Revision Guide for Chapter 6

Contents

Student's Checklist

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I can show my understanding of effects, ideas and relationships by describing and explaining:

how standing waves are formed by sets of wave travelling in opposite directions e.g. by drawing diagrams to show what happens Revision Notes: Amplitude, frequency, wavelength and wave speed; Travelling and standing waves Summary Diagrams: Standing waves; Standing waves on a guitar; Standing waves in pipes	
how waves passing through two slits combine and interfere to produce a wave / no-wave pattern Revision Notes: Interference; Path difference; Double slit interference Summary Diagrams: Two slit interference	
what happens when waves pass through a single narrow gap (diffraction) Revision Notes: Diffraction; Phase and phasors Summary Diagrams: Diffraction	
how a diffraction grating works in producing a spectrum Revision Notes: Gratings and spectra; Phase and phasors Summary Diagrams: Transmission grating	

I can use the following words and phrases accurately when describing effects and observations:

wave, standing wave, frequency, wavelength, amplitude, phase, phasor Revision Notes: Amplitude, frequency, wavelength and wave speed; Travelling and standing waves; Phase and phasors; Summary Diagrams: Phase and angle; Adding oscillations using phasors;	
path difference, interference, diffraction, superposition, coherence Revision Notes: Interference; Path difference; Double slit interference; Diffraction; Superposition; Coherence Summary Diagrams: Two slit interference; Coherence	

I can sketch and interpret diagrams:

illustrating the propagation of waves Revision Notes: Amplitude, frequency, wavelength and wave speed; Travelling and standing waves;	
showing how waves propagate in two dimensions using Huygens' wavelets Revision Notes: Huygens' wavelets;	
showing how waves that have travelled to a point by different paths combine to produce the wave amplitude at that point, i.e. by adding together the different phases of the waves, using phasors Revision Notes: Interference; Double slit interference; Diffraction; Gratings and spectra; Summary Diagrams: Two slit interference; Transmission grating	

I can calculate:

wavelengths, wave speeds and frequencies by using (and remembering) the equation $v = f\lambda$ Revision Notes: Amplitude, frequency, wavelength and wave speed;	
calculating the wavelengths of standing waves *e.g. in a string or a column of air* Revision Notes: Travelling and standing waves; Summary Diagrams: Standing waves; Standing waves on a guitar; Standing waves in pipes	
path differences for waves passing through double slits and diffraction gratings Revision Notes: Interference; Double slit interference; Diffraction; Gratings and spectra; Summary Diagrams: Two slit interference; Transmission grating	
the unknown quantity when given other relevant data in using the equation $n\lambda = d \sin\theta$ Revision Notes: Gratings and spectra Summary Diagrams: Transmission grating	

I can give and explain an example of:

a phenomenon or application involving the superposition (addition) of waves, *e.g. standing waves, interference, diffraction* Revision Notes: Beats; Travelling and standing waves; Interference; Double slit interference; Diffraction; Gratings and spectra; Summary Diagrams: Standing waves on a guitar; Standing waves in pipes; Two slit interference; Diffraction; Transmission grating	

Revision Notes

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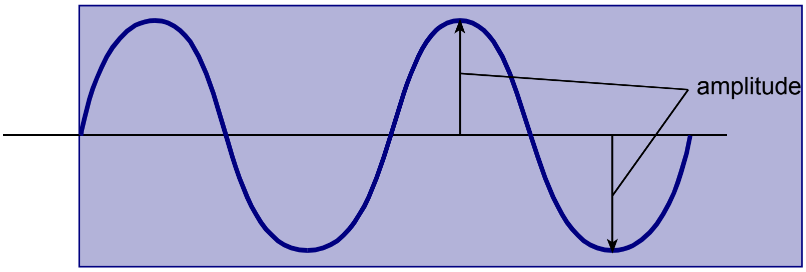
Amplitude, frequency, wavelength and wave speed

The amplitude of a wave at a point is the maximum displacement from equilibrium of the material at that point.

Amplitude of a transverse wave



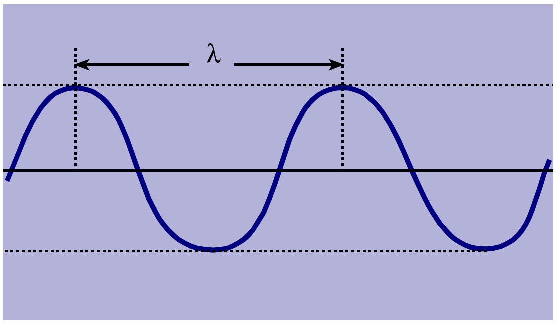
The period *T* of an oscillation is the time taken for one complete oscillation.
The frequency *f* of an oscillation is the number of complete cycles of oscillation each second.

The SI unit of frequency is the hertz (Hz), equal to one complete cycle per second.

The wavelength λ of a wave is the distance along the direction of propagation between adjacent points where the motion at a given moment is identical, for example from one wave crest to the next.

The SI unit of wavelength is the metre.

Wavelength



Relationships

Frequency *f* and period *T*

$$f = \frac{1}{T}$$

$$T = \frac{1}{f}$$

Frequency *f*, wavelength λ and wave speed *v* $v = f\lambda$
Displacement *s* at any one point in a wave $s = A\sin(2\pi ft + \phi)$ where ϕ is the phase.

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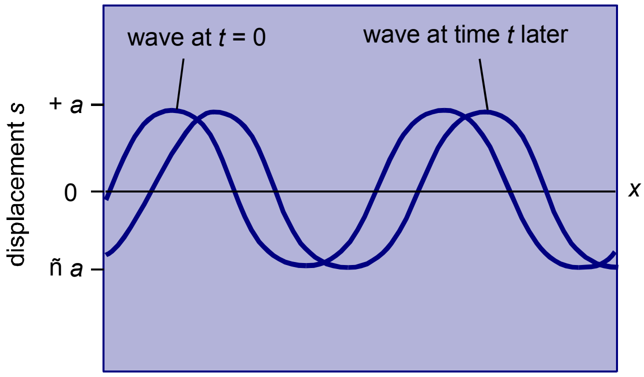
Travelling and standing waves

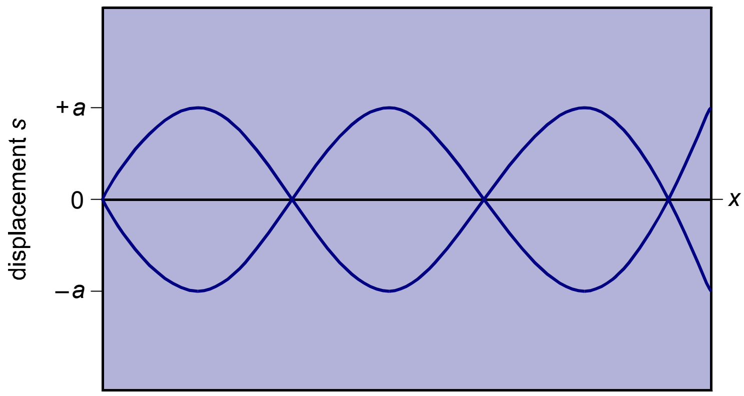
Travelling waves propagate through space or through a substance.

A travelling wave



Stationary or **standing** waves are produced when travelling waves of the same frequency and amplitude pass through one another in opposing directions.

A standing wave



The resultant wave has the same frequency of oscillation at all points. The wave does not travel. Its amplitude varies with position. Positions of minimum amplitude are called displacement nodes and positions of maximum amplitude are called displacement antinodes.

Nodes and antinodes alternate in space. The nodes (and the antinodes) are half a wavelength apart.

Standing waves are an example of **wave superposition**. The waves on a guitar string or in an organ pipe are standing waves.

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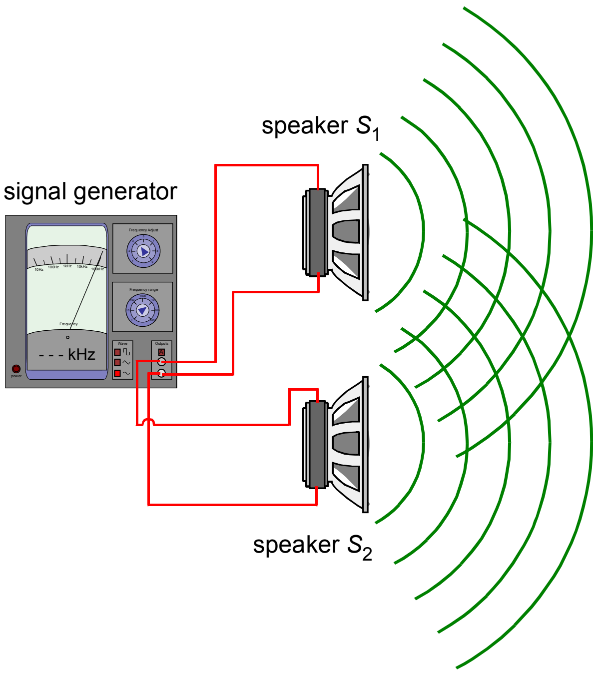
Interference

When waves overlap, the resultant displacement will be equal to the sum of the individual displacements at that point and at that instant (if the waves superpose linearly).

Interference is produced if waves from two coherent sources overlap or if waves from a single source are divided and then reunited.

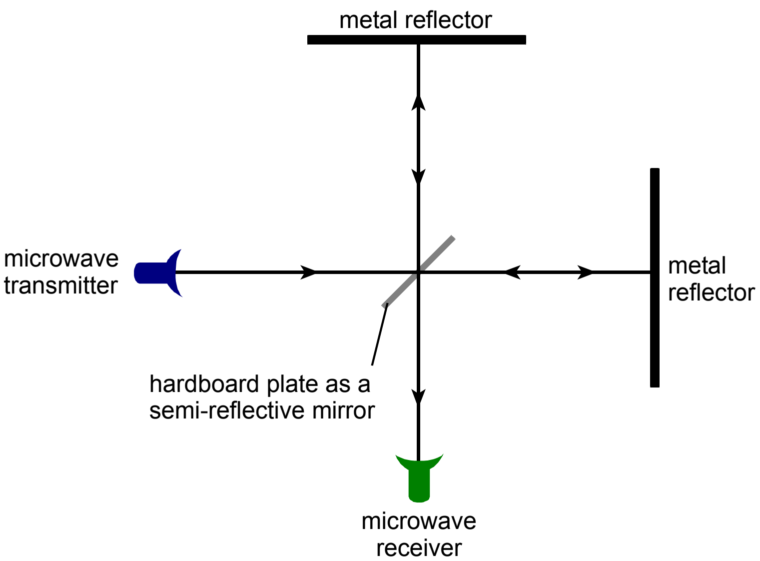
Interference of sound



Interference using sound waves can be produced by two loudspeakers connected together to an oscillator. If you move about in the overlap area you will detect points of reinforcement and of cancellation.

Another way to produce interference is to divide the waves from one source and then recombine them. The diagram below shows this being done for microwaves, sending part of the wave along one path and part along another. The receiver gives a minimum response when the paths differ by half a wavelength.

Division of amplitude



Other examples of interference include the ‘blooming’ of camera lenses, and the colours of oil films and soap bubbles.

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Path difference

The path difference between two waves will determine what happens when they superpose.

If the path difference between two wavefronts is a whole number of wavelengths, the waves reinforce.

If the path difference is a whole number of wavelengths plus one half of a wavelength, the waves cancel.

The importance of a path difference is that it introduces a time delay, so that the phases of the waves differ. It is the difference in phase that generates interference effects.

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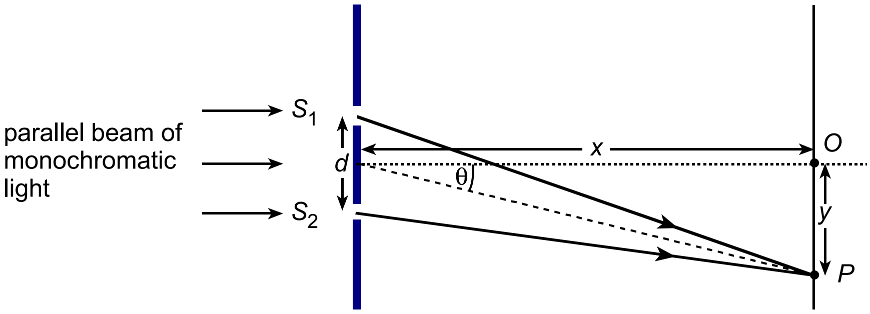
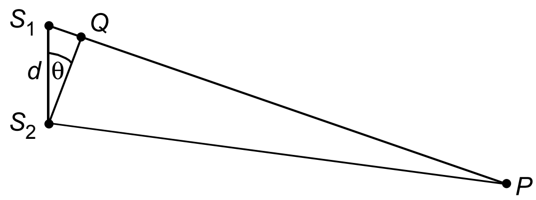
Double-slit interference

The double-slit experiment with light requires light from a narrow source to be observed after passing through two closely spaced slits. A pattern of alternate bright and dark fringes is observed.

In the diagram below the path difference between light from the two slits to a point P on the screen is equal to $d \sin \theta$, where d is the spacing between the slit centres and θ is the angle between the initial direction of the beam and the line from the centre of the slits to the point P.

Double slit interference





$QP = S_2P$

$S_1Q = S_1P - S_2P$

since $S_1Q = d \sin\theta$
then $S_1P - S_2P = d \sin\theta$ = path difference

Bright fringes: the waves arriving at P **reinforce** if the path difference is a whole number of wavelengths, i.e. $d \sin \theta = n \lambda$, where λ is the wavelength of the light used and n is an integer.

Dark fringes: the waves arriving at P **cancel** if the path difference is a whole number of wavelengths plus a half wavelength, i.e. $d \sin \theta = (n + ½) \lambda$, where λ is the wavelength of the light used and n is an integer.

The angle $\sin \theta = y / L$ where y is the distance OP to the fringe and L is the distance from the fringe to the centre of the slits. However, y is very small so L does not differ appreciably from X, the distance from the centre of the fringe pattern to the slits. Hence, for a bright fringe:

$$\sin\theta = \frac{y}{X} = \frac{n\lambda}{d}$$

which gives

$$\frac{y}{X} = \frac{n\lambda}{d}$$

Adjacent fringes have values of n equal to n and n+1. Thus the spacing between pairs of adjacent bright (or dark) fringes = $\frac{\lambda X}{d}$. That is:

$$\frac{\text{fringe width}}{\text{slit to screen distance}} = \frac{\text{wavelength}}{\text{slit separation}}$$

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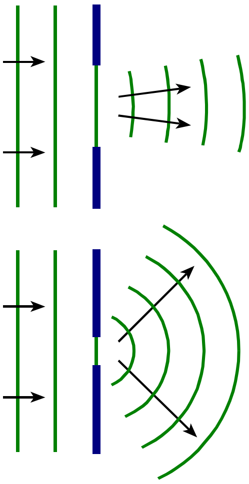
Diffraction

Diffraction is the spreading of waves after passing through a gap or past the edge of an obstacle.

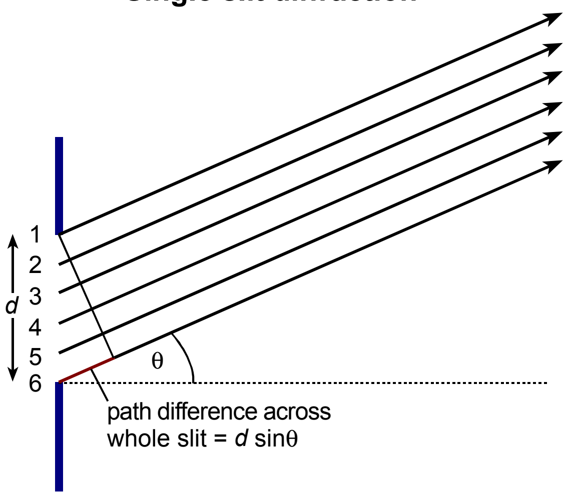
The spreading increases if the gap is made narrower or if the wavelength of the waves is increased.

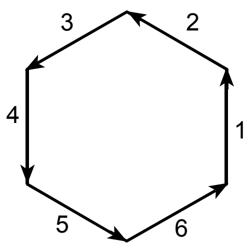
Diffraction



Monochromatic light passing through a single narrow slit produces a pattern of bright and dark fringes. Intensity minima are observed at angles θ given by the equation $d \sin \theta = n\lambda$, where d is the gap width, n is a positive integer and θ is the angle between the incident direction and the direction of diffraction.

Single slit diffraction





phasors add to zero

If the distance across the gap is taken to be a large number of equally spaced point sources, **1**, **2**, **3**, etc, the phasor due to **1** will be a certain fraction of a cycle behind the phasor due to **2,** which will be the same fraction behind the phasor due to **3** etc. The resultant phasor is therefore zero at those positions where the last phasor is back in phase with the first phasor.

The path difference between the top and bottom of the slit is $d \sin \theta$. If this path difference is equal to a whole number of wavelengths, $n\lambda$, the first and last phasors will be in phase. Thus minima occur when

$d \sin \theta = n\lambda$

For small angles, $\sin \theta = \theta$ giving an angular width $2\lambda / d$ for the central maximum.

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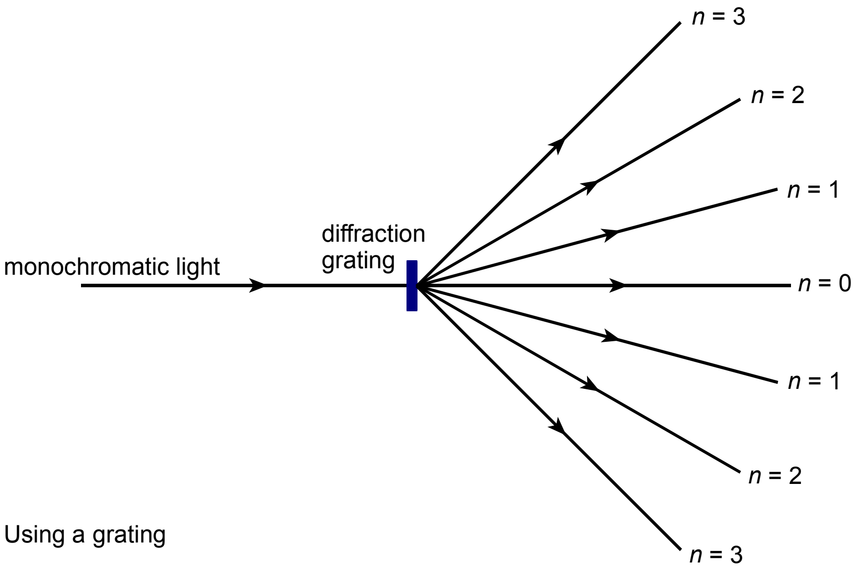
Gratings and spectra

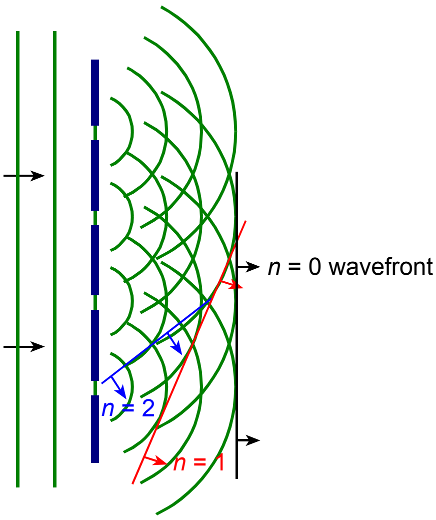
A grating is a plate with a large number of parallel grooves ruled on it. A transmission grating transmits and diffracts light into spectra.

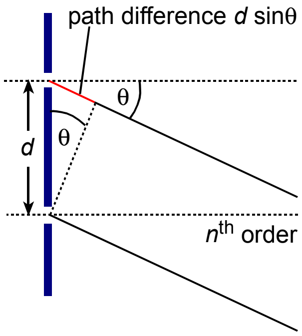
When a narrow beam of monochromatic light is directed normally at a transmission grating, the beam passes through and is diffracted into well-defined directions given by $d \sin \theta = n \lambda$, where d, the grating spacing, is the distance between adjacent slits and n is an integer, the spectral order. The path difference between waves from adjacent slits is $d \sin \theta$ and this must be equal to a whole number n of wavelengths for reinforcement.

The diffraction grating



Using a grating





Formation of wavefronts

Path difference

Using a white light source, a continuous spectrum is observed at each order, with blue nearer the centre and red away from the centre. This is because blue light has a smaller wavelength than red light so is diffracted less. Spectra at higher orders begin to overlap because of the spread.

Using light sources that emit certain wavelengths only, a line emission spectrum is observed which is characteristic of the atoms in the light source.

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Phase and phasors

'Phase' refers to stages in a repeating change, as in 'phases of the Moon'.

The phase difference between two objects vibrating at the same frequency is the fraction of a cycle that passes between one object being at maximum displacement in a certain direction and the other object being at maximum displacement in the same direction.

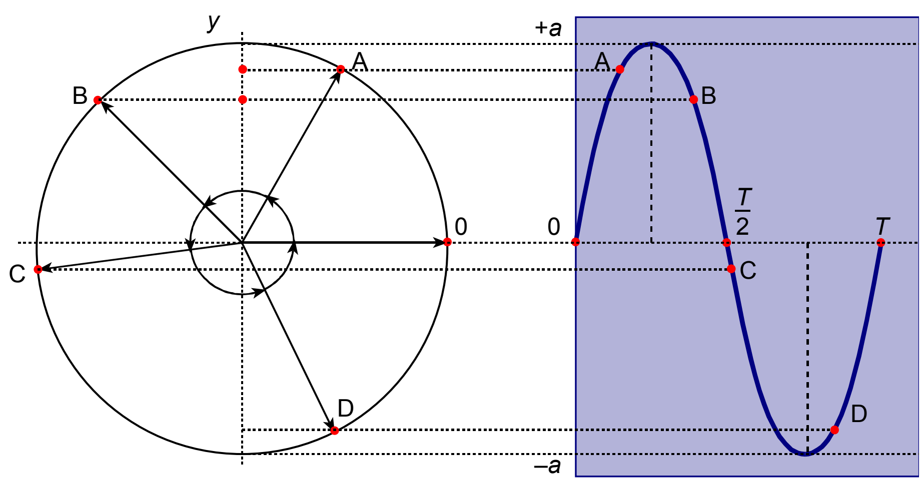
Phase difference is expressed as a fraction of one cycle, or of 2π radians, or of 360°.

Phasors are used to represent amplitude and phase in a wave. A phasor is a rotating arrow used to represent a sinusoidally changing quantity.

Suppose the amplitude s of a wave at a certain position is $s = a \sin(2\pi ft)$, where a is the amplitude of the wave and f is the frequency of the wave. The amplitude can be represented as the projection onto a straight line of a vector of length a rotating at constant frequency f, as shown in the diagram. The vector passes through the $+x$-axis in an anticlockwise direction at time $t = 0$ so its projection onto the y-axis at time t later is $a \sin(2\pi ft)$ since it turns through an angle $2\pi ft$ in this time.

Phasors can be used to find the resultant amplitude when two or more waves superpose. The phasors for the waves at the same instant are added together 'tip to tail' to give a resultant phasor which has a length that represents the resultant amplitude. If all the phasors add together to give zero resultant, the resultant amplitude is zero at that point.

Generating a sine wave



phasor rotating at constant frequency f

time t

$s = a \sin(2\pi ft)$

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Superposition

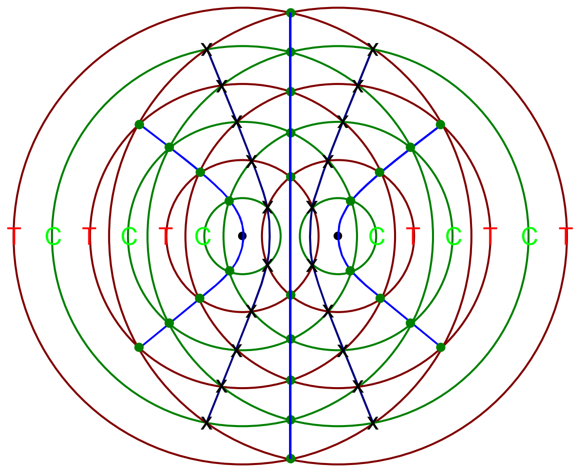
When two or more waves meet, their displacements superpose.

The principle of superposition states that when two or more waves overlap, the resultant displacement at a given instant and position is equal to the sum of the individual displacements at that instant and position.

In simple terms, where a wave crest meets another wave crest, the two wave crests pass through each other, forming a 'super crest' where and when they meet. If a wave trough meets another wave trough, they form a 'super trough' where they meet. In both cases, the waves reinforce each other to increase the displacement momentarily. If a wave crest meets a wave trough, the waves cancel each other out momentarily.

An example of superposition is the interference pattern produced by a pair of dippers in a ripple tank, as shown below.

Interference



C = crest
T = trough
• = constructive interference = C + C or T + T
x = destructive interference = C + T

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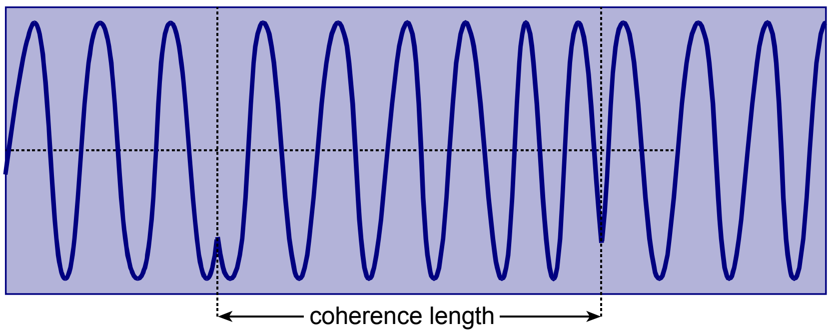
Coherence

Coherence is an essential condition for observing the interference of waves.

Two sources of waves are coherent if they emit waves with a constant phase difference. Two waves arriving at a point are said to be coherent if there is a constant phase difference between them as they pass that point.

The coherence length of light from a given source is the average length of a wavetrain between successive sudden phase changes.

Coherence along a wave



To see interference with light, the two sets of waves need to be produced from a single source, so that they can be coherent. For this, the path difference must not be larger than the coherence length of the source.

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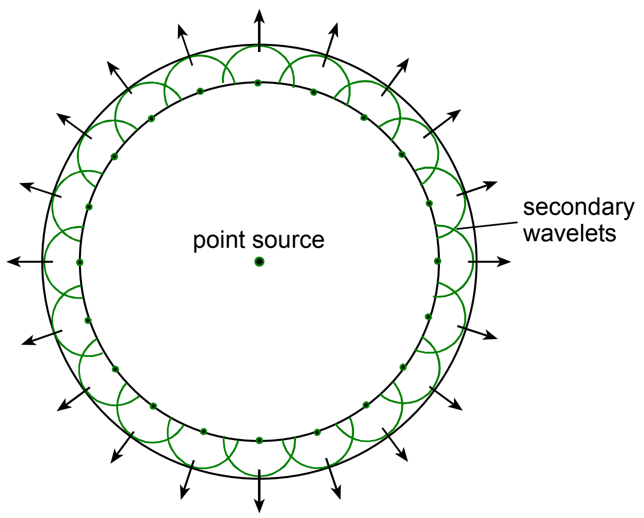
Huygens' wavelets

Huygens' wavelet theory can be used to explain reflection, refraction, diffraction and interference of light.

Huygens' theory of wavelets considers each point on a wavefront as a secondary emitter of wavelets. The wavelets from the points along a wavefront create a new wavefront, so that the wave propagates.

Huygens' wavelets



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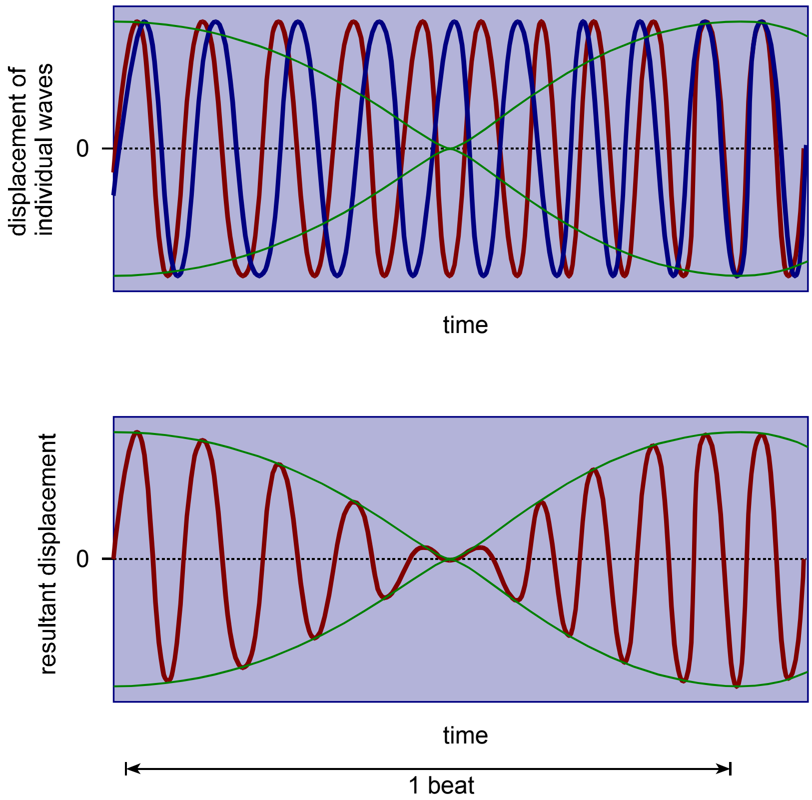
Beats

Beats are a slow variation of intensity produced by two oscillations having nearly equal frequencies.

When two sound waves of almost identical frequencies are heard at the same time, the loudness varies periodically. The beat frequency is equal to the difference in frequency of the two sources, $f_1 - f_2$.

Beats



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Summary Diagrams (OHTs)

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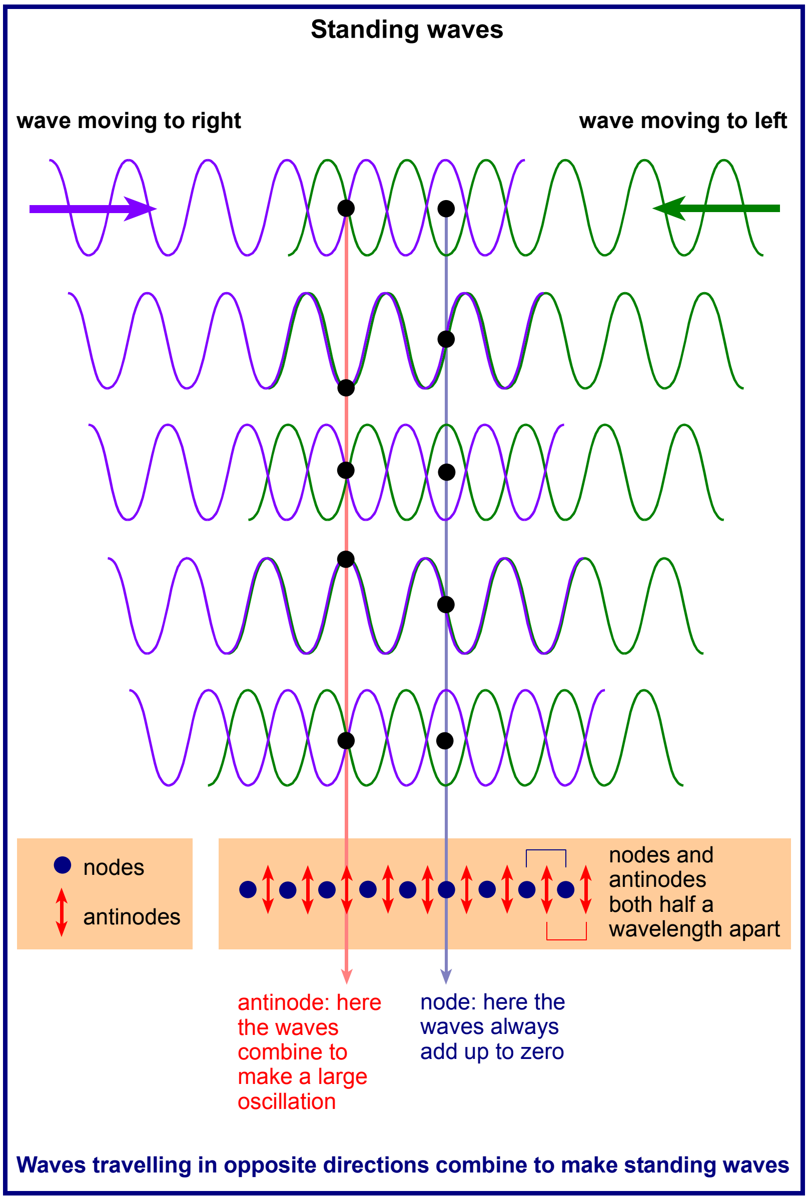
Standing waves



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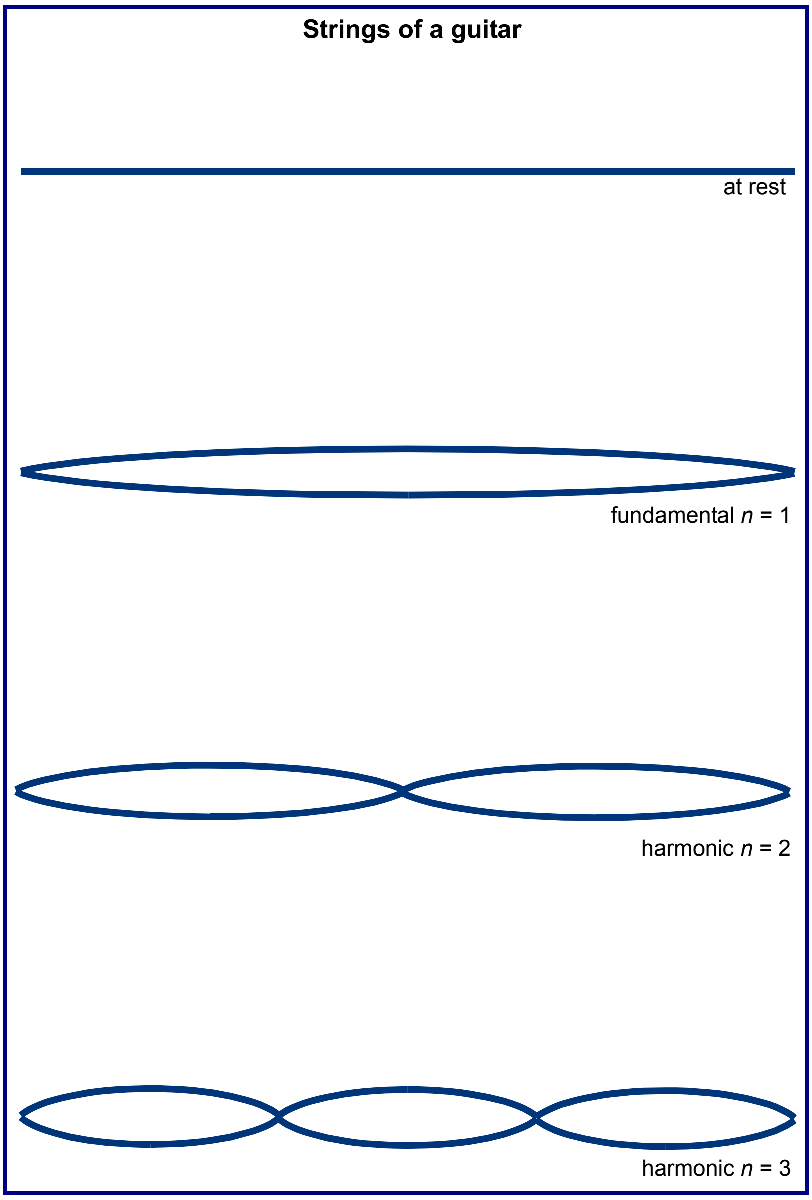
Standing waves on a guitar

An example of superposition.



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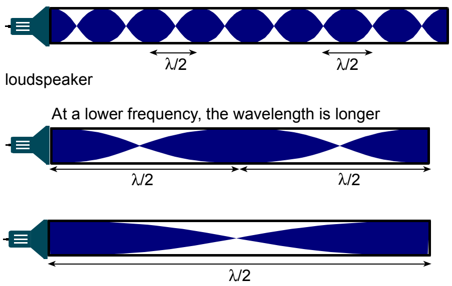
Standing waves in pipes

An example of superposition.

Standing waves in pipes

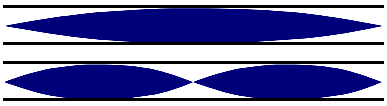
Closed pipes



A loudspeaker sends a sound into a long tube. Dust in the tube can show nodes and antinodes. Nodes are half a wavelength apart. So are antinodes. Maximum amplitude shows maximum pressure variation and minimum motion of air (pressure antinode). Minimum amplitude shows minimum pressure variation and maximum motion of air (pressure node).

The fundamental: The lowest frequency which can form a standing wave has wavelength equal to twice the length of the tube

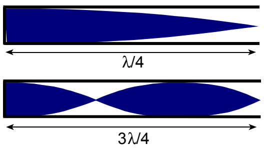
Pipes open at both ends



Sound can be reflected from an open end as well as from a closed end.

This is how open organ pipes and flutes work.

Pipes closed at one end



Pipes closed at one end are shorter, for the same note.

A clarinet is like this. An oboe is too, but with a tapered tube.

Some organ pipes are stopped at one end.

Frequencies of standing waves

	pipes open or closed at both ends strings fixed at both ends	pipes open at one end
length L	$L = n\lambda/2$	$L = (2n-1)\ \lambda/4$
fundamental	$f = v/2L$	$f = v/4L$
harmonics	$2f$ $3f$ ... nf	$3f$ $5f$ ... $(2n-1)f$

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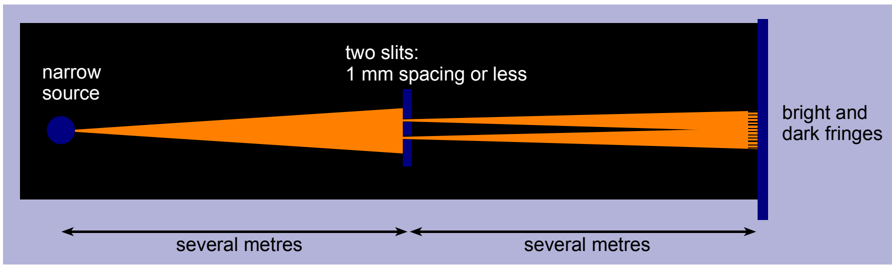
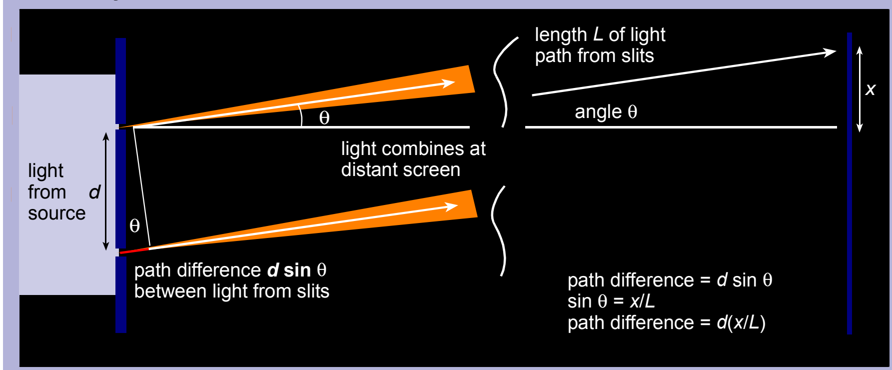
Two-slit interference

Young’s two-slit interference experiment



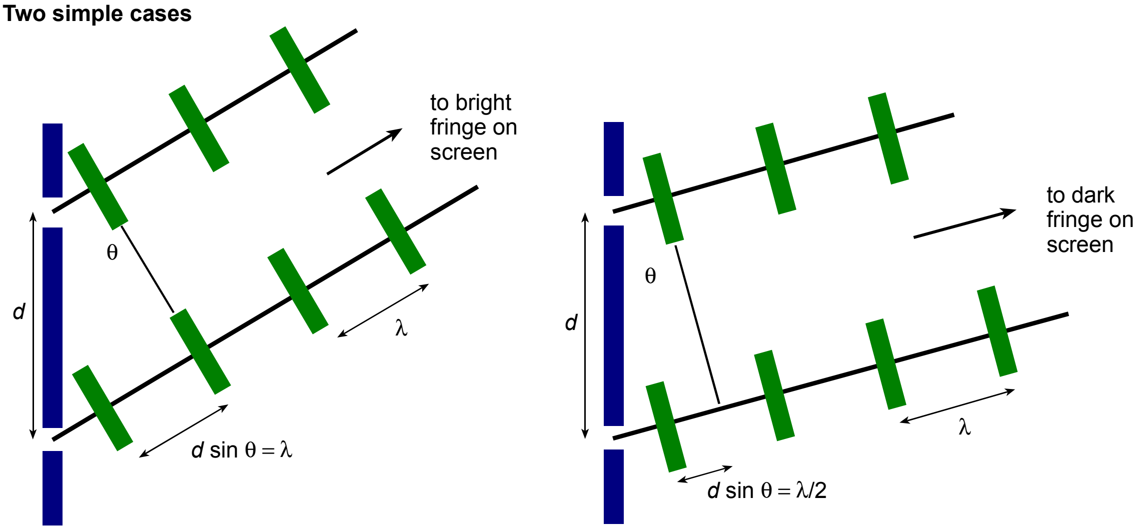
Geometry



Approximations: angle θ very small; paths effectively parallel; distance L equal to slit–screen distance. Error less than 1 in 1000

Young’s two-slit interference experiment

Two simple cases



waves in phase:
$\lambda = d \sin \theta$
$\lambda = d(x/L)$

In general:
for a bright fringe $n\lambda = d \sin \theta$
spacing between fringes = $\lambda (L/d)$

waves in antiphase:
$\lambda/2 = d \sin \theta$
$\lambda/2 = d(x/L)$

Wavelength can be measured from the fringe spacing

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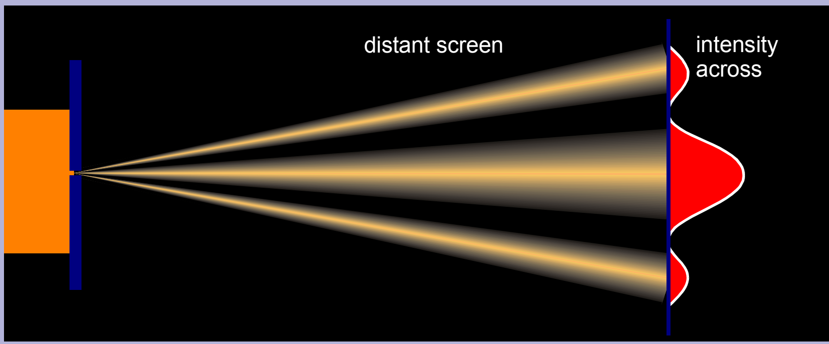
Diffraction

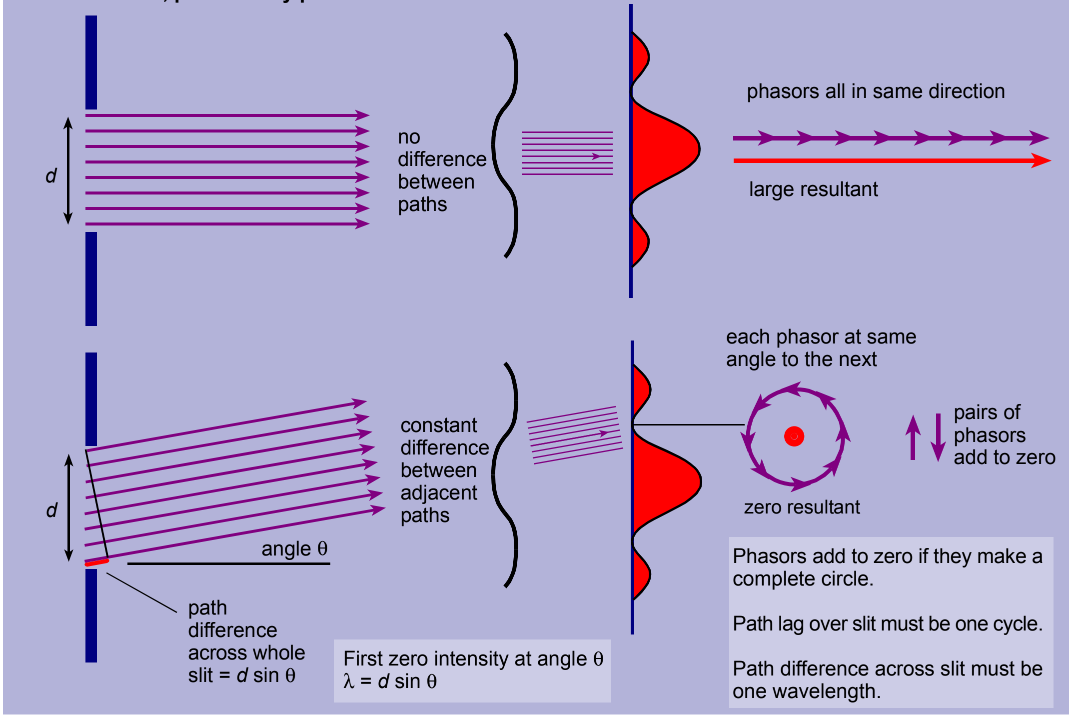
Diffraction at a single aperture

Single slit



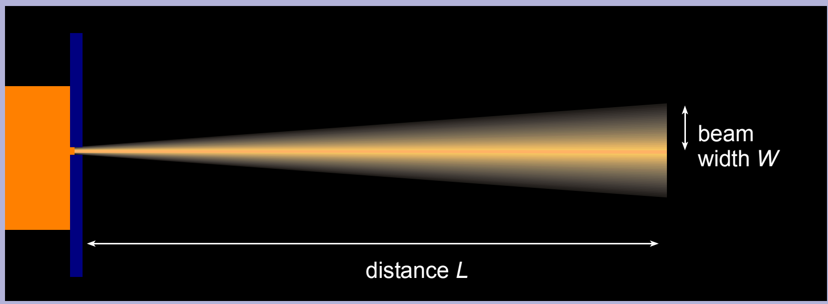
Diffraction at a single aperture

Simplified case:
screen distant, paths nearly parallel



Diffraction at a single aperture

Useful approximation



sin θ = *W*/*L* approximately
= beam angle in radian

Beam angle θ in radian = λ/*d*

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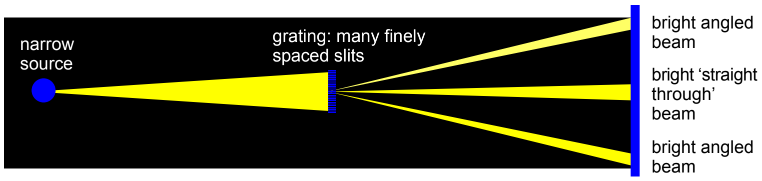
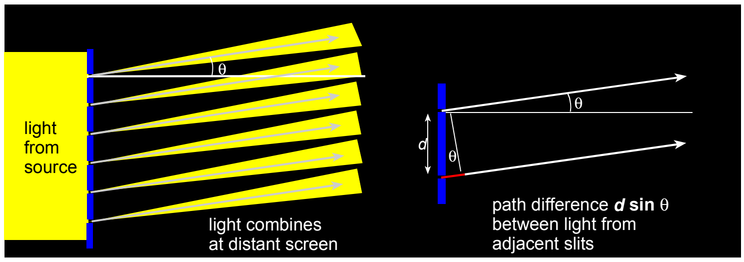
Transmission grating

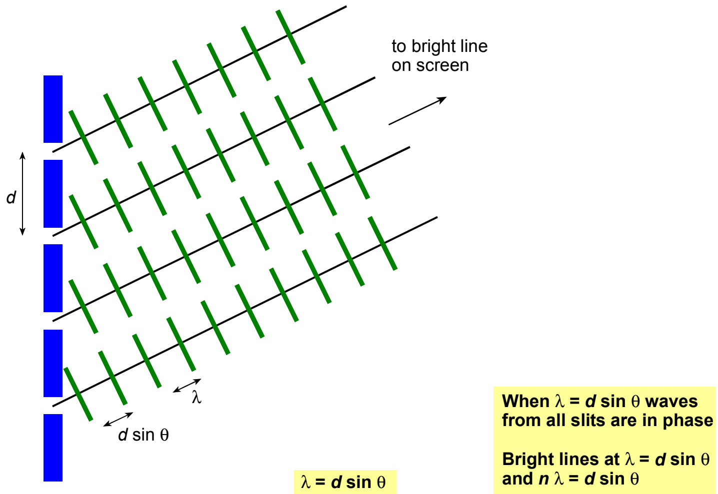
Diffraction grating



Geometry



Waves from many sources all in phase



Sharp bright spectral lines at angles where $n\lambda = d\sin\theta$

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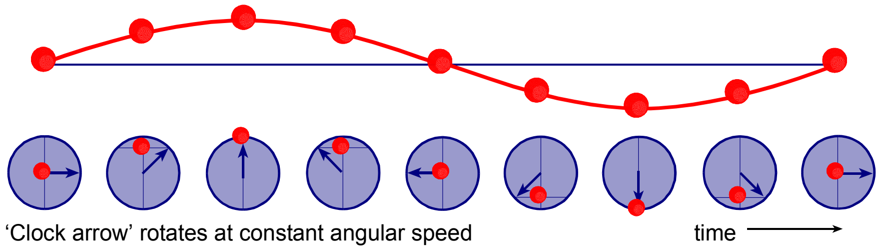
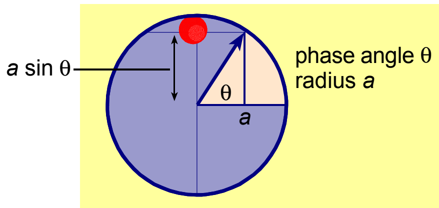
Phase and angle

Phase and angle



Phase angle

degrees	0	45	90	135	180	225	270	315	360
radians	0	$\pi/4$	$\pi/2$	$3\pi/4$	π	$5\pi/4$	$3\pi/2$	$7\pi/4$	2π



'Clock arrow' rotates 2π in periodic time T

angle $\theta = 2\pi\,(t/T)$
$T = 1/f$ (f = frequency)
angle $\theta = 2\pi ft$
displacement = $a \sin\theta = a \sin 2\pi ft$

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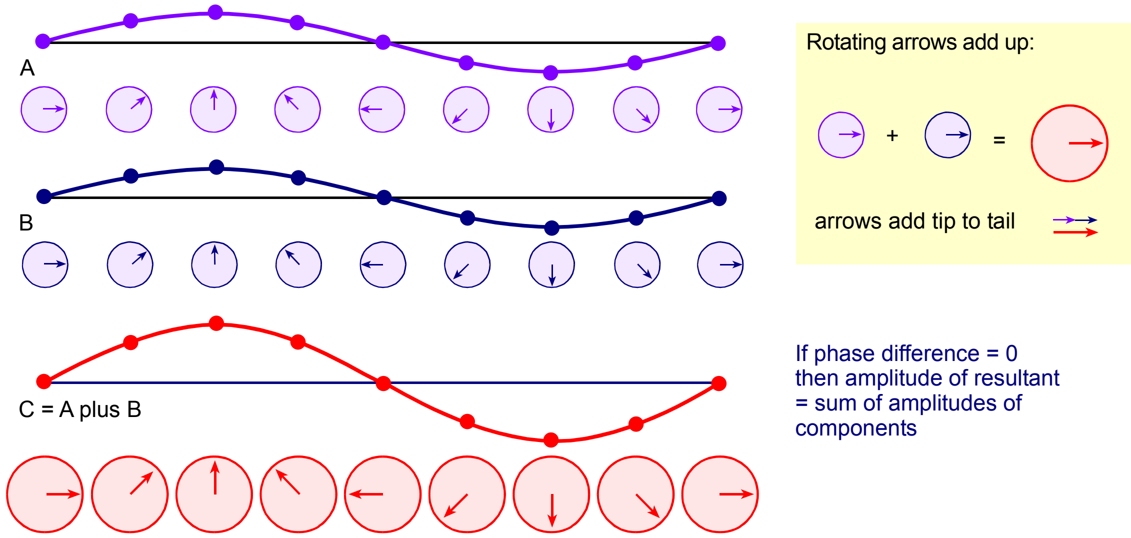
Adding oscillations using phasors

The diagrams show pairs of oscillations being added (superposed), with different phases between the two oscillations.

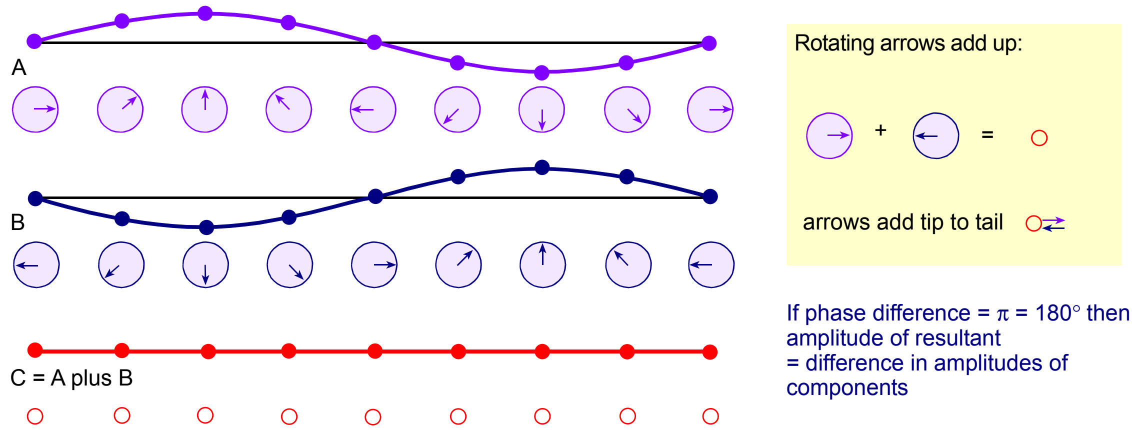
Superposition and phase difference

Oscillations in phase

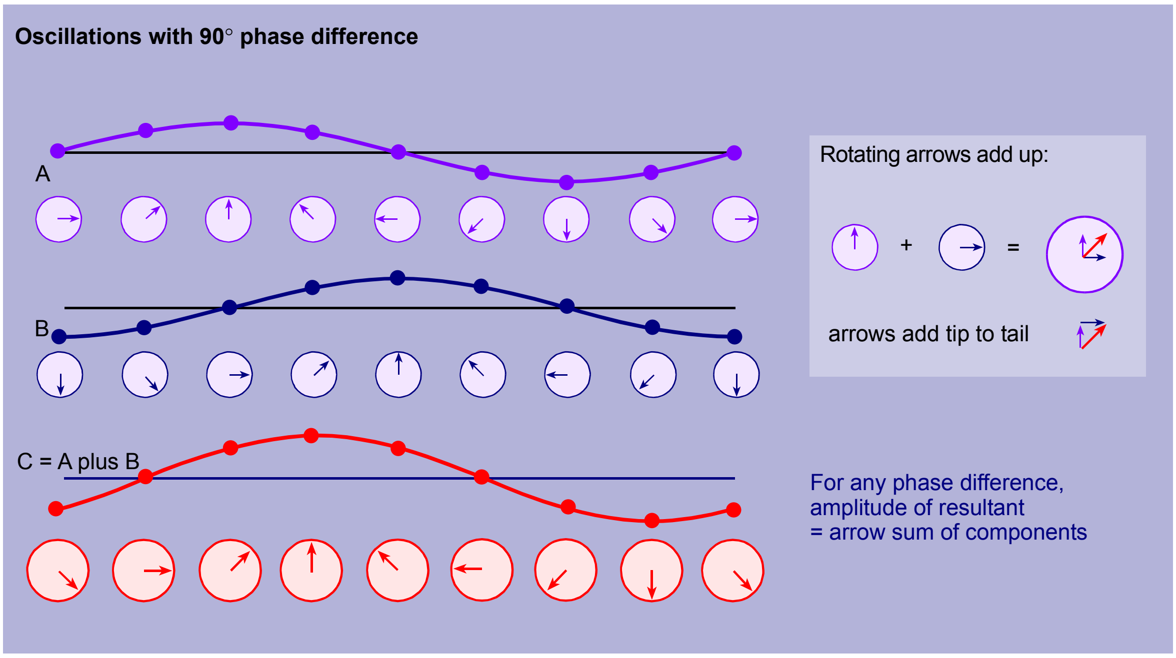


Superposition and phase difference

Oscillations in antiphase



Superposition and phase difference



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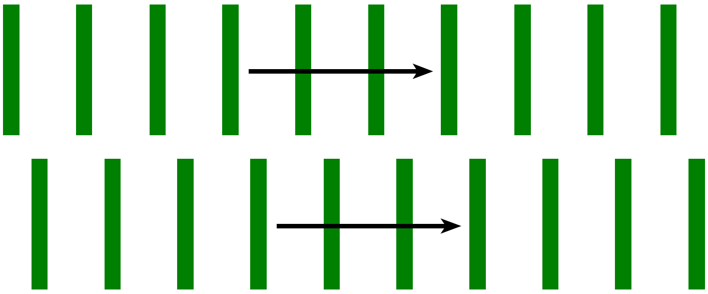
Coherence

Coherence

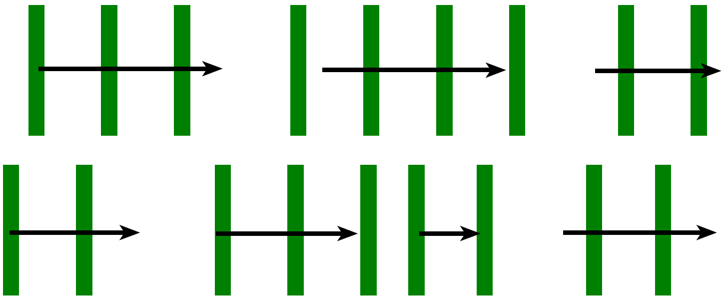
Two waves will only show stable interference effects if they have a constant unchanging phase difference. If so they are said to be **coherent**.

coherent waves with constant phase difference



Atoms emit bursts of light waves. A burst from one atom is not in phase with a burst from another. So light waves from atoms are coherent only over quite short distances.

incoherent wave bursts with changing phase difference



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