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Light

Of all the forms of energy in nature, light is the most important to our lives. Without light there would be no life on Earth. Plants could not grow. And with no plants for food, animals could not exist. Light also enables humans and other animals to see.

For as long as people have asked questions, they have wondered about light. Ancient peoples created myths to explain how the bright objects of the sky—the Sun, Moon, stars, and planets—made their light and how they moved. They knew how to make light from fire. They invented torches, oil lamps, candles, and other ways to control it. Today we make light in many different ways. And we control and use it in many different devices.

A source of light is an object that creates its own light. The Sun is the most important source of light for Earth. Other stars are also sources of light. But the Sun appears much brighter because it is much closer to us.

Most objects are not sources of light. We see them only when light from a source strikes them and bounces off toward our eyes. This bouncing of light from matter is called reflection. The ancients thought the Moon and planets were sources of light. But we now know they are not. We see them because sunlight reflects from their surfaces and travels to Earth.

☐ Nature of Light

As people developed science, they had more and more questions about light. They wanted to know how it is produced and how it behaves. One of the most important questions was posed in the 1600s by the English scientist and mathematician Isaac Newton. Newton wondered whether light spreads out from its source as a stream of tiny particles, or whether it travels through space as waves, like ripples in a pond.

A wave theory had been proposed earlier in the century by the Dutch physicist and astronomer Christiaan Huygens. And it had already been widely accepted by many scientists. Huygens's ideas successfully explained the way light behaves as it reflects from matter or passes through it.

Newton did some experiments with shadows that showed that light travels in straight lines. If light behaved like water waves, it would not cast shadows. Instead, when light passed by an object, it would quickly fill in the space behind it, as water waves do when they pass a rock. Newton therefore concluded that light must not travel in waves. Rather, he theorized, it was made of tiny particles, which he called corpuscles. For many years, Newton's corpuscular, or particle, theory of light prevailed over wave theory. Which theory was correct?

Scientists now accept that light has properties of both waves and particles. As a wave, light is a special kind of energy transmission. The energy is carried in the form of paired electric and magnetic fields. Scientists have these fields in mind when they call light a form of electromagnetism.

When a ray of light travels through space, paired electric and magnetic fields oscillate back and forth. These motions create wave-shaped patterns along the ray's path. The distance from one wave crest to the next is the light's wavelength.

Under certain circumstances, light seems to act less like a continuous wave and more like a stream of individual particles. These particles are called photons. They amount to individual bundles of energy. Interpreting light this way has helped scientists explain various phenomena, including laser light.

☐ Reflection, Refraction, and Dispersion

When light strikes matter, it can bounce off, be absorbed by, or pass through the material. Lines can be drawn to show the direction in which light is moving. Such lines are called rays of light. When a ray of light shines on an ordinary surface such as a piece of cloth, it bounces off that surface in every direction. The one bright ray coming in becomes many not-so-bright rays going out. It is the way we see most objects.

Some surfaces, especially metals, are smooth and shiny. When a bright ray of light strikes a shiny surface, it bounces off in only one direction. If the ray strikes the surface perpendicularly (head-on), it bounces straight back in the opposite direction. If the ray strikes the surface at an angle, the outgoing ray makes the same angle with the surface as the incoming ray. The law of reflection says that these two angles are always equal. The reflecting surface is called a mirror.

Newton's Prism Experiment and Refraction

As Newton studied light and color, one of his first findings was that sunlight contains all the colors. Newton observed sunlight as it came through a hole in the window shade of a darkened room. When this light passed through a prism (a solid, three-sided piece of glass), a band of colors appeared on the opposite wall. The colors changed gradually from red at one end to violet on the other, with regions of orange, yellow, green, blue, and indigo in between. Newton called this spread of colors a spectrum.

Newton kept experimenting with the spectrum. Eventually, he was convinced that sunlight was a mixture of all the colors and that the prism separated the colors.

How does a prism produce a spectrum? A material that lets light pass through is said to be transparent. When light crosses a boundary from one transparent material, such as air, to another, such as glass, it changes direction, unless it is traveling exactly perpendicular to the boundary. This change of direction is called refraction.

When a narrow beam of light strikes one side of a prism it changes direction, shifting closer to the perpendicular. Each color in the light refracts a different amount. Red changes direction the least and violet the most.

When the separated colors pass through the opposite side of the prism, they again refract, this time shifting away from the perpendicular. Again the red changes direction less than the violet. As a result, each color is now going in a different direction. When the light strikes and reflects off the wall, the spectrum is clearly visible. This spreading of colors due to refraction is called dispersion. Dispersion of light in raindrops is responsible for producing rainbows.

Scattering

When light passes through a gas or liquid, each time it strikes a dust particle or a molecule it changes direction. Thus the beam of light is made to spread out in every direction. This process is called scattering. Colors near the violet end of the spectrum scatter more than those at the red end. Scattering causes dispersion of colors just as refraction does. But it does not create a spectrum.

Color

The color of an object depends on the way it reflects and absorbs light. The object absorbs certain colors and reflects others. The color we see is a combination of all the colors that the object reflects. An apple looks red because the surface of the apple reflects colors from the red end of the spectrum and absorbs the rest. Black objects absorb all colors. White objects reflect all colors.

Intensity of Light

If light is discussed casually, words such as "intensity" and "brightness" seldom need explanation. But they are usually too vague for scientists who measure light.

Scientists use two parallel groups of terms to quantify light energy. They use radiometric terms when they describe light energy that is actually there. They use photometric terms to describe light energy that is perceptible by the human eye. Humans do not perceive all kinds of light energy, only certain colors. And even these colors are perceived with different sensitivities.

A basic unit used to measure energy, the joule, can be used to quantify light energy. Like other forms of energy, light energy is the ability to perform work. And the rate at which energy is expended (and work performed) is called power.

The radiometric term for power is radiant flux. And the unit used in measurements of radiant flux is the watt. (One watt equals 1 joule per second.) The corresponding photometric unit is luminous flux. It has its own unit, the lumen. Like other photometric quantities, the lumen accounts for the eye's sensitivities.

Radiant flux and luminous flux are often used to describe the strength of a light source. Other terms are used to describe the amount of light that is received by an illuminated surface. This is typically measured in terms of power per unit area. In radiometry, this quantity is irradiance (watts per square meter). In photometry, it is illuminance (lumens per square meter).

Light typically spreads out from a source. As a result, irradiance and illuminance decrease with distance. In the case of a point source, light spreads evenly in all directions. The light from a point source that radiates in a particular direction—a cone of light—may be expressed in terms of luminous intensity. (This photometric quantity is measured in candelas, so named because this kind of intensity was once measured in candles, which related the intensities of light sources to the intensity of a standard candle.)

Luminous intensity follows the inverse square law. Light that travels three times as far from a point source is spread over nine times the area. Hence the light over a given area seems one-ninth as bright.

Diffraction, Interference, and Wave Theory

A different behavior of light was incorporated into an experiment by the English physicist Thomas Young in 1801. The results made a convincing case for the wave theory of light.

Scientists had noticed that objects with sharp edges cast shadows that are not as sharp. Light seems to bend a little bit around the edge of the object. This produces a fuzzy boundary between light and darkness. This bending of light as it passes the edge of an object is called diffraction. Young wondered if diffraction could be used to prove that light is made of waves.

It was known that diffraction also occurs when light passes through a very small opening. In this case, diffraction causes the light to spread out on the other side of the opening. Young created a point source of light by passing sunlight through a pinhole in a light-absorbing screen. He allowed that light to spread out a bit before it struck a second screen with two pinholes close together. It then continued to a third screen, where any patterns might be observed.

If the particle theory was right, the third screen would be brightest in the middle, with the intensity dropping off toward the edges. If the wave theory was right, the brightness pattern would be very different.

Since the original light came from a tiny hole, Young reasoned that the crest, or high point, of each wave would reach the two pinholes at the same time. The two pinholes would then act like two sources, putting out crests and troughs (low points of waves) in perfect step with each other. The waves would not simply add together when they reached the third screen. Instead, they would interfere with each other.

Young realized that this interference would distinguish wave behavior from particle behavior. At the center of the screen, the waves would meet crest-to-crest and trough-to-trough, making the combined wave much brighter. A short distance to the left or right of the screen's center, one of the two pinhole waves would have traveled a half-wavelength farther than the other. (A wavelength is the distance between crests or troughs.) There the two waves would meet crest-to-trough. They would cancel each other and leave a dark spot. A little farther left or right and the waves would have traveled distances that differ by a whole wavelength. Again these waves would meet crest-to-crest and trough-to-trough, producing bright spots.

The net result would be a series of bright and dark bands on the third screen. This is exactly what Young saw. From that point on, the wave theory of light was favored over the particle theory.

Electromagnetic Waves

In 1865 the wave theory of light became even stronger. At this time, the Scottish physicist James Clerk Maxwell published a set of mathematical formulas to describe the relationships between electricity and magnetism. His formulas led him to predict the existence of electromagnetic waves.

An important part of Maxwell's work was his computation for the speed of electromagnetic waves. He found that it nearly matched the best experimental measurement of the speed of light at that time. He concluded that light itself was an electromagnetic wave.

Today the speed of light and all other electromagnetic waves traveling through empty space are usually given as approximately 186,000 miles (300,000 kilometers) per second.

Electromagnetic waves have many similarities to ocean waves—and some important differences. As ocean waves pass through water, the water level rises and falls at a steady rate. This rate is called the frequency. The wave crests are evenly spaced, separated by a distance called the wavelength. The speed of the wave can be calculated by multiplying the frequency by the wavelength. The wave crests and troughs are above and below the normal ocean level by an amount that is called the amplitude.

Electromagnetic waves have wavelength, frequency, and amplitude as well. But one of the important differences between water waves and electromagnetic waves is that water waves need matter to exist, whereas electromagnetic waves can travel in empty space.

Maxwell's equations also predicted that an electromagnetic wave can have any frequency. Visible light has very short wavelengths and very high frequencies. Each color on the visible light band has a different frequency. Frequencies for visible light range from about 425 trillion cycles (or waves) per second for red to about 750 trillion cycles per second for violet.

Visible light is just one part of the electromagnetic spectrum. Most of the spectrum is not visible. Lower frequencies include radio waves, microwaves, and infrared light. Higher frequencies correspond to ultraviolet light, X-rays, and gamma rays.

Polarized Light

Maxwell's equations also allow for a kind of light called polarized light. For example, the electric field of a particular light ray may be moving up and down while the magnetic field moves from left to right. We can describe that ray as having up-down polarization. Another light ray may have the electric field moving from left to right while the magnetic field moves up and down. We can say that ray has left-right polarization. Or we may imagine the polarization direction of a ray at any angle between up and down or left and right.

A light source may put out all its rays in the same direction of polarization. This light is called polarized. If the rays have random polarizations, it is unpolarized.

Particle Theory Returns

Because of Maxwell's work, scientists were now convinced that light was an electromagnetic wave. It appeared to be the end of the particle-or-wave debate, but it was not. Toward the end of the 1800s, the German physicist Max Planck discovered a new way to explain some peculiar results in the study of radiation from hot bodies.

Quantum Theory

Every object, no matter how hot or cold, produces some electromagnetic radiation. If an object is hot enough, it radiates visible light. In the late 1800s scientists were measuring the spectra of radiating bodies, examining how much energy is radiated at each wavelength. They found that the theory they were using was in very good agreement with the measured spectrum in the visible light range. But it matched very poorly in the ultraviolet range. The theory predicted a rapid increase of intensity in the ultraviolet part of the spectrum. However, the experiment showed that the intensity was actually decreasing instead.

Planck devised a theory that explained this spectrum mathematically. However, it required light energy to be radiated in packets. He called these packets quanta (singular: quantum, from the Latin word for "bundle"). The energy of each quantum was mathematically equal to the frequency of the light wave times a value that came to be known as Planck's constant.

Planck's ideas started a whole new line of scientific thinking. This thinking came to be called quantum theory, or quantum mechanics.

The Photoelectric Effect

In 1905 the German-American physicist Albert Einstein applied Planck's theory to a recently discovered phenomenon called the photoelectric effect.

When light shines on certain metals, it releases electrons from the metal and creates an electric current. This is called photoelectricity. American physicist Robert Millikan studied this phenomenon. He discovered that applying a high enough electrical voltage to the metal would completely halt the photoelectricity. This voltage was called the stopping potential. Even the most intense light would fail to free electrons from the metal. But Millikan could start the current again. He did so by changing to a source of higher-frequency light (more toward the violet and ultraviolet portion of the spectrum). This light would work, no matter how dim.

Einstein realized that if light really came in quantized packages, Millikan's discovery would make sense. When a light quantum struck the metal, an electron would absorb its energy and fly off. It would carry that energy as kinetic energy

(energy of motion). The stopping potential would be like an electrical hill. If the quantum had enough energy, the freed electron would be able to clear the hill. A current would flow. Otherwise, no matter how many electrons absorbed quanta, the result would be nothing but a lot of electrons that do not quite escape from the metal. No current would be produced.

Using Planck's theory, Einstein calculated the energy of the light quanta. Then he computed the energy necessary to clear the stopping potential. The results were the same. The photoelectric effect demonstrated that Planck's quanta were far more than just a mathematical invention. They were real. Light came in packets of energy—particles called photons—just as surely as it came in electromagnetic waves.

Today, as noted earlier in this article, scientists agree that light has both a wave nature and a particle nature.

Light and Matter

The quantum theory describes not only the behavior of light, but also the properties of atoms and subatomic particles. These are the building blocks of all matter. It was no longer possible to avoid the conclusion that light has both wave and particle properties. As a result, scientists posed a new question: Do electrons and other particles have wavelike properties?

One of the first scientists to show how quantum theory could be used to understand the behavior and structure of atoms was the Danish physicist Niels Bohr. Bohr's research in the early 1900s involved working with a particular kind of spectrum.

Line Spectra

Sunlight or radiation from a hot body, such as a lamp filament, can be dispersed by passing it through a prism or a raindrop. The colors spread out and blend into one another with no breaks between colors. This spread is called a continuous spectrum.

Although light with a continuous spectrum is most familiar in everyday life, one has also seen light with a different kind of spectrum. A number of stores and other businesses use signs with colored lighting. The colors are created by passing electricity through a gas-filled tube. A tube filled with neon gas produces a bright red light. Other colors are produced by other gases and metallic vapors, such as mercury and sodium.

Only certain frequencies are present in the light emitted by each different kind of material. And only certain colors will show up in its spectrum. When the light from one of these gas-filled tubes is dispersed, the resulting spectrum is a series of bright narrow lines of different colors separated by dark spaces. This is called a line spectrum, or an emission spectrum. Each element or material produces its own pattern of spectrum lines. As a result, line spectra can be used to identify which materials are present in a given sample.

Bohr Model

Hydrogen is the simplest of all atoms. It has only one electron and one proton. It has a line spectrum whose frequencies follow a simple mathematical relationship. For these reasons, Bohr set out to see if he could discover a way to understand the spectrum of hydrogen using the newly discovered quantum. Bohr's idea was to describe an atom as a miniature solar system, with electrons carrying a negative charge in orbit around a positively charged nucleus. This is called the Bohr model of the atom.

The Bohr model had one serious problem, which Bohr himself recognized. According to the laws of electromagnetism, when a charged particle moves in a curved path (such as the curved orbit of an electron), it radiates electromagnetic waves and loses energy. This energy loss would cause the electron to spiral inward into the nucleus. And that would be the end of the atom.

So Bohr invented a rule. Electrons in certain special orbits, he proposed, do not radiate. What makes such orbits special? If you multiply the mass of the electron by its speed, and then multiply that by the circumference of the orbit, you get Planck's constant, or twice Planck's constant, or three times Planck's constant, and so forth.

From that model Bohr developed a formula for the energy level of each special, or "allowed," orbit. To go from one orbit to another, the electron must either absorb or emit a photon. The energy of that photon must be equal to the gain or loss of energy between the orbits. Knowing the photon's energy and Planck's constant, Bohr computed the frequency of the light that would be produced. Considering all the allowed orbits, Bohr computed the line spectrum of hydrogen. The computed spectrum matched the actual measured spectrum.

With Bohr's successful theory, quantum mechanics was established as the basis of understanding all matter and energy in the universe. After Bohr's work, other scientists continued to work on quantum theory, developing it more completely. A fuller understanding of atomic spectra now requires one to think of an electron as having both particlelike and wavelike properties. This idea first emerged from the study of light.

See also: Color ; Photoelectricity ; Radiation ; Waves and Wave Motion .

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