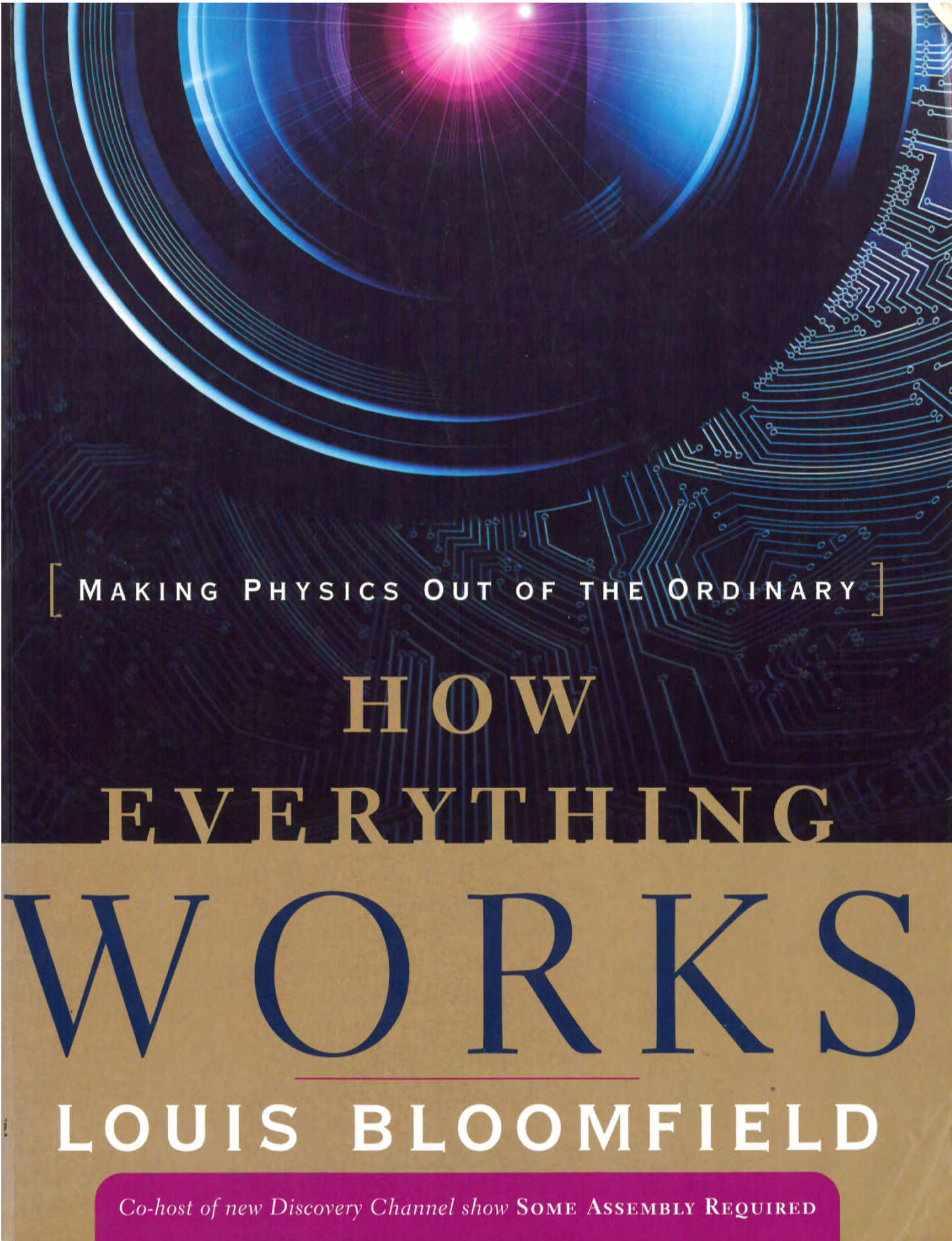




[MAKING PHYSICS OUT OF THE ORDINARY]

HOW
EVERYTHING
WORKS

LOUIS BLOOMFIELD

Co-host of new Discovery Channel show **SOME ASSEMBLY REQUIRED**

HOW EVERYTHING WORKS

MAKING PHYSICS OUT OF THE ORDINARY

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THE UNIVERSITY OF VIRGINIA



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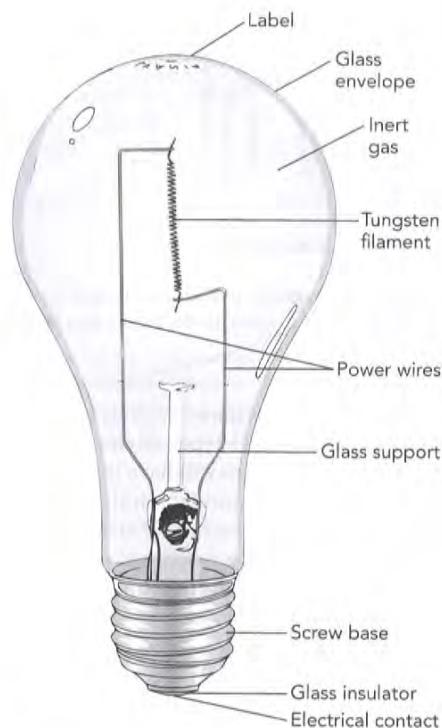
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SECTION 7.3 Incandescent Lightbulbs

For more than a century, incandescent lightbulbs have provided light at the flip of a switch. Their invention brought to a close the era of candles and gaslights and spurred the development of electric power. While the variety of incandescent bulbs has grown over the years to include everything from heat lamps to halogen headlights, all incandescent bulbs have at their hearts one simple object: an extremely hot filament.

Light, Temperature, and Color

Light from an incandescent lightbulb is part of the thermal radiation emitted by its hot filament. While most types of electromagnetic waves are invisible, our eyes are sensitive to a narrow range of waves that we call visible light. Any object that's hotter than about 400°C (750°F) emits enough visible light for us to see it in a dark room. At higher temperatures, that visible light brightens and shifts in color from red to orange to yellow to white. At 500°C (930°F), an object glows a dull red. At 1700°C (3100°F), it emits the orange light of a candle. And at 5800°C ($10,500^{\circ}\text{F}$), the temperature of the sun's surface, it gives off the brilliant white light of the sun.

To reproduce pure white sunlight, the bulb's filament should be heated to 5800°C . Unfortunately, nothing is solid at that high temperature. Even tungsten metal, the best filament material known, readily sublimates at temperatures above 2500°C (4500°F). Since incandescent lightbulbs must operate at lower temperatures, they can't really reproduce sunlight. Most give off the warm, yellow-white light that's characteristic of tungsten metal at about 2500°C .

The filament's brightness and color both depend on its temperature (Fig. 7.3.1). Since light carries energy, we can measure its brightness as the number of watts



Fig. 7.3.1 As you increase the power to an incandescent lightbulb, its filament becomes hotter and emits a brighter and whiter light. The cooler filament on the left is dim and red while the hotter one on the right is bright and yellow-white. Because these bulbs are frosted, you can't see their filaments directly.

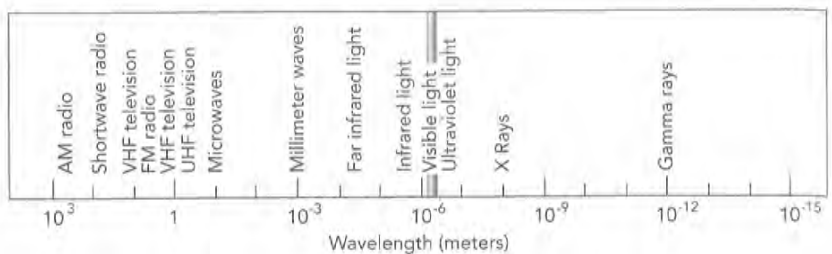


Fig. 7.3.2 The spectrum of electromagnetic radiation, arranged by wavelength. The scale here is logarithmic, meaning that the wavelength decreases by a factor of 10 with each tick mark to the right.

of visible light it emits. But how do we characterize its color? Moreover, what distinguishes visible light from the invisible types of electromagnetic radiation? Although the full answers to those questions will have to wait until Chapters 13 and 14, we can make a few essential observations about them now.

Visible light is part of a continuous spectrum of electromagnetic radiation that extends from radio waves at one extreme to gamma rays at the other (Fig. 7.3.2). Different types of electromagnetic radiation are distinguished by their wavelengths, that is, the distance between their wave crests. Wavelength is easy to see in the waves on a lake or sea, where the crests are visible and you can directly measure the distance from one to the next. But while the wave crests of electromagnetic waves aren't so easy to observe, they exist and it's possible to measure the distance between them.

The electromagnetic radiation produced by a hot filament is mostly infrared, visible, and ultraviolet light. Although this light is just a tiny portion of the overall electromagnetic spectrum, it's particularly important to our everyday world. Figure 7.3.3 gives an expanded view of the visible portion of the electromagnetic spectrum. Various colors that we see correspond to specific wavelength ranges. For example, light with a wavelength of 530 nanometers (billionths of a meter, abbreviated nm) appears green to our eyes.

But the thermal radiation emitted by a filament isn't a single electromagnetic wave with one specific wavelength. Instead, it's many individual waves that cover a broad range of wavelengths. Some of these waves are red light, some green, some blue, and some are invisible.

The distribution of wavelengths emitted by the filament depends on its temperature and surface properties, particularly its emissivity—the efficiency with which it emits and absorbs light. Emissivity is measured on a scale from 0 to 1, with 1 being ideal efficiency. A perfectly black object has an emissivity of 1; it absorbs all light that strikes it and emits thermal light as efficiently as possible. Although tungsten's emissivity is only 0.43, the filament wire is wound in such a way that it has many dark nooks and crannies. The filament is thus so nearly black that its emissivity is essentially 1.

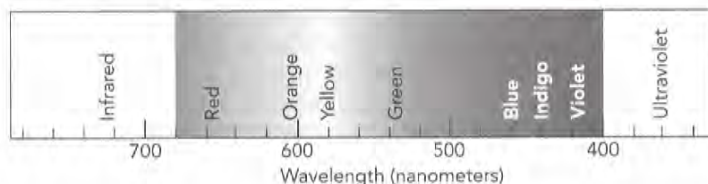


Fig. 7.3.3 A portion of the electromagnetic radiation spectrum around visible light. Wavelengths are measured in nanometers (nm or billionths of a meter).

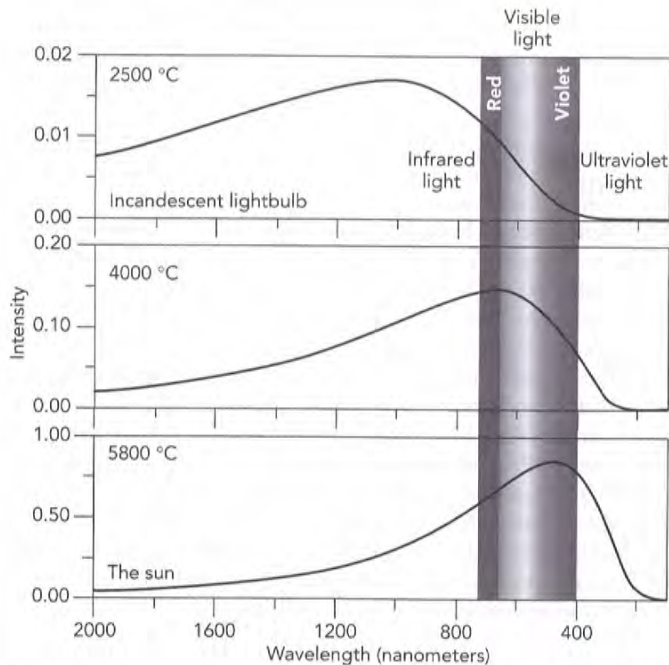


Fig. 7.3.4 The distributions of light emitted by black objects at 2500 °C (*top*), 4000 °C (*middle*), and 5800 °C (*bottom*). In addition to containing a larger fraction of visible light, the 5800 °C object is much brighter than the 2500 °C object (note the different intensity scales on the left).

The distribution of wavelengths emitted by a black object is determined by its temperature alone and is called a blackbody spectrum. As you can see from the examples in Fig. 7.3.4, the spectrum of a blackbody brightens and shifts toward shorter wavelengths as its temperature increases. An object that isn't black emits somewhat less thermal radiation, but that radiation still brightens and shifts toward shorter wavelengths as the object becomes hotter.

Our eyes make an average assessment of the distribution of wavelengths emitted by a black object, and we observe reddish, orangish, yellowish, whitish, or bluish light, depending on the object's temperature (Table 7.3.1). The temperature associated with a particular distribution of wavelengths is the color temperature of that light.

Table 7.3.1 Temperatures and Colors of Light Emitted by Hot Objects

Object	Temperature	Color
Heat lamp	500 °C (930 °F)	Dull red
Candle flame	1700 °C (3100 °F)	Dim orange
Bulb filament	2500 °C (4500 °F)	Bright yellow-white
Sun's surface	5800 °C (10500 °F)	Brilliant white
Blue star	6000 °C (10800 °F)	Dazzling blue-white

We can already see two of the principal shortcomings of an incandescent lightbulb: its poor efficiency at converting electric energy into visible light and its low color temperature. At 2500 °C, only about 12% of its thermal radiation is visible light; the rest is invisible infrared light. Its filament would have to reach 5000 °C before the infrared fraction of its thermal radiation would drop below 50%. More-

❶ Lewis Howard Latimer (African-American scientist and inventor, 1848–1928) was only eight when the U.S. Supreme Court's *Dred Scott* decision made his escaped-slave father a fugitive and forced him to disappear. Left behind with his mother, Latimer did well in school and became a skilled draftsman and engineer. While working for Edison's rival, Hiram Maxim, Latimer became an expert in fabricating carbon filaments for incandescent lamps. When Latimer later joined Edison's team of inventors, the "Edison Pioneers," his sturdy carbon filaments quickly replaced Edison's own fragile bamboo ones and provided the crucial ingredient necessary for Edison's lamps to become a commercial success.

❷ While most incandescent bulbs contain inexpensive argon and nitrogen gases, some specialized bulbs contain krypton gas. Krypton-filled bulbs transfer less heat from the filament to the glass envelope than ordinary bulbs because krypton gas is an especially poor conductor of heat. Krypton bulbs are therefore more energy efficient than conventional bulbs, but they're also more expensive. Krypton is a rare inert gas that is present in the atmosphere at the level of about one part in a million. Krypton bulbs are used in flashlights where the energy efficiency of the lamp is critical to battery life.

over, its 2500 °C color temperature makes it look yellowish when compared to sunlight because it doesn't emit enough blue light. Most of the developments in lighting over the past half century have focused on improving energy efficiency and color temperature.

The Filament

The bulb's filament is heated by an electric current, which provides it with thermal power in the amount specified on the bulb. For example, the filament of a 60-watt bulb produces 60 watts of thermal power from the 60 watts of electric power it consumes. Although the filament accumulates thermal energy at first, its temperature quickly rises until thermal energy flows out of it as heat as quickly as it's produced from electricity. Thus a 60-watt bulb sends 60 watts of thermal power into its environment as heat. Much of that heat is thermal radiation.

The temperature at which this heat balance occurs is surprisingly specific. That's because the filament's thermal radiation increases so rapidly with temperature that even a small excursion above its normal operating temperature will cause the filament to radiate away more thermal energy than it produces from electricity, and it will quickly cool back down to normal. Like any hot object, the power radiated by the filament is proportional to the fourth power of its absolute temperature. The precise relationship between temperature and emitted power is:

$$\text{radiated power} = \text{emissivity} \cdot \text{Stefan-Boltzmann constant} \cdot \text{temperature}^4 \cdot \text{surface area.} \quad (7.3.1)$$

This relationship is called the Stefan–Boltzmann law, and the Stefan–Boltzmann constant that appears in it has a measured value of $5.67 \times 10^{-8} \text{ J}/(\text{s} \cdot \text{m}^2 \cdot \text{K}^4)$. Remember that the temperature must be measured in kelvin.

Increasing the filament's temperature therefore increases both its color temperature and its brightness. Each of these characteristics is important to you, so it's fortunate that you can adjust them somewhat independently. Unless you're enjoying a romantic dinner and want the reddish glow of candlelight, you usually prefer higher color temperatures. For an incandescent bulb, that normally means a hotter filament. But once you've chosen the filament temperature, you can still make the filament brighter by increasing its surface area.

While the concept of an incandescent bulb is simple, finding a material that can tolerate extremely high temperatures is not. Early filaments were made of carbon and platinum. Of these materials, carbon showed the most promise. In 1879, Thomas Edison developed an incandescent lamp with a carbon filament that operated for several hundred hours. His wasn't the first incandescent bulb ever made but rather the first practical one. (For more about the development of carbon filaments, see ❶.)

However, while carbon has the highest melting temperature of any element (3550 °C or 6422 °F), it sublimates relatively quickly even at much lower temperatures. Thus a carbon filament that is heated close to its melting temperature quickly disappears as a gas. When a gap appears in the filament, it stops carrying electricity and "burns out." Carbon is also flammable, so it must be enclosed in an airtight glass bulb that contains either inert gases or a vacuum.

A better choice for filaments, now used in virtually all incandescent bulbs, is tungsten metal. Tungsten melts at 3410 °C (6170 °F) and sublimates extremely slowly below that temperature. Tungsten filaments can thus operate at higher temperatures than carbon filaments, producing richer, whiter light. Like carbon, however, hot tungsten burns in air and must be protected in a glass bulb.

To ensure that most of the electric power passing through the filament is converted into thermal power, the filament must be long and thin. A typical 60-W lightbulb has about 0.5 m (20 inches) of 25-micron (0.001-inch) tungsten wire, coiled up into a filament only about 2 cm (0.8 inches) long. To minimize the filament's length, it's wound into a double spiral. First it's wound into a thin springlike coil about 0.25 mm wide. Then this coil is wound into another coil to form the actual filament (Fig. 7.3.5). Fabricating such a complicated tungsten filament is so difficult that it wasn't accomplished until 1937.

The Glass Bulb

To keep the white-hot filament from burning, it's surrounded by a glass bulb that usually contains oxygen-free inert gas. This gas, typically nitrogen and argon, slows sublimation by bouncing some of the escaping tungsten atoms back onto the filament. Although the gas extends the filament's life, it has at least two drawbacks. First, it allows conduction and convection to carry some heat away from the filament (see 2). Second, tiny tungsten particles that form in this gas rise with convection currents to produce a dark spot on the top of the bulb.

The glass bulb presents another challenge: operating a filament inside it involves passing wires right through the glass. This step isn't so easy because the glass and metal must seal to one another perfectly. Complicating this sealing requirement is the fact that materials expand as their temperatures increase. If the glass and metal don't expand equally as the bulb warms up, the bulb may leak or even break.

A material's thermal expansion is caused by atomic vibrations. Because of thermal energy, adjacent atoms vibrate back and forth about their equilibrium separations (Fig. 7.3.6). This vibrational motion isn't symmetric; the repulsive force the atoms experience when they're too close together is stiffer than the attractive force they experience when they're too far apart. As a result of this asymmetry, they push apart more quickly than they draw together and thus spend most of their time at more than their equilibrium separation. On average, their actual separation is larger than their equilibrium separation, and the material containing them is bigger than it would be without thermal energy.

As an object's temperature rises, its atoms move farther apart on average and the object grows larger in all directions. The extent to which an object expands with increasing temperature is normally described by its coefficient of volume expansion: the fractional change in the object's volume per unit of temperature increase. Fractional change in volume is the net change in volume divided by the total volume. Since most materials expand only a small amount when becoming 1 °C (or 1 K) hotter, coefficients of volume expansion are small, typically about 10^{-5} K^{-1} for metals, about 10^{-6} K^{-1} for special low-expansion glasses, and about 10^{-4} K^{-1} for liquids. In a lightbulb, the metal wires and the glass are carefully selected to have similar coefficients of volume expansion. As the bulb warms up, the wires and glass expand together and the seals remain intact.

Extended Life, Halogen, and Three-Way Bulbs

One way to prolong the life of the filament is to increase its surface area while providing it with the same electric power. With more surface area to radiate away thermal power, the filament doesn't get quite as hot and doesn't sublime as quickly. The result is an extended life bulb. Unfortunately, extended life bulbs are redder than conventional bulbs and also less energy efficient. Because an extended life bulb emits a smaller fraction of its input power as visible light, it must have a higher wattage to give equivalent lighting. As a result, extended life bulbs aren't always a bargain; the money you save on replacement bulbs may well be spent on

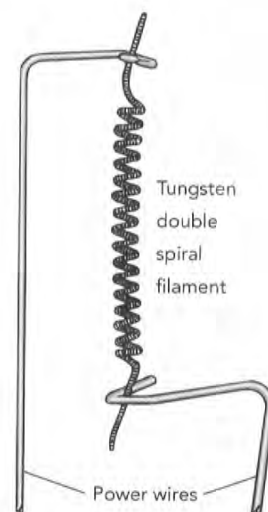


Fig. 7.3.5 The tungsten filament of a modern incandescent lightbulb is a double spiral—a coil wound from a smaller coil of extremely fine tungsten wire. The double spiral allows the manufacturers to put a long length of wire in a small space.

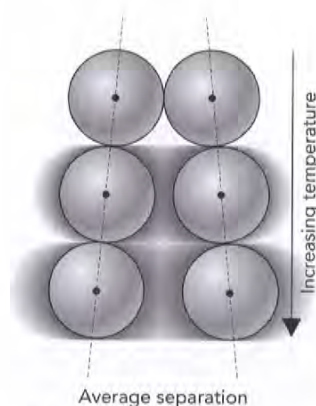


Fig. 7.3.6 The thermal kinetic energy of a solid increases with temperature, causing its atoms to bounce against one another more vigorously. As they vibrate, the atoms repel more strongly than they attract so their average separation increases slightly.



Fig. 7.3.7 Different 100-W lightbulbs produce different amounts of useful light, as revealed by the lumens listed on their packaging.

increased energy costs. When you're choosing bulbs, it's worth looking at how many lumens—the measure of useful illumination—they produce per watt of electric power consumed (Fig. 7.3.7).

You're much better off buying a halogen bulb, which is both longer-lived and more energy efficient than a conventional bulb. A halogen bulb uses a chemical trick to rebuild its filament continuously during operation. This filament is enclosed in a small tube of quartz or aluminosilicate glass, which can tolerate high temperatures and reactive chemicals (Fig. 7.3.8). The tube contains molecules of the halogen elements bromine and/or iodine. During operation, the tube becomes extremely hot and the halogen reacts with any tungsten atoms on its inside surface. They form a gas of tungsten–halogen molecules that drift about the tube until they encounter the white-hot filament. The molecules then break apart and the tungsten atoms stick to the filament.



Fig. 7.3.8 These halogen bulbs operate at higher temperatures than normal incandescent bulbs and produce whiter light. The large glass envelope of the upper bulb protects a smaller lamp inside.

The halogens act as recycling agents, seeking out tungsten atoms that have sublimed from the filament and returning them to it. Unfortunately, this recycling process slowly changes the structure of the filament. The returning tungsten atoms deposit unevenly, so that the filament gradually develops thin spots and eventually burns out. Nonetheless, the filament lives more than 2000 hours, even when it runs several hundred degrees hotter than in a conventional bulb. Its higher filament temperature allows a halogen bulb to produce whiter light than a conventional bulb and increases its energy efficiency.

Halogen bulbs do have some drawbacks. The quartz glass tube is small, extremely hot, and filled with toxic halogen gas. It's a fire and safety hazard, which is why it's often protected by an outer glass tube. The quartz tube is sensitive to fingerprints, which discolor and damage it when it becomes hot. Finally, the tungsten recycling system only functions at high temperatures. When a halogen lamp operates on a dimmer at less than full power, tungsten can accumulate on the quartz tube, dark-

ening the bulb and reducing its life. The bulb needs to operate at full power periodically to clean off the quartz tube and return the tungsten to the filament.

Bulbs with different power ratings have filaments with different amounts of surface area. The filament in a 100-W bulb has four times the surface area of the filament in a 25-W bulb and thus emits four times as much light. To support this fourfold increase in thermal power, the 100-W filament also consumes four times as much electric power. Both filaments operate at the same temperature and emit light with the same color temperature.

One way to make an incandescent bulb with a variable light output is to put several independent filaments in it. A "three-way bulb" has two filaments (Figs. 7.3.9 and 7.3.10) that can be turned on and off separately. In a 50-100-150 W bulb, one filament uses 50 W of electric power and the other uses 100 W. If only the low-power filament is on, the bulb appears to be a 50-W bulb. If only the high-power filament is on, it appears to be a 100-W bulb. But when both filaments are on, the bulb appears to be a 150-W bulb. Since one of the filaments invariably burns out before the other, the bulb fails by going from having three light levels to only one.

Toasters and Space Heaters

If the filament of a lightbulb never operated above red-hot, it wouldn't need to be made of expensive tungsten. It could be made instead of an inexpensive nickel-chromium alloy called nichrome. Although nichrome will melt if heated beyond red-hot, it has an advantage over tungsten at lower temperatures: it doesn't burn in air. So while nichrome filaments aren't suitable for lightbulbs that are meant to emit lots of visible light, they're great for "lightbulbs" that emit red and infrared light. In fact, nichrome is wonderful for all sorts of electrical heating elements!

Nichrome-based filaments and heating elements are common in homes, where they appear in toasters, space heaters, hot-water heaters, clothes irons, and many other appliances. They're also standard in electric stovetops and electric ovens. You can often see these nichrome filaments directly in devices that can protect them from contact. And in other devices, the nichrome filaments are typically encased in electrically insulating tubes to form sturdy, reliable electrical heating elements.

A toaster offers a good starting point because you can see its red-hot nichrome filament at work. That filament is relatively large because it operates cooler and radiates far less thermal power per unit of surface area than an ordinary lightbulb filament. As long as bread never touches the toaster's filament directly, that filament transfers heat to the bread only by convection and radiation. In most cases, the bread is placed beside or below the filament, so natural convection isn't effective at transferring heat to the bread. Instead, the toaster heats the bread primarily by radiation and the bread experiences the high surface temperatures that are necessary for caramelizing and browning. In a pinch, you can make toast in a broiler because it also cooks with radiation. Baked toast usually doesn't brown as well and doesn't taste the same.

If you turn the toaster inside-out, you'll have a space heater. While a real space heater may have a fan to circulate heated air or a fluid-filled radiator to diffuse the heat, it's still a first cousin to the toaster. A space heater uses a nichrome filament to convert electric power into thermal power and that thermal power flows out into the room. With space heaters that allow you to see their hot filaments directly, you can feel their radiant heat bathing your skin. Even in cold room air, this radiative heat transfer can warm your skin significantly and make you feel comfortable.

Other space heaters hide their hot filaments to reduce the radiant heat transfer and depend instead on forced convection to carry heat from their filaments to the room air. These space heaters use fans to blow warm air into the room. Hairdryers work exactly the same way, except that they're specialized to blowing warm air at

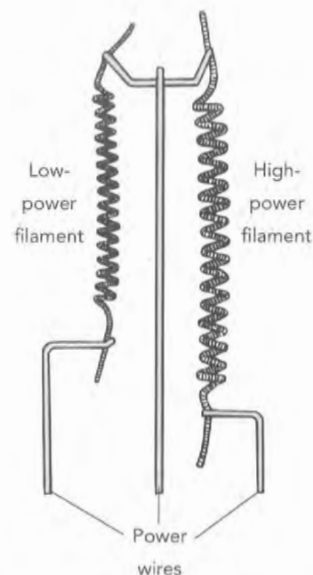


Fig. 7.3.9 A three-way bulb has two independent filaments. The filament on the left is shorter and thinner than the one on the right and emits about half as much light. The three different light levels correspond to having the left filament on, the right filament on, and both filaments on.



Fig. 7.3.10 The glass envelope of this three-way lightbulb has been removed to expose its two filaments. The shorter, thinner filament (*left*) uses 50 W, while the longer, thicker one (*right*) uses 100 W.

your hair. You can usually see the nichrome heating element inside a hairdryer, although it never gets hot enough to emit visible light. The filaments in electric heat guns, however, do glow red-hot and should obviously never be used with hair!

Finally, there are space heaters in which heat from a nichrome heating element flows into a fluid that's sealed inside a radiator. This fluid undergoes natural convection inside the radiator and the entire radiator warms up simultaneously. The large heated surface of that radiator then transfers heat to the room by convection and radiation. The surface temperature of this radiator is warm but not overly hot, which makes it safe for use around children. Touching it won't burn them and there's no chance that they'll start a fire by poking things into it.

Hot Water Heaters and Lava Lamps

An electric hot water heater works like one of the radiator space heaters. The water in a large tank is heated by an electric element that's immersed in the water. Since the heated water rises convectively, all of the water near or above the heating element warms up simultaneously to the desired temperature. When that temperature is reached, a thermostat turns off the heating element. Hot water is extracted through a pipe at the top of the tank and cold water is introduced into the bottom of the tank to replace it. Since hot water floats on cold water, the entering cold water sits at the bottom of the tank and you can continue to extract hot water from the top of the tank until there is no hot water left.

As soon as the cold water level rises above the heating element, the thermostat senses the temperature drop and turns the heating element back on. As long as you don't remove too much hot water too quickly, the hot water heater will successfully replace it and you'll never run out. But if you do run out of hot water, the system will take some time to recover. That's because the heating element heats all of the cold water above it at the same time—the convection cell that forms inside the hot water heater then reaches all the way from the heating element up to the top of the tank.

To speed the recovery process, many electric hot water heaters have two heating elements: one located near the bottom of the tank and one located near the middle of the tank. Activating both heating elements simultaneously would overload the hot water heater's electrical supply, so it can only turn on one heating element at a time. When you've depleted all the hot water, it turns on the middle heating element and heats only the water from the middle of the tank on up. With only half as much water to heat, the hot water heater is able to start delivering hot water in half the time.

Once the top half of the tank is hot, the middle heating element turns off and the bottom heating element turns on. A new convection cell forms that reaches from that heating element up to the bottom of the existing hot water. Water in the lower half of the tank now heats up. If you only use a little hot water at a time, it is always the bottom heating element that warms up the incoming cool water.

Since the bottom heating element does most of the work in a typical hot water heater, it's usually the first to fail. When it does, you must turn off and drain the hot water heater, swap in a replacement heating element, refill the hot water heater with water, and then turn it back on. If you accidentally turn the hot water heater on before filling it with water, the heating element will have no water around it to carry away its thermal energy and that element will overheat and melt in a matter of seconds.

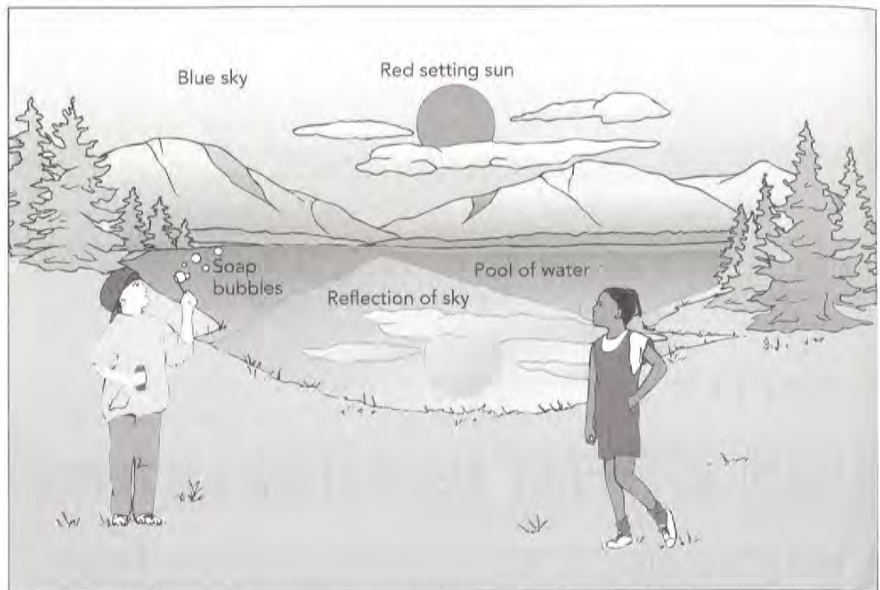
A Lava[®] Lamp is charming toy in which heat from an incandescent lightbulb causes blobs of softened wax to float up through another liquid in a glass bottle and then cool and descend to repeat the trip again (Fig. 7.3.11). The convection cell that carries the wax up and down in the bottle would be easy to understand



Fig. 7.3.11 The wax in this Lava Lamp melts when heated from below by an incandescent lightbulb. The molten wax has a low density, so it floats up through the other liquid until it reaches the top of the bottle. There the wax cools and begins to solidify, experiencing a rise in density so that it sinks back to the bottom of the bottle. The wax repeats this journey over and over again.

except that there are two liquids in the bottle and they seem to circulate in opposite directions: the heated wax rises through the other liquid and the cooled wax descends through it.

The phenomenon that makes this system work is that the wax is close to its melting temperature and it becomes more liquid-like when it's heated by the incandescent lightbulb at the bottom of the bottle and more solid-like when it cools at the top of the bottle. Like most materials, the wax is significantly denser as a solid than it is as a liquid. When the lightbulb heats the wax, the wax becomes more fully liquid. The liquid or melting wax is buoyant in the other liquid and floats toward the top of the bottle. But once the wax reaches the top of the bottle, it cools and begins to transform into its solid phase. Solid or solidifying wax is relatively dense and sinks through the other liquid toward the bottom of the bottle. This cycle then repeats over and over again.



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 miles) from the sun to our eyes and provides most of the energy and heat that make life on earth possible. While 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. And so we'll begin by looking at how sunlight interacts with our world.

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 the previous chapter have wavelengths longer than 1 mm. In this 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.

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.

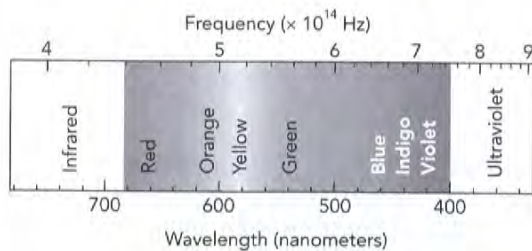


Fig. 14.1.1 The visible portion of the spectrum of sunlight. Each wavelength of visible light has a particular frequency and is associated with a particular color. At the ends of the visible spectrum are invisible infrared and ultraviolet lights.

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 °C. 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, like the incandescent lightbulbs we discussed in Section 7.3. Because the photosphere's temperature is 5800 °C, the jostling motions are extremely rapid and most of the sunlight falls in the visible portion of the electromagnetic spectrum (Fig. 14.1.2).

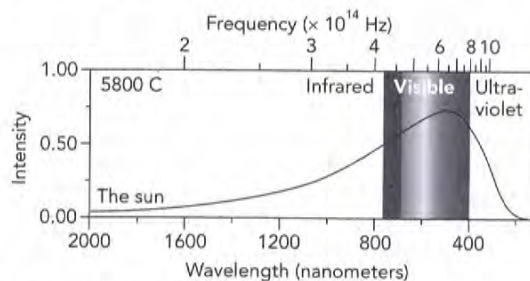


Fig. 14.1.2 Sunlight comes from the sun's photosphere, where the temperature is 5800 °C. This light has a blackbody distribution of wavelengths, with much of its intensity concentrated in the visible portion of the overall electromagnetic spectrum.

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.

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. While 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.

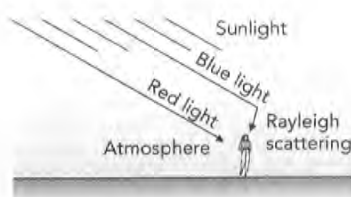


Fig. 14.1.3 As sunlight passes through the atmosphere, some of its blue light undergoes Rayleigh scattering from particles in the air. We see this redirected blue light as the diffuse blue sky. The remaining light reaches our eyes directly from the sun and tends to be reddish, particularly at sunrise and sunset.

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. While 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.

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.

While 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. 14.1.3). But 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 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. But 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.

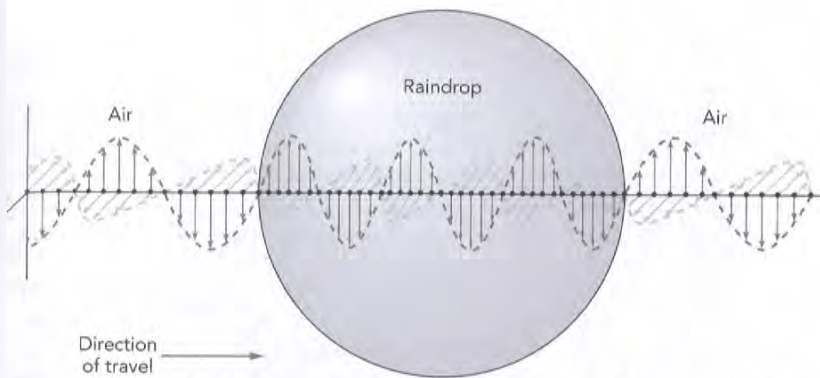


Fig. 14.1.4 As an electromagnetic wave enters a material, its speed decreases and the waves bunch up together. Its wavelength decreases.

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. 14.1.4). While 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. 14.1.5a). But if that wave strikes the raindrop near the top, it will bend as it enters the water (Fig. 14.1.5b). 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.

As the wave in Fig. 14.1.5b 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. Imped-

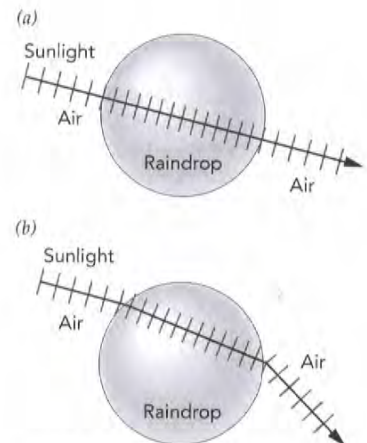


Fig. 14.1.5 A side view of two narrow waves of sunlight entering and leaving raindrops. The lines drawn across each light wave represent upward electric field maxima and are bunched together as light slows down in water.

❶ 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.

❷ 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.

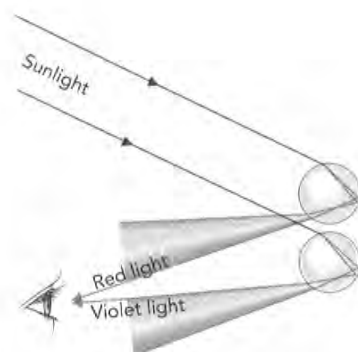


Fig. 14.1.6 As sunlight passes through spherical raindrops, its colors separate. Violet light bends more at each air/water boundary than does red light, and the two emerge from raindrops heading in different directions. You see red light coming toward you from the upper raindrops and violet light from the lower raindrops.

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

The impedance of empty space is high because an electric field there has nothing to aid it in producing a magnetic field. But inside most materials, 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 ❷). In contrast, metals polarize so easily that their impedances are essentially zero and they reflect light almost perfectly.

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

Soap Bubbles

Soap bubbles also separate sunlight into its various colors (Fig. 14.1.7), but they use another wave phenomenon: interference. We encountered interference of me-



Fig. 14.1.7 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.

chanical waves in Section 9.3 when we studied surf beat at the seashore (p. 322) and interference of electromagnetic waves in Section 13.2 when we considered the unevenness of microwave cooking (p. 439). 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 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. 14.1.8*a*). But 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. 14.1.8*b*).

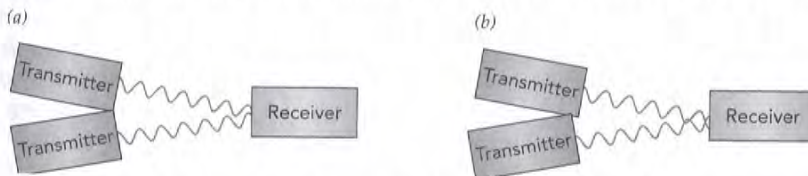


Fig. 14.1.8 (a) When waves from two separate paths arrive in phase at the receiver, constructive interference produces a strong effect on the receiver. (b) When waves arrive out of phase, destructive interference produces a weak effect on the receiver.

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. 14.1.9). 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.

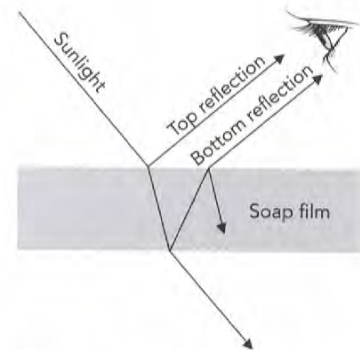


Fig. 14.1.9 Sunlight reflects from both the front and back surfaces of a soap film. The back surface reflection is delayed relative to the front surface reflection because it must pass twice through the soap film itself. If the two reflected waves arrive in phase, you see a bright reflection. If they are out of phase, you see a dim reflection.

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.

Sunlight and Polarizing Sunglasses

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. But 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.

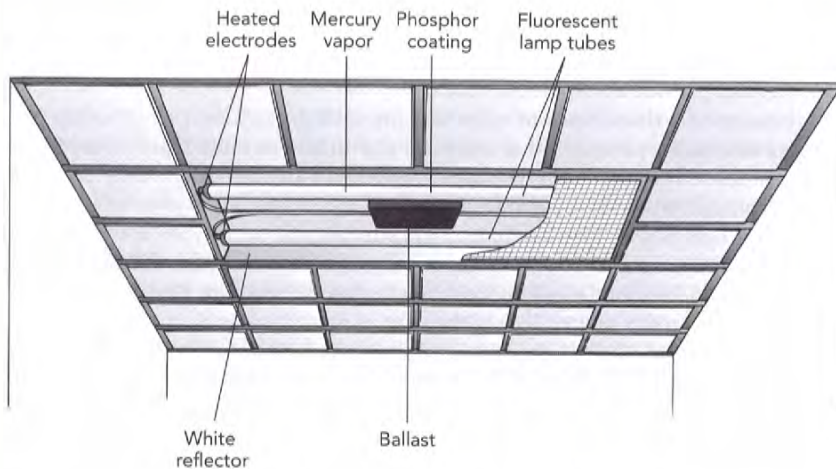
But vertically polarized light's vertical electric field pushes electric charges up and down vertically. At shallow angles, this field acts to lift the charges in and out of a horizontal surface. Since the charges can't leave the surface, the surface becomes harder to polarize as the angle becomes shallower. 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. 14.1.10). That's why polarizing sunglasses are so effective at reducing glare.



Fig. 14.1.10 (a) Ordinary sunglasses simply darken the scene. (b) Polarizing sunglasses block horizontally polarized light, the main component of glare.

Rayleigh-scattered light from the blue sky, however, tends to be mostly horizontally polarized light, which is absorbed by polarizing sunglasses. That's why the blue sky looks relatively dark when viewed through polarizing sunglasses.



SECTION 14.2 Discharge Lamps

Energy efficiency is crucial to modern lighting. While incandescent lamps provide pleasant, warm illumination, 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.

How We See Light and Color

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

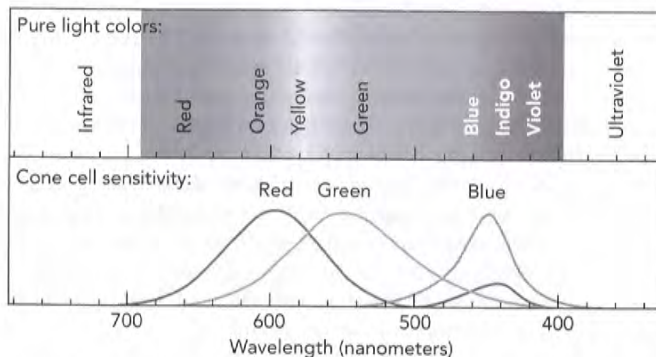
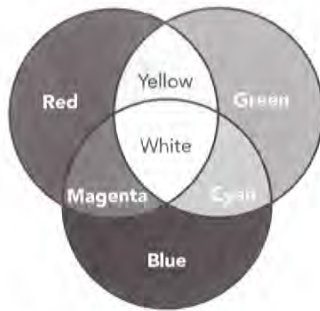


Fig. 14.2.1 The red-sensitive cells in our retina detect light near 600 nm, the green-sensitive cells near 550 nm, and the blue-sensitive cells near 450 nm. The red-sensitive cells also respond near 440 nm, so that we see violet.

(a) Additive colors (light)



(b) Subtractive colors (pigment)

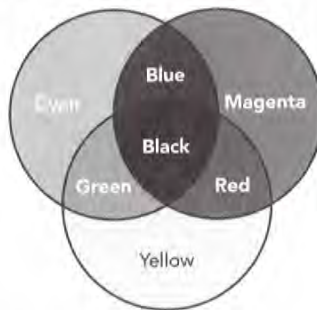


Fig. 14.2.2 (a) The primary colors of light or additive colors, red, green, and blue, can be combined to form any colors of light. (b) The primary colors of pigment or subtractive colors, cyan, magenta, and yellow, subtract red, green, and blue, respectively, from reflected or transmitted light and can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

While our retinas also contain rod cells, which are more light-sensitive than cone cells, 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.

While 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.

But 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. 14.2.2a). Color televisions and computer screens use tiny sources of red, green, and blue light to produce their full-color images.

While 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. 14.2.2b). 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.

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.

While 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 °C), 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.

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. While some discharge lamps are colored, others do excellent jobs of producing white light. And 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% of 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.

While 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). While 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.

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.

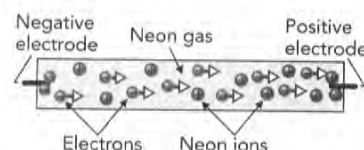


Fig. 14.2.3 A neon sign tube sends electrons through low-pressure neon gas. These electrons collide with neon atoms, transferring energy to them and causing them to emit primarily red light. Positively charged neon ions, created by particularly energetic collisions, keep the electrons from repelling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

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 ❶).

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. 9.2.7 on p. 309. And 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

❶ 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 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 crystal-line structure, making it possible to observe the interferences.

has one node surface passing through the atom's center. Since filling the 2s and 2p 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.

But 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:

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

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. And while 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. And, as we shall soon see, so do scientists and engineers working on illumination.

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, 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. While 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. But regardless of how the discharge is started, the result is current flowing through the gas and the emission of light.

But the fluorescent lamp has a problem. 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. While this light doesn't have the same spectrum as sunlight, it appears white because it stimulates the red-, green-, and blue-sensitive cells in our eyes about equally. The blending of phosphors 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 create the right balance between red, green, and blue lights. While some advertising and novelty lamps use brightly colored, unblended phosphors, fluorescent lighting tubes come in six standard color blends: cool white, deluxe cool white, warm white, deluxe warm white, white, and daylight.

When they were first introduced, fluorescent tubes used the daylight phosphor. This phosphor emits too much blue light and makes everything look cold and medicinal. Phosphors have improved over the years so that the most common phosphors today, cool white and warm white, look much more pleasant. Light from the "cool" phosphors resembles daylight, while that from the "warm" phosphors resembles incandescent lighting. Household fluorescent lamps often use deluxe cool white and deluxe warm white, which are even more pleasant versions of white but which are slightly less energy efficient.

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 often colored fluorescent tubes used in artwork or advertising require much higher voltages.

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 usually 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.

Unfortunately, the filament/electrodes are fragile. They're damaged by a process called sputtering, in which positive mercury ions from the plasma collide with the filament/electrodes and chip away their tungsten atoms. Because sputtering is particularly severe during start-up, a typical filament/electrode breaks after a few thousand starts. That's why you shouldn't turn a fluorescent lamp on and off more than once every few minutes.

Mercury, Metal-Halide, and Sodium Lamps

While a low-pressure mercury discharge emits mostly ultraviolet light, a high-pressure mercury discharge emits more visible light than ultraviolet light. This change

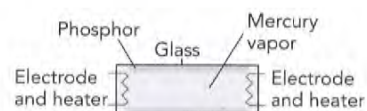


Fig. 14.2.5 In a hot-electrode fluorescent tube, the electrodes are actually filaments and are heated by running currents through them.

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. But 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.

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

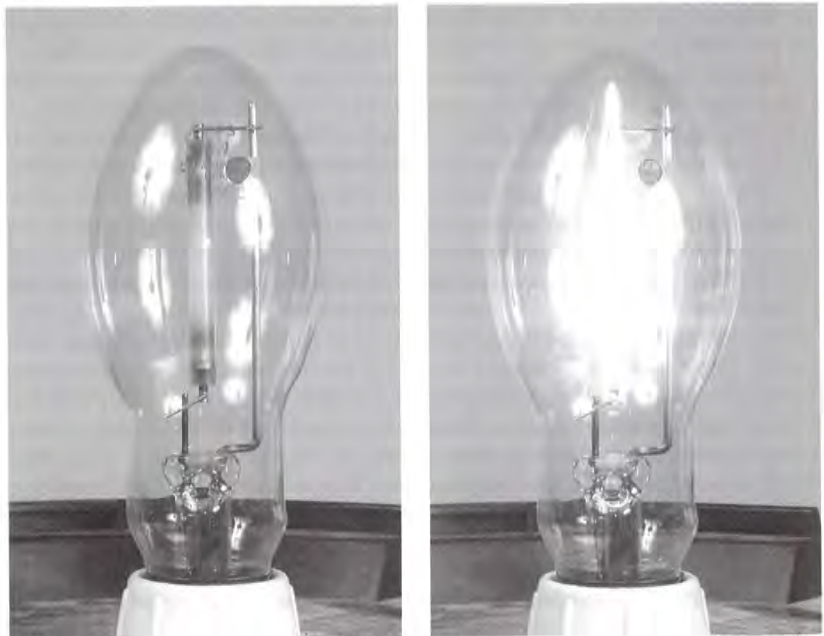


Fig. 14.2.6 The active component of a high-pressure sodium vapor lamp is a small translucent tube. As the lamp warms up, sodium metal in the tube evaporates to form a brilliant yellow discharge. The dense vapor of sodium atoms in the tube traps the 590-nm light so that the lamp emits a richer spectrum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

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 ($3p \rightarrow 3s$). Many highways are illuminated by the yellow-orange glow of low-pressure sodium lamps.

But this monochromatic illumination is unpleasant and permits no color vision at all. While 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).

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 ($3p \rightarrow 3s$). 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 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.

GLOSSARY

absolute temperature scale A scale for measuring temperature in which 0 K corresponds to absolute zero.

absolute zero The temperature at which all thermal energy has been removed from an object or system of objects. Because it's impossible to find and remove all the thermal energy from an object, absolute zero can be approached but is not actually attainable.

acceleration A vector quantity that measures how quickly an object's velocity is changing; the greater the acceleration, the more the object's velocity changes each second. It consists of both the amount of acceleration and the direction in which the object is accelerating. This direction is identical to the direction of the force causing the acceleration. The SI unit of acceleration is the meter-per-second².

acceleration due to gravity A physical constant that specifies how quickly a freely falling object accelerates and also relates an object's weight to its mass. At the earth's surface, the acceleration due to gravity is 9.8 m/s² (or 9.8 N/kg).

accelerometer A device that senses acceleration by measuring the position of a test mass suspended in stable equilibrium on springs or other elastic supports. As the overall device accelerates, the test mass shifts away from its equilibrium position because it requires a net force in order to accelerate with the device.

acid A chemical that when dissolved in water increases the density of hydrogen ions in solution and lowers the water's pH.

acidic Having a pH of less than 7.

activation energy The energy required to initiate a chemical reaction. This energy serves to break or weaken the bonds in the starting chemicals so that the reaction can proceed to form the reaction products.

adverse pressure gradient A region of fluid flow in which the fluid must flow toward higher pressure. The fluid's momentum and kinetic energy carry it through this situation, although the fluid does slow down.

aerodynamic forces The forces exerted on an object by the motion of the air surrounding it. The two types of aerodynamic forces are lift and drag.

aerodynamics The study of the dynamic (moving) interactions of air with objects.

airfoil An aerodynamically engineered surface, designed to obtain particular lift and drag forces from the air flowing around it.

airspeed An object's speed relative to the air through which it moves.

alpha decay A radioactive decay in which a helium nucleus (two protons and two neutrons) escapes from a larger proton-rich nucleus via quantum tunneling.

alternating current An electric current that periodically reverses its direction of flow. Abbreviated as AC.

amorphous solid A solid that is non-crystalline and has no long-range order.

ampere (A) The SI unit of electric current (synonymous with the coulomb-per-second). One ampere is defined as the passage of 6.25×10^{18} charged particles per second and is roughly the current flowing through a 100-W lightbulb operating on household electric power.

ampere-meter (A·m) The SI unit of magnetic pole.

amplifier A device that replicates an input signal as a larger output signal.

amplitude modulation A technique for representing sound or data by changing the amplitude (strength) of a wave.

amplitude The maximal displacement of an oscillator away from its equilibrium position.

analog representation The representation of numbers directly as continuous values of physical quantities such as voltage, charge, or pressure.

angle of attack The angle at which an airfoil is tilted relative to the airflow that is taking place around it.

angular acceleration A vector quantity that measures how quickly an object's angular velocity is changing: the greater the angular acceleration, the more the object's angular velocity changes each second. It consists of both the amount of angular acceleration and the direction about which the angular acceleration occurs. This direction is identical to the direction of the torque causing the angular acceleration. The SI unit of angular acceleration is the radian-per-second².

angular impulse The mechanical means for transferring angular momentum. One object gives an angular impulse to a second object by exerting a certain torque on the second object for a certain amount of time. In return, the second object gives an equal but oppositely directed angular impulse to the first object.

angular momentum A conserved vector quantity that measures an object's rotational motion. It is the product of that object's rotational mass times its angular velocity. The SI unit of angular momentum is the kilogram-meter²-per-second.

angular position A quantity that describes an object's orientation relative to some reference orientation.

angular speed A measure of the angle through which an object rotates in a certain amount of time.

angular velocity A vector quantity that measures how rapidly an object's angular position is changing: the greater the angular velocity, the farther the object turns each second. It consists of both the object's angular speed and the direction about which the object is rotating. This direction points along the axis of rotation in the direction established by the right-hand rule. The SI unit of angular velocity is the radian-per-second.

anharmonic oscillator An oscillator in which the restoring force on an object is not proportional to its displacement from a stable equilibrium. The period of an anharmonic oscillator depends on the amplitude of its motion.

annealing Heating a material to relieve internal stresses and to allow recrystallization and grain growth, followed by gradual cooling to room temperature.

antiferromagnetic Composed of magnetic atoms that effectively alternate back and forth in magnetic orientation so that their magnetic fields cancel.

antimatter Matter resembling normal matter, but with many of its characteristics such as electric charge reversed.

aperture The diameter or effective diameter of a lens or opening.

apparent weight The sum of a person's weight plus their feeling of acceleration. All three quantities are vectors, so that apparent weight can be quite large if the weight and feeling point in the same direction or quite small if they point in opposite directions.

Archimedes' principle The observation that an object partially or wholly immersed in a fluid is acted on by an upward buoyant force equal to the weight of the fluid it's displacing.

atmospheric pressure The pressure of air in the earth's atmosphere. Atmospheric pressure reaches a maximum of about 100,000 Pa near sea level and diminishes with increasing altitude.

atom The smallest portion of a chemical element that retains the chemical properties of that element.

atomic number The number of protons present in an atomic nucleus and equal to the number of electrons in a neutral atom.

atomize Reduce a liquid to droplets that are so small that they are easily suspended in the air by drag forces.

axis of rotation The straight line in space about which an object or group of objects rotates. More specifically, the axis of rotation points in a particular direction along that line to reflect the sense of rotation according to the right-hand rule.

back emf The self-induced electromotive force that develops in an inductor when its current changes or in the coil of an electromechanical system such as a motor when its current causes magnets to move.

band A group of levels in a solid that involve similar standing waves and thus have similar energies.

band gap A range of energies over which a solid has no levels available.

bandwidth The range of frequencies involved in a group of electromagnetic waves.

base A chemical that when dissolved in water decreases the density of hydrogen ions in solution and increases the water's pH.

base of support A surface outlined on the ground by the points at which an object is supported.

basic Having a pH of more than 7.

Bernoulli effect The drop in pressure that occurs when the speed of an effectively incompressible fluid in steady-state flow increases as it moves along a streamline.

Bernoulli's equation An equation relating the total energy of an incompressible fluid in steady-state flow to the sum of its pressure potential energy, kinetic energy, and gravitational potential energy.

beta decay A radioactive decay in which the weak force allows a neutron in a neutron-rich nucleus to disintegrate into an electron, a proton, and an antineutrino. The proton remains in the nucleus, but the electron and antineutrino escape.

binary The digital representation of numbers in terms of the powers of two. The number 6 is represented in binary as 110, meaning 1 four (2^2), 1 two (2^1), and 0 ones (2^0).

bit A single binary value, either a 0 or a 1.

black hole A region of space, normally spherical, within which the gravitational distortions of space and time are so severe that not even light can escape.

blackbody spectrum The distribution of thermal electromagnetic radiation emitted by a black object. This distribution is the amount of radiation emitted at each wavelength and depends only on the temperature of the black object.

blunt Not streamlined so that the fluid flowing around it stalls and experiences flow separation and pressure drag.

boiling Accelerated evaporation that occurs when stable gas-phase bubbles form and grow inside a material's liquid-phase.

boiling temperature The threshold temperature at which gas-phase bubbles first become stable within a material's liquid phase.

Boltzmann constant The constant of proportionality relating a gas's pressure to its particle density and temperature. It has a measured value of $1.381 \times 10^{-23} \text{ Pa}\cdot\text{m}^3/(\text{particle}\cdot\text{K})$.

boundary layer A thin region of fluid near a surface that, because of viscous drag, is not moving at the full speed of the surrounding airflow.

bremsstrahlung The process in which a rapidly accelerating charge emits electromagnetic radiation, usually an X-ray or gamma-ray photon.

Brewster's angle The angle at which no vertically polarized light reflects from a transparent surface that is oriented horizontally. The precise angle depends on the surface's index of refraction.

brittle fracture Material fracture that occurs without plastic deformation when layers of atoms separate completely during stress.

brittleness A material's tendency toward brittle fracture during stress.

buoyant force The upward force exerted by a fluid on an object immersed in that fluid. The buoyant force is actually caused by pressure from the fluid. That pressure is highest below the object so the force exerted upward on the object's bottom is greater than the force exerted downward on the object's top.

byte Eight binary bits that collectively can represent a number from 0 to 255. Bytes are often used to represent letters and other characters, where a convention associates each character with a specific number.

calibration The process of comparing a local reference object to a generally accepted standard.

capacitance The amount of separated charge on the plates of a capacitor divided by the voltage difference across those plates. The SI unit of capacitance is the farad.

capacitor An electronic component that stores separated electric charge on a pair of plates that are separated by an insulating layer.

carrier wave An electromagnetic wave with only a single frequency. This wave is modulated in order to represent an audio or video signal, or digital information.

catalyst A chemical surface that assists a chemical reaction by reducing the activation energy needed to initiate the reaction.

Celsius A temperature scale in which 0 °C is defined as the melting point of water and 100 °C is defined as the boiling point of water at sea level. Absolute zero is -273.15 °C.

center of gravity The unique point about which all of an object's weight is evenly distributed and therefore balanced. Because weight is proportional to mass, the center of mass is identical to the center of gravity for objects that are much smaller than the earth. For larger objects, the centers of mass and gravity differ slightly. An object suspended from its center of gravity will balance and will experience no net torque due to gravity. In many situations, you can accurately predict an object's behavior by assuming that all of the object's weight acts at its center of gravity.

center of mass The unique point about which all of the object's mass is balanced. The center of mass is the natural pivot point for a free object. In the absence of outside forces or torques, a rigid object's center of mass travels at constant velocity while the object rotates at constant angular velocity about this center of mass.

center of percussion The special spot on a bat or racket where a collision with a second object will not cause any acceleration of the bat's handle.

centripetal acceleration An acceleration that is always directed toward the center of a circular trajectory.

centripetal force A centrally directed force on an object. A centripetal force is not an independent force but rather the sum of other forces, such as gravity, acting on the object.

chain reaction A process in which one event triggers an average of one or more similar events so that the process becomes self-sustaining.

chaos Unpredictable behavior in which minute changes in a system's initial arrangement lead to very different final arrangements. These differences grow more dramatic with each passing second.

chaotic system A dynamic system that is exquisitely sensitive to initial conditions. Minute changes in how you set up a chaotic system can lead to wildly different final configurations.

characteristic X-ray An X-ray emitted by X-ray fluorescence from an atom. The energy of the characteristic X-ray is determined by the atom's orbital structure.

charges Objects, particularly small particles, that carry electric charge.

chemical bond An energy deficit that holds two or more atoms together to form a molecule and that must be repaid in order to separate the atoms. Chemical bonds form when chemical potential energy is released during a molecule's assembly.

chemical potential energy Energy stored in the chemical forces between atoms. Those chemical forces are electromagnetic in origin.

chemical reaction An encounter between two or more atoms and molecules that results in a rearrangement of the atoms to form different atoms and molecules.

circularly polarized A light wave in which the electric and magnetic fields rotate about the direction in which that wave is heading.

closed circuit A complete electric circuit through which electric current can flow continuously.

coaxial cable A two-conductor electric cable in which an insulated central conductor is surrounded by a cylindrical outer conductor. Electromagnetic waves can travel within the gap between the two conductors, and they propagate along the cable at almost the speed of light.

coefficient of restitution The measure of a ball's liveliness, determined by bouncing the ball from a rigid, immovable surface. It's the ratio of the ball's rebound speed to its collision speed.

coefficient of volume expansion The fractional change in an object's volume caused by a temperature increase of 1 °C.

coherent light Light consisting of identical photons that together form a single electromagnetic wave.

collision energy The amount of kinetic energy removed from two objects as they collide.

color temperature The temperature at which a black object will emit thermal electromagnetic radiation with this particular distribution of wavelengths.

components The portions of a vector quantity that lie along particular directions.

compressible A substance that changes density significantly as its pressure changes. A gas is compressible since its density is proportional to its pressure.

compressive stress A stress involving compression.

Compton scattering The process in which a photon bounces off a charged particle, usually an electron. The photon and charged particle exchange energy and momentum during the collision.

concave mirror A mirror that is bowed inward at the center, like the inside of a bowl.

condensation The phase transformation whereby a gas becomes a liquid.

conduction band The group of quantum levels in an insulator that lies above the Fermi level.

conduction level A quantum level in an insulator that requires more energy than the Fermi level and that is normally unoccupied by electrons.

conduction The transmission of heat through a material by a transfer of energy from one atom or molecule to the next. The atoms themselves don't move with the heat. In metals, mobile electrons also contribute to heat conduction.

conserved quantity A physical quantity, such as energy, that is neither created nor destroyed within an isolated system when that system undergoes changes. A conserved quantity may pass among the objects within an isolated system, but its total amount remains constant.

constructive interference Interference in which two or more waves arrive at a location in space and time in phase with one another and produce a particularly strong effect.

convection cell A loop of fluid flow that is propelled by convection. Fluid in a convection cell normally rises in a hotter region and descends in a colder region.

convection current A fluid flow propelled by convection.

convection The transmission of heat by the movement of a fluid. Convection normally entails the natural circulation of the fluid that accompanies differences in temperatures and densities.

converging lens A lens that bends the individual light rays passing through it toward one another so that they either converge more rapidly than before or at least diverge less rapidly from one another. A converging lens has a positive focal length and often produces real images.

convex mirror A mirror that is bowed outward at the center, like the outside of a bowl.

corona discharge A faintly glowing discharge that surrounds a small, highly charged object in the presence of a gas. In the discharge, electric charge is transferred from the object to the gas molecules.

coulomb (C) The SI unit of electric charge. One coulomb is about 1 million times the charge you acquire by rubbing your feet across a carpet in winter.

Coulomb constant The fundamental constant of nature that determines the electrostatic forces two charges exert on one another. Its measured value is $8.988 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$.

Coulomb's law The magnitudes of the electrostatic forces between two objects are equal to the Coulomb constant times the product of their two electric charges divided by the square of the distance separating them. If the charges are like, then the forces are repulsive. If the charges are opposite, then the forces are attractive.

covalent bond A strong chemical bond between atoms in which the two atoms share one or more pairs of electrons in the region of space between them.

crest A peak positive excursion of an extended system that is experiencing a wave.

critical mass A portion of a fissionable material that is able to sustain a fission chain reaction. The amount of material required depends on its mass, shape, and density.

crystal An orderly arrangement of atoms or molecules that has both positional and orientational orders. The particles are organized in a simple, geometrical pattern that repeats endlessly in all directions.

crystalline Having its atoms arranged in an orderly pattern that extends for many atomic spacings in all directions.

current The amount of electric charge flowing past a point or through a surface per unit of time. The SI unit of current is the ampere.

cycle-per-second (1/s) The SI unit of frequency (synonymous with hertz).

cyclotron motion The circular or spiral motion of a charged particle in a magnetic field. The charged particle tends to loop around the magnetic flux lines.

decimal The digital representation of numbers in terms of the powers of ten. The number 124 is represented in decimal as 124, meaning 1 hundred (10^2), 2 tens (10^1), and 4 ones (10^0).

demagnetization The disappearance of magnetic polarization in a material.

density The mass of an object divided by its volume. The SI unit of density is the kilogram-per-meter³.

depletion region The nonconducting region around a p-n junction in which all of the valence levels are filled with electrons and there are no conduction level electrons.

deposition The phase transformation whereby a gas becomes a solid.

destructive interference Interference in which two or more waves arrive at a location in space and time out of phase with one another and produce a particularly weak effect.

diffraction A wave phenomenon that limits the focusability of light and alters the way in which it travels after passing through an opening.

digital representation The representation of numbers by decomposition into digits that are then individually represented by discrete values of physical quantities such as voltage, charge, or pressure.

diode A semiconductor device that allows charge to flow through it only in one direction. Diodes are commonly formed by bringing n-type silicon into contact with p-type silicon.

direct current An electric current that always flows in one direction. Abbreviated as DC.

direction The line or course on which something is moving, is aimed to move, or along which something is pointing or facing.

discharge A flow of electric current through a gas.

dislocation An incomplete sheet of atoms that appears as a defect in a crystal.

dispersion The dependence of light's speed through a material on the frequency of that light.

dissolve Separate into individual atoms, molecules, or ions and disperse throughout a fluid.

distance The length between two positions in space. The SI unit of distance is the meter.

diverging lens A lens that bends the individual light rays passing through it away from one another so that they either converge less rapidly than before or don't converge at all. A diverging lens has a negative focal length and often produces virtual images.

domain wall A boundary surface between magnetic domains having different directions of magnetic orientation.

doped Modified by adding chemical impurities that change its physical properties.

Doppler effect A difference between the frequency at which a wave is sent and the frequency at which that wave is received caused by relative motion between the sender and receiver.

drag forces The frictionlike forces exerted by a fluid and a solid on one another as the solid moves through the fluid. These forces act to reduce the relative velocity between the two.

ductile Capable of undergoing extensive plastic deformation before fracturing.

ductile fracture Material fracture that occurs during plastic deformation when layers of atoms separate completely during stress.

dynamic stability An object's stability when it's in motion.

dynamic variations Changes in a physical quantity such as pressure that are caused by motion.

elastic collision A collision in which all of the kinetic energy present before the impact is again present as kinetic energy after the impact.

elastic deformation A stress-induced change in shape that doesn't involve permanent rearrangement of the atoms in a material. The material returns to its original shape when the stress is removed.

elastic limit The most extreme distortion of an object from which it can return to its original size and shape without permanent deformation.

elastic potential energy The energy stored by the forces within a distorted elastic object.

elastic scattering The process in which two particles bounce off one another without losing any of their kinetic energies.

electric charge An intrinsic property of matter that gives rise to electrostatic forces between charged particles. Electric charge is a conserved physical quantity. A specific charge can have a positive amount of electric charge (a positive charge) or a negative amount (a negative charge). The SI unit of electric charge is the coulomb.

electric charges Objects, particularly small particles, that carry electric charge.

electric circuit A complete loop of conductors, loads, and power sources through which an electric current can flow continuously.

electric current The movement or flow of electric charge.

electric field An attribute of each point in space that exerts forces on electrically charged particles. An electric field has a magnitude and direction proportional to the force it would exert on a unit of positive charge at that location. While electric fields are often created by nearby charges, they can also be created by other electromagnetic phenomena. The SI unit of electric field is the volt-per-meter or, equivalently, the newton-per-coulomb.

electric polarization A distribution of electric charge that is nonuniform so that the object has a region of positive charge and a region of negative charge.

electrical conductor A material that permits electric charges to flow through it.

electrical insulator A material that prevents any net movement of electric charge through it.

electrical resistance The measure of how much an object impedes the flow of electric current. The SI unit of electrical resistance is the ohm.

electromagnet A coil of wire, with or without an iron core, that becomes a magnet when an electric current flows through the coil.

electromagnetic waves Waves consisting of electric and magnetic fields that travel through empty space at the speed of light. These waves carry energy and momentum and are emitted and absorbed as particles called photons. Radio waves, microwaves, infrared, visible, and ultraviolet light, X-rays, and gamma rays are examples of electromagnetic waves.

electron volt (eV) A unit of energy equal to the energy obtained by an elementary charge (electron or proton) as it moves through a voltage difference of 1 V. One electron volt is equal to about 1.602×10^{-19} J.

electronic shell A quantum mechanical structure that exists within an atom wherein the electron standing waves have related structures and similar energies. Atoms that complete their electronic shells become very stable chemically.

electron–positron pair production The formation of an electron and a positron during an energetic collision.

electrons The tiny negatively charged particles that make up the outer portions of atoms and that are the main carriers of electricity and heat in metals.

electrostatic force The force experienced by a charged particle in the presence of other charged particles.

electrostatic potential energy Energy stored in the forces between electric charges.

elementary unit of electric charge The basic quantum of electric charge, equal to about 1.6×10^{-19} C.

emissivity A surface's capacity to emit or absorb thermal radiation, relative to that of a perfectly black object at the same temperature.

energy The capacity to do work. Each object has a precise quantity of energy, which determines exactly how much work that object could do in an ideal situation. The SI unit of energy is the joule.

English system of units An assortment of antiquated units that were used throughout the English colonies and remain in common use in the United States today. Units in this system include feet, ounces, and miles-per-hour.

entrainment The phenomenon in which a particle or portion of fluid is carried along in the flow of another fluid.

entropy The physical quantity measuring the amount of disorder in a system. The system's entropy would be zero at absolute zero.

equilibrium position The point at which an object experiences zero net force and doesn't accelerate.

equilibrium The state of an object in which zero net force (or zero net torque) acts on it. An object that is stationary or in uniform motion is in equilibrium.

escape velocity The speed a spacecraft needs in order to follow a parabolic orbital path and escape forever from a particular celestial object.

eutectic An alloy or solution of two or more materials that has a lower melting temperature than any of the individual materials.

evaporation The phase transformation whereby a liquid becomes a gas.

excited state A configuration of a system having excess energy; its electrons (or other particles) are in an arrangement of quantum waves (e.g., orbitals or levels) that has more than the least possible energy.

exhaust velocity The velocity of exhaust gas relative to the rocket engine from which it emerged.

explosive chain reaction A chain reaction in which each fission induces an average of much more than one subsequent fission and the fission rate skyrockets.

eyepiece The final lens of a telescope or microscope; the lens that prepares the light for your eye.

Fahrenheit A temperature scale in which 32 °F is defined as the melting point of water and 212 °F is defined as the boiling point of water at sea level. Absolute zero is -459.67 °F.

farad (F) The SI unit of electric capacitance. A 1-farad capacitor will have a voltage difference between its plates of 1 volt when storing 1 coulomb each of separated positive and negative charge.

feedback The process of using information about a system's current situation to control changes you are making in that system.

feeling of acceleration A person undergoing acceleration experiences a weight-like sensation in the direction exactly opposite the direction of acceleration. The amount of this feeling of acceleration is proportional to the amount of the acceleration.

Fermi energy The energy of an electron in the Fermi level.

Fermi level A hypothetical level located halfway between the highest occupied level and the lowest unoccupied level in a solid.

Fermi particles A class of fundamental particles that includes electrons, protons, and neutrons and that obeys the Pauli exclusion principle.

ferrimagnetic Composed of magnetic atoms that alternate back and forth in magnetic orientation but have different magnetic strengths so that their magnetic contributions don't cancel completely.

ferromagnetic Composed of magnetic atoms that all have the same magnetic orientation within a magnetic domain.

firm Having a large spring constant and thus experiencing large restoring forces in response to small distortions.

first law of thermodynamics The change in a stationary object's internal energy is equal to the heat transferred into that object minus the work that object does on its surroundings. This law restates the conservation of energy.

fissionable Able to undergo induced fission.

fluid A substance that has mass but no fixed shape. A fluid can flow to match its container. Gases and liquids are both fluids.

fluorescence An emission of light that immediately follows an absorption of light.

f-number The ratio of a lens's focal length to its effective aperture.

focal length The distance after a converging lens at which the real image of a distant object forms. The focal length of a diverging lens is negative and is the distance *before* the lens at which the virtual image of a distant object forms.

force An influence that if exerted on a free body results chiefly in an acceleration of the body and sometimes in deformation and other effects. A force is a vector quantity, consisting of both the amount of force and its direction. The SI unit of force is the newton.

forward biased A p-n junction in which the voltage of the p-type semiconductor has been raised relative to the voltage of the n-type semiconductor.

freezing The phase transformation whereby a liquid becomes a solid.

frequency modulation A technique for representing sound or data by changing the exact frequency of a wave.

frequency The number of cycles completed by an oscillating system in a certain amount of time. The SI unit of frequency is the hertz.

friction The force that resists relative motion between two surfaces in contact. Frictional forces are exerted parallel to the surfaces in the directions opposing their relative motion.

fundamental forces The four basic forces that act between objects in the universe—the gravitational force, the electromagnetic force, the strong force, and the weak force.

fundamental vibrational mode The slowest and often broadest vibration that an extended object can support.

gamma rays Extremely high-energy photons of electromagnetic radiation, often produced during radioactive decays.

gas or gaseous A form of matter consisting of tiny, individual particles (atoms or molecules) that travel around independently. A gas takes on the shape and volume of its container.

general theory of relativity The physical rules governing all motion, even motion involving speeds comparable to the speed of light and occurring in the presence of massive objects.

glass A non-crystalline material having no long-range order.

glass transition temperature The temperature below which the atoms in a liquid are no longer able to rearrange and the material responds elastically to shear stress.

glass–rubber transition regime A regime in which the atoms of an amorphous polymer can move freely enough to make it pliable and leathery.

glassy regime A regime in which the atoms of an amorphous polymer can't move relative to one another, making it rigid and hard.

grain A tiny crystallite that is part of a polycrystalline material.

grain boundary The thin layer of atoms between two separate crystals or grains of a polycrystalline material.

gravitational constant The fundamental constant of nature that determines the gravitational forces two masses exert on one another. Its value is $6.6720 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2$.

gravitational mass The mass associated with the gravitational attraction between objects.

gravitational potential energy Potential energy stored in the gravitational forces between objects.

gravity The gravitational attraction of the mass of the earth, the moon, or a planet for bodies at or relatively near its surface. All objects exert gravitational forces on all other objects.

ground state The lowest energy configuration of a system; its electrons (or other particles) are in the arrangement of quantum waves (e.g., orbitals or levels) that has the least possible energy.

gyroscope A spinning disk which will continue to point in one direction in space as long as it is not subjected to any outside torques.

half-life The time needed for half the nuclei of a particular radioactive isotope to undergo radioactive decay.

hard magnetic material A material that is relatively difficult to magnetize and that retains its magnetization once the magnetizing field is removed. Hard magnetic materials are suitable for permanent magnets.

hardness A material's ability to resist penetration.

harmonic An integer multiple of the fundamental frequency of oscillation for a system. The second harmonic is twice the frequency of the fundamental, and the third harmonic is three times the frequency of the fundamental. In principle, harmonics can continue forever.

harmonic oscillator An oscillator in which the restoring force on an object is proportional to its displacement from a stable equilibrium. The period of a harmonic oscillator doesn't depend on the amplitude of its motion.

heat capacity The amount of heat that must be added to an object to cause its temperature to rise by 1 unit.

heat engine A device that converts thermal energy into work as heat flows from a hot object to a cold object.

heat exchanger A device that allows heat to flow naturally from a hotter material to a colder material without any actual exchange of those materials.

heat pump A device that pumps heat against its natural direction of flow, transferring it from a cold object to a hot object. To satisfy the second law of thermodynamics, a heat pump normally converts some ordered energy into thermal energy.

heat The energy that flows from one object to another as a result of a difference in temperature between those two objects.

Heisenberg uncertainty principle A quantum physical law that states that an object's position (a particle characteristic) and momentum (a wave characteristic) can't be sharply defined at the same time. This principle gives objects with small masses a fuzzy character.

henry (H) The SI unit of inductance. A 1-henry inductor will experience a 1-ampere change in the current flowing through it each second when subjected to a 1-volt voltage drop.

hertz (Hz) The SI unit of frequency (synonymous with cycles-per-second).

higher-order vibrational mode A vibrational mode that is more complicated than the fundamental mode and in which different parts of the extended system move in opposite directions.

Hooke's law The general law covering spring and elastic behavior. Hooke's law states that a spring exerts a restoring force that is proportional to the distance the spring is distorted from its equilibrium length.

horizontal polarization An electromagnetic wave in which the electric field always points left or right (horizontally). The magnetic field always points vertically.

hydrogen bond A moderately strong chemical bond in which an uncovered hydrogen nucleus is attracted to the electrons of a nearby oxygen atom.

ideal gas law The law relating the pressure, temperature, and particle density of an ideal gas. An ideal gas is one that is composed of perfectly independent particles. The particles don't stick and bounce perfectly from one another.

image distance The distance between the lens and the image that the lens creates. Real images form at positive image distances while virtual images form at negative image distances.

impedance A measure of a system's opposition to the passage of a current or a wave.

impedance mismatch An abrupt change in the opposition to a wave's passage, typically accompanied by reflections.

impulse The mechanical means for transferring momentum. One object gives an impulse to a second object by exerting a certain force on the second object for a certain amount of time. In return, the second object gives an equal but oppositely directed impulse to the first object.

in phase The relationship between two waves in which they complete the same portions of their oscillatory cycles at the same time and place.

incandescence The emission of thermal radiation from a hot object.

incoherent light Light consisting of individual photons, each its own independent electromagnetic wave.

incompressible A substance that doesn't change density significantly as its pressure changes. Liquids and solids are incompressible since their densities change very little as their pressures change dramatically.

index of refraction The factor by which the speed of light in a material is reduced from its speed in empty space, equal to the speed of light in empty space divided by light's speed in the material.

induced drag The drag force that occurs when a wing deflects the stream of air passing across it to obtain lift.

induced emf An overall voltage difference between the ends of a coil produced by a changing magnetic field in that coil and the resulting electric field.

induced fission A fission event that's caused by a collision, usually with a neutron.

inductance The voltage drop across an inductor divided by the rate at which current through that inductor is changing with time. The SI unit of inductance is the henry.

inductor An electronic component that stores magnetic energy in a coil of wire and opposes changes in current in that wire.

inelastic collision A collision in which some of the kinetic energy present before the impact is no longer present as kinetic energy after the impact.

inert gas A gas consisting of atoms that are chemically inactive and rarely bond permanently with other atoms or molecules. Inert gases include helium, neon, argon, krypton, and xenon.

inertia A property of matter by which it remains at rest or in uniform motion in the same straight line unless acted on by some outside force.

inertial frame of reference A frame of reference that is not accelerating and is thus either stationary or traveling at constant velocity. The laws of motion accurately describe any situation that is observed from an inertial frame of reference.

inertial mass The mass associated with an object's inertia, its resistance to acceleration.

inertial Moving because of inertia alone and therefore not accelerating.

infrared light Invisible light having wavelengths longer than about 750 nanometers.

insulator A solid in which the Fermi level falls within a band gap.

interference A wave phenomenon in which waves passing through the same location from different directions reinforce or oppose one another.

interference pattern A pattern of intensity variations in time and space that occurs when two or more waves are superposed and experience constructive and destructive interferences.

internal energy The sum of an object's thermal energy and any additional potential energy stored entirely within the object.

internal kinetic energy The portion of an object's kinetic energy that involves only the relative motion of particles within the object and that excludes the object's overall translation or rotation.

internal potential energy The portion of an object's potential energy that involves only forces between particles within the object and that excludes the object's interactions with its surroundings.

ion An atom or molecule with a net electric charge.

ionic bond A chemical bond in which ions are held together by their opposite electric charges.

isotopes Chemically indistinguishable atoms containing nuclei that differ only in their numbers of neutrons.

joule (J) The SI unit of energy and work (synonymous with newton-meter). Lifting 1 liter of water upward 10 centimeters near the earth's surface requires about 1 joule of work.

joule-per-kilogram-kelvin (J/kg·K) The SI unit of specific heat.

joule-per-second (J/s) The SI unit of power (synonymous with watt).

Kelvin The SI scale of absolute temperature, in which 0 K is defined as absolute zero. The spacing between units is the same as that used in the Celsius scale.

Kepler's first law All planets move in elliptical orbits, with the sun at one focus of the ellipse.

Kepler's second law A line stretching from the sun to a planet sweeps out equal areas in equal times.

Kepler's third law The square of a planet's orbital period is proportional to the cube of that planet's mean distance from the sun.

kilogram (kg) The SI unit of mass. (The standard kilogram is a platinum–iridium cylinder kept at the International Bureau of Weights and Measures near Paris.) A liter of water has a mass of about 1 kilogram.

kilogram-meter² (kg·m²) The SI unit of rotational mass. One kilogram-meter² is roughly the rotational mass of your forearm as it pivots about your elbow.

kilogram-meter²-per-second (kg·m²/s) The SI unit of angular momentum. One kilogram-meter²-per-second is about the angular momentum of a 7.3 kg (16 lbm) bowling ball spinning 34 times/second as it rolls down the lane.

kilogram-meter-per-second (kg·m/s) The SI unit of momentum. One kilogram-meter-per-second is about the momentum in a baseball traveling 25 km/h (16 mph).

kilogram-meter-per-second² (kg·m/s²) The SI unit of force (synonymous with newton).

kilogram-per-meter³ (kg/m³) The SI unit of density. One kilogram-per-meter³ is about the density of air at 2000 m (about 1 mile) above sea level.

kinetic energy The form of energy contained in an object's translational and rotational motion.

laminar flow Smooth, predictable fluid flow in which nearby portions of the fluid remain nearby as they travel along.

laser amplifier A device that amplifies weak incoming light to produce brighter outgoing light. The outgoing light is a brighter copy of the incoming light.

laser medium An assembly of excited atoms or other quantum systems that is capable of amplifying passing light through stimulated emission.

laser oscillator A laser amplifier that is surrounded by mirrors so that it can amplify one or more spontaneously emitted photons to form an intense beam of coherent light.

latent heat of evaporation The heat required to transform a unit mass of material from liquid to gas without changing its temperature.

latent heat of fusion Latent heat of melting.

latent heat of melting The heat required to transform a unit mass of material from solid to liquid without changing its temperature.

latent heat of vaporization Latent heat of evaporation.

lattice A regular geometrical pattern that repeats endlessly in all directions.

law of universal gravitation Every object in the universe attracts every other object in the universe with a force equal to the gravitational constant times the product of the two masses, divided by the square of the distance separating the two objects.

laws of thermodynamics The four laws that govern the movement of heat between objects.

lens A transparent optical device that uses refraction to bend light, often to form images.

lens equation The equation relating a lens's focal length to the object and image distances.

Lenz's law When a changing magnetic field induces a current in a conductor, the magnetic field from that current always opposes the change that induced it.

level An electron standing wave in a solid, one of the basic electron wave modes allowed in a solid by quantum physics.

lever arm The directed distance from the pivot or axis of rotation to the point at which the force is exerted.

lift forces Forces exerted by a fluid on a solid that are at right angles to the fluid flow around that solid.

light See visible, infrared, and ultraviolet light.

linear momentum A conserved vector quantity that measures an object's motion. It is the product of that object's mass times its velocity. The SI unit of linear momentum is the kilogram-meter-per-second.

liquid A form of matter consisting of particles (atoms or molecules) that are touching one another but that are free to move relative to one another. A liquid has a fixed volume but takes the shape of its container.

liquid crystal A liquid consisting of rod-like or disk-like molecules that exhibit orientational order.

liquid flow regime A regime in which the chains of an amorphous polymer reptate quickly enough to support liquid flow. The polymer is a viscous liquid.

longitudinal wave A wave in which the underlying oscillation is parallel to the wave itself.

long-range order Uniform spatial structure that extends for many nanometers in a solid.

Lorentz force The force experienced by a charged particle when it moves through a magnetic field.

lumen A common unit of total radiated light as perceived by a human eye.

luminescence The emission of light by any means other than thermal radiation.

magnetic dipole A pair of equal but opposite poles separated by a distance.

magnetic domains Regions of uniform alignment within a magnetic material.

magnetic field An attribute of each point in space that exerts forces on magnetic poles. A magnetic field has a magnitude and direction proportional to the force it would exert on a unit of north magnetic pole at that location. The SI unit of magnetic field is the tesla.

magnetic flux lines Abstract strands following along the local magnetic field direction and having a density proportional to that local field. Flux lines can only begin at north poles and end at south poles.

magnetic induction The process whereby a time-changing magnetic field initiates or influences an electric current.

magnetic monopole An isolated magnetic pole, either north or south. None has ever been observed.

magnetic polarization A distribution of magnetic poles that is nonuniform so that the object has a region of north pole and a region of south pole.

magnetic pole A property of nature that gives rise to magnetostatic forces between magnetic poles. A specific pole can have a positive amount of magnetic pole (a north pole) or a negative amount (a south pole). The SI unit of magnetic pole is the ampere-meter.

magnetic poles Objects that carry magnetic pole.

magnetization The development of magnetic polarization in a material.

magnetostatic force The force experienced by a magnetic pole in the presence of other magnetic poles.

magnitude The amount of some physical quantity.

Magnus force A lift force experienced by a spinning object as it moves through a fluid. The Magnus force points toward the side of the ball moving away from the onrushing airstream.

mass The property of a body that is a measure of its inertia or resistance to acceleration, that is commonly taken as a measure of the amount of material it contains, and that causes it to have weight in a gravitational field. The SI unit of mass is the kilogram.

mechanical advantage The process whereby a mechanical device redistributes the amounts of force and distance that go into performing a particular amount of mechanical work.

mechanical wave A natural and often rhythmic motion of an extended object about its stable equilibrium shape or situation.

melting temperature The temperature at which a material's solid and liquid phases can coexist in stable equilibrium.

melting The phase transformation whereby a solid becomes a liquid.

metal A solid in which the Fermi level falls within a band of levels.

metal fatigue Material fracture that occurs when manipulation allows surface blemishes to propagate into a metal as tears.

metallic bonds The form of bonding that occurs in metals. Electrons are shared generally among many atoms and this sharing binds the atoms together.

meter (m) The SI unit of length or distance. (One meter is formally defined as the distance light travels through empty space in 1/299,792,458th of a second.) One meter is about the length of a long stride or about 3.28 feet.

meter² (m²) The SI unit of area. One square meter is about twice the area of an opened newspaper.

meter³ (m³) The SI unit of volume. One cubic meter is about the volume of a four-drawer file cabinet.

meter-per-second (m/s) The SI unit of velocity or speed. One meter-per-second is a typical walking pace or about 2.2 mph.

meter-per-second² (m/s²) The SI unit of acceleration. One meter-per-second² is about the acceleration of an elevator as it first begins to move upward.

microwaves Electromagnetic waves with wavelengths between about 1 meter and 1 millimeter.

mode A basic pattern of distortion or oscillation.

moderator A material with which fast neutrons can collide and give up energy without being absorbed. Neutrons leave a moderator with only thermal energies.

modulated carrier wave A wave that has been modulated so that it contains not only the carrier frequency, but also video, audio, or other information.

molecule A particle formed out of two or more atoms. A molecule is the smallest portion of a chemical compound that retains the chemical properties of that compound.

moment of inertia Rotational mass.

momentum Linear momentum.

monomer A small molecule from which a polymer forms.

natural resonance A mechanical process in which an isolated object's energy causes it to perform a certain motion over and over again. The rate at which this motion occurs is determined by the physical characteristics of the object.

net electric charge The sum of all charges on an object, both positive and negative. Positive charges increase the net charge while negative charges decrease it. Net charge can be negative.

net force The sum of all forces acting on an object, considering both the magnitude of each individual force and its direction. The magnitude of the net force is often less than the sum of the magnitudes of the individual forces, since they often oppose one another in direction.

net magnetic pole The sum of all poles on an object, both north and south. Since there are no isolated magnetic poles, an object's net magnetic pole is always zero.

net torque The sum of all torques acting on an object, considering both the magnitude of each individual torque and its direction. The magnitude of the net torque is less than the sum of the magnitudes of the individual torques, since they often oppose one another in direction.

neutral Having zero net electric charge.

neutrinos Chargeless and nearly massless particles created during radioactive decays and other nuclear events. They rarely interact with matter.

neutrons The electrically neutral subatomic particles that, together with protons, make up atomic nuclei.

newton (N) The SI unit of force (synonymous with the kilogram-meter-per-second²). Eighteen U.S. quarters have a weight equal to about 1 newton. The common English unit of force, the pound, is about 4.45 newtons.

Newton's first law of motion An object that is free from all outside forces travels at a constant velocity, covering equal distances in equal times along a straight-line path.

Newton's first law of rotational motion An object that is not wobbling and is free from all outside torques rotates with constant angular velocity, spinning steadily about a fixed axis.

Newton's second law of motion An object's acceleration is equal to the force exerted on that object divided by the object's mass. This equality can be manipulated algebraically to state that the force on the object is equal to the product of the object's mass times its acceleration (Eq. 1.1.2).

Newton's second law of rotational motion An object's angular acceleration is equal to the torque exerted on that object divided by the object's rotational mass. This equality can be manipulated algebraically to state that the torque on the object is equal to the product of the object's rotational mass times its angular acceleration (Eq. 2.1.2). The law doesn't apply to wobbling objects.

Newton's third law of motion For every force that one object exerts on a second object, there is an equal but oppositely directed force that the second object exerts on the first object.

Newton's third law of rotational motion For every torque that one object exerts on a second object, there is an equal but oppositely directed torque that the second object exerts on the first object.

newton-meter (N·m) The SI unit of energy and work (synonymous with the joule). Also the SI unit of torque, exerted by a 1-newton force located 1 meter from the axis of rotation. One newton-meter is about the torque exerted on your shoulder by the weight of a baseball held in your outstretched arm.

newton-per-ampere-meter (N/A·m) The SI unit of magnetic field (synonymous with tesla).

newton-per-coulomb (N/C) The SI unit of electric field (synonymous with volt-per-meter).

newton-per-meter² The SI unit of pressure (synonymous with pascal).

normal Directed exactly away from (perpendicular to) a surface. A line that is normal to a surface meets that surface at a right angle.

normal force Support force.

n-type semiconductor A semiconductor such as silicon that contains impurity atoms such as phosphorus, arsenic, antimony, or bismuth that place electrons in the semiconductor's conduction level.

nuclear fission The shattering of a heavy nucleus into smaller fragments. During fission, the positively charged fragments repel one another and release energy.

nuclear force An attractive force that binds nucleons together once they touch one another.

nuclear fusion The merging of two small nuclei to form a larger nucleus. During fusion, the nuclear force binds the nucleons together and releases energy.

nucleation Forming an initial seed of one material phase in the midst of another material phase.

nucleon A general name given to the particles that make up atomic nuclei: protons and neutrons.

nucleus The positively charged central component of an atom, containing most of the atom's mass and about which the electrons are arranged. Plural is nuclei.

object distance The distance between the lens and the object that it is imaging.

objective The first lens or mirror of a telescope or microscope; the first significant optical component that light encounters after leaving the object.

ohm (Ω) The SI unit of electrical resistance. A 1-ohm resistor exhibits a voltage drop of 1 volt when 1 ampere of current flows through it.

Ohm's law The observation that the voltage drop across an ordinary electrical conductor is proportional to both the electric current passing through it and to its electrical resistance.

ohmic Exhibiting a voltage drop that's proportional to current, consistent with Ohm's law.

open circuit An incomplete electric circuit where a gap in the electrical conductors stops electric current from flowing.

orbit The path an object takes as it moves in the presence of a centripetal force.

orbital An electron standing wave in an atom, one of the basic electron wave modes allowed in an atom by quantum physics.

orbital period The time required to complete one full orbit.

ordered energy Energy that can easily be used to do work.

orientational order The characteristic of particles that all point in the same direction.

oscillation A repetitive and rhythmic movement or process that usually takes place about an equilibrium situation.

out of phase The relationship between two waves in which they complete opposite portions of their oscillatory cycles at the same time and place.

parallel (wiring arrangement) An arrangement in which the current reaching two or more electric devices divides into separate parts to flow through those devices and then joins back together as it leaves them. Current experiences the same change in voltage in each device.

particle density The number of particles in an object divided by its volume. The particle density of water is about 3.35×10^{28} molecules-per-meter³. The particle density of air at sea level is about 2.687×10^{25} molecules-per-meter³.

pascal (Pa) The SI unit of pressure (synonymous with newton-per-meter²). Atmospheric pressure at sea level is about 100,000 pascals. A 1-millimeter-high water droplet exerts a pressure of about 10 pascals on your hand.

Pascal's principle A change in the pressure of an enclosed incompressible fluid is conveyed undiminished to every part of the fluid and to the surfaces of its container.

Pauli exclusion principle An observed property of nature that indistinguishable Fermi particles must each have their own unique quantum wave.

period The time required to complete one full cycle of a repetitive motion.

permanent magnet An object that can be magnetized and that retains that magnetization for a long time.

permeability of free space The defined constant that relates two poles and the magnetostatic forces they exert on one another. Its value is $4\pi \times 10^{-7}$ N/A².

pH A measure of the hydrogen ion concentration, equal to the negative of the log base-10 of the molar hydrogen ion concentration.

phase A form of matter, notably solid, liquid, gas, and plasma.

phase equilibrium A situation in which two material phases coexist stably, neither one growing at the expense of the other.

phase transition A transformation from one material phase to another.

phosphor A solid that luminesces (emits light) when energy is transferred to it by light or by a collision with a particle.

photoconductor A solid that is an electrical insulator in the dark but that becomes an electrical conductor when exposed to light of the correct wavelength.

photodiode A diode that permits current to flow backward across the p-n junction when exposed to light. Light provides the energy needed to move charges across the junction's depletion region in the wrong direction. The current flowing in the reverse direction through a photodiode is proportional to the light intensity.

photoelectric effect The process in which an atom absorbs a photon in a radiative transition that ejects one of the electrons out of the atom.

photon A particle or quantum of light, having energy and momentum but no mass.

pitch The frequency of a sound.

Planck constant The fundamental constant of quantum physics, equal to the energy of an object divided by the frequency of its quantum wave. It is about 6.626×10^{-34} J·s.

plane polarized A light wave in which the electric field (and the magnetic field) fluctuates back and forth in a plane as the light travels through space.

plasma A gaslike phase of matter consisting of electrically charged particles, such as ions and electrons. The strong electromagnetic interactions between its particles distinguish a plasma from a gas.

plastic deformation A stress-induced change in shape that involves permanent rearrangement of the atoms in a material. The material doesn't return to its original shape when the stress is removed.

plasticizer A chemical additive that lowers a polymer's glass transition temperature and reduces its crystallinity.

p-n junction The interface between an n-type semiconductor and a p-type semiconductor that gives the diode its unidirectional characteristic for electrons.

Poiseuille's law The volume of fluid flowing through a pipe each second is equal to $(\pi/128)$ times the pressure difference across that pipe times the pipe's diameter to the fourth power, divided by the pipe's length times the fluid's viscosity.

polar molecule A molecule that is electrically polarized, effectively having a positive end and a negative end.

poles Objects that carry a magnetic pole.

polycrystalline Composed of many individual crystallites.

polymer A giant molecule that forms when many monomer molecules bind together in a permanent chain. To be called a polymer, the chain must be about a thousand or more atoms in length.

polymerization The process in which individual monomer molecules are chemically bound together to form a polymer chain.

population inversion A nonequilibrium population of quantum systems in which more are in a higher energy state than in a lower energy state.

position A vector quantity that specifies the location of an object relative to some reference point. It consists of both the length and the direction from the reference point to the object.

- positional order** The characteristic of particles that are uniformly spaced and aligned so that they form a lattice.
- positron** The antimatter counterpart of the electron. The positron is positively charged.
- potential energy** The stored form of energy that can produce motion. Potential energy is stored in the forces between or within objects.
- power** The measure of how quickly work is done on an object. The SI unit of power is the watt.
- precession** The change in orientation of a spinning object's rotational axis that occurs when it's subject to an outside torque.
- pressure drag** The drag force that results from higher pressures at the front of an object than at its rear.
- pressure gradient** A distribution of pressures that varies continuously with position.
- pressure potential energy** The product of a fluid's volume times its pressure. However, this energy isn't really stored in the fluid. Instead, it's energy that's provided by a pump (or other source) when the fluid is delivered.
- pressure** The average amount of force a fluid exerts on a certain region of surface area. Pressure is reported as the amount of force divided by the surface area over which that force is exerted. The SI unit of pressure is the pascal.
- primary colors of light** The three colors of light (red, green, and blue) that are sensed by the three types of color-sensitive cone cells in our eyes. Mixtures of these three colors of light can make our eyes perceive any possible color.
- primary colors of pigment** The three colors of pigment (cyan, magenta, and yellow) that absorb the three primary colors of light (red, green, and blue, respectively). Mixtures of these three pigments can be applied to a white surface to make it reflect any possible mixture of the three primary colors of light and thus to make our eyes perceive any possible color.
- principle of equivalence** The principle that gravitational mass and inertial mass are truly identical and therefore that no experiment you can perform in a small region of space can distinguish between free fall and the absence of gravity
- proton** The positively charged subatomic particles found in atomic nuclei.
- p-type semiconductor** A semiconductor such as silicon that contains impurity atoms such as boron, aluminum, gallium, indium, or tellurium that remove electrons from the semiconductor's valence levels.
- quanta** The fundament, discrete units in which an item is emitted, absorbed, or otherwise observed, reflecting the particulate character of that item.
- quantized** Existing only in discrete units or quanta. Quantized physical quantities are only observed in integer multiples of the elementary quantum.

quenching Cooling rapidly from high temperature so that the material doesn't have time to adopt its normal low-temperature state.

radian The natural unit in which angles are measured. There are 2π radians in a full circle, so 1 radian is $180/\pi$ degrees or approximately 57.3° .

radian-per-second (1/s) The SI unit of angular velocity or angular speed. An object turning at 1 radian-per-second completes a full revolution in just less than 6.3 seconds.

radian-per-second² (1/s²) The SI unit of angular acceleration.

radiation The transmission of heat through the passage of electromagnetic radiation between objects.

radiation trapping The phenomenon in which a particular wavelength of light has trouble propagating through a material that eagerly absorbs and emits it. The light passes from one atom or atomlike system to the next and makes little headway.

radiative transition The shift of an atom or atomlike system from one state to another through the emission or absorption of an electromagnetic wave.

radio waves Electromagnetic waves, usually with wavelengths longer than about 1 m.

radioactive decay The spontaneous decay of a nucleus into fragments.

ramp An inclined plane that allows work to be done over a longer distance, thereby requiring less force.

Rayleigh scattering The redirection of light due to its interaction with small particles of matter.

real image A pattern of light, projected in space, that exactly reproduces the pattern of light at the surface of the original object. A real image forms after the lens that creates it and can be projected onto a surface.

rebound energy The amount of kinetic energy returned to two objects as they push apart following a collision.

reflection The redirection of all or part of a wave so that it returns from a boundary between media.

refraction The bending of a wave's path that occurs when the wave crosses a boundary between media and experiences a change in speed.

relative humidity The actual humidity as a percentage of the humidity required to achieve phase equilibrium between liquid and gaseous water.

relative motion The movement of one object from the perspective of another object. Two objects that are moving relative to one another have different velocities.

relativistic energy An object's energy according to the relativistic laws of motion and including its rest energy.

relativistic laws of motion The laws of motion in the special theory of relativity. They correct deficiencies in the Newtonian laws of motion that appear primarily at speeds comparable to the speed of light.

relativistic momentum An object's momentum according to the relativistic laws of motion.

reptation A thermally induced slithering motion of polymer chains, backward and forward, that allows them to get past entanglements in order to flow. Reptation is so named because of its similarity to the motion of snakes.

resistor An electronic component that impedes the flow of electric current, converting some of its energy into heat.

resonant cavity A simple resonant circuit consisting of a carefully shaped conducting strip or shell and equivalent to a capacitor and an inductor. Energy flows back and forth between the cavity's electric and magnetic fields.

resonant energy transfer The gradual transfer of energy to or from a natural resonance caused by small forces timed to coincide with a particular part of each oscillatory cycle.

restoring force A force that acts to return an object to its equilibrium shape. A restoring force is directed toward the position the object occupies when it's in its equilibrium shape.

reverse biased A p-n junction in which the voltage of the p-type semiconductor has been lowered relative to the voltage of the n-type semiconductor.

Reynolds number A dimensionless number that characterizes fluid flow through a system. At low Reynolds numbers a fluid's viscosity dominates the flow, while at high Reynolds numbers a fluid's inertia dominates.

right-hand rule The convention whereby the specific direction of an object's angular velocity is established. According to this rule, if the fingers of your right hand are curled to point in the direction of the object's rotation, your thumb will point in the direction of the angular velocity.

root mean square (RMS) voltage A measure of AC voltage defined as the DC voltage that would cause the same average power consumption in an ohmic device.

rotational equilibrium The state of an object in which zero net torque acts on it. An object that has constant angular momentum is in rotational equilibrium.

rotational inertia A property of matter by which it remains at rest or in steady rotation about the same rotational axis unless acted on by some outside torque.

rotational mass The property of a body that is a measure of its rotational inertia. An object's rotational mass is determined by its mass and by how far that mass is from the axis of rotation. The SI unit of rotational mass is the kilogram-meter².

rotational motion Motion in which an object rotates about an axis. The orientation of an object undergoing only rotational motion will change, but its position will remain unchanged.

rubbery flow regime A regime in which the chains of an amorphous polymer can reptate just enough to flow very slowly past one another. The polymer is elastic and flows very slowly.

rubbery plateau regime A regime in which the individual atoms of an amorphous polymer can move freely but the chains can't flow past one another because of entanglements. The polymer is soft and elastic.

saturated In phase equilibrium with another material phase. The gaseous phase of a material is saturated when it is in phase equilibrium with that material's liquid and/or solid phase.

schematic diagram A symbolic picture of the conceptual structure of an electronic device.

second (s or sec) The SI unit of time. (One second is formally defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium 133 atom.)

second law of thermodynamics The entropy of a thermally isolated system of objects never decreases. This law recognizes that creating disorder is easy; restoring order is hard.

Seebeck effect A charge transfer that occurs between the two ends of a metal when one end is hotter than the other. It's caused by the thermal motion of the conduction electrons, which tend to drift away from the hot end and accumulate at the cold end.

seed crystal An initial crystal on which a solidifying liquid can crystallize.

selective reflection Reflection only of light with a particular wavelength or color.

semiconductor An insulator with a small band gap, so that only a modest amount of energy is needed to shift an electron from an occupied valence level to an unoccupied conduction level.

series (wiring arrangement) An arrangement in which the current reaching two or more electric devices flows sequentially through one device after the next before leaving them. Current may experience different changes in voltage in the different devices.

Shannon limit The maximum amount of digital information that can be carried by a signal each second; equal to the bandwidth of that signal times $\log_2(1+\text{signal/noise})$.

shear strain The angle by which a material bends when experiencing a shear stress.

shear stress A stress in which the top of a material is pushed to the left while the bottom is pushed to the right.

shell A group of atomic orbitals having similar energies.

shock wave A narrow region of high pressure and temperature that forms when the speed of an object through a medium exceeds the speed at which sound, waves, or other vibrations travel in that medium.

short circuit A defect in a circuit that allows current to bypass the load it's supposed to operate.

SI units A system of units (Système Internationale d'Unités) that carefully defines related units according to powers of 10. SI units are now used almost exclusively throughout most of the world, with the notable exception of the United States.

sideband waves Waves at frequencies above and below the carrier wave that are produced when the carrier wave is modulated.

signal An electrical or optical representation of information.

simple harmonic motion The regular, repetitive motion of a harmonic oscillator. The period of simple harmonic motion doesn't depend on the amplitude of oscillation.

sliding friction The forces that resist relative motion as two touching surfaces slide across one another.

slip Plastic deformation of a crystal that occurs when one sheet of atoms slides across another sheet.

soft Having a small spring constant and thus experiencing small restoring forces in response to large distortions.

soft magnetic material A material that is relatively easy to magnetize and that loses its magnetization once the magnetizing field is removed. Soft magnetic materials are suitable for electromagnets.

solid A form of matter consisting of particles (atoms or molecules) that touch and that are not free to move relative to one another. A solid has a fixed volume and shape.

solvation shell A cloud of oriented liquid molecules that surrounds a molecule or ion and carries it around a liquid in solution.

sound In air, sound consists of density waves, patterns of compressions and rarefactions that travel outward from their source at the speed of sound.

special theory of relativity The physical rules governing all motion, even motion involving speeds comparable to the speed of light.

specific heat The amount of heat that must be added to a unit mass of a material to cause a unit rise in its temperature. The SI unit of specific heat is the joule-per-kilogram-kelvin.

speed A measure of the distance an object travels in a certain amount of time. The SI unit of speed is the meter-per-second.

speed of light The speed with which an electromagnetic wave travels through space. In empty space, a vacuum, the speed of light is exactly 299,792,458 m/s.

speed of sound The speed at which sound's compressions and rarefactions travel in a medium such as air or water.

spontaneous emission of radiation Light emission that occurs when an excited atom or atomlike system releases stored energy randomly through a radiative transition. The photon that results is independent and unique.

spring constant As a measure of the stiffness of an elastic object, the spring constant relates the object's distortion to the restoring force it exerts. The larger the spring constant, the stiffer the spring.

springlike force A force that is proportional to displacement, consistent with Hooke's law.

sputtering Ejection of atoms from a surface caused by the impact of energetic ions, atoms, or other tiny projectiles.

stable equilibrium A state of equilibrium to which an object will return if it's disturbed. At equilibrium, the object is free of net force or torque. If an object is moved away from that equilibrium state, however, the net force or torque that will then act on it will tend to return it to equilibrium.

stall When a fluid flow stops and spoils steady-state flow. In the aerodynamic flow around an airfoil, stalling refers to airflow separation triggered by a stall in the flow near the airfoil's surface.

standard units Agreed on amounts of various physical quantities, which define a system in which those quantities are subsequently measured.

standing wave A wave in which all the nodes and antinodes remain in place.

state A possible arrangement of electrons (or other particles) in a quantum system.

static friction The forces that resist relative motion as outside forces try to make two touching surfaces begin to slide across one another.

static stability An object's stability when it's not in motion.

static variations Changes in a physical quantity such as pressure that are not caused by motion.

steady-state flow A situation in a fluid where the characteristics of the fluid at any fixed point in space don't change with time.

Stefan–Boltzmann constant The constant of proportionality relating a surface's radiated power to its emissivity, temperature, and surface area. It has a measured value of $5.67 \times 10^{-8} \text{ J}/(\text{s}\cdot\text{m}^2\cdot\text{K}^4)$.

Stefan–Boltzmann law The equation relating a surface's radiated power to its emissivity, temperature, and surface area.

stiffness A measure of how rapidly a restoring force increases as the system exerting that force is distorted.

stimulated emission of radiation Light emission that occurs when an excited atom or atomlike system releases stored energy through a radiative transition by duplicating a photon passing through that system.

strain The stress-induced change in a material's length divided by its original length.

streamline The path followed by a particular portion of a flowing fluid.

streamlined Carefully tapered so that the fluid flowing around it doesn't stall and doesn't experience flow separation or pressure drag.

stress A compressive or tensile force exerted on a material divided by the area over which that force is exerted.

strong force The fundamental force that gives structure to nuclei and nucleons and is the basis for the nuclear force.

subatomic particles The fundamental building blocks of the universe, from among which atoms and matter are constructed.

subcritical mass A portion of fissionable material that is too small to sustain a chain reaction.

sublimation The process by which atoms or molecules go directly from a solid to a gas.

superconductor An electrical conductor that permits electrons to flow without losing any of their kinetic energy to thermal energy. Electrons will continue to flow in a superconductor indefinitely. Materials only become superconducting at extremely low temperatures.

supercooled Below the temperature at which a phase transition should have occurred. Supercooling results from a failure to nucleate the new phase and/or a loss of mobility in the material before the new phase could fully develop.

supercritical mass A portion of fissionable material that is well in excess of a critical mass so that it undergoes an explosive chain reaction.

superheated Above the temperature at which a phase transition should have occurred. Superheating results from a failure to nucleate the new phase.

superposition The overlapping of two or more waves so that their amplitudes add together and they form a combined wave.

supersaturated Containing more of something than phase equilibrium will allow. A phase separation should occur, but it may be delayed by a failure to nucleate the second phase and/or inadequate mobility within the existing supersaturated phase.

support force A force that is exerted when two objects come into contact. Each object exerts a force on the other object to keep the two from passing through one another. Support forces are always normal, or perpendicular, to the surfaces of objects.

surface area The extent of a two-dimensional surface bounded by a particular border. The SI unit of surface area is the meter².

surface tension An inward tension that appears whenever a surface has extra potential energy. It acts to make that surface as small as possible.

surface waves Disturbances in the stable equilibrium shape of a surface.

sympathetic vibration The transfer of energy between two natural resonances that share a common frequency of oscillation.

tank circuit A simple resonant circuit consisting of a capacitor and an inductor. Energy flows back and forth between these two devices repetitively.

temper (glass) To soften glass at high temperature and then cool its surface quickly so as to put that surface under compressive stress.

temper (metals) Bake a material at moderate temperatures to relieve trapped stresses.

temperature A measure of the average internal kinetic energy per particle in a material. In a gas, temperature measures the average kinetic energy of each atom or molecule.

tensile strength The maximum tensile stress that a material can withstand before fracturing.

tensile stress A stress involving tension.

tension Outward forces on an object that tend to stretch it.

terminal velocity The velocity at which an object moving through a fluid experiences enough drag force to balance the other forces on it and keep it from accelerating.

tesla (T) The SI unit of magnetic field (synonymous with newton-per-ampere-meter).

thermal conductivity The measure of a material's capacity to transport heat by conduction from its hotter end to its colder end.

thermal energy A disordered form of energy contained in the kinetic and potential energies of the individual atoms and molecules that make up a substance. Because of its random distribution, this disordered energy can't be converted

directly into useful work. Other names for thermal energy include internal energy and heat.

thermal equilibrium A situation in which no heat flows in a system because all of the objects in the system are at the same temperature.

thermal motion The random motions of individual particles in a material due to the internal or thermal energy of that material.

thermal neutrons Neutrons that move with only thermal energies so that their kinetic energies are consistent with the local temperature.

thermionic emission The emission of electrons that occurs when thermal energy in a hot surface ejects those electrons from the surface.

thermistor A semiconductor temperature sensor that experiences a dramatic increase in electric conductivity as its temperature increases.

thermocouple A metallic temperature sensor in which two dissimilar metals joined at two junctions respond electrically to temperature differences between the junctions.

thermoplastic A polymer composed only of individual chains. In principle, a thermoplastic can melt and flow, although some thermoplastics decompose or burn before melting.

thermoset A polymer in which the individual chains have been cross-linked with covalent bonds so that it's one giant molecule. A thermoset can't melt or flow.

third law of thermodynamics As an object's temperature approaches absolute zero, its entropy approaches zero. This law points out that absolute zero is the unattainable state in which an object has no disorder.

thrust A forward, propulsive force.

tidal forces The differences between one celestial object's gravity at particular locations on the surface of a second object and the average of that gravity for the entire second object. Tidal forces tend to stretch the second object into an egg shape.

timbre The mixture of tones in an instrument's sound that are characteristic of that instrument.

torque An influence that if exerted on a free body results chiefly in an angular acceleration of the body. A torque is a vector quantity, consisting of both the amount of torque and its direction. The SI unit of torque is the newton-meter.

total internal reflection Complete reflection of a light wave that occurs when that wave tries unsuccessfully to leave a material with a large refractive index for a material with a small refractive index at too shallow an angle.

toughness A measure of how much mechanical energy a material can absorb without fracturing.

traction The largest frictional force that an object can obtain in its present situation.

trajectory The path taken by an object as it moves.

transformer A device that uses magnetic fields to transfer electric power from one circuit to another circuit. The two circuits are electrically isolated since no charges actually travel between the two circuits.

transistor An electronic component that allows a tiny amount of electric charge, either moving or stationary, to control the flow of a large electric current.

translational motion Motion in which an object moves as a whole along a straight or curved line.

transmutation of elements Changing the atoms of one element into another via nuclear processes that alter the numbers of protons in their nuclei.

transverse wave A wave in which the underlying oscillation is perpendicular to the wave itself.

traveling wave A wave that moves steadily through space in a particular direction.

trough A peak negative excursion of an extended system that is experiencing a wave.

tunneling Because of the Heisenberg uncertainty principle, small objects have somewhat ill-defined positions and occasionally move through energy barriers to places they can't reach classically. That quantum process is tunneling.

turbulence The unpredictable swirls and eddies of turbulent fluid flow.

turbulent flow Irregular, fluctuating, unpredictable fluid flow in which nearby portions of the fluid quickly become widely separated.

ultraviolet light Invisible light having wavelengths shorter than about 400 nanometers.

uniform circular motion Motion at a constant speed around a circular trajectory. An object undergoing uniform circular motion is accelerating toward the center of the circle.

unstable equilibrium An equilibrium situation to which the object will not return if it's disturbed. At equilibrium, the object is free of net force or torque. However, if the object is moved away from that equilibrium situation, the net force or torque that will then act on it will tend to accelerate it further away from the equilibrium situation.

vacuum tube A device in which the flow of electrons through empty space between a filament and a plate is controlled by a small amount of charge on one or more control grids.

valence band The group of quantum levels in an insulator that lies below the Fermi level.

valence electrons The outermost electrons of an atom. These atoms are principally responsible for the chemical properties of the atom.

valence level A quantum level in an insulator that requires less energy than the Fermi level and that is normally occupied by electrons.

van der Waals bond An extremely weak chemical bond in which nearby molecules are held together by quantum charge fluctuations.

van der Waals forces Weak, non-directional intermolecular forces that are created by temporary quantum fluctuations in the positions of electric charges in atoms or molecules.

vector quantity A quantity, characterizing some aspect of a physical system, that consists of both a magnitude and a direction in space.

velocity A vector quantity that measures how quickly an object's position is changing; the greater the velocity, the farther the object travels each second. It consists of both the object's speed and the direction in which the object is traveling. The SI unit of velocity is the meter-per-second.

Venturi effect The increase in speed and drop in pressure that occur when an incompressible fluid in steady-state flow passes through a narrow channel.

vertical polarization An electromagnetic wave in which the electric field always points up or down (vertically). The magnetic field always points horizontally.

vibration A spontaneous repetitive and rhythmic movement about an equilibrium position.

vibrational antinode A region of a vibrating object that is experiencing maximal motion.

vibrational node A region of a vibrating object that is not moving at all.

virtual image A pattern of light that appears to come from a particular region of space and reproduces the pattern of light at the surface of the original object. A virtual image forms before the lens that creates it and can't be projected onto a surface.

viscosity The measure of a fluid's resistance to relative motion within that fluid.

viscous drag A drag force that results from viscous forces on a moving surface immersed in a fluid.

- viscous forces** The forces exerted within a fluid that oppose relative motion. Layers of fluid that are moving across one another exert viscous forces on each other.
- visible light** Light having wavelengths between about 400 nanometers (violet) and 750 nanometers (red). This small portion of the electromagnetic spectrum is all that we are able to detect with our eyes.
- volt (V)** The SI unit of voltage (synonymous with joule-per-coulomb). The voltage on the positive terminal of a common battery is about 1.5 volts above that on its negative terminal.
- voltage drop** The amount of electrostatic potential energy that each coulomb of positive charge loses in passing through a device. It's equal to the voltage of the charges entering the device minus the voltage of the charges leaving that device.
- voltage gradient** A gradual slope in the voltage across a region of space. A voltage gradient is an electric field.
- voltage rise** The amount of electrostatic potential energy that each coulomb of positive charge receives in passing through a device. It's equal to the voltage of the charges leaving the device minus the voltage of the charges entering that device.
- voltage** The electrostatic potential energy of each unit of positive electric charge at a particular location. The SI unit of voltage is the volt.
- volt-per-meter (V/m)** The SI unit of electric field (synonymous with newton-per-coulomb).
- volume** The extent of a three-dimensional region of space bounded by a particular enclosure. The SI unit of volume is the meter³.
- vortex** A whirling region of fluid that is moving in a circle above a central cavity.
- vulcanization** A process in which the individual chains of a thermoplastic are cross-linked to produce a thermoset.
- wake deflection force** A lift force experienced by a spinning ball when it deflects its turbulent wake to one side. The wake deflection force points toward the side of the ball moving away from the onrushing airstream.
- wake** The trail left behind by an object as it moves through a fluid.
- water hammer** The impact of a moving mass of water that is suddenly stopped.
- watt (W)** The SI unit of power, equal to the transfer of 1 joule-per-second. One watt is the power used by the bulb of a typical flashlight.
- wave velocity** The speed and direction of the moving crests of a wave.
- wavelength** A structural characteristic of a wave, corresponding to the distance separating adjacent crests or troughs.

wave-particle duality The observation that everything in nature has both particle and wave characteristics. An item is primarily particlelike when it is emitted, absorbed, or otherwise observed and primarily wavelike as it travels through time and space.

weak force The fundamental force that allows electrons and neutrinos to interact and that's responsible for beta decay.

weight (near the earth's surface) The downward force exerted on an object due to its gravitational interaction with the earth. An object's weight is equal to the product of that object's mass times the acceleration due to gravity. The direction of the weight is always toward the center of the earth.

work hardening Hardening that occurs when extensive manipulation reduces the size of grains in a polycrystalline material.

work The mechanical means of transferring energy. Work is defined as the force exerted on an object times the distance that object travels in the direction of the force. A large force exerted for a short distance or a small force exerted for a long distance can perform the same amount of work. The SI unit of work is the joule.

X-ray fluorescence The process in which an electron in one of the outer orbitals of an atom undergoes a radiative transition to an empty inner orbital, emitting an X-ray photon.

X-rays Very high-energy photons of electromagnetic radiation.

yield strength The stress at which a material first begins to undergo plastic deformation.

zeroth law of thermodynamics Two objects that are each in thermal equilibrium with a third object are also in thermal equilibrium with one another. This law is the basis for a meaningful system of temperatures.