How Light Works

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What Is Light?

Ancient Greeks argued over whether light rays emanated from a person's eye or the object being viewed.

.Over the centuries, our view of light has changed dramatically. The first real theories about light came from the ancient Greeks. Many of these theories sought to describe light as a ray -- a straight line moving from one point to another. Pythagoras, best known for the theorem of the right-angled triangle, proposed that vision resulted from light rays emerging from a person's eye and striking an object. Epicurus argued the opposite: Objects produce light rays, which then travel to the eye. Other Greek philosophers -- most notably Euclid and Ptolemy -- used ray diagrams quite successfully to show how light bounces off a smooth surface or bends as it passes from one transparent medium to another.

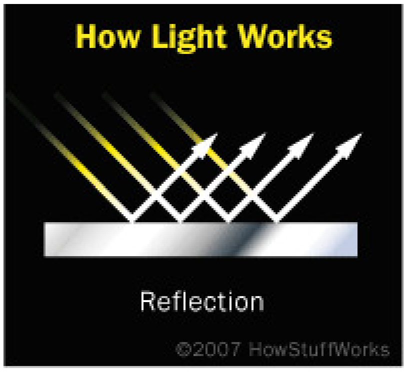
Arab scholars took these ideas and honed them even further, developing what is now known as geometrical optics -- applying geometrical methods to the optics of lenses, mirrors and prisms. The most famous practitioner of geometrical optics was Ibn al-Haytham, who lived in present-day Iraq between A.D. 965 and 1039. Ibn al-Haytham identified the optical components of the human eye and correctly described vision as a process involving light rays bouncing from an object to a person's eye. The Arab scientist also invented the pinhole camera, discovered the laws of refraction and studied a number of light-based phenomena, such as rainbows and eclipses.

By the 17th century, some prominent European scientists began to think differently about light. One key figure was the Dutch mathematician-astronomer Christiaan Huygens. In 1690, Huygens published his "Treatise on Light," in which he described the undulatory theory. In this theory, he speculated on the existence of some invisible medium -- an ether -- filling all empty space between objects. He further speculated that light forms when a luminous body causes a series of waves or vibrations in this ether. Those waves then advance forward until they encounter an object. If that object is an eye, the waves stimulate vision.

This stood as one of the earliest, and most eloquent, wave theories of light. Not everyone embraced it. Isaac Newton was one of those people. In 1704, Newton proposed a different take -- one describing light as corpuscles, or particles. After all, light travels in straight lines and bounces off a mirror much like a ball bouncing off a wall. No one had actually seen particles of light, but even now, it's easy to explain why that might be. The particles could be too small, or moving too fast, to be seen, or perhaps our eyes see right through them.

As it turns out, all of these theories are both right and wrong at once. And they're all useful in describing certain behaviors of light.

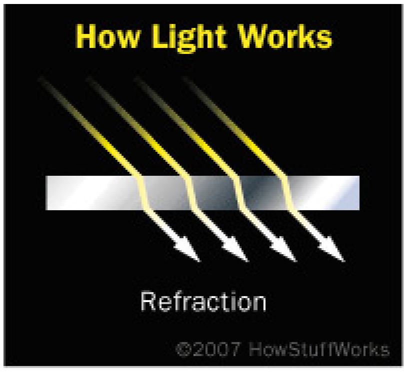
Light as Rays



Imagining light as a ray makes it easy to describe, with great accuracy, three well-known phenomena: reflection, refraction and scattering. Let's take a second to discuss each one.

In **reflection**, a light ray strikes a smooth surface, such as a mirror, and bounces off. A reflected ray always comes off the surface of a material at an angle equal to the angle at which the incoming ray hit the surface. In physics, you'll hear this called the **law of reflection**. You've probably heard this law stated as "the angle of incidence equals the angle of reflection."

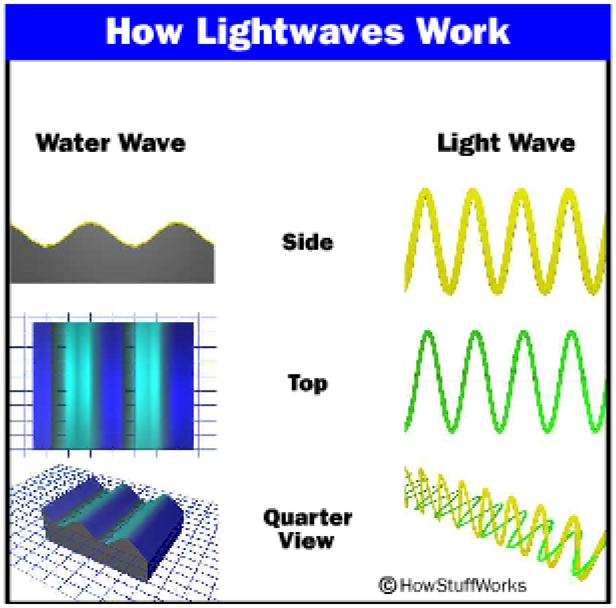
Of course, we live in an imperfect world and not all surfaces are smooth. When light strikes a rough surface, incoming light rays reflect at all sorts of angles because the surface is uneven. This **scattering** occurs in many of the objects we encounter every day. The surface of paper is a good example. You can see just how rough it is if you peer at it under a microscope. When light hits paper, the waves are reflected in all directions. This is what makes paper so incredibly useful -- you can read the words on a printed page regardless of the angle at which your eyes view the surface.



efraction occurs when a ray of light passes from one transparent medium (air, let's say) to a second transparent medium (water). When this happens, light changes speed and the light ray bends, either toward or away from what we call the **normal line**, an imaginary straight line that runs perpendicular to the surface of the object. The amount of bending, or **angle of refraction**, of the light wave depends on how much the material slows down the light. Diamonds wouldn't be so glittery if they didn't slow down incoming light much more than, say, water does. Diamonds have a higher index of refraction than water, which is to say that those sparkly, costly light traps slow down light to a greater degree.

Lenses, like those in a telescope or in a pair of glasses, take advantage of refraction. A lens is a piece of glass or other transparent substance with curved sides for concentrating or dispersing light rays. Lenses serve to refract light at each boundary. As a ray of light enters the transparent material, it is refracted. As the same ray exits, it's refracted again. The net effect of the refraction at these two boundaries is that the light ray has changed directions. We take advantage of this effect to correct a person's vision or enhance it by making distant objects appear closer or small objects appear bigger.

Unfortunately, a ray theory can't explain all of the behaviors exhibited by light. We'll need a few other explanations, like the one we'll cover next.



Unlike water waves, light waves follow more complicated paths, and they don't need a medium to travel through.

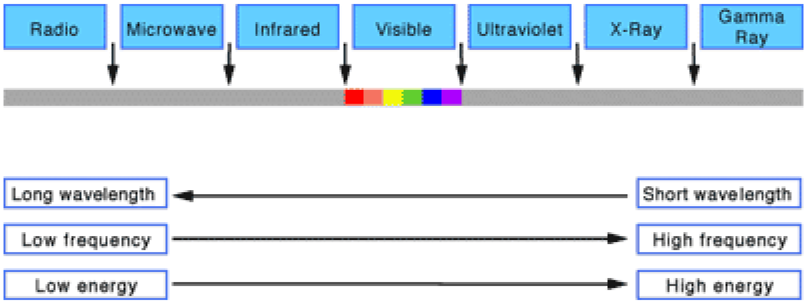
When the 19th century dawned, no real evidence had accumulated to prove the wave theory of light. That changed in 1801 when Thomas Young, an English physician and physicist, designed and ran one of the most famous experiments in the history of science. It's known today as the double-slit experiment and requires simple equipment -- a light source, a thin card with two holes cut side by side and a screen.

To run the experiment, Young allowed a beam of light to pass through a pinhole and strike the card. If light contained particles or simple straight-line rays, he reasoned, light not blocked by the opaque card would pass through the slits and travel in a straight line to the screen, where it would form two bright spots. This isn't what Young observed. Instead, he saw a bar code pattern of alternating light and dark bands on the screen. To explain this unexpected pattern, he imagined light traveling through space like a water wave, with crests and troughs. Thinking this way, he concluded that light waves traveled through each of the slits, creating two separate wave fronts. As these wave fronts arrived at the screen, they interfered with each other. Bright bands formed where two wave crests overlapped and added together. Dark bands formed where crests and troughs lined up and canceled each other out completely.

Young's work sparked a new way of thinking about light. Scientists began referring to light waves and reshaped their descriptions of reflection and refraction accordingly, noting that light waves still obey the laws of reflection and refraction. Incidentally, the bending of a light wave accounts for some of the visual phenomena we often encounter, such as mirages. A mirage is an optical illusion caused when light waves moving from the sky toward the ground are bent by the heated air.

In the 1860s, Scottish physicist James Clerk Maxwell put the cherry on top of the light-wave model when he formulated the theory of electromagnetism. Maxwell described light as a very special kind of wave -- one composed of electric and magnetic fields. The fields vibrate at right angles to the direction of movement of the wave, and at right angles to each other. Because light has both electric and magnetic fields, it's also referred to as electromagnetic radiation. Electromagnetic radiation doesn't need a medium to travel through, and, when it's traveling in a vacuum, moves at 186,000 miles per second (300,000 kilometers per second). Scientists refer to this as the speed of light, one of the most important numbers in physics.

Light Frequencies



Once Maxwell introduced the concept of electromagnetic waves, everything clicked into place. Scientists now could develop a complete working model of light using terms and concepts, such as wavelength and frequency, based on the structure and function of waves. According to that model, light waves come in many sizes. The size of a wave is measured as its wavelength, which is the distance between any two corresponding points on successive waves, usually peak to peak or trough to trough. The wavelengths of the light we can see range from 400 to 700 nanometers (or billionths of a meter). But the full range of wavelengths included in the definition of electromagnetic radiation extends from 0.1 nanometers, as in gamma rays, to centimeters and meters, as in radio waves.

Light waves also come in many frequencies. The frequency is the number of waves that pass a point in space during any time interval, usually one second. We measure it in units of cycles (waves) per second, or hertz. The frequency of visible light is referred to as color, and ranges from 430 trillion hertz, seen as red, to 750 trillion hertz, seen as violet. Again, the full range of frequencies extends beyond the visible portion, from less than 3 billion hertz, as in radio waves, to greater than 3 billion billion hertz (3 x 1019), as in gamma rays.

The amount of energy in a light wave is proportionally related to its frequency: High frequency light has high energy; low frequency light has low energy. So, gamma rays have the most energy (part of what makes them so dangerous to humans), and radio waves have the least. Of visible light, violet has the most energy and red the least. The whole range of frequencies and energies, shown in the accompanying figure, is known as the electromagnetic spectrum. Note that the figure isn't drawn to scale and that visible light occupies only one-thousandth of a percent of the spectrum.

This might be the end of the discussion, except that Albert Einstein couldn't let speeding light waves lie. His work in the early 20th century resurrected the old idea that light, just maybe, was a particle after all.

Light as Particles

Maxwell's theoretical treatment of electromagnetic radiation, including its description of light waves, was so elegant and predictive that many physicists in the 1890s thought that there was nothing more to say about light and how it worked. Then, on Dec. 14, 1900, Max Planck came along and introduced a stunningly simple, yet strangely unsettling, concept: that light must carry energy in discrete quantities. Those quantities, he proposed, must be units of the basic energy increment, hf, where h is a universal constant now known as Planck's constant and f is the frequency of the radiation.

Albert Einstein advanced Planck's theory in 1905 when he studied the photoelectric effect. First, he began by shining ultraviolet light on the surface of a metal. When he did this, he was able to detect electrons being emitted from the surface. This was Einstein's explanation: If the energy in light comes in bundles, then one can think of light as containing tiny lumps, or photons. When these photons strike a metal surface, they act like billiard balls, transferring their energy to electrons, which become dislodged from their "parent" atoms. Once freed, the electrons move along the metal or get ejected from the surface.

The particle theory of light had returned -- with a vengeance. Next, Niels Bohr applied Planck's ideas to refine the model of an atom. Earlier scientists had demonstrated that atoms consist of positively charged nuclei surrounded by electrons orbiting like planets, but they couldn't explain why electrons didn't simply spiral into the nucleus. In 1913, Bohr proposed that electrons exist in discrete orbits based on their energy. When an electron jumps from one orbit to a lower orbit, it gives off energy in the form of a photon.

The quantum theory of light -- the idea that light exists as tiny packets, or particles, called photons -- slowly began to emerge. Our understanding of the physical world would no longer be the same.

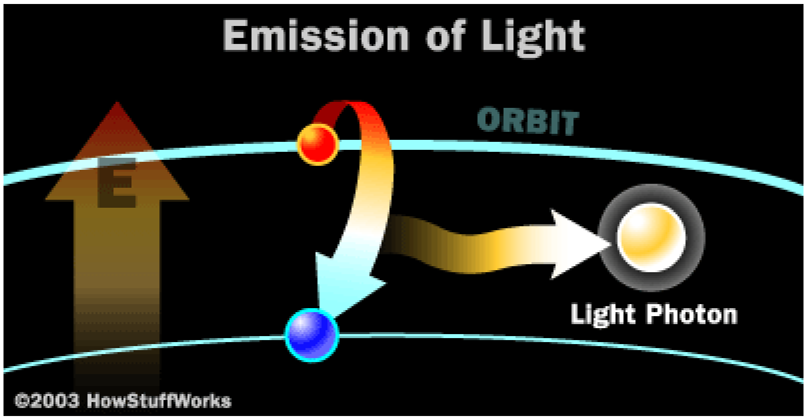
Wave-Particle Duality

At first, physicists were reluctant to accept the dual nature of light. After all, many of us humans like to have one right answer. But Einstein paved the way in 1905 by embracing wave-particle duality. We've already discussed the photoelectric effect, which led Einstein to describe light as a photon. Later that year, however, he added a twist to the story in a paper introducing special relativity. In this paper, Einstein treated light as a continuous field of waves -- an apparent contradiction to his description of light as a stream of particles. Yet that was part of his genius. He willingly accepted the strange nature of light and chose whichever attribute best addressed the problem he was trying to solve.

Today, physicists accept the dual nature of light. In this modern view, they define light as a collection of one or more photons propagating through space as electromagnetic waves. This definition, which combines light's wave and particle nature, makes it possible to rethink Thomas Young's double-slit experiment in this way: Light travels away from a source as an electromagnetic wave. When it encounters the slits, it passes through and divides into two wave fronts. These wave fronts overlap and approach the screen. At the moment of impact, however, the entire wave field disappears and a photon appears. Quantum physicists often describe this by saying the spread-out wave "collapses" into a small point.

Similarly, photons make it possible for us to see the world around us. In total darkness, our eyes are actually able to sense single photons, but generally what we see in our daily lives comes to us in the form of zillions of photons produced by light sources and reflected off objects. If you look around you right now, there is probably a light source in the room producing photons, and objects in the room that reflect those photons. Your eyes absorb some of the photons flowing through the room, and that's how you see.

Producing a Photon



There are many different ways to produce photons, but all of them use the same mechanism inside an atom to do it. This mechanism involves the energizing of electrons orbiting each atom's nucleus. How Nuclear Radiation Works describes protons, neutrons and electrons in some detail. For example, hydrogen atoms have one electron orbiting the nucleus. Helium atoms have two electrons orbiting the nucleus. Aluminum atoms have 13 electrons circling the nucleus. Each atom has a preferred number of electrons zipping around its nucleus.

Electrons circle the nucleus in fixed orbits -- a simplified way to think about it is to imagine how satellites orbit the Earth. There's a huge amount of theory around electron orbitals, but to understand light there is just one key fact to understand: An electron has a natural orbit that it occupies, but if you energize an atom, you can move its electrons to higher orbitals. A photon is produced whenever an electron in a higher-than-normal orbit falls back to its normal orbit. During the fall from high energy to normal energy, the electron emits a photon -- a packet of energy -- with very specific characteristics. The photon has a frequency, or color, that exactly matches the distance the electron falls.

You can see this phenomenon quite clearly in gas-discharge lamps. Fluorescent lamps, neon signs and sodium-vapor lamps are common examples of this kind of electric lighting, which passes an electric current through a gas to make the gas emit light. The colors of gas-discharge lamps vary widely depending on the identity of the gas and the construction of the lamp.

For example, along highways and in parking lots, you often see sodium vapor lights. You can tell a sodium vapor light because it's really yellow when you look at it. A sodium vapor light energizes sodium atoms to generate photons. A sodium atom has 11 electrons, and because of the way they're stacked in orbitals one of those electrons is most likely to accept and emit energy. The energy packets that this electron is most likely to emit fall right around a wavelength of 590 nanometers. This wavelength corresponds to yellow light. If you run sodium light through a prism, you don't see a rainbow -- you see a pair of yellow lines.

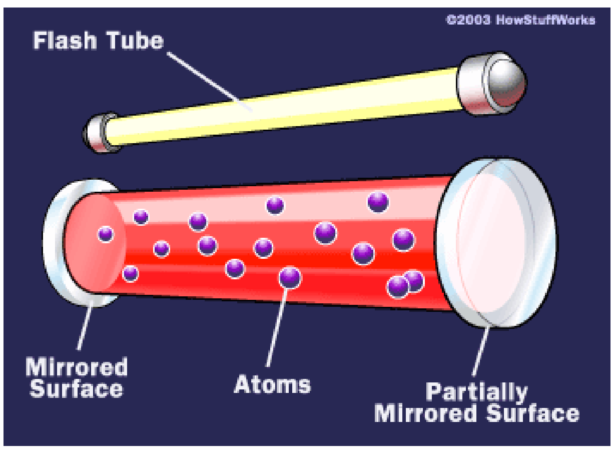
Incandescence: Creating Light With Heat

Probably the most common way to energize atoms is with heat, and this is the basis of incandescence. If you heat up a horseshoe with a blowtorch, it will eventually get red-hot, and if you indulge your inner pyromaniac and heat it even more, it gets white hot. Red is the lowest-energy visible light, so in a red-hot object the atoms are just getting enough energy to begin emitting light that we can see. Once you apply enough heat to cause white light, you are energizing so many different electrons in so many different ways that all of the colors are being generated -- they all mix together to look white.

Heat is the most common way we see light being generated -- a normal 75-watt incandescent bulb is generating light by using electricity to create heat. Electricity runs through a tungsten filament housed inside a glass sphere. Because the filament is so thin, it offers a good bit of resistance to the electricity, and this resistance turns electrical energy into heat. The heat is enough to make the filament glow white-hot. Unfortunately, this isn't very efficient. Most of the energy that goes into an incandescent bulb is lost as heat. In fact, a typical light bulb produces perhaps 15 lumens per watt of input power compared to a fluorescent bulb, which produces between 50 and 100 lumens per watt.

Combustion offers another way to produce photons. Combustion occurs when a substance -- the fuel -- combines rapidly with oxygen, producing heat and light. If you study a campfire or even a candle flame carefully, you will notice a small colorless gap between the wood or the wick and the flames. In this gap, gases are rising and getting heated. When they finally get hot enough, the gases combine with oxygen and are able to emit light. The flame, then, is nothing more than a mixture of reacting gases emitting visible, infrared and some ultraviolet light.

Lasers



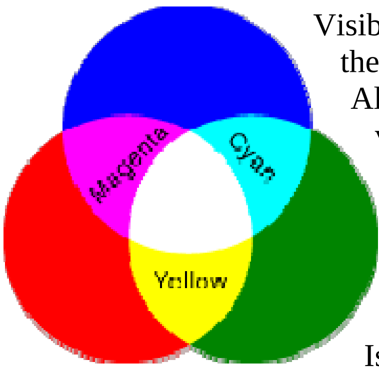
An interesting application of the quantum nature of light is the laser. You can get the whole story on lasers in How Lasers Work, but we're going to cover some of the key concepts here. Laser is an acronym for "light amplification by stimulated emission of radiation," which is a tongue-tying way to describe light in which the photons are all at the same wavelength and have their crests and troughs in phase. Research physicist Theodore H. Maiman developed the world's first working laser, the ruby laser, in 1960. The ruby laser contained a ruby crystal, a quartz flash tube, reflecting mirrors and a power supply.

Let's review how Maiman used these components to create laser light, starting with the characteristics of ruby. Ruby is an aluminum oxide crystal in which some of the aluminum atoms have been replaced with chromium atoms. Chromium gives ruby its characteristic red color by absorbing green and blue light and emitting or reflecting only red light. Of course, Maiman couldn't use a ruby in its naturally occurring crystalline state. First, he had to form the ruby crystal into a cylinder. Next, he wrapped a high-intensity quartz lamp around the ruby cylinder to provide a flash of white light. The green and blue wavelengths in the flash excited electrons in the chromium atoms to a higher energy level. As these electrons returned to their normal state, they emitted their characteristic ruby-red light.

Here's where it got interesting. Maiman placed a fully reflecting mirror on one end of the crystal and a partially reflecting mirror on the other. The mirrors reflected some of the red-wavelength photons back and forth inside the ruby crystal. This, in turn, stimulated other excited chromium atoms to produce more photons, until a flood of precisely aligned photons bounced back and forth within the laser. At each bounce, some of the photons escaped, which allowed observers to perceive the beam itself.

Today, scientists make lasers out of many different materials. Some, like the ruby laser, emit short pulses of light. Others, like helium-neon gas lasers or liquid dye lasers, emit a continuous beam of light.

Making Colors



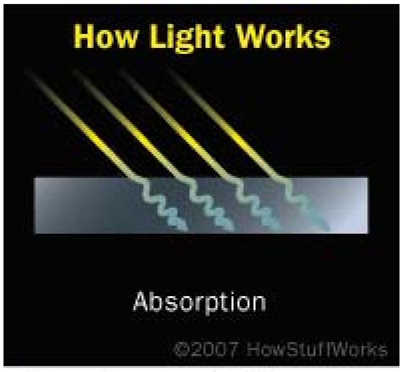
Visible light is light that the human eye can perceive. When you look at the sun's visible light, it appears to be colorless, which we call white. Although we can see this light, white isn't considered part of the visible spectrum. That's because white light isn't the light of a single color but instead many colors.

When sunlight passes through a glass of water to land on a wall, we see a rainbow on the wall. This wouldn't happen unless white light were a mixture of all of the colors of the visible spectrum. Isaac Newton was the first person to demonstrate this. Newton passed sunlight through a glass prism to separate the colors into a rainbow spectrum. He then passed sunlight through a second glass prism and combined the two rainbows. The combination produced white light. His simple experiment proved conclusively that white light is a mixture of colors.

You can do a similar experiment with three flashlights and three different colors of cellophane -- red, green and blue (commonly referred to as RGB). Cover one flashlight with one to two layers of red cellophane and fasten the cellophane with a rubber band (don't use too many layers or you'll block the light from the flashlight). Cover another flashlight with blue cellophane and a third flashlight with green cellophane. Go into a darkened room, turn the flashlights on and shine them against a wall so that the beams overlap, as shown in the figure. Where red and blue light overlap, you will see magenta. Where red and green light overlap, you will see yellow. Where green and blue light overlap, you will see cyan. You will notice that white light can be made by various combinations, such as yellow with blue, magenta with green, cyan with red, and by mixing all of the colors together.

By adding various combinations of these so-called additive colors -- red, green and blue light -- you can make all the colors of the visible spectrum. This is how computer monitors (RGB monitors) generate colors.

Pigments and Absorption



Pigments are created by modifying which colors are absorbed.

Another way to make colors is to absorb some of the frequencies of light, and thus remove them from the white light combination. The absorbed colors are the ones you don't see -- you see only the colors that come bouncing back to your eye. This is known as subtractive color, and it's what happens with paints and dyes. The paint or dye molecules absorb specific frequencies and bounce back, or reflect, other frequencies to your eye. The reflected frequency (or frequencies) are what you see as the color of the object. For example, the leaves of green plants contain a pigment called chlorophyll, which absorbs the blue and red colors of the spectrum and reflects the green.

You can explain absorption in terms of atomic structure. The frequency of the incoming light wave is at or near the vibration frequency of the electrons in the material. The electrons take in the energy of the light wave and start to vibrate. What happens next depends upon how tightly the atoms hold on to their electrons. Absorption occurs when the electrons are held tightly, and they pass the vibrations along to the nuclei of the atoms. This makes the atoms speed up, collide with other atoms in the material, and then give up as heat the energy they acquired from the vibrations.

The absorption of light makes an object dark or opaque to the frequency of the incoming wave. Wood is opaque to visible light. Some materials are opaque to some frequencies of light, but transparent to others. Glass is opaque to ultraviolet light, but transparent to visible light.