely* identical and form a single electromagnetic wave (Fig. 14.3.1*b*). Unlike electrons, which are Fermi particles, many identical photons can have the same quantum wave because photons are Bose particles and Bose particles don't obey the Pauli exclusion principle. Light consisting of many identical photons and a single electromagnetic wave is called **coherent light**. Because of its single wave nature, coherent light exhibits remarkable interference effects. These effects are easily seen in the coherent light emitted by lasers.

Check Your Understanding #1: A Light Dusting of Photons

If you were to measure the electric field in the light from a flashlight, you would find that it fluctuates about randomly. Why is the light's electric field so disorderly?

Answer: The flashlight produces incoherent light, with many independent light waves contributing their individual electric fields to the overall electric field. If you were to measure that overall field, you would find it very disorderly.

Why: Because the photons of incoherent light are independent, their individual electric fields don't fluctuate together. At any place and time, the individual electric fields will add in a complicated, random fashion. As time passes, this overall field will fluctuate randomly. Coherent light, in which each photon is the same as all the others, has a much more orderly electric field because all of the photons contribute equally.

Fig. 14.3.2 A laser amplifier uses excited atoms or atomlike systems to increase the number of light particles leaving the laser medium. The incoming light is duplicated by stimulated emission.

Light Amplifiers and Oscillation

Producing coherent light requires amplification. You must start with only one particle of light and duplicate it many times. The basic tool for this duplication of light is a **laser amplifier** (Fig. 14.3.2). When weak light enters an appropriate collection of excited atoms or atomlike systems—the **laser medium**—that light is amplified and becomes brighter. The new light has exactly the same characteristics as the original light, but it contains more photons.

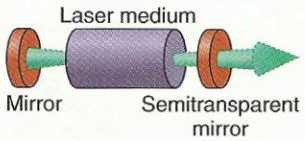


Fig. 14.3.3 A laser oscillator is a laser amplifier enclosed in mirrors. Oscillation occurs when the laser medium spontaneously emits one photon in just the right direction. This photon bounces back and forth between the two mirrors and is duplicated many times. Some of the light is extracted from this laser by making one of the mirrors semitransparent.

When we think of lasers, however, we rarely imagine a device that duplicates photons from somewhere else. We usually picture one that creates light entirely on its own. To do that, the laser must produce the initial particle of light that it then duplicates to produce others. A **laser oscillator** is a device that uses the laser medium itself to provide the seed photon, which it then duplicates many times (Fig. 14.3.3). If a laser medium is enclosed in a pair of carefully designed mirrors, it's possible for the stimulation process to become self-initiating and self-sustaining. However, the mirrors must be curved properly and must have the correct reflectivities. One mirror must normally be extremely reflective, while the other must transmit a small fraction of the light that strikes its surface.

When the laser medium is placed between the two mirrors, there is a chance that a photon, emitted spontaneously by one of the excited systems, will bounce off a mirror and return toward the laser medium. As that returning photon passes through the laser medium, it's amplified. Because the photon was emitted by one of the excited systems, it has the right wavelength to be amplified by other excited systems. (For a discussion of a photon's properties, see ■.)

By the time the original photon leaves the laser medium, it has already been duplicated many times. This group of identical photons then bounces off the second mirror

and returns for another pass through the laser medium. It continues to bounce back and forth between the mirrors until the number of identical photons in the collection is astronomical.

Eventually there are so many identical photons that the laser medium is no longer able to amplify them. The laser medium has only so much stored energy and only so many excited systems in it. If the laser medium continues to receive additional energy, it may continue to amplify the light somewhat. If it doesn't receive more energy, light amplification will eventually cease.

To let the light out of this laser oscillator, one of its mirrors is normally *semitransparent*—that is, some of the photons that strike the surface of the mirror travel through it rather than reflecting. The two-way glass used for surveillance is actually a semitransparent mirror. This transmission creates a beam of outgoing light, a *laser beam*. The laser beam continues to emerge from the mirror as long as the amplification process can support it.

Because this laser beam consists of duplicates of one original photon, it's coherent light. For technical reasons, many lasers duplicate more than one original photon simultaneously, so that their laser beams are a little less coherent than they might be. However, with suitable fine-tuning, one original photon can usually be made to dominate the laser beam.

When you focus a flashlight's beam with a lens, its independent photons won't end up exactly together at the focus of the lens. That's because the photons leave the flashlight heading in somewhat different directions and because their broad range of wavelengths leads to dispersion problems in the lens. However, since virtually all of the photons in a laser beam are identical—they travel along the same path and their wavelengths are the same—they can all focus together to an extremely small spot. That's why a laser printer employs a laser; a laser beam can illuminate a very small spot on the photoconductor drum that is used in the xerographic process (Section 10.2) to produce a printed image.

■ Although it might seem that a photon should have an exact wavelength and frequency and travel in only one direction, that's not the case. Photons travel as electromagnetic waves and spread in more than a single direction. Also, because each photon has a beginning and an end, its wave contains more than a single wavelength or a single frequency. Thus while lasers can produce some of the most perfect electromagnetic waves imaginable, those waves still spread outward slightly and still have a range of wavelengths and frequencies.

Common Misconceptions: Laser Beams

Misconception: A laser beam is a narrow glowing cylinder that travels through space at the speed of an arrow.

Resolution: A laser beam is light and it travels through space at the speed of light. To be visible from the side, a laser beam must scatter off something in its path, such as dust, mist, or air molecules. In empty space, a laser beam is invisible except when it directly illuminates your eyes.

Check Your Understanding #2: More of a Good Thing

If you take the laser beam from a particular laser oscillator and send it through a similar laser amplifier, what will happen to the laser beam?

Answer: It will become even brighter.

Why: A laser oscillator normally emits as intense a beam of light as it can, based on the amount of stored energy in the laser medium. This beam of light can be amplified further by sending it through a separate laser amplifier. Most high-powered lasers use a laser oscillator and one or more laser amplifiers to create particularly bright beams of light.

How a Laser Medium Works

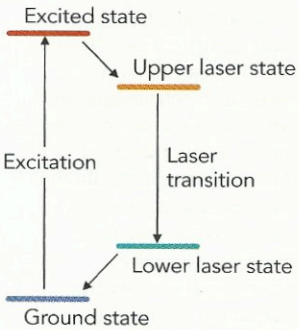


Fig. 14.3.4 An ideal laser system passes through four different states during the laser's operation.

Obtaining the excited systems needed to amplify light is a critical issue for lasers. Ideally, a laser involves four different states of an atom or atomlike system: the ground state, an excited state, the upper laser state, and the lower laser state. The reason for having four separate states should become clear in a moment.

Let's consider an atom that acts as an ideal laser amplifier (Fig. 14.3.4). The atom starts in its ground state. A collision or the absorption of a photon shifts it to the excited state, giving it the energy it needs to amplify light. The atom then shifts to the upper laser state, either by emitting a photon or as the result of a collision. This preliminary shift is important because it prevents the excited atom from returning directly back to the ground state and avoiding the amplification process. Once it has shifted to the upper laser state, the atom is stuck there and will wait around long enough to amplify light.

The atom is poised to duplicate a passing photon. But not any old photon will do; it must match the photons that the atom is capable of emitting. For example, a neon atom with an excited $3p$ electron (Section 14.2) can duplicate a red photon, but not a blue photon. This color selectivity of a laser amplifier is why most laser beams have a single, pure color.

When a suitable photon passes through the atom, that photon stimulates the emission of a duplicate photon and the atom undergoes a radiative transition to the lower laser state. So far, so good. However, if the atom remains in the lower laser state, it might absorb a photon of the laser light and return to the upper laser state. To prevent this sort of radiation trapping, the atom must quickly shift to the ground state, either by emitting a photon or as the result of another collision. The atom is then ready to begin the cycle all over again.

This four-state cycle, or something close to it, is found in nearly all lasers. The cycle helps the laser develop a **population inversion** between its upper and lower laser states—a situation in which there are more atoms in the upper laser state prepared to *emit* the laser light than there are atoms in the lower laser state prepared to *absorb* that light. Developing a population inversion is critical to laser amplification because without it, the laser medium is more absorbing than amplifying and there can't be a buildup of light intensity.

In each laser, something provides the energy needed to shift atoms or atomlike systems in the laser medium from their ground states to their excited states in order to develop a population inversion. This transfer of energy into the laser medium to prepare it for amplifying light is called *pumping*. How a particular laser medium is pumped depends on the laser.

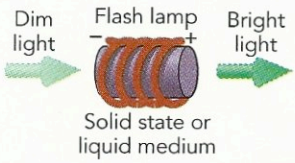
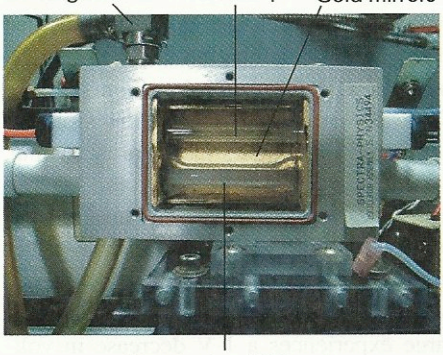


Fig. 14.3.5 In an optically pumped laser, intense light from a flashlamp, an arc lamp, or even another laser transfers energy to the laser medium. Atoms or atomlike systems inside the medium store this energy and use it to amplify light.

The most common pumping mechanisms are electronic and optical. In electronic pumping, currents of charged particles use their kinetic or electrostatic energies to excite the medium's atoms or atomlike systems from their ground states to their excited states. In optical pumping, intense light is shone on the laser medium, causing a similar excitation.

The most important examples of optical pumping are ion-doped solid-state lasers. These lasers are based on atomic ions embedded in transparent solids. Common ions are titanium (Ti), neodymium (Nd), and erbium (Er), and they are often embedded in sapphire, yttrium aluminum garnet (YAG), or glass. Ti:sapphire, Nd:YAG, and Er:glass lasers are important to modern research, technology, and optical communications systems. When these laser media are exposed to extremely bright light, their ions become excited, and they can act as laser oscillators or amplifiers (Figs. 14.3.5 and 14.3.6).



Courtesy Lou Bloomfield

Fig. 14.3.6 This flashlamp-pumped laser amplifier contains a purple neodymium:YAG rod. The rod is in the bottom half of the opened, gold-lined amplifier box and is protected by a glass tube. Light from a long flashlamp in the top half of the box excites the neodymium ions so that they can amplify infrared light passing horizontally through the rod.

Check Your Understanding #3: **Not So Fast, 007**

A secret agent in a movie uses a tiny, hand-held laser to burn a hole through a thick metal plate. From the point of view of power, why is such a laser essentially impossible to make?

Answer: The light in such a laser beam would carry an enormous amount of power. Something must transfer that power to the laser medium, an impossible task in a tiny, hand-held unit.

Why: The power in a laser beam comes from the laser medium. The laser medium must have gotten it from somewhere else. Since batteries aren't up to delivering thousands of watts of electric power, it's unlikely that powerful hand-held lasers will ever be developed. Even if a suitable power source were available, these lasers would tend to overheat. The conversion of power to light is not perfectly efficient, and most of the energy ends up as thermal energy in the laser's components. Lasers require cooling to remove this wasted energy.

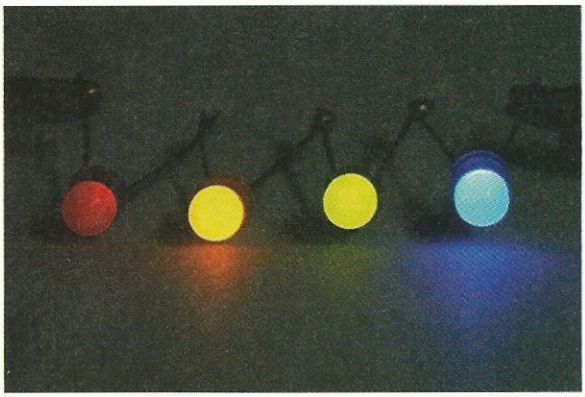
Light-Emitting Diodes and Laser Diodes

The most common electronically pumped lasers are diode lasers. Found in pointers, barcode readers, printers, and CD and DVD players, these lasers are closely related to light-emitting diodes, which themselves resemble the ordinary diodes we discussed in Section 12.1. But whereas ordinary diodes are designed merely to control currents while wasting as little power as possible, laser and light-emitting diodes are optimized to produce light.

When a diode is forward biased and current flows from its anode to its cathode, conduction level electrons in the n-type cathode travel across the p-n junction to become conduction level electrons in the p-type anode. In effect, the anode is then in an excited state: it has conduction-level electrons and empty valence levels.

What happens next depends on the characteristics of the diode. In a normal silicon diode, those conduction-level electrons shift to empty valence levels without producing significant light. Silicon's band structure has characteristics that discourage light emission, so most of these electron transitions produce internal vibrations and heat the diode instead of producing light.

In specialized diodes made from more exotic semiconductors, conduction-level electrons in the p-type anode frequently undergo radiative transitions to empty valence levels and thereby emit light. Composed primarily from combinations of gallium, indium,



Courtesy Lou Bloomfield

Fig. 14.3.7 These LEDs are connected in series, so that the same current flows sequentially through each of them. However, their different band gaps cause them to emit different colors of light.

aluminum, arsenic, phosphorus, and nitrogen, they are known as light-emitting diodes or LEDs. LEDs now come in just about any color of the rainbow, including infrared, red, orange, yellow, green, blue, violet, and ultraviolet (Fig. 14.3.7). Although white LEDs also exist, they're actually violet or ultraviolet LEDs with built-in phosphors that fluoresce white.

An LED's color is directly related to the energy released when an electron in its p-type anode shifts from a conduction level to a valence level. The most convenient unit in which to measure that energy is the **electron volt** (abbreviated eV)—the energy released when 1 elementary unit of electric charge experiences a 1-V decrease in voltage (1 eV is equal to 1.6021×10^{-19} J). In a typical red LED, an electron releases 1.9 eV as it shifts from a conduction level to a valence level and can produce a photon with an energy of 1.9 eV. Since energy and frequency are related by Eq. 14.2.1 and frequency and wavelength are related by Eq. 9.2.1, that 1.9-eV photon has a frequency of 4.6×10^{14} Hz and a wavelength of 650 nm.

To operate and produce these 1.9-eV photons, the red LED must be forward biased with a voltage drop of at least 1.9 V. The current-carrying diode uses that voltage drop to inject electrons into the anode's conduction band, where they have energies 1.9 eV above the valence band. Many of those electrons subsequently release their excess energies as 1.9-eV photons of light.

The shorter the wavelength of the light an LED emits, the more energy each electron must release as it shifts from a conduction level to a valence level and the larger the semiconductor's band gap must be. A violet LED that emits 400-nm light requires a band gap of about 3.1 eV to produce its 3.1-eV photons. That LED also needs a forward-bias voltage in excess of 3.1 V. The larger voltage drops required by LEDs near the violet end of the spectrum explain why those LEDs need higher voltage power sources.

Unfortunately, less than half of the electrons sent across an LED's p-n junction succeed in lighting the room. Although a substantial fraction of those electrons emit photons, most of the photons are reabsorbed by the semiconductor before they leave the LED; the same radiative transitions that emit this light (conduction level → valence level) can also absorb it (valence level → conduction level). Despite those difficulties, modern LEDs can produce visible light with energy efficiencies comparable to those of fluorescent lamps. LED efficiencies continue to rise along with their operating lifetimes, and they are gradually becoming a primary form of illumination.

Courtesy SDL, Inc.

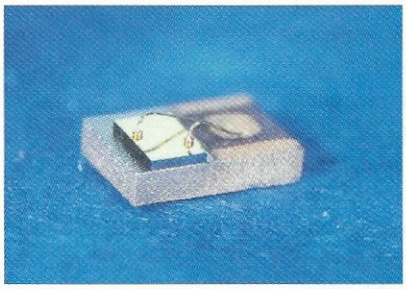


Fig. 14.3.8 This tiny semiconductor chip is a diode laser that emits an intense beam of coherent light when a current flows through it.

A laser diode is quite similar to an LED, except that a laser diode uses its radiative transitions to amplify light. Since that amplification can only occur when light emission exceeds light absorption, the laser diode must produce a population inversion between an upper laser state and a lower laser state.

The laser diode achieves such an inversion by concentrating current into a very narrow p-n junction made from heavily doped semiconductors. The intense current injects an enormous density of electrons into the anode's conduction band, where they quickly settle into the lowest energy conduction levels—the upper laser state. The heavy doping empties most of the anode's highest energy valence levels—the lower laser state. With many electrons in the upper laser state and few in the lower laser state, the diode has a population inversion and can amplify light.

Most laser diodes act as laser oscillators (Fig. 14.3.8), amplifying their own spontaneously emitted light until it forms an intense coherent beam. The ends of the anode itself are usually reflective enough to act as mirrors and form a complete laser oscillator. How-

ever, to concentrate the laser light in one direction and to control its beam characteristics, many laser diodes have complicated structures and coatings.

As in an LED, a laser diode's wavelength and color depend primarily on the band gap of its anode. Infrared and red laser diodes were developed first and quickly incorporated into a variety of household products. Developing laser diodes with larger band gaps and shorter wavelengths has been a long and arduous process. However, the spectrum of laser diode colors now extends into the ultraviolet, and as these short-wavelength lasers become less expensive and more reliable, they begin to appear in everyday products.

Check Your Understanding #4: Lighten Up

When you increase the current flowing through an incandescent lightbulb, it brightens and its color shifts toward the blue end of the spectrum. If you increase the current flowing through an LED or laser diode, what happens to its brightness and color?

Answer: The diode becomes brighter, but its color doesn't change significantly.

Why: The diode's brightness depends on how many electrons cross its p-n junction each second, and increasing that number increases the brightness. However, the color of light the diode emits depends mostly on its band gap and therefore doesn't change much when you increase the current in the diode.

Epilogue for Chapter 14

In this chapter we explored the creation and movement of light. In *sunlight*, we looked at how light is scattered during its passage through the atmosphere and at how it bends and reflects when it moves from one material to another. We also examined interference effects that occur when a light wave follows more than one path to a particular destination and learned how polarizing sunglasses can diminish glare.

In *discharge lamps*, we examined electrical discharges in gases. We saw that atoms excited by collisions with charged particles can subsequently emit light through radiative transitions. We studied the primary colors of light to see how the phosphors on the inside surface of a fluorescent tube are able to produce a reasonable facsimile of white sunlight. In *lasers and LEDs*, we looked at the difference between common incoherent light and the unusual coherent light emitted by a laser. We saw that lasers use stimulated emission to duplicate photons, so that a small number of initial photons can be amplified into an enormous number.

Explanation: Splitting the Colors of Sunlight

Light bends as it passes through the cut facets of the crystal glass or bowl. Because of dispersion, the angle of each bend depends slightly on the wavelength of the light involved, so that the different colors of sunlight follow slightly different paths through the crystal. When the light emerges from the crystal, its various wavelengths head in somewhat different directions; you see colors. Color sequences progress from long wavelength to short wavelength, or vice versa. You see red, orange, yellow, green, blue, indigo, and violet, or the reverse—the colors of the rainbow.

Chapter Summary

How Sunlight Works: Sunlight originates at the 5800 K outer surface of the sun, when electrically charged particles there accelerate back and forth rapidly and emit electromagnetic waves. This sunlight travels at the speed of light through empty space until it reaches the earth's atmosphere. There it slows slightly and some of it Rayleigh-scatters. Short-wavelength light is Rayleigh scattered more strongly than long-wavelength light, so the sky appears blue.

As the sunlight passes through various objects, it slows down and its colors separate. When sunlight passes through falling raindrops, its different wavelengths follow different paths and create rainbows. As sunlight reflects from thin films such as soap bubbles, its waves are divided and may follow several different paths to the same destination. These light waves then interfere with one another so that some waves appear strong and bright while others are weak and dim. Interference depends on the wavelengths of light, so thin films appear brightly colored.

How Discharge Lamps Work: Discharge lamps produce light by passing electric currents through gases. Those gases are turned into electrical conducting plasmas by filling them with charged particles, either by exposing them to strong voltage gradients or by injecting electrons into them from heated electrodes. Once a plasma is formed, current can pass through it, and collisions within that current-carrying plasma cause the gas particles to emit light.

A fluorescent lamp emits visible light when the phosphor coating on the inside of its tube is exposed to 254-nm ultraviolet light produced inside the tube by a low-pressure mercury vapor discharge. This ultraviolet light excites the phosphor coating and causes it to emit visible light. In contrast, mercury, metal–halide, and sodium lamps use discharges to produce visible light directly and don't employ phosphors. By operating at high pressures, those discharge lamps produce relatively broad light spectrums and provide energy-efficient illumination.

How Lasers and LEDs Work: Lasers amplify light through the process of stimulated emission. In this process, energy is transferred to atoms or atomlike systems contained in a laser medium. These excited systems might emit light spontaneously, and they can be stimulated into emitting duplicates of a passing photon. When a photon with just the right wavelength passes through an excited system, that system is likely to give up its stored energy by emitting an exact copy of the initial photon. In a laser oscillator, two mirrors cause light to bounce back and forth through the laser medium. An initial photon is duplicated endlessly to produce coherent light. One of the mirrors is semitransparent, so part of the light emerges from the laser as a laser beam.

In an LED, light is emitted when electrons that have crossed the diode's p-n junction into the anode's conduction levels undergo radiative transitions to the empty valence levels. The color of light produced by the LED is determined primarily by the anode's band gap. A diode laser uses the same concepts as an LED, except that a population inversion is developed between the relatively empty valence levels and the relatively full conduction levels. With more electrons prepared to emit light than absorb it, the diode laser can then amplify light.

Important Laws and Equations

1. Relationship between Energy and Frequency: The energy in a photon of light is equal to the product of the Planck constant times the frequency of the light wave, or

$$\text{energy} = \text{Planck constant} \cdot \text{frequency}. \qquad (14.2.1)$$

Exercises

1. How long should an antenna be to receive or transmit red light well?

2. How long should an antenna be to receive or transmit violet light well?

3. When astronauts aboard the space shuttle look down at the earth, its atmosphere appears blue. Why?

4. When astronauts walked on the surface of the moon, they could see the stars even though the sun was overhead. Why can't we see the stars while the sun is overhead?

5. If you shine a flashlight horizontally at a glass full of water, the glass will redirect the light beam. How?

6. A laser light show uses extremely intense beams of light. When one of these beams remains steady, you can see the path it takes through the air. What makes it possible for you to see this beam even though it isn't directed toward you?

7. To make the beams at a laser light show (see Exercise 6) even more visible, they're often directed into mist or smoke. Why do such particles make the beams particularly visible?

8. Why can you see your reflection in a calm pool of water?

9. Use the concepts of refraction, reflection, and dispersion to explain why a diamond emits a spray of colored lights when sunlight passes through its cut facets.

10. Diamond has an index of refraction of 2.42. If you put a diamond in water, you see reflections from its surfaces. However, if you put it in a liquid with an index of refraction of 2.42, the diamond is invisible. Why is it invisible, and how is this effect useful to a jeweler or gemologist?

11. Why is a pile of granulated sugar white while a single large piece of rock candy (solid sugar) is clear?

12. Basic paper consists of many transparent fibers of cellulose, the main chemical in wood and cotton. Why does paper appear white, and why does it become relatively clear when you get it wet?

13. On a rainy day you can often see oil films on the surfaces of puddles. Why do these films appear brightly colored?

14. When two sheets of glass lie on top of one another, you can often see colored rings of reflected light. How do the nearby glass surfaces cause these colored rings?

15. If you're wearing polarizing sunglasses and want to see who else is wearing polarizing sunglasses, you only have to turn your head sideways and look to see which people now have sunglasses that appear completely opaque. Why does this test work?

16. Why is it easier to see into water when you look directly down into it than when you look into it at a shallow angle?

17. Light near 480 nm has a color called cyan. What mixture of the primary colors of light makes you perceive cyan?

18. What is different about the two mixtures of red and green lights that make you see yellow and orange, respectively?

19. What colors of light does red paint absorb?

20. What colors of light does yellow paint absorb?

21. If you illuminate red paint with pure blue light, what color will that paint appear?

22. Fancy makeup mirrors allow users to choose either fluorescent or incandescent illumination to match the lighting in which they'll be seen. Why does the type of illumination affect their appearances?

23. While a sodium atom is in its ground state, it cannot emit light. Why not?

24. When a sodium atom is in its lowest energy excited state, it can emit light. Why?

25. You expose a gas of argon atoms to light with photon energies that don't correspond to the energy difference between any pair of states in the argon atom. Explain what happens to the light.

26. A discharge in a mixture of gases is more likely to emit a full white spectrum of light than a discharge in a single gas. Why?

27. If the low-pressure neon vapor in a neon sign were replaced by low-pressure mercury vapor, the sign would emit almost no visible light. Why not?

28. Increasing the power to an incandescent bulb makes its filament hotter and its light whiter. Why doesn't increasing the power to a neon sign change its color?

29. Although many disposable products no longer contain mercury, a potential pollutant, fluorescent tubes still do. Why can't the manufacturers eliminate mercury from their tubes?

30. When white fabric ages it begins to absorb blue light. Why does this give the fabric a yellow appearance?

31. To hide yellowing (see Exercise 30), fabric is often coated with fluorescent "brighteners" that absorb ultraviolet light and emit blue light. In sunlight, this coated fabric appears white, despite absorbing some blue sunlight. Explain.

32. Camera flashes use discharges in high-pressure xenon and krypton gases to produce brief, intense white light. Why is it important that they use these complicated atoms?

33. A CD player uses a beam of laser light to read the disc, focusing that light to a spot less than 1 μm (10^{-6} m) in diameter. Why can't the player use a cheap incandescent lightbulb for this task, rather than a more expensive laser?

34. Why can't a CD player (Exercise 33) use a light-emitting diode (LED) in place of its diode laser?

35. Explain why the electromagnetic wave emitted by a radio station is coherent—a low-frequency equivalent of coherent light.

36. One of the most accurate atomic clocks is the hydrogen maser. This device uses excited hydrogen molecules to duplicate 1.420-GHz microwave photons. In the maser, the molecules have only two states: the upper maser state and the lower maser state (which is actually the ground state). To keep the maser operating, an electromagnetic system constantly adds excited state hydrogen molecules to the maser and a pump constantly removes ground-state hydrogen molecules from the maser. Why does the maser require a steady supply of new excited state molecules?

37. Why must ground-state molecules be pumped out of a hydrogen maser (see Exercise 36) as quickly as possible to keep it operating properly?

38. While some laser media quickly lose energy via the spontaneous emission of light, others can store energy for a long time. Why is a long storage time essential in lasers that produce extremely intense pulses of light?

39. One of the first lasers used synthetic ruby as its laser medium. However, a ruby laser is a three-state laser; its lower laser state is its ground state. Why does that arrangement make the ruby laser relatively inefficient?

40. If most of the highest energy valence levels in a diode laser's p-type anode weren't empty, it would become relatively inefficient and probably wouldn't emit laser light at all. Why not?

41. Why doesn't increasing the current passing through an LED affect the color of its light?

42. Why does increasing the current passing through an LED affect the brightness of its light?

Problems

1. The yellow light from a sodium vapor lamp has a frequency of 5.08×10^{14} Hz. How much energy does each photon of that light carry?

2. If a low-pressure sodium vapor lamp emits 50 W of yellow light (see Problem 1), how many photons does it emit each second?

3. A particular X-ray has a frequency of 1.2×10^{19} Hz. How much energy does its photon carry?

4. A particular light photon carries an energy of 3.8×10^{-19} J. What are the frequency, wavelength, and color of this light?

5. If an AM radio station is emitting 50,000 W in its 880-kHz radio wave, how many photons is it emitting each second?

6. If an FM radio station is emitting 100,000 W in its 88.5-MHz radio wave, how many photons is it emitting each second?