Electric Fields (Chapter 8):

- **Field of force**: a region of space where an object feels a force.
  - Electric field – objects with electric charge
  - Magnetic field – magnetic materials and moving charges
  - Gravitational field – objects with mass
- **Field lines**: lines drawn to represent the strength and direction of a field of force.

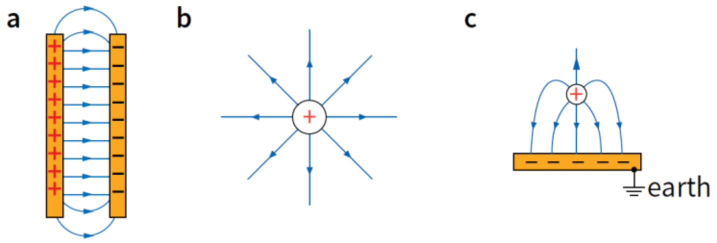


Figure 8.6 Field lines are drawn to represent an electric field. They show the direction of the force on a positive charge placed at a point in the field. **a** A uniform electric field is produced between two oppositely charged plates. **b** A radial electric field surrounds a charged sphere. **c** The electric field between a charged sphere and an earthed plate.

- **Electric field strength** at a point is the force per unit charge exerted on a stationary positive charge at that point; units: N C^{-1}

$$E = \frac{F}{Q}.$$

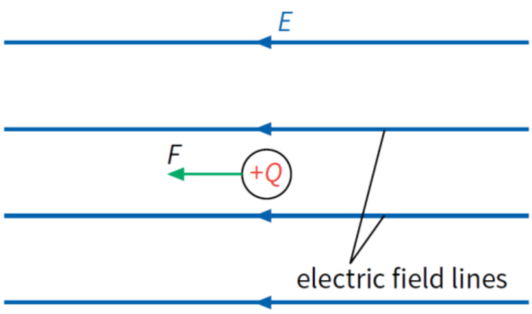


Figure 8.10 A field of strength *E* exerts force *F* on charge +*Q*.

- The strength of the electric field between two parallel metal plates depends on:
  - The voltage *v* between the plates
  - The separation *d* between the plates

$$E = \frac{V}{d}$$

- The units of electric field strength: 1 V m^{-1} = 1 N C^{-1}
- Hence the formula to calculate the force *F* on a charge *Q* in a uniform field between two parallel plates is:

$$F = QE = -\frac{QV}{d}$$

- For an electron:

$$F = \frac{eV}{d}$$

- An electric charge moving initially at right-angles to a uniform electric field follows a parabolic path.

Electric current, potential difference and resistance (Chapter 9):

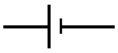
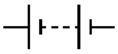
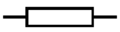
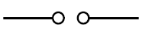
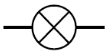
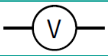
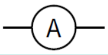
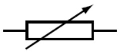
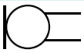
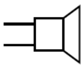
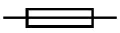
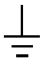
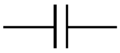
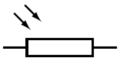
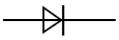
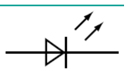
Symbol	Component name
	connecting lead
	cell
	battery of cells
	fixed resistor
	power supply
	junction of conductors
	crossing conductors (no connection)
	filament lamp
	voltmeter
	ammeter
	switch
	variable resistor
	microphone
	loudspeaker
	fuse
	earth
	alternating signal
	capacitor
	thermistor
	light-dependent resistor (LDR)
	semiconductor diode
	light-emitting diode (LED)

Table 9.1 Electrical components and their circuit symbols.

- **Electric current** is the rate of flow of electric charge.

$$\text{current} = \frac{\text{charge}}{\text{time}} \qquad I = \frac{\Delta Q}{\Delta t}$$

- **Number density** *n*: the number of free electrons, per unit volume in a material.

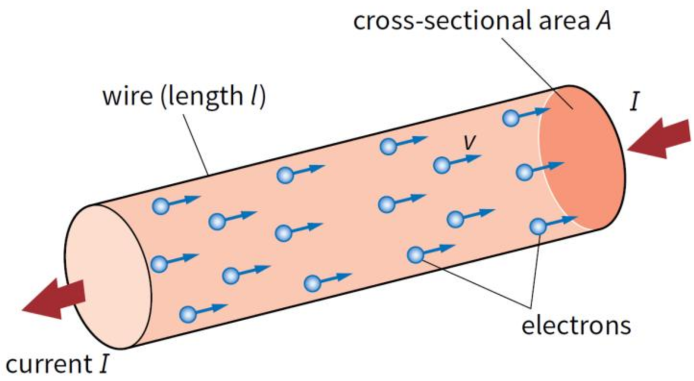


Figure 9.9 A current I in a wire of cross-sectional area A. The charge carriers are mobile conduction electrons with mean drift velocity v.

number of electrons = number density × volume of wire

$$= n \times A \times l$$

charge of electrons = number × electron charge

$$= n \times A \times l \times e$$

We can find the current I because we know that this is the charge that flows in time t, and current = charge/time:

$$I = n \times A \times l \times e / t$$

Substituting v for l / t gives

$$I = nAve$$

- General version of the equation:

$$I = nAvq$$

  - v is the mean drift velocity of the charged particles
  - q is the charge of each particle carrying the current
- If the current increases, the drift velocity v must increase ($v \propto I$)
- If the wire is thinner, the electrons move more quickly for a given current ($v \propto I/A$)
- In a material with a lower density of electrons (smaller n), the mean drift velocity must be greater for a given current ($v \propto 1/n$)
- **Potential difference** *V* is defined as the energy transferred per unit charge
- **e.m.f** transfers energy to electrical charges in a circuit – total work done per unit charge when charge flows round a complete circuit

$$W = V\Delta Q$$

- **Electrical resistance** is defined as the ratio of the potential difference to the current

$$R = \frac{V}{I}$$

- Electrical power:

$$P = \frac{W}{\Delta t} = \frac{V\Delta Q}{\Delta t} = V\left(\frac{\Delta Q}{\Delta t}\right)$$

The ratio of charge to time, $\frac{\Delta Q}{\Delta t}$, is the current I in the component. Therefore:

$$P = VI$$

As a word equation, we have:

power = potential difference × current

$$P = I^2R$$

$$P = \frac{V^2}{R}$$

- Energy transferred in a circuit:

power = current × voltage

and:

energy = power × time

we have:

energy transferred = current × voltage × time

$$W = IV\Delta t$$

Kirchhoff's laws (Chapter 10):

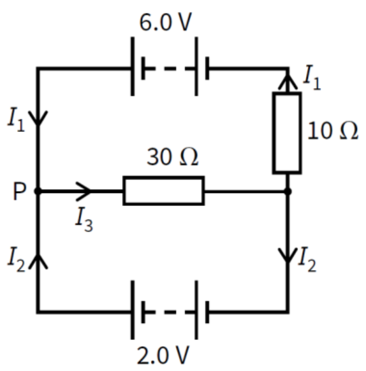
- **Kirchhoff's first law** states that the sum of currents entering any point in a circuit is equal to the sum of the currents leaving that same point (conservation of charge)

$$\Sigma I_{\text{in}} = \Sigma I_{\text{out}}$$

- **Kirchhoff's second law** states that the sum of the e.m.f.s around any loop in a circuit is equal to the sum of the p.d.s around the loop

$$\Sigma E = \Sigma V$$

  - ΣE is the sum of the e.m.f.s
  - ΣV is the sum of the potential differences



Calculate the current in each of the resistors in the circuit shown in Figure 10.11.

Step 1 Mark the currents flowing. The diagram shows I_1, I_2 and I_3.

Hint: *It does not matter if we mark these flowing in the wrong directions, as they will simply appear as negative quantities in the solutions.*

Step 2 Apply Kirchhoff's first law. At point P, this gives:

$$I_1 + I_2 = I_3 \quad (1)$$

Step 3 Choose a loop and apply Kirchhoff's second law. Around the upper loop, this gives:

$$6.0 = (I_3 \times 30) + (I_1 \times 10) \quad (2)$$

Step 4 Repeat step 3 around other loops until there are the same number of equations as unknown currents. Around the lower loop, this gives:

$$2.0 = I_3 \times 30 \quad (3)$$

We now have three equations with three unknowns (the three currents).

Step 5 Solve these equations as simultaneous equations. In this case, the situation has been chosen to give simple solutions. Equation 3 gives $I_3 = 0.067$ A, and substituting this value in equation 2 gives $I_1 = 0.400$ A. We can now find I_2 by substituting in equation 1:

$$I_2 = I_3 - I_1 = 0.067 - 0.400 = -0.333\text{ A}$$
$$\approx -0.33\text{ A}$$

Thus I_2 is negative – it is in the opposite direction to the arrow shown in Figure 11.11.

Note that there is a third 'loop' in this circuit; we could have applied Kirchhoff's second law to the outermost loop of the circuit. This would give a fourth equation:

$$6 - 2 = I_1 \times 10$$

However, this is not an independent equation; we could have arrived at it by subtracting equation 3 from equation 2.

- The combined resistance of resistors in series is given by the formula:
  - R = R1 + R2 + …
- The combined resistance of resistors in parallel is given by the formula:
  - 1/R = 1/R1 + 1/R2 + …
- Ammeters have a low resistance and are connected in series in a circuit.
- Voltmeters have a high resistance and are connected in parallel in a circuit.

Resistance and resistivity (Chapter 11):

- **Ohm's law**: a conductor obeys Ohm's law if the current in it is directly proportional to the potential difference across its ends.
- Ohmic components include a wire at constant temperature and a resistor
- Non-ohmic components include a filament lamp and a light-emitting diode
- A semiconductor diode allows current in one direction only
- A thermistor is a component which shows a rapid change in resistance over a narrow temperature range
- **Resistivity** ρ: a property of a material, a measure of its electrical resistance

$$\text{resistance} = \frac{\text{resistivity} \times \text{length}}{\text{cross-sectional area}} \qquad R = \frac{\rho L}{A}$$

- Resistivity increases with temperature

Practical circuits (Chapter 12):

- A source of e.m.f., such as a battery, has an internal resistance.
- The terminal p.d. of a source of e.m.f. is less than the e.m.f. because of ‘lost volts’ across the internal resistor:
    - Terminal p.d. = e.m.f. – ‘lost volts’
    - $V = E - Ir$
- A potential divider circuit consists of two or more resistors connected in series to a supply. The output voltage V_{out} across the resistor of resistance R_2 is given by:

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_{in}$$

Waves (Chapter 13):

- **Progressive wave** transfers energy from one position to another through a material or a vacuum.

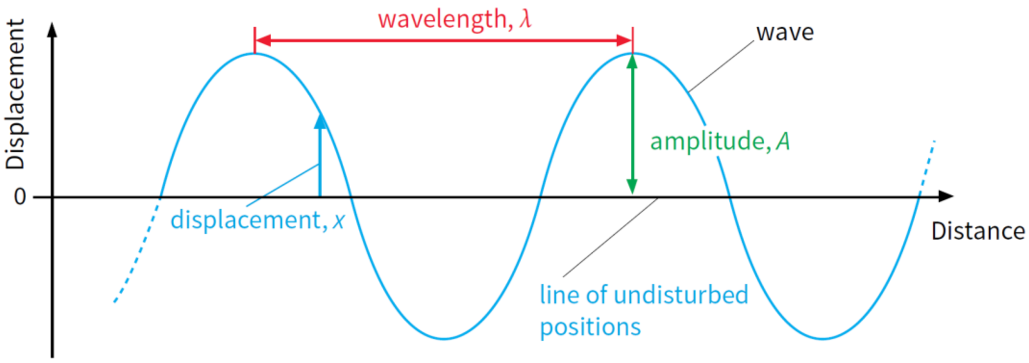


Figure 13.3 A displacement–distance graph illustrating the terms displacement, amplitude and wavelength.

- **Displacement**: the distance of a point of the wave from its equilibrium position
- **Period**: the time taken for one complete oscillation of a point
- **Frequency**: the number of oscillations per unit time of a point

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

- Two distinct types of wave:
    - Longitudinal waves – the particles of the medium vibrate parallel to the direction of the wave velocity (sound waves)
    - Transverse waves – the particles of the medium vibrate at right angles to the direction of the wave velocity (electromagnetic and light waves)

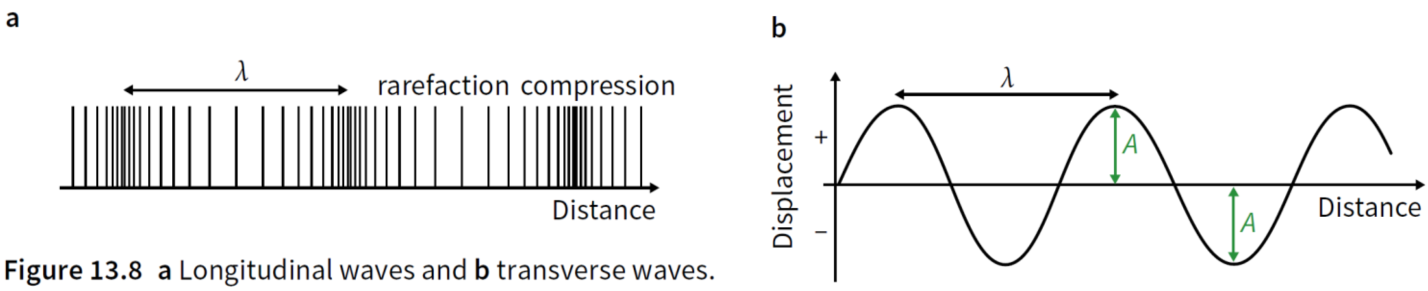
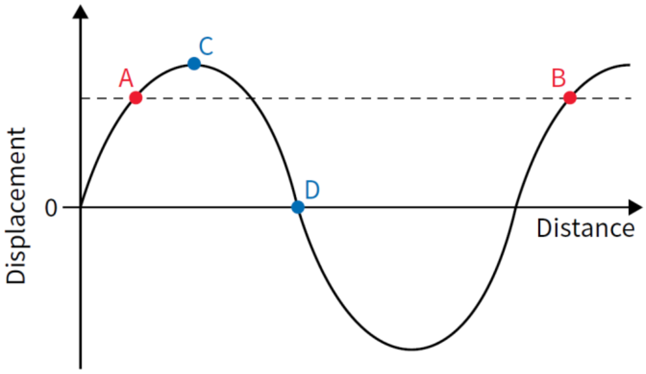


Figure 13.8 **a** Longitudinal waves and **b** transverse waves. A = amplitude, λ = wavelength.

- **Phase different**: the amount by which one oscillation leads or lags behind another; measured in degrees



Points A and B are vibrating; they have a phase difference of 360° or 0°. They are 'in phase'

Points C and D have a phase difference of 90°.

- The **intensity** of a wave is defined as the rate of energy transmitted (power) per unit area at right angles to the wave velocity

$$\text{intensity} = \frac{\text{power}}{\text{cross-sectional area}}$$

- Correlation between intensity and amplitude:

$$\text{intensity} \propto \text{amplitude}^2 \quad (I \propto A^2)$$

The relationship also implies that, for a particular wave:

$$\frac{\text{intensity}}{\text{amplitude}^2} = \text{constant}$$

So, if one wave has **twice** the amplitude of another, it has **four** times the intensity. This means that it is carrying energy at four times the rate.

- The wave equation:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$ hence $$\text{wave speed} = \frac{\text{wavelength}}{\text{period}}$$

$v = \frac{\lambda}{T}$ or $v = f \times \lambda$ or $c = f\lambda$

- Doppler effect:

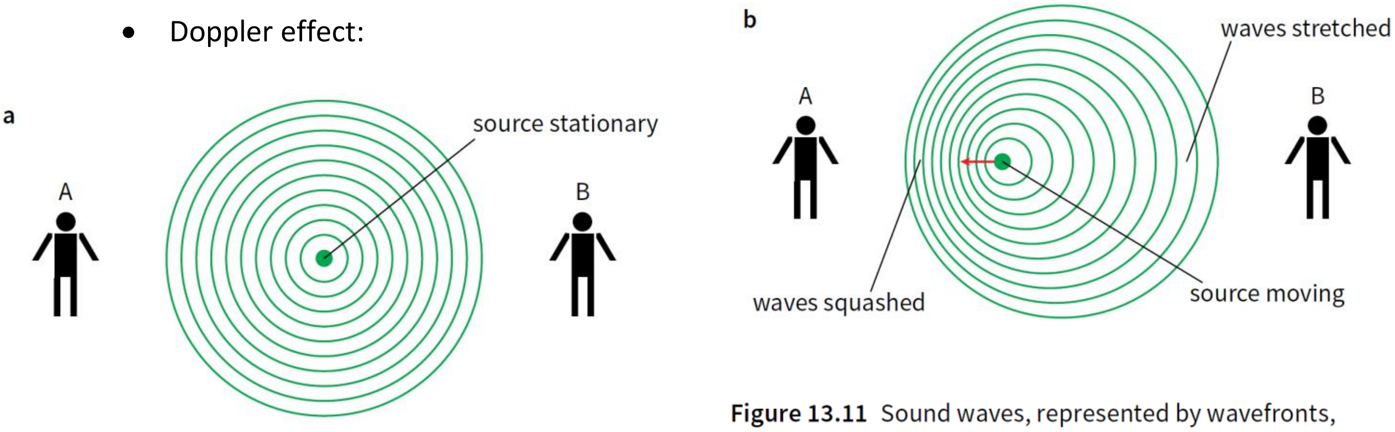


Figure 13.11 Sound waves, represented by wavefronts, emitted at constant frequency by **a** a stationary source, and **b** a source moving with speed v_s.

- There are two different speeds involved in this situation:
  - Source is moving with speed v_s
  - Sound waves travel through the air with speed v
- The frequency and wavelength observed by the observer will change according to the speed v_s

$$\text{observed frequency } f_o = \frac{f_s \times v}{(v \pm v_s)}$$

- Where the plus sign applies to a receding source and the minus sign to an approaching source.

- All electromagnetic waves travel at the same speed of 3.0×10^{8} m s^{-1} in a vacuum, but have different wavelengths and frequencies.
- The regions of the electromagnetic spectrum in order of increasing wavelength are: γ-rays, X-rays, ultraviolet, visible, infrared, microwaves and radio waves.

Superposition of waves (Chapter 14):

- **Principle of superposition**: when two or more waves meet at a point, the resultant displacement is the algebraic sum of the displacements of the individual waves.
- All waves can be reflected, refracted and diffracted (spreading of a wave as it passes through a small gap)

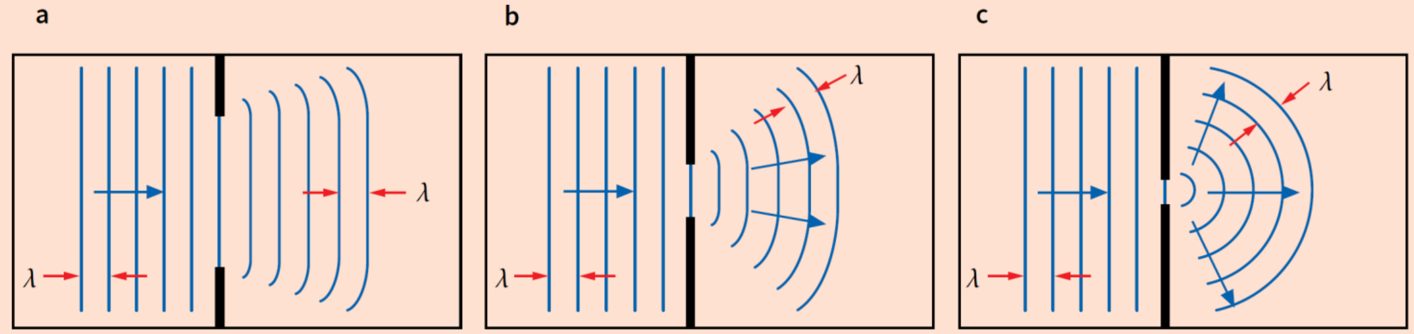


Figure 14.7 The extent to which ripples spread out depends on the relationship between their wavelength and the width of the gap. In **a**, the width of the gap is very much greater than the wavelength and there is hardly any noticeable diffraction. In **b**, the width of the gap is greater than the wavelength and there is limited diffraction. In **c**, the gap width is approximately equal to the wavelength and the diffraction effect is greatest.

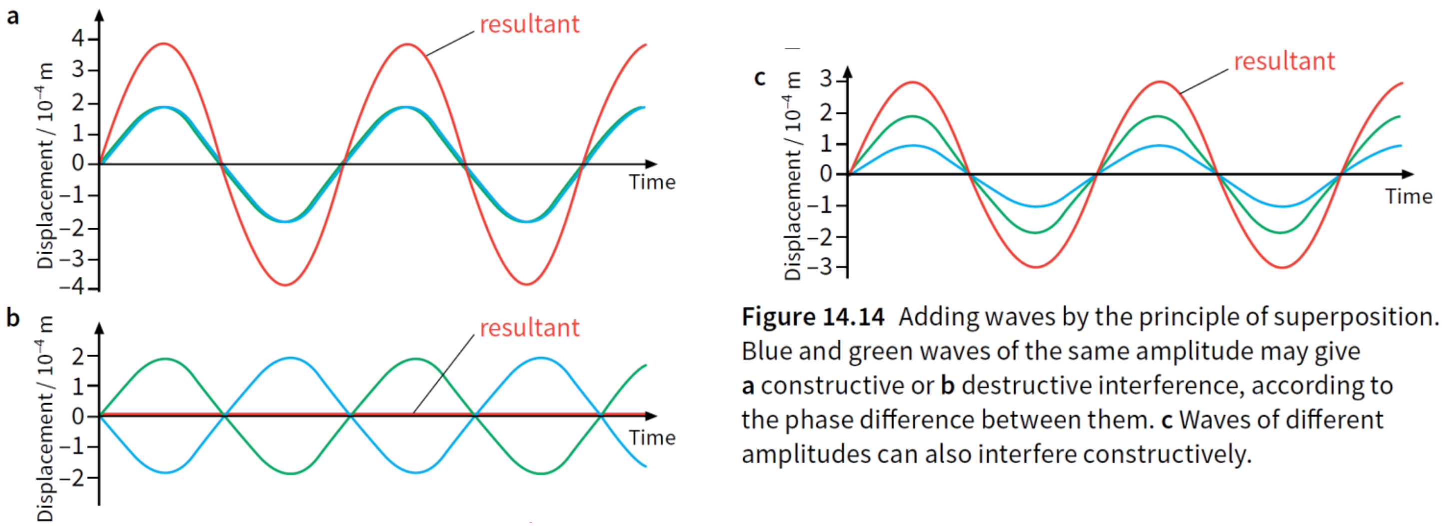
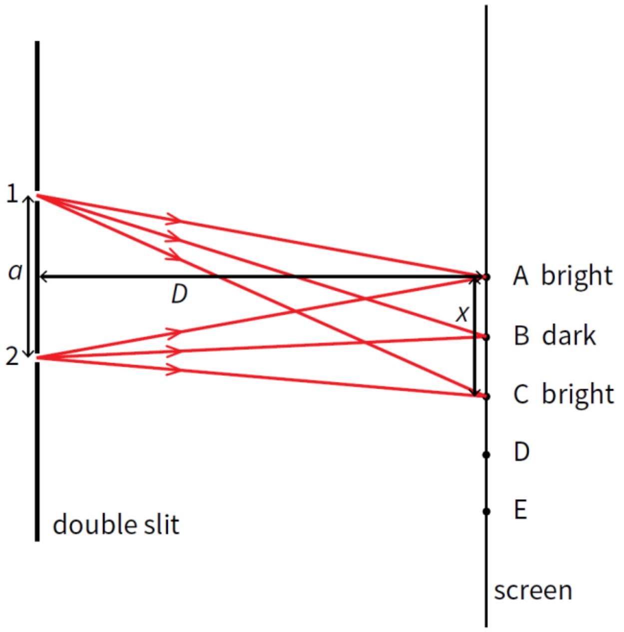


Figure 14.14 Adding waves by the principle of superposition. Blue and green waves of the same amplitude may give **a** constructive or **b** destructive interference, according to the phase difference between them. **c** Waves of different amplitudes can also interfere constructively.

- **Interference**: the formation of points of cancellation and reinforcement where two coherent waves pass through each other.
- **Coherent**: two sources are coherent when they emit waves with a constant phase difference.

- For **constructive interference** the path difference is a whole number of wavelengths:
  path difference = 0, λ, 2λ, 3λ, etc.
  or path difference = $n\lambda$
- For **destructive interference** the path difference is an odd number of half wavelengths:
  path difference = $\frac{1}{2}\lambda$, $1\frac{1}{2}\lambda$, $2\frac{1}{2}\lambda$, etc.
  or path difference = $(n + \frac{1}{2})\lambda$

- The young double-slit experiment
  - To observe interference, we need two sets of coherent waves – the phase difference between the waves emitted at the sources must remain constant (same wavelength).
  - This is done by passing a single beam of laser light through the two slits to be diffracted so that it spreads out and overlaps on the screen.
  - An interference pattern of light and dark bands called 'fringes' formed on the screen, which shows the result of the interference.



The double-slit experiment can be used to determine the wavelength λ of light. The following three quantities have to be measured:

- **Slit separation *a*** – This is the distance between the centres of the slits, which is the distance between slits 1 and 2 in Figure 14.22.
- **Fringe separation *x*** – This is the distance between the centres of adjacent bright (or dark) fringes, which is the distance AC in Figure 14.22.
- **Slit-to-screen distance *D*** – This is the distance from the midpoint of the slits to the central fringe on the screen.

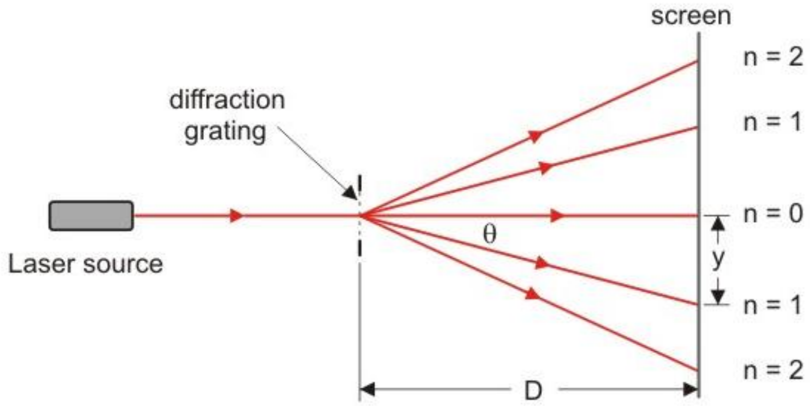
Figure 14.22 Rays from the two slits travel different distances to reach the screen.

- The wavelength λ of the light can be found using:

$$\lambda = \frac{ax}{D}$$

- Observing diffraction with a transmission grating

- Monochromatic light from a laser is incident normally on a transmission diffraction grating
- Interference fringes formed
- Calculations done by measuring the angle θ at which they are formed, rather than measuring their separation – fringes are not equally spaced in diffraction grating and the angles are much greater than with double slits
- The fringes are called **maxima**
- The central fringe is the zeroth-order maximum ($\theta = 0$) which is bright as all of the rays are travelling parallel to one another and in phase, so the interference is constructive
- First-order maximum follows, where rays of light emerge from all of the slits to form a bright fringe, hence are in phase, travelling a path difference of one wavelength λ, while ray 2 have a phase different of 2 wavelengths



$$d \sin\theta = n\lambda$$

- *d* is the distance between adjacent lines of the grating (grating spacing)
- *n* is the **order** of the maximum (integer values)

Monochromatic light is incident normally on a diffraction grating having 3000 lines per centimetre. The angular separation of the zeroth- and first-order maxima is found to be 10°. Calculate the wavelength of the incident light.

Step 1 Calculate the slit separation (grating spacing) *d*. Since there are 3000 slits per centimetre, their separation must be:

$$d = \frac{1\,\text{cm}}{3000} = 3.33 \times 10^{-4}\,\text{cm} = 3.33 \times 10^{-6}\,\text{m}$$

Step 2 Rearrange the equation $d\sin\theta = n\lambda$ and substitute values:

$\theta = 10.0°, n = 1$

$$\lambda = \frac{d\sin\theta}{n} = \frac{3.36 \times 10^{-6} \times \sin 10°}{1}$$

$$\lambda = 5.8 \times 10^{-7}\,\text{m} = 580\,\text{nm}$$

- Diffracting white light:
  - Violet closest to the centre and red furthest away
  - Different wavelengths have their maxima at different angles

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

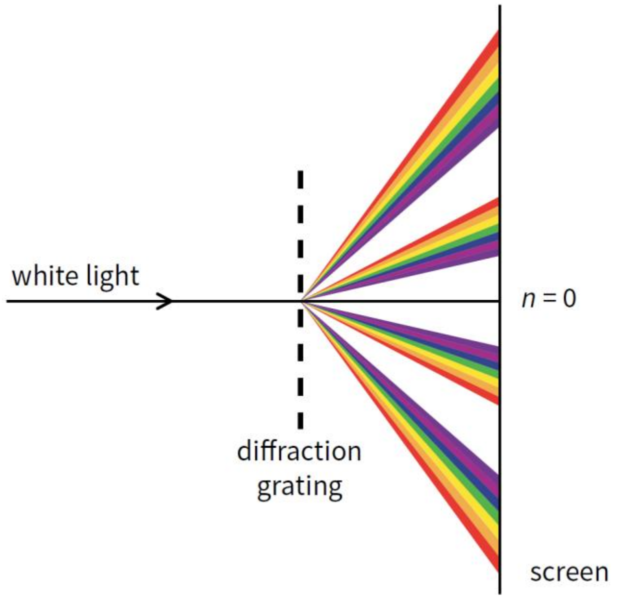


Figure 14.27 A diffraction grating is a simple way of separating white light into its constituent wavelengths.

Stationary waves (Chapter 15):

- The waves we have considered so far in Chapters 13 and 14 have been progressive waves; they start from a source and travel outwards, transferring energy from one place to another. A second important class of waves is stationary waves (standing waves).

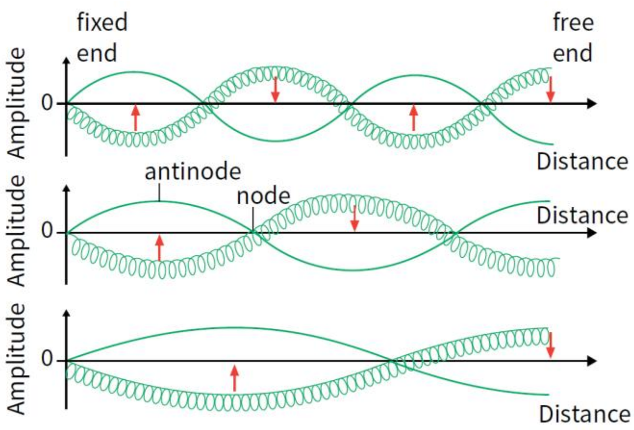


Figure 15.3 Different stationary wave patterns are possible, depending on the frequency of vibration.

- The points which do not move are called **nodes**, and points where spring oscillates with maximum amplitude are called **antinodes**.

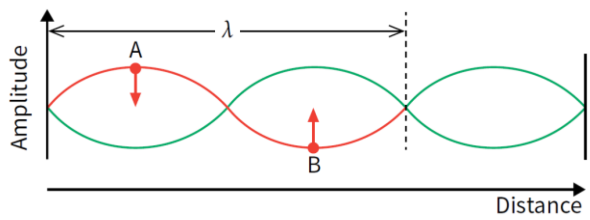
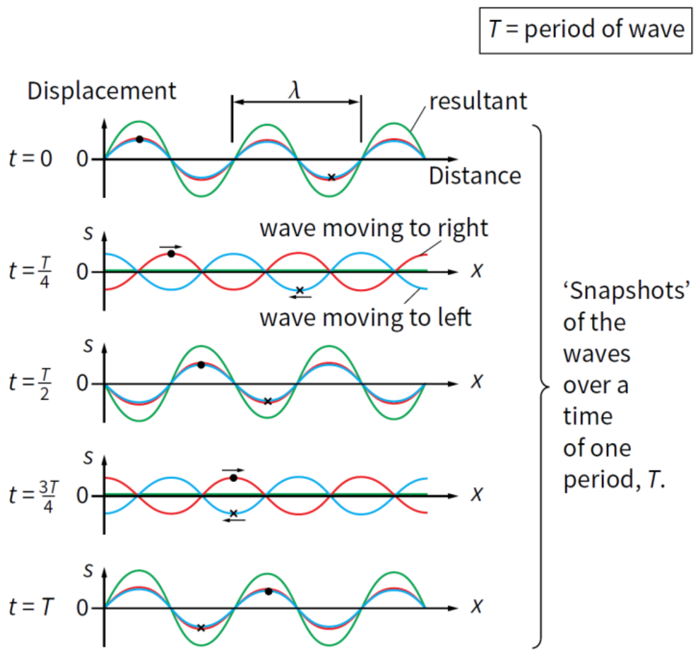


Figure 15.4 The fixed ends of a long spring must be nodes in the stationary wave pattern.

- A stationary wave is formed whenever two progressive waves of the same amplitude and wavelength, travelling in **opposite** directions, superpose. This usually happens when one wave is a reflection of the other.

- Figure 15.5 uses a displacement–distance graph (s–x) to illustrate the formation of a stationary wave along a long spring



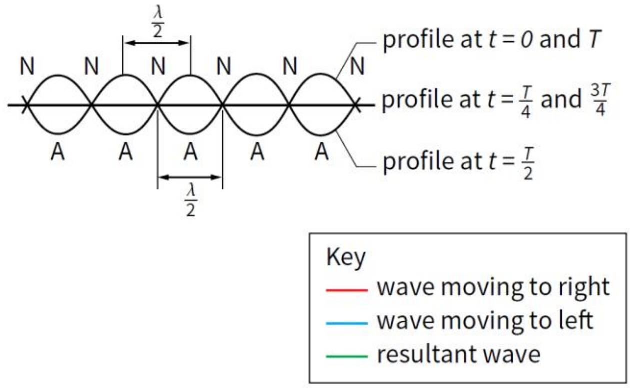


Figure 15.5 The blue-coloured wave is moving to the left and the red-coloured wave to the right. The **principle of superposition** of waves is used to determine the resultant displacement. The profile of the long spring is shown in green.

- At time t = 0, the progressive waves travelling to the left and right are in phase. The waves combine **constructively**, giving amplitude twice that of each wave.
- After a time equal to one-quarter of a period (t = T/4), each wave has travelled a distance of one quarter of a wavelength to the left or right. Consequently, the two waves are in antiphase (phase difference = 180°). The waves combine **destructively**, giving zero displacement.
- After a time equal to one-half of a period (t = T/2), the two waves are back in phase again. They once again combine **constructively**.
- After a time equal to three-quarters of a period (t = 3T/4), the waves are in antiphase again. They combine **destructively**, with the resultant wave showing zero displacement.
- After a time equal to one whole period (t = T), the waves combine **constructively**. The profile of the spring is as it was at t = 0.

$$\text{separation between two adjacent nodes (or between two adjacent antinodes)} = \frac{\lambda}{2}$$

$$\text{separation between adjacent node and antinode} = \frac{\lambda}{4}$$

- The wavelength λ of any progressive wave can be determined from the separation between neighbouring nodes or antinodes of the resulting standing wave pattern. (This separation is = λ/2). This can then be used to determine either the speed v of the progressive wave or its frequency f by using the wave equation: $v = f\lambda$

It is worth noting that a stationary wave does not travel and therefore has no speed. It does not transfer energy between two points like a progressive wave. Table 15.1 shows some of the key features of a progressive wave and its stationary wave.

	Progressive wave	Stationary wave
wavelength	λ	λ
frequency	f	f
speed	v	zero

Table 15.1 A summary of progressive and stationary waves.

- When the string is plucked half-way along its length, it vibrates with an antinode at its midpoint. This is known as the fundamental mode of vibration of the string.
- The fundamental frequency is the minimum frequency of a standing wave for a given system or arrangement.
- The frequency of a harmonic is always a multiple of the fundamental frequency.

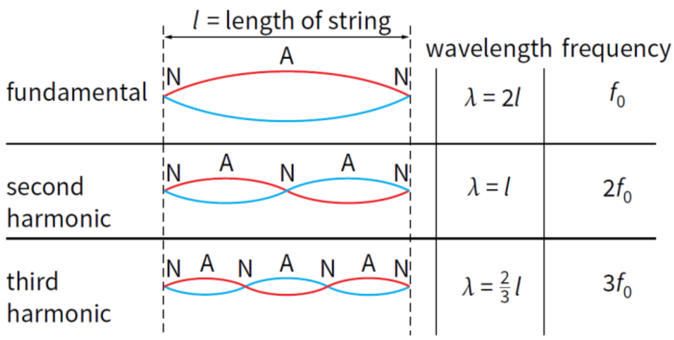


Figure 15.14 Some of the possible stationary waves for a fixed string of length l. The frequency of the harmonics is a multiple of the fundamental frequency f_0.

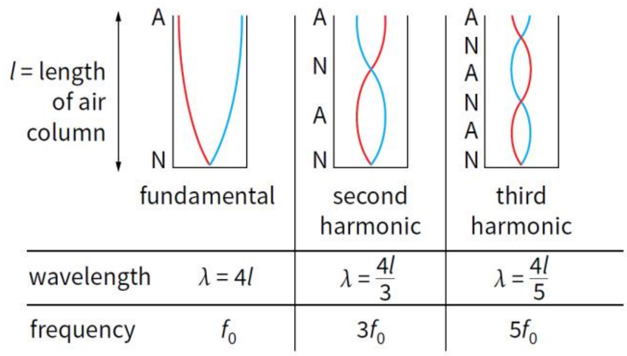


Figure 15.15 Some of the possible stationary waves for an air column, closed at one end. The frequency of each harmonic is an odd multiple of the fundamental frequency f_0.