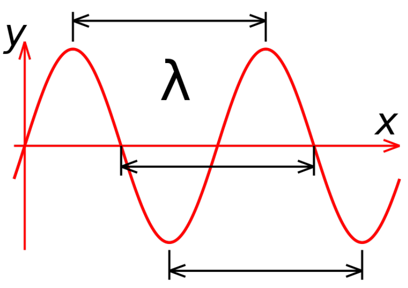
Wavelength



Wavelength of a sine wave, λ, can be measured between any two points with the same phase, such as between crests, or troughs, or corresponding zero crossings as shown.

In physics, the **wavelength** of a sinusoidal wave is the spatial period of the wave – the distance over which the wave's shape repeats.[1] It is usually determined by considering the distance between consecutive corresponding points of the same phase, such as crests, troughs, or zero crossings, and is a characteristic of both traveling waves and standing waves, as well as other spatial wave patterns.[2] [3] Wavelength is commonly designated by the Greek letter *lambda* (λ). The concept can also be applied to periodic waves of non-sinusoidal shape.[1] [4] The term *wavelength* is also sometimes applied to modulated waves, and to the sinusoidal envelopes of modulated waves or waves formed by interference of several sinusoids.[5]

Assuming a sinusoidal wave moving at a fixed wave speed, wavelength is inversely proportional to frequency: waves with higher frequencies have shorter wavelengths, and lower frequencies have longer wavelengths.[6]

Examples of wave-like phenomena are sound waves, light, and water waves. A sound wave is a periodic variation in air pressure, while in light and other electromagnetic radiation the strength of the electric and the magnetic field vary. Water waves are periodic variations in the height of a body of water. In a crystal lattice vibration, atomic positions vary periodically in both lattice position and time.

Wavelength is a measure of the distance between repetitions of a shape feature such as peaks, valleys, or zero-crossings, not a measure of how far any given particle moves. For example, in waves over deep water a particle in the water moves in a circle of the same diameter as the wave height, unrelated to wavelength.[7]

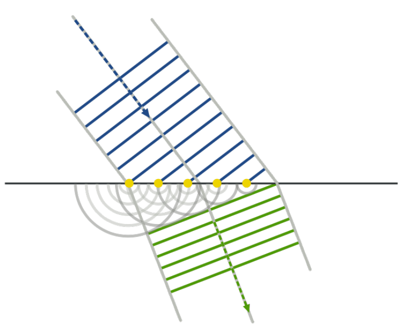
Sinusoidal waves

In linear media, any wave pattern can be described in terms of the independent propagation of sinusoidal components.

The wavelength λ of a sinusoidal waveform traveling at constant speed v is given by:[8]

$$\lambda = \frac{v}{f},$$

where v is called the phase speed (magnitude of the phase velocity) of the wave and f is the wave's frequency.

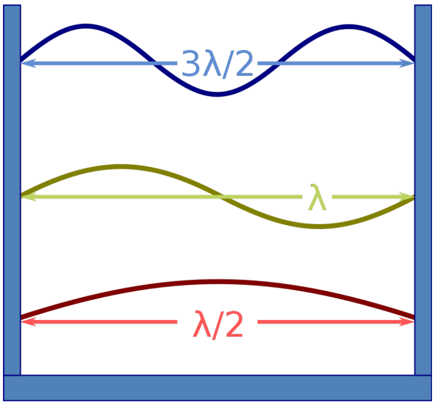


Refraction: when a plane wave encounters a medium in which it has a slower speed, the wavelength decreases, and the direction adjusts accordingly.

In the case of electromagnetic radiation such as light in free space, the speed is the speed of light, about $3{\times}10^8$ m/s. For sound waves in air, the speed of sound is 343 m/s (1238 km/h) (at room temperature and atmospheric pressure). As an example, the wavelength of a 100 MHz electromagnetic (radio) wave is about: $3{\times}10^8$ m/s divided by $100{\times}10^6$ Hz = 3 metres.

Visible light ranges from deep red, roughly 700 nm, to violet, roughly 400 nm (430–750 THz) (for other examples, see electromagnetic spectrum). The wavelengths of sound frequencies audible to the human ear (20 Hz–20 kHz) are between approximately 17 m and 17 mm, respectively, assuming a typical speed of sound of about 343 m/s; the wavelengths in audible sound are much longer than those in visible light.

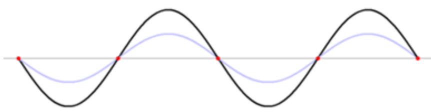
Frequency and wavelength can change independently, but only when the speed of the wave changes. For example, when light enters another medium, its speed and wavelength change while its frequency does not; this change of wavelength causes refraction, or a change in propagation direction of waves that encounter the interface between media at an angle.



Sinusoidal standing waves in a box that constrains the end points to be nodes will have an integer number of half wavelengths fitting in the box.

Standing waves

A standing wave is an undulatory motion that stays in one place. A sinusoidal standing wave includes stationary points of no motion, called nodes, and the wavelength is twice the distance between nodes. The wavelength, period, and wave velocity are related as before, if the stationary wave is viewed as the sum of two traveling sinusoidal waves of oppositely directed velocities.[9]



A standing wave (black) depicted as the sum of two propagating waves traveling in opposite directions (red and blue).

Mathematical representation

Traveling sinusoidal waves are often represented mathematically in terms of their velocity v (in the x direction), frequency f and wavelength λ as:

$$y(x,\ t) = A\cos\left(2\pi\left(\frac{x}{\lambda} - ft\right)\right) = A\cos\left(\frac{2\pi}{\lambda}(x - vt)\right)$$

where y is the value of the wave at any position x and time t, and A is the amplitude of the wave. They are also commonly expressed in terms of (radian) wavenumber k (2π times the reciprocal of wavelength) and angular frequency ω (2π times the frequency) as:

$$y(x,\ t) = A\cos\left(kx - \omega t\right) = A\cos\left(k(x - vt)\right)$$

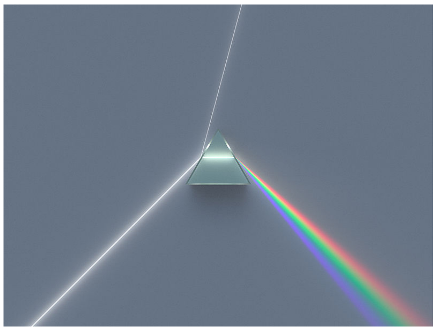
in which wavelength and wavenumber are related to velocity and frequency as:

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{v} = \frac{\omega}{v}$$

or

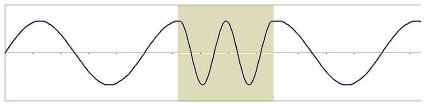
$$\lambda = \frac{2\pi}{k} = \frac{2\pi v}{\omega} = \frac{v}{f}$$

The relationship between ω and λ (or k) is called a dispersion relation. This is not generally a simple inverse relation because the wave velocity itself typically varies with frequency.[10]



Dispersion causes separation of colors when light is refracted by a prism.

In the second form given above, the phase ($kx - \omega t$) is often generalized to ($\mathbf{k}\cdot\mathbf{r} - \omega t$), by replacing the wavenumber k with a wave vector that specifies the direction and wavenumber of a plane wave in 3-space, parameterized by position vector **r**. In that case, the wavenumber k, the magnitude of **k**, is still in the same relationship with wavelength as shown above, with v being interpreted as scalar speed in the direction of the wave vector. The first form, using reciprocal wavelength in the phase, does not generalize as easily to a wave in an arbitrary direction.



Wavelength is decreased in a medium with higher refractive index.

Generalizations to sinusoids of other phases, and to complex exponentials, are also common; see plane wave. The typical convention of using the cosine phase instead of the sine phase when describing a wave is based on the fact that the cosine is the real part of the complex exponential in the wave

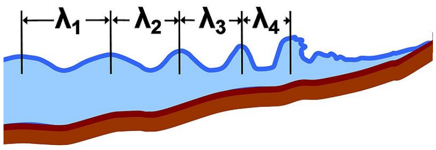
$$Ae^{i(kx-\omega t)}.$$

General media

The speed of a wave depends upon the medium in which it propagates. In particular, the speed of light in most media is lower than in vacuum, which means that the same frequency will correspond to a shorter wavelength in the medium than in vacuum. The wavelength in the medium is

$$\lambda = \frac{\lambda_0}{n},$$

where λ_0 is the wavelength in vacuum, and n is the refractive index of the medium. When wavelengths of electromagnetic radiation are quoted, the vacuum wavelength is usually intended unless the wavelength is specifically identified as the wavelength in some other medium. In acoustics, where a medium is essential for the waves to exist, the wavelength value is given for a specified medium.

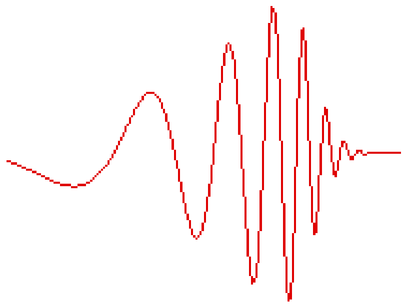


Various local wavelengths on a crest-to-crest basis in an ocean wave approaching shore.[11]

In general, the refractive index is a function of wavelength. This variation of n with λ, called dispersion, causes different colors of light to be separated when light is refracted by a prism.

Nonuniform media

Wavelength can be a useful concept even if the wave is not periodic in space. For example, in an ocean wave approaching shore, shown in the figure, the incoming wave undulates with a varying *local* wavelength that depends in part on the depth of the sea floor compared to the wave height. The analysis of the wave can be based upon comparison of the local wavelength with the local water depth.[11]

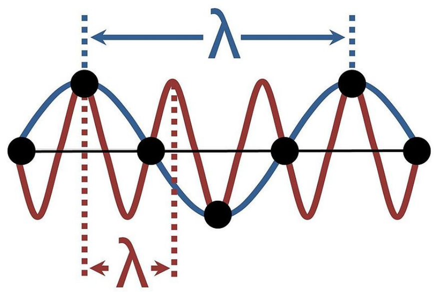


A sinusoidal wave in a nonuniform medium, with loss. As the wave slows down, the wavelength gets shorter and the amplitude increases; after a place of maximum response, the short wavelength is associated with a high loss and the wave dies out.

Waves that are sinusoidal in time but propagate through a medium whose properties vary with position (an *inhomogeneous* medium) may propagate at a velocity that varies with position, and as a result may not be sinusoidal in space. The analysis of differential equations of such systems is often done approximately, using the *WKB method* (also known as the *Liouville–Green method*). The method integrates phase through space using a local wavenumber, which can be interpreted as indicating a "local wavelength" of the solution as a function of time and space.[12] [13] This method treats the system locally as if it were uniform with the local properties; in particular, the local wave velocity associated with a frequency is the only thing needed to estimate the corresponding local wavenumber or wavelength. In addition, the method computes a slowly changing amplitude to satisfy other constraints of the equations or of the physical system, such as for conservation of energy in the wave.

Crystals

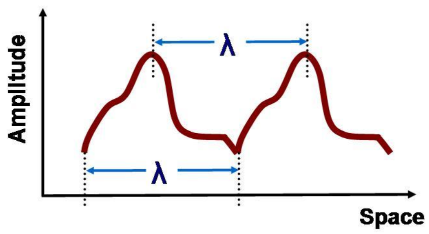
Waves in crystalline solids are not continuous, because they are composed of vibrations of discrete particles arranged in a regular lattice. This produces aliasing because the same vibration can be considered to have a variety of different wavelengths, as shown in the figure.[14] Descriptions using more than one of these wavelengths are redundant; it is conventional to choose the longest wavelength that fits the phenomenon. The range of wavelengths sufficient to provide a description of all possible waves in a crystalline medium corresponds to the wave vectors confined to the Brillouin zone.[15]



A wave on a line of atoms can be interpreted according to a variety of wavelengths.

This indeterminacy in wavelength in solids is important in the analysis of wave phenomena such as energy bands and lattice vibrations. It is mathematically equivalent to the aliasing of a signal that is sampled at discrete intervals.

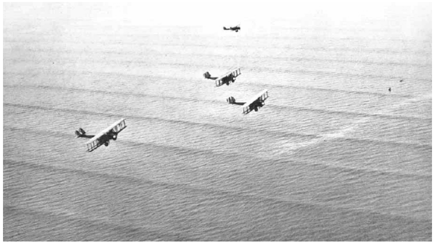
More general waveforms



Wavelength of an irregular periodic waveform at a particular moment in time. The same λ separates any two similarly situated points in the waveform.[16]

A wave moving in space is called a traveling wave. If the shape repeats itself, it is also a *periodic wave*.[16] At a fixed moment in time, a snapshot of the wave shows a repeating form in space, with characteristics such as peaks and troughs repeating at equal intervals. To an observer at a fixed location the amplitude appears to vary in time, and repeats itself with a certain *period*, for example T. If the spatial period of this wave is referred to as its wavelength, then during every period, one wavelength of the wave passes the observer. If the wave propagates with unchanging shape and the velocity in the medium is uniform, this period implies the wavelength is:

$$\lambda = vT \ .$$


Near-periodic waves over shallow water have sharper crests and flatter troughs than those of a sinusoid.

This duality of space and time is expressed mathematically by the fact that the wave's behavior does not depend independently on position x and time t, but rather on the combination of position and time $x - vt$. A wave's amplitude u is then expressed as $u(x - vt)$ and in the case of a periodic function u with period λ, that is, $u(x + \lambda - vt) = u(x - vt)$, the periodicity of u in space means that a snapshot of the wave at a given time t finds the wave varying periodically in space with period λ. In a similar fashion, this periodicity of u implies a periodicity in time as well: $u(x - v(t + T)) = u(x - vt)$ using the relation $vT = \lambda$ described above, so an observation of the wave at a fixed location x finds the wave undulating periodically in time with period $T = \lambda/v$.[16]

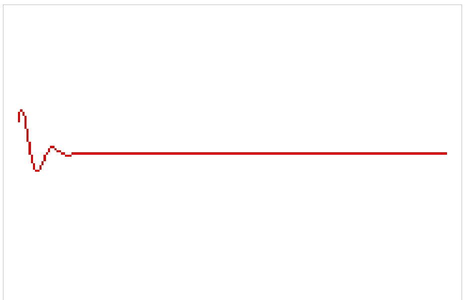
Traveling waves with non-sinusoidal wave shapes can occur in linear dispersionless media such as free space, but also may arise in nonlinear media under certain circumstances. For example, large-amplitude ocean waves with certain shapes can propagate unchanged, because of properties of the nonlinear surface-wave medium.[17] An example is the cnoidal wave, a periodic traveling wave named because it is described by the Jacobian elliptic function of m-th order, usually denoted as *cn (x; m)*.[18]

Envelope waves

The term *wavelength* is also sometimes applied to the envelopes of waves, such as the traveling sinusoidal envelope patterns that result from the interference of two sinusoidal waves close in frequency; such envelope characterizations are used in illustrating the derivation of group velocity, the speed at which slow envelope variations propagate.[19] [20]

Wave packets

Localized wave packets, "bursts" of wave action where each wave packet travels as a unit, find application in many fields of physics; the notion of a wavelength also may be applied to these wave packets.[22] The wave packet has an *envelope* that describes the overall amplitude of the wave; within the envelope, the distance between adjacent peaks or troughs is sometimes called a *local wavelength*.[23] [24] Using Fourier analysis, wave packets can be analyzed into infinite sums (or integrals) of sinusoidal waves of different wavenumbers or wavelengths.[25]



A propagating wave packet; in general, the *envelope* of the wave packet moves at a different speed than the constituent waves.[21]

Louis de Broglie postulated that all particles with a specific value of momentum have a wavelength

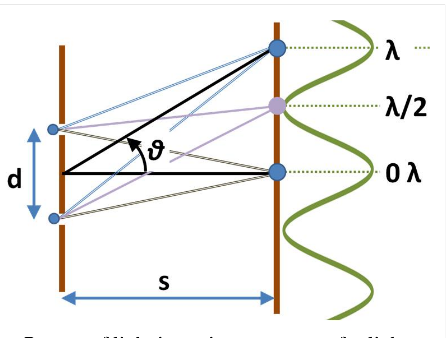
$$\lambda = \frac{h}{p},$$

where h is Planck's constant, and p is the momentum of the particle. This hypothesis was at the basis of quantum mechanics. Nowadays, this wavelength is called the de Broglie wavelength. For example, the electrons in a CRT display have a De Broglie wavelength of about 10^{-13} m. To prevent the wave function for such a particle being spread over all space, De Broglie proposed using wave packets to represent particles that are localized in space.[26] The spread of wavenumbers of sinusoids that add up to such a wave packet corresponds to an uncertainty in the particle's momentum, one aspect of the Heisenberg uncertainty principle.[25]

Interference and diffraction

Double-slit interference

When sinusoidal waveforms add, they may reinforce each other (constructive interference) or cancel each other (destructive interference) depending upon their relative phase. This phenomena is used in the interferometer. A simple example is an experiment due to Young where light is passed through two slits.[27] As shown in the figure, light is passed through two slits and shines on a screen. The path of the light to a position on the screen is different for the two slits, and depends upon the angle θ the path makes with the screen. If we suppose the screen is far enough from the slits (that is, *s* is large compared to the slit separation *d*) then the paths are nearly parallel, and the path difference is simply *d* sin θ. Accordingly the condition for constructive interference is:[28]



Pattern of light intensity on a screen for light passing through two slits. The pattern is idealized: an observed intensity pattern is modified by diffraction.

$$d \sin \theta = m\lambda \ ,$$

where m is an integer, and for destructive interference is:

$$d \sin \theta = (m + 1/2)\lambda \ .$$

Thus, if the wavelength of the light is known, the slit separation can be determined from the interference pattern or *fringes*, and *vice versa*.

It should be noted that the effect of interference is to *redistribute* the light, so the energy contained in the light is not altered, just where it shows up.[29]

Single-slit diffraction

The notion of path difference and constructive or destructive interference used above for the double-slit experiment applies as well to the display of a single slit of light intercepted on a screen. The main result of this interference is to spread out the light from the narrow slit into a broader image on the screen. This distribution of wave energy is called diffraction.

Two types of diffraction are distinguished, depending upon the separation between the source and the screen: Fraunhofer diffraction or far-field diffraction at large separations and Fresnel diffraction or near-field diffraction at close separations.

In the analysis of the single slit, the non-zero width of the slit is taken into account, and each point in the aperture is taken as the source of one contribution to the beam of light (*Huygen's wavelets*). On the screen, the light arriving from each position within the slit has a different path length, albeit possibly a very small difference. Consequently, interference occurs.

In the Fraunhofer diffraction pattern sufficiently far from a single slit, within a small-angle approximation, the intensity spread *S* is related to position *x* via a squared sinc function:[30]

$$S(u) = \mathrm{sinc}^2(u) = \left(\frac{\sin \pi u}{\pi u} \right)^2 \ ; \text{ with } u = \frac{xL}{\lambda R} \ ,$$

where *L* is the slit width, *R* is the distance of the pattern (on the screen) from the slit, and λ is the wavelength of light used. The function *S* has zeros where *u* is a non-zero integer, where are at *x* values at a separation proportion to wavelength.

Diffraction-limited resolution

Diffraction is the fundamental limitation on the resolving power of optical instruments, such as telescopes (including radiotelescopes) and microscopes.[31] For a circular aperture, the diffraction-limited image spot is known as an Airy disk; the distance *x* in the single-slit diffraction formula is replaced by radial distance *r* and the sine is replaced by $2J_1$, where J_1 is a first order Bessel function.[32]

The resolvable *spatial* size of objects viewed through a microscope is limited according to the Rayleigh criterion, the radius to the first null of the Airy disk, to a size proportional to the wavelength of the light used, and depending on the numerical aperture:[33]

$$r_{Airy} = 1.22 \frac{\lambda}{2\mathrm{NA}} \ ,$$

where the numerical aperture is defined as $\mathrm{NA} = n \sin \theta$ for θ being the half-angle of the cone of rays accepted by the microscope objective.

The *angular* size of the central bright portion (radius to first null of the Airy disk) of the image diffracted by a circular aperture, a measure most commonly used for telescopes and cameras, is:[34]

$$\delta = 1.22 \frac{\lambda}{D} \ ,$$

where λ is the wavelength of the waves that are focused for imaging, *D* the entrance pupil diameter of the imaging system, in the same units, and the angular resolution δ is in radians.

As with other diffraction patterns, the pattern scales in proportion to wavelength, so shorter wavelengths can lead to higher resolution.

Subwavelength

The term *subwavelength* is used to describe an object having one or more dimensions smaller than the length of the wave with which the object interacts. For example, the term *subwavelength-diameter optical fibre* means an optical fibre whose diameter is less than the wavelength of light propagating through it.

A subwavelength particle is a particle smaller than the wavelength of light with which it interacts (see Rayleigh scattering). Subwavelength apertures are holes smaller than the wavelength of light propagating through them. Such structures have applications in extraordinary optical transmission, and zero-mode waveguides, among other areas of photonics.

Subwavelength may also refer to a phenomenon involving subwavelength objects; for example, subwavelength imaging.

See also

- Emission spectrum
- Fraunhofer lines – dark lines in the solar spectrum, traditionally used as standard optical wavelength references
- Spectral line
- Spectrum
- Spectrum analysis

External links

- Conversion: Wavelength to Frequency and vice versa - Sound waves and radio waves [35]
- Teaching resource for 14–16 years on sound including wavelength [36]
- The visible electromagnetic spectrum displayed in web colors with according wavelengths [37]

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