MACMILLAN ENCYCLOPEDIA OF PHYSICS

John S. Rigden

Editor in Chief

Volume 1

MACMILLAN REFERENCE USA
Simon & Schuster Macmillan
NEW YORK

Simon & Schuster and Prentice Hall International
LONDON   MEXICO CITY   NEW DELHI   SINGAPORE   SYDNEY   TORONTO

Bibliography

BELOPOLSKY, A. "On an Apparatus for the Laboratory Demonstration of the Doppler–Fizeau Principle." *Astrophys. J.* **13,** 15 (1901).

DRAIN, L. E. *The Laser Doppler Technique* (Wiley, New York, 1980).

GILLIPSIE, C., ed. *Dictionary of Scientific Biography,* Vol. IV (Scribner, New York, 1971).

HALLIDAY, D., and RESNICK, R. *Fundamentals of Physics,* 4th ed. (Wiley, New York, 1992).

IVES, H. E., and STILWELL, G. R. "An Experimental Study of the Rate of a Moving Atomic Clock." *J. Opt. Soc. Am.* **31,** 369 (1941).

RADIN, S., and FOLK, R. *Physics for Scientists and Engineers* (Prentice Hall, Englewood Cliffs, NJ, 1982).

ANDRZEJ HERCZYŃSKI

DOUBLE-SLIT EXPERIMENT

Two sets of light waves can be made to cross each other with neither producing any modification in the amplitude, frequency, polarization, or phase of the other. In the region of crossing, the resultant electromagnetic field at any point is given by the sum of those due to each wave separately. This is known as the principle of superposition and was first clearly stated by the English physician, architect, Egyptologist, and physicist Thomas Young in 1802. The general phenomenon whereby two or more waves overlap to produce a resultant wave is called interference. The resultant intensity in the overlap region can be either greater or less than the separate intensities, correspondingly referred to as constructive and destructive interference. However, in order for interference effects in the overlap region to be stationary and thereby observable, it is necessary for the two light sources to be coherent, that is, to have precisely and persistently the same frequency and phase difference.

In a conventional optical light source, energy is pumped into an atomic sample by collisions, and the light is produced by spontaneous emission from individual atoms within a coherence time of approximately 10^{-9} to 10^{-8} s. This leads to sudden changes of phase on this time scale and precludes persistent coherence between separate sources of this type. This "granular" nature of radiation was demon-

strated by Albert Einstein to be required by the atomic properties of matter and a necessary replacement for the earlier continuum interpretation of James Clerk Maxwell. This limitation in coherence time is in contrast to modern laser devices, where energy is pumped into ensembles of atoms that can then be triggered into coherent stimulated emission by the presence of other photons of the proper frequency. Electrical charges can also be driven in phase at lower frequencies in a radio transmitter, and coherent sources of radio frequency radiation can be obtained by connecting two spatially separated antennas to the same oscillator. Although separate, independent, coherent sources of visible light did not exist until the development of modern lasers, in 1801 Thomas Young observed interference with visible light by an ingenious method that effectively created spatially separated sources from a single wave front.

Young's experiment can be understood in terms of a principle advanced in 1678 by the Dutch physicist Christiaan Huygens, who proposed that each point on a wave front can be regarded as a new source of waves. This leads to a geometrical construction that predicts the position of a given wave front at any time in the future as the surface of tangency of the common envelope of these secondary wavelets. Young allowed sunlight to fall on a pinhole punched in a screen, thus creating a point source of light by diffraction. The emerging light was allowed to spread and to fall upon a second screen through which two pinholes with a small separation had been punched. These two spherical waves also spread and overlapped on the downstream side of the second screen. The overlapping region was not a simple area of intensified light but was observed to exhibit a striped pattern alternating light and darkness, analogous to the phenomenon of sound beats that Young had also studied.

Young's experiment was especially convincing because he was able to use the separation between the holes d and the angle θ, at which the mth constructive interference fringe occurred, to deduce the wavelength of the light λ, using $d \sin\theta = m\lambda$ (Fig. 1). Young obtained a value for the average wavelength of sunlight that is quite close to the presently accepted value. The method can also be inverted to measure an unknown value for d given a known value for λ. Subsequent to Young's measurement it has been found convenient to replace the pinholes with narrow slits and to use a monochromatic light source. This yields two dimensional cylindrical wave
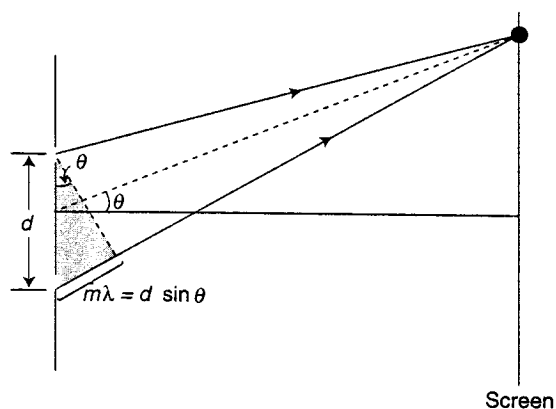
Figure 1 Set-up for the double-slit experiment.

fronts that produce light and dark lines at the positions of constructive and destructive interference. The transmission can also be enhanced by using a large number of equally spaced slits to form a diffraction grating. Similar interference patterns can be readily observed in water waves, for example, in the region of overlap of the ripples that spread from the impacts of two adjacent raindrops striking the surface of a body of water.

Young's work culminated more than a century of controversy as to whether light consisted of particles or waves. Objections were initially raised that the pattern might be an artifact caused by the edges of the slits, but these were resolved when the work was confirmed by Augustin Fresnel and others using alternative devices such as the Fresnel biprism, the Fresnel double-mirror, and Lloyd's mirror. Young's work so dramatically demonstrated the wave properties of light that this view was accepted for more than 100 years, until the advent of the modern quantum theory. Although Young's work seemed to refute Newton's corpuscular theory of light, Newton had partially foreseen this modern view (often described as wave–particle duality), having proposed that light is a stream of material particles capable of

setting up vibrations in the quintessential ether. It is now known that light (and all other forms of electromagnetic radiation) consists of photons that propagate in a wavelike fashion with a single characteristic speed, but which behave like streams of particlelike concentrations of energy when interacting with matter in the processes of emission and absorption. Thus light is neither a "wave" nor a "particle" but can exhibit either of these macroscopic attributes under appropriately limiting conditions.

See also: COHERENCE; EINSTEIN, ALBERT; FRESNEL, AUGUSTIN-JEAN; HUYGENS, CHRISTIAAN; INTERFERENCE; LASER; LIGHT; LIGHT, ELECTROMAGNETIC THEORY OF; LIGHT, WAVE THEORY OF; MAXWELL, JAMES CLERK; NEWTON, ISAAC; PHOTON; POLARIZATION; POLARIZED LIGHT; WAVE–PARTICLE DUALITY; YOUNG, THOMAS

Bibliography

HECHT, E. *Physics* (Brooks/Cole, Pacific Grove, CA, 1994).
JENKINS, F. A., and WHITE, H. E. *Fundamentals of Optics*, 4th ed. (McGraw-Hill, New York, 1976).

LORENZO J. CURTIS

DRIFT SPEED

See ELECTRON, DRIFT SPEED OF

DUALITY

See WAVE–PARTICLE DUALITY

plitude, and the motion will not be well approximated by a sine or cosine function of the time.

An interesting physical consequence of anharmonic motion is the expansion of solids as they are heated. If the forces between the molecules were exactly harmonic, then adding heat would cause the amplitude of the oscillations between molecules to increase but the average distance between the molecules would not change and the material would not expand. Because the forces are anharmonic, the increase in the amplitude of the oscillations with an increase in temperature also produces an increase in the average distance between the particles and, hence, expansion of the solid.

See also: MOTION, PERIODIC; OSCILLATOR; OSCILLATOR, HARMONIC; PENDULUM

BIBLIOGRAPHY

HALLIDAY, D.; RESNICK, R.; and WALKER, J. *Fundamentals of Physics*, 4th ed. (Wiley, New York, 1993).

NAYFEH, A. H., and MOOK, D. T. *Nonlinear Oscillations* (Wiley, New York, 1979).

DAVID J. ERNST

OSCILLATOR, FORCED

Many physical systems have one or more natural vibration frequencies and one or more natural modes of energy dissipation (damping) that characterize its behavior when stimulated by a transient impulse. These damped oscillations will eventually stop unless energy is supplied to sustain them. If driven by a series of external impulses at some arbitrary frequency, the system will necessarily vibrate at the driver frequency, but with an amplitude and phase that depend not only on the driver amplitude and frequency, but also on the natural frequencies and damping constants of the system. If the frequency of the external stimulus is varied, the amplitude of the response at or near one of the natural frequencies can exceed the amplitude of the driver, a condition known as resonance. The amount of damping controls the size of the resonant response, the sharpness of the resonance as a function of frequency, and the

phase shift between the stimulus and the response. For small damping the amplitude is maximum when the frequencies of the driver and the oscillator coincide, but for large damping there is a frequency shift. If the damping time of the oscillator is large, the resonance width is small, and vice versa. Thus the product of the frequency width and the damping time is of order unity. This property is known as the uncertainty principle, and it expresses the impossibility of measurements that are arbitrarily precise in both time and frequency.

If the driver and response frequencies are equal but 180 degrees out of phase, the stimulus tends to suppress the response oscillations (e.g., the driven tuned mass dampers in tall buildings that are used to decrease their sway during high winds). If the driver exactly compensates for the energy dissipated by damping, it will sustain the motion (e.g., the escapement in a pendulum clock). If the driver supplies more energy than is dissipated by damping, the amplitude of the system will increase dramatically, and perhaps catastrophically. Many examples of resonance exist, such as the shattering of a wine glass by sound, the use of a microwave oven to drive electrons in water molecules at their natural frequencies, the use of a tuned electrical circuit to filter electromagnetic waves detected in a radio receiver, and the bridge collapses that have occurred when marching troops failed to break cadence. In some cases the external driving force can be initiated by the presence of the responding oscillator itself. For example, alternating vortex swirls can be formed when a fluid flows past an object, which can exert a periodic force on the object that forms them. When the resonance condition is met, huge amplitudes have been observed (e.g., the collapse of the Tacoma Narrows bridge in 1940 and the failure of aircraft wings in the 1960s).

Another application of driven oscillation is given by resonance fluorescence, which is used as a tool in the study of atomic structure. In one application of this technique, observation of the absorption and reemission of laser light of known but variable frequency by an atomic sample permits the determination of the natural frequencies (that characterize the energy level separations) and damping constants (that characterize the level lifetimes) of the atoms.

See also: DAMPING; FLUORESCENCE; FREQUENCY, NATURAL; PENDULUM; PHASE; RESONANCE

Bibliography

FEYNMAN, R. P.; LEIGHTON, R. B.; and SANDS, M. *The Feynman Lectures on Physics,* Vol. 1 (Addison-Wesley, Reading, MA, 1963).

FISHBANE, P. M.; GASIOROWICZ, S.; and THORTON, S. T. *Physics for Scientists and Engineers* (Prentice Hall, Englewood Cliffs, NJ, 1993).

MARION, J. B., and THORTON, S. T. *Classical Dynamics of Particles and Systems,* 4th ed. (Saunders, Fort Worth, TX, 1995).

LORENZO J. CURTIS

OSCILLATOR, HARMONIC

A harmonic oscillator is a physical system that oscillates back and forth around its stable equilibrium position r_e due to a restoring "force" proportional linearly to the "displacement" from r_e. If the displacement is sufficiently small, its motion is called simple harmonic motion (SHM). The harmonic oscillator is not necessarily limited to a mechanical system, such as the spring-mass system and the diatomic molecule discussed under simple harmonic motion. For example, the energy transfer between electric and magnetic fields in a circuit containing an inductance L and a capacitance C (i.e., an L–C circuit) can also be described by an SHM with an angular frequency $\omega = (LC)^{-1/2}$.

Pendulum

In general, a pendulum (or, a physical pendulum) is a rigid body of mass m with an arbitrary shape, pivoted about a fixed horizontal frictionless axis through a point P, at a distance L, from its center of mass O, as shown in Fig. 1. Its moment of inertia about the pivot point P is I. When the pendulum is displaced from the vertical by an angle θ under the gravity, it is subject to a restoring torque

$$\Gamma = -mgL \sin \theta. \tag{1}$$

When θ is small, $\sin \theta \approx \theta$. Together with the relation $\Gamma = I d^2\theta/dt^2$, the motion of the pendulum is described by

$$\frac{d^2\theta}{dt^2} + \frac{mgL}{I}\theta = 0, \tag{2}$$

or, an SHM with an angular frequency $\omega = (mgL/I)^{1/2}$. For a simple pendulum, the mass is concentrated at the end of a weightless rigid rod with $I = mL^2$ and the system oscillates with an angular frequency $\omega = (g/L)^{1/2}$.

Floating Objects

An object with a density that is less than the density of a liquid may float partially submerged in stable equilibrium at the surface of the liquid. According to the Archimedes' principle, the weight of the object, for example, Mg, is balanced by a buoyant force that equals the weight of the liquid replaced by the floating object. If the floating object is slightly pushed into the liquid from its stable equilibrium position by a small vertical displacement y, it will experience a restoring force that equals the increase in the weight of the additional liquid that is replaced by the floating object. Assuming a constant cross section A of the floating object near the floating level, the restoring force is given by $-\rho g A y$, where ρ is the density of the liquid and g is the acceleration due to gravity. The motion is described by a SHM according to the equation

$$\frac{d^2y}{dt^2} + \left(\frac{\rho g A}{M}\right)y = 0 \tag{3}$$

with an angular frequency $\omega = (\rho g A/M)^{1/2}$.
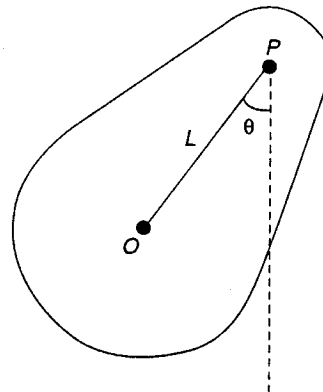

Figure 1   A physical pendulum.

sibly lose energy by the same fractional amount, even if there were a means of achieving this in, say, the optical region of the spectrum. In the meantime, the motivation for seeking a tired light theory largely vanished after Baade's revision of the distance scale in 1952 to imply an expansion age for the universe that comfortably exceeded the age of the solar system.

See also: DOPPLER EFFECT; GALAXIES AND GALACTIC STRUCTURE; HUBBLE, EDWIN POWELL; HUBBLE CONSTANT; UNIVERSE, EXPANSION OF; UNIVERSE, EXPANSION OF, DISCOVERY OF

Bibliography

MADORE, B. F., and TULLY, R. B., eds. *Galaxy Distances and Deviations from Universal Expansion* (Reidel, Dordrecht, 1986).

ROWAN-ROBINSON, M. *The Cosmological Distance Ladder* (W. H. Freeman, New York, 1985).

SILK, J. *A Short History of the Universe* (W. H. Freeman, New York, 1994).

JOSEPH SILK

REFERENCE FRAME

See FRAME OF REFERENCE

REFLECTION

When a wave propagating in one medium encounters a boundary with a second medium, part of the incident wave is returned to the first medium. For sound waves this is called an echo. If the reflecting surface is rough, the waves will undergo diffuse scattering in a variety of directions. If the reflecting surface is smooth, optical light will undergo specular reflection, in which the incident and reflected rays lie in the same plane at opposed equal angles to a line perpendicular to the surface. The reflected intensity depends on the angle and polarization of the light and the nature of the surface. Depending on

the media, the phase of the reflected wave can be preserved, inverted, or shifted relative to that of the incident wave.

The phenomenon of reflection has certainly been known since humans first recognized their own images in a surface of water. Aristotle understood the equality of incident and reflected angles. Plato described the properties of a corner reflector, whereby mirrors abutted at a right angle avert the normal left-right reflected inversion when viewed along the abutment, and reverse up and down when viewed perpendicular to it. Corner reflectors also have the property of reflecting all rays back parallel to their incident direction and have applications such as reflective paint on road signs. Corner-cube retroreflector arrays were placed on the Moon by the Apollo astronauts, permitting highly accurate measurements of the Earth–Moon separation by laser ranging.

The intensities of the reflected rays differ for components with polarizations parallel and perpendicular to the plane containing the incident and reflected rays and are given by formulas developed by Augustin Fresnel. Light polarized with its electric field perpendicular to this plane is favored, and at Brewster's angle (where the refracted and reflected rays are perpendicular to each other), the polarization component parallel to this plane vanishes. Polaroid sun glasses are designed to filter out the horizontal component, which dominates specularly reflected light but is only 50 percent of diffusely reflected light.

In moving from a more dense to a less dense medium, there is a critical angle beyond which refraction can no longer occur and the ray is totally reflected (and absorbed). This is the principle by which light can be channeled around corners using fiber optics (which have important communications and medical applications). Channeling of light also occurs in phenomena such as mirages and looming, where differences in air temperature at and near Earth's surface form an optical interface. The rainbow is a result of total internal reflection within rain droplets of rays that are ultimately dispersed into their colors by refraction when they emerge.

Optical reflectivity is related to the presence of conduction electrons as evidenced by the high reflective lustre of metals. Ancient mirrors were made from polished metal, but glass mirrors backed with a tin amalgam were introduced in the seventeenth century, and in 1840 a process was developed for producing silvered glass mirrors. A plane mirror forms a laterally reversed unmagnified virtual image, whereas a convex mirror forms a virtual

image with a wider field of view than a flat mirror. Concave spherical mirrors form real inverted images of objects farther away than half the radius of curvature of the mirror (which can fool the eye into seeing a three-dimensional object where none exists), and virtual images of closer objects. Concave mirrors are often used in astronomical telescopes.

See also: Brewster's Law; Fiber Optics; Fresnel, Augustin-Jean; Image, Virtual; Mirror, Plane; Optics; Optics, Geometrical; Polarization; Polarized Light; Rainbow; Refraction
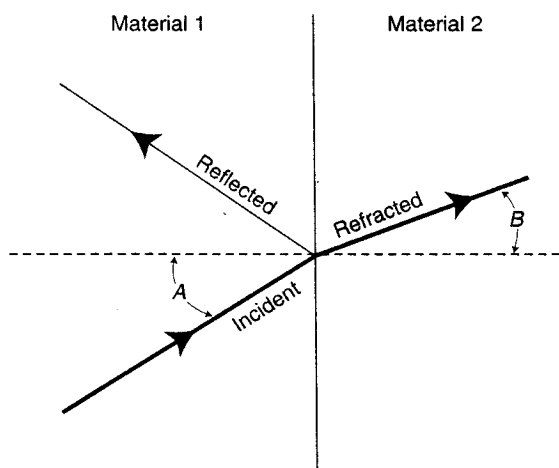
Bibliography

Boyer, C. B. *The Rainbow: From Myth to Mathematics* (Princeton University Press, Princeton, NJ, 1987).

Jenkins, F. A., and White, H. E. *Fundamentals of Optics*, 4th ed. (McGraw-Hill, New York, 1976).

Lorenzo J. Curtis

REFRACTION

Refraction is the bending of a wavefront as it passes across the barrier (interface) from one material to another. Refraction can occur with all types of waves, but it is most commonly discussed in terms of light waves. While Fig. 1 shows the general principle
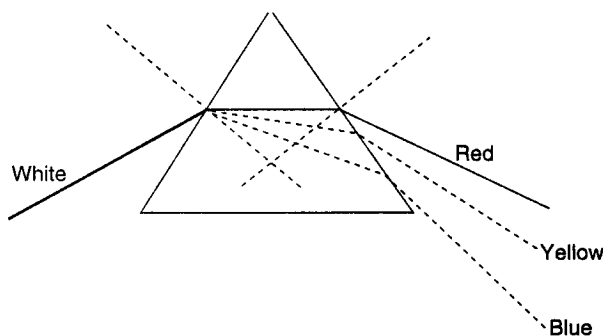
involved with refraction, application of Snell's law will determine the exact amount of bending that occurs for light waves at the interface:

$$n_1 \sin A = n_2 \sin B,$$

where n_1 and n_2 are the refraction indices for the two media, A is the angle of incidence, and B is the angle of refraction.

The index of refraction depends on the materials involved and the wavelength of the light. This variation is responsible for the phenomenon known as dispersion, the splitting of a light ray of mixed wavelengths into its components. For most materials, the index of refraction for blue light is greater than the index of refraction for red light. Therefore, when a beam of white light (a mixture of all colors) is incident upon a prism, each color is bent at a slightly different angle at both the entering and exiting surfaces of the prism, as shown in Fig. 2. This refraction process produces a spectrum of color coming out of the prism with red light bent the least and blue the most. Isaac Newton was one of the first people to study this effect to determine that the colors produced were actually a property of the light, not the prism or any other object. Since that time, it has been well-established that color is related to the wavelength of the light involved.

Refraction at a curved surface, which gives rise to more complicated behavior, is an important consideration in the creation of lenses. The most general solution has been to place two curved surfaces back-to-back, as shown in Fig. 3. By combining curved lenses in this way, the refraction upon entering the lens and refraction upon exiting the lens combine

Material 1   Material 2

Figure 1 Refraction and reflection at the plane interface between two materials.

Figure 2 Refraction through a prism to create a color spectrum.