Light

Lexile

Light is electromagnetic radiation in the wavelength range extending from about 0.4 micron to about 0.7 micron (1 micron equals one-millionth of a meter); or, perhaps more properly, the visual response to electromagnetic radiation in this range. By extension, the term is frequently applied to adjacent wavelength ranges that the eye cannot detect: ultraviolet **light** (also known as black **light**) and infrared **light** (see infrared radiation). In addition to wavelength, frequency (expressed in hertz) and wave number (in inverse units of length) are also used to specify and designate the character and quality of the radiation. Associated with wavelength or frequency is the visual response of color. The term *monochromatic* is applied to the idealized situation in which the **light** in a beam is all of one wavelength.

Characterization of Light

Light is characterized not only by wavelength, essentially a temporal quality, but also by state and degree of polarization (see polarized **light**), a geometric or directional quality, and by intensity, essentially a physical quality. The visual response to intensity is brightness. In the human visual system, at least, there is no counterpart response to the state and degree of polarization, but ample evidence exists that certain arthropods—bees in particular—are sensitive to the state of polarization of sky **light**. There is some speculation that certain migrating birds may also respond to this quality of **light**.

Light is further characterized by its degree of coherence (see coherent **light**). Coherence, closely related to the degree of polarization and to the degree of monochromaticity, refers to the ability of a beam of **light** to interfere (see interference) with itself. Coherence is therefore an interferometric property of **light**. By the use of a Michelson interferometer, most **light** sources can be made to produce interference fringes. These are clearest when the length of the two arms of the interferometer are equal. As one arm is lengthened, however, the contrast of the fringes is seen to decrease until they are no longer visible. Unfiltered **light** from an incandescent source will barely produce fringes under any circumstances. **Light** from a mercury arc lamp will produce fringes over a range of one or two centimeters. On the other hand,

light from a continuous-wave gas laser has produced fringes at a distance of more than 100 m (328 ft).

Light is moving energy that travels at a speed of 300,000 km/sec (186,000 mi/sec). It can be regarded both as a particulate flow and as a wave phenomenon. These two apparently diametrically opposed views have been brought together in a theory that combines the best features of each. The particulate unit is the photon, which has associated with it a central frequency or wavelength that determines (or is determined by) the amount of energy it contains. In a so-called monochromatic beam, the photons are all of the same energy and therefore have the same frequency. They can be made to interfere, which indicates a high degree of coherence as well as a more or less uniform state of polarization. If the distribution of the energy in the photons is more random, however, the beam will be less coherent and will have a lower degree of polarization.

It is also convenient to think of **light** as propagating as wave fronts (see Huygens's principle). These waves, like the crest of an ocean wave, are surfaces on which the phase relationship is constant. Unlike an ocean wave, a wave front or surface of constant phase is unobservable and undetectable. **Light** may be considered as energy being transported in a train of wave fronts. The direction of propagation (except for anisotropic media) is in a direction perpendicular to the wave front. Rays can be conceived as trajectories of photons.

Light Production

Light, like any other electromagnetic radiation, results from either an accelerating electric charge or a nuclear fusion or fission reaction. In nuclear reactions a photon is created in the same manner as other elemental partial products of the reaction. With the exception of sunlight and starlight, however, **light** usually is the result of changes in the electronic structure of atoms and molecules as they absorb and reemit energy.

The incandescent electric **light** has as its **light** source the heat that results from the ohmic resistance of the filament to the electric current. A red-hot poker absorbs heat directly from the fire resulting from the liberation of chemical energy. As the material in the filament or poker heats up, the atoms and molecules gain kinetic energy, which is realized by an increase in the number of collisions among the particles. Boiling off of some of the material is one mechanism that can be used to maintain an equilibrium temperature. Another mechanism is for the electrons associated with the various atoms in the metal to move to higher energy levels. When they drop back to lower energy levels they emit a photon, keeping the temperature of the material more or less constant despite the fact that energy is continually supplied. The excess energy is emitted as **light**.

Thermal production of **light** is essentially random and is idealized as blackbody radiation. The **light** produced contains a mixture of wavelengths skewed around a central maximum λm, which is related to the temperature *T* of the material in degrees Kelvin. This relation, λm*T* = constant, is known as the Wien displacement law (see Wien, Wilhelm Jan). The spectrum produced by the **light** from such a source is continuous. Although there is a dominant wavelength, this **light** is not monochromatic. It is generally unpolarized and has a relatively short coherence length.

Another type of **light** source is energized plasma, such as a flame, or the gas in a discharge tube, such as a neon bulb. Although **light** is produced by a mechanism similar to thermal emission, the atoms are in a gaseous phase and less random. The energy levels reached by the electrons depend more on the electronic structure of the atoms themselves, and therefore the photons emitted tend to be clustered around specific wavelengths. The spectrum produced by such a source is not at all continuous but consists of lines or bands that are characteristic of the atoms or molecules in the gas. Highly monochromatic **light** can be obtained from this type of source, particularly if the **light** is filtered. The **light** has a much longer coherence length but is generally unpolarized.

A third type of source is the laser. Two principles are involved in laser operation. First, the lasing material is composed of atoms, or mixtures of atoms, that have a peculiar energy level structure. As they absorb energy, their electrons move up to higher energy levels, tending to accumulate at certain metastable levels. This is called *population inversion.* There they remain until stimulated by a photon of the proper frequency. Then the electrons drop to a lower energy level, emitting a photon of the same frequency and traveling in the same direction as the incident. Because a single photon may stimulate the release of a large number of additional photons, the total number of photons is increased, thus increasing the intensity of the **light** within the medium. The process is referred to as *gain.*

The second principle is the geometry of the laser itself. The laser can be regarded as a hollow tube, much like an organ pipe, which is tuned to the wavelength of the emitted photons. The process can be visualized as a wave front being reflected back and forth between the two ends of the laser, picking up more photons with each reflection. The portion of the **light** that is permitted to escape from the cavity is highly monochromatic, with a long coherence length. In some circumstances the laser output is highly polarized.

Dualistic Nature of Light

The historical development of a theory of **light**, at least from the 17th century on, involved two apparently contradictory descriptions. One concept was the corpuscular theory, which envisioned **light** as a stream, or flow, of small particles. René Descartes modified this concept. He viewed **light** more as a pressure than as a flow—not as motion but as a tendency to motion. And since **light** was not motion it was not limited by a finite velocity. In other words, a beam of **light** required no time of transit. Pierre Fermat held a different view. He believed not only that **light** propagated at a finite velocity, but also that its particles described trajectories or rays. Christiaan Huygens, on the other hand, was a believer that **light** was a wave phenomenon. **Light** propagated at a finite velocity in the form of a moving disturbance, just as a water wave moves as a ripple on a smooth pond.

As a ray of **light** passes across a surface from one medium to another (for example, from air to glass), its direction is changed—a phenomenon known as refraction. The law of refraction, discovered first empirically by Willebrord Snell, then subsequently derived formally by Descartes and Fermat, states that sin $r = K$ sin i, where i is called the angle of incidence, the angle between the incident ray and the normal (perpendicular) to the refracting surface. The angle of refraction, r, is the angle between the refracted ray and the surface normal.

Fermat and Descartes agreed on the form of the refraction law, but they disagreed violently on the meaning of the constant K. Fermat saw K as being proportional to the reciprocal of the velocity of propagation. Descartes, even though he believed that the velocity of propagation was infinite, concluded, on a different level of logic, that *K* was proportional to a velocity. The distinction is important because whether **light** speeds up or slows down as it passes into a denser medium determines the meaning of *K.*

Two opposing points of view evolved. Descartes and Fermat were both proponents of a corpuscular theory; Huygens believed in a wave theory. He also obtained a proof of the refraction law in terms of the existence of wave fronts, a construction now called Huygens's principle.

If **light** is a wave phenomenon, then a medium is required. Sound waves travel through the air but not through a vacuum; ripples require a watery medium. At first it was thought that air would be the medium that would support the propagation of **light**. The simple experiment of shining **light** through an evacuated jar, however, showed clearly that this theory was not correct. Theorists chose to hypothesize the existence of a medium called the ether.

Experimental evidence to support the wave theory of **light** was particularly strong. Diffraction, the ability of **light** to bend around a sharp edge, certainly gave credence to the idea that **light** was a form of wave motion. Further support came with the discovery of polarization, which indicated that the undulations of a **light** wave were transverse to the direction of propagation and were not longitudinal, as were sound and water waves. Thus, if **light** was to be a wave phenomenon, the ether was required, and if so, then certain effects should be observed when a massive body passed through the ether. To detect such effects, telescope tubes were filled with water to determine the effect on starlight. No effect was observed. Experiments to detect an ether "drag" also failed.

On the other hand, James Bradley discovered stellar aberration in 1729 when he found that he had to aim his telescope a little in the direction of the Earth's motion ahead of the theoretical position of a star. This effect could be compared to a person in a rainstorm tilting the umbrella forward as he or she walks into the rain. Bradley's discovery supported a corpuscular theory, or at least it did not support the idea of an ether drag.

It was postulated, however, that if ether exists, then another observable phenomenon, ether "drift," must also exist. If both the Earth and **light** are moving through the ether, then the velocity of **light** observed on the Earth would depend on the direction of observation. The ether was regarded as stationary; the Earth and other planets, the Sun and the stars, and **light** moved through it. By measuring the apparent velocity of **light** in various directions, one could determine the absolute velocity and direction of the motion of the Earth.

In the late 19th century A. A. Michelson and E. W. Morley (1838–1923) attempted to measure the absolute motion of the Earth through the ether (see Michelson-Morley experiment). No ether drift was observed. The conclusion was the inconceivable notion that the velocity of **light** was constant and independent of the motion of the observer. This paradox led to Einstein's special theory of relativity, a cosmological theory of major significance.

Apparent Variations in the Speed of Light

As just stated, it has become one of the fundamentals of modern physics that the velocity of **light**—300,000 km/sec (186,000 mi/sec)—is invariant. This theory underlies current understanding of the space-time continuum. Although this velocity does not change, however, it can be affected by the relative motion of objects with respect to an observer in a manner similar to the way in which sound waves are affected by relative motion. That is, sound coming from an object moving away from a person appears lower in pitch because the sound wave are relatively longer for that person (see Doppler effect). Similarly, as objects in space move away from an observer, the **light** from them appears to lengthen and become redder (see red shift). This effect, along with corresponding blue shifts as objects in space move toward the observer, are phenomena familiar in astronomy, where distance scales are vast enough for these shifts to be readily observed.

The velocity of **light** also varies with the density of the medium through which the **light** is passing. This is not observable in ordinary experience—**light** is either transmitted or it is not, without any notable slowing—but the slowing can be dramatic in scientific experiments where **light** is subjected to extreme densities. For example, two separate experiments reported at the turn of the 21st century described how scientific researchers have brought **light** to a virtual "stop." in effect, by using quantum-interference effects on optical pulses of **light** passing through an otherwise opaque medium. That is, the information about this **light** was stored and then released.

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