

O Level Physics 5054: full syllabus summary notes

These notes summarise the whole Cambridge O Level Physics 5054 course, topic by topic. Each section gives the definitions you should learn, the equations with units, short descriptions of the diagrams you need to be able to draw, and worked examples. Learn the boxed definitions word for word. The Quick check at the end has exam-style questions covering every topic, with full worked answers. Unless a question says otherwise, take the acceleration of free fall g as 9.8 m/s^2 (check the value given on your own paper).

1. Physical quantities and measurement

1.1 SI units and prefixes

Every physical quantity has a numerical value and a unit. The SI base quantities you need are: mass (kilogram, kg), length (metre, m), time (second, s), electric current (ampere, A) and temperature (kelvin, K). Other units are derived from these, for example the newton: $1 \text{ N} = 1 \text{ kg m/s}^2$.

Prefix	Symbol	Multiplier
giga	G	10^9
mega	M	10^6
kilo	k	10^3
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}

1.2 Scalars and vectors

Scalar quantity: a quantity that has magnitude only.
Vector quantity: a quantity that has both magnitude and direction.

Scalars: distance, speed, time, mass, energy, temperature. Vectors: displacement, velocity, acceleration, force, weight, momentum, electric field strength, gravitational field strength.

Two vectors at right angles are added by drawing them nose to tail and completing the triangle. The resultant is found by Pythagoras, or by a scale drawing measured with a ruler and protractor.

Worked example: a boat heads north at 4.0 m/s across a river flowing east at 3.0 m/s .
Resultant speed = $\sqrt{4.0^2 + 3.0^2} = \sqrt{25} = 5.0 \text{ m/s}$.
The direction makes an angle θ east of north where $\tan \theta = 3.0 / 4.0$, so $\theta = 37^\circ$.

1.3 Measuring length, volume and time



- **Metre rule:** resolution 1 mm. Read with the eye directly above the mark to avoid parallax error.
- **Vernier calipers:** resolution 0.1 mm. Used for internal and external diameters and depths.
- **Micrometer screw gauge:** resolution 0.01 mm. Used for the diameter of a wire or the thickness of a sheet. Check for zero error before use and subtract it from readings.
- **Measuring cylinder:** read the bottom of the meniscus at eye level.
- **Stopwatch:** human reaction time (about 0.2 to 0.3 s) is much larger than the stopwatch resolution.

To measure something too small for the instrument, measure many and divide. For example, measure the thickness of 100 sheets of paper and divide by 100; time 20 oscillations of a pendulum and divide by 20 to find the period. This reduces the percentage uncertainty.

Period of a pendulum: the time taken for one complete oscillation (from one side, to the other side and back again).

1.4 Errors

A **zero error** is a systematic error: an instrument reads a non-zero value when it should read zero. A **random error** causes readings to scatter either side of the true value and is reduced by repeating and averaging. **Precision** describes how close repeated readings are to each other; **accuracy** describes how close a reading is to the true value.

2. Kinematics: describing motion

2.1 Speed, velocity and acceleration

Speed: distance travelled per unit time. $\text{speed} = \text{distance} / \text{time} \text{ (m/s)}$.

Velocity: the rate of change of displacement, or speed in a stated direction.

Acceleration: the rate of change of velocity. $a = (v \text{ minus } u) / t \text{ (m/s}^2\text{)}$.

Average speed = total distance travelled / total time taken. A negative acceleration (slowing down) is called a deceleration or retardation.

2.2 Distance-time graphs

- The gradient of a distance-time graph equals the speed.
- A horizontal line means the object is stationary.
- A straight sloping line means constant speed.
- A curve getting steeper means increasing speed (acceleration); a curve getting less steep means decreasing speed.

2.3 Speed-time graphs

- The gradient of a speed-time graph equals the acceleration.
- The area under a speed-time graph equals the distance travelled.
- A horizontal line means constant speed (zero acceleration).
- A straight line sloping up means constant acceleration; a curve whose gradient decreases

means decreasing acceleration.

Worked example: a car accelerates uniformly from rest to 20 m/s in 8.0 s, then travels at 20 m/s for a further 10 s.

Acceleration = $(20 \text{ minus } 0) / 8.0 = 2.5 \text{ m/s}^2$.

Distance in the first 8.0 s = area of triangle = $\frac{1}{2} \times 8.0 \times 20 = 80 \text{ m}$.

Distance in the next 10 s = area of rectangle = $10 \times 20 = 200 \text{ m}$.

Total distance = 280 m. Average speed = $280 / 18 = 16 \text{ m/s}$ (to 2 significant figures).

2.4 Free fall

In the absence of air resistance, all objects near the Earth's surface fall with the same constant acceleration, the acceleration of free fall g , approximately 9.8 m/s^2 . With air resistance, an object falling through air first accelerates at g . As its speed increases, air resistance increases, so the resultant force and acceleration decrease. Eventually air resistance equals weight, the resultant force is zero and the object falls at a constant **terminal velocity**. On a speed-time graph this appears as a curve whose gradient starts at g and decreases to zero, levelling off at the terminal velocity. Opening a parachute increases air resistance suddenly, so the parachutist decelerates to a new, lower terminal velocity.

3. Dynamics: forces and motion

3.1 Effects of forces

A force can change the speed, direction of motion, or shape and size of an object. Forces are measured in newtons (N). When several forces act, they can be replaced by a single **resultant force**. Forces in the same direction add; forces in opposite directions subtract.

3.2 Newton's laws

Newton's first law: an object remains at rest or continues to move with constant velocity in a straight line unless acted on by a resultant force.

Newton's second law: resultant force = mass $\times$ acceleration, $F = ma$, where F is in N, m in kg and a in m/s^2 . The acceleration is in the direction of the resultant force.

Newton's third law: when object A exerts a force on object B, object B exerts an equal and opposite force on object A; the two forces are of the same type and act on different objects.

When the resultant force is zero, the object is in equilibrium: it is either at rest or moving at constant velocity. A car moving at steady speed on a level road has a driving force equal to the total resistive force.

Worked example: a 1,200 kg car has a driving force of 3,000 N and total resistive forces of 600 N.

Resultant force = $3,000 \text{ minus } 600 = 2,400 \text{ N}$.

Acceleration = $F / m = 2,400 / 1,200 = 2.0 \text{ m/s}^2$.

3.3 Friction and stopping distances

Friction opposes motion between surfaces in contact and produces heating. Air resistance (drag) is

friction from a fluid and increases with speed.

Stopping distance = thinking distance + braking distance. Thinking distance (distance travelled during the driver's reaction time) increases with speed, tiredness, alcohol, drugs and distraction. Braking distance increases with speed, mass, worn brakes or tyres, and wet or icy roads.

3.4 Circular motion

An object moving in a circle at constant speed is accelerating because its direction, and so its velocity, is continually changing. The resultant force needed acts towards the centre of the circle. If the force is removed, the object moves off in a straight line along the tangent. The required force increases with greater mass, greater speed, and smaller radius.

3.5 Momentum and impulse

Momentum: the product of mass and velocity. $p = mv$ (kg m/s).

Impulse: the product of force and the time for which it acts. $\text{impulse} = Ft = \text{change in momentum}$ (N s).

Principle of conservation of momentum: in any collision or explosion, the total momentum of a system remains constant provided no external resultant force acts on it.

Newton's second law can also be written as: resultant force = change in momentum / time taken.

Safety features such as crumple zones, airbags and seatbelts increase the time over which a person's momentum changes, which reduces the force on them.

Worked example: a 2.0 kg trolley moving at 3.0 m/s collides with a stationary 1.0 kg trolley and they stick together.

Momentum before = $2.0 \times 3.0 + 1.0 \times 0 = 6.0$ kg m/s.

Momentum after = $(2.0 + 1.0) \times v = 6.0$, so $v = 2.0$ m/s.

4. Mass, weight and density

4.1 Mass and weight

Mass: a measure of the quantity of matter in an object at rest relative to the observer; it resists a change in motion (inertia).

Weight: the gravitational force acting on an object that has mass.

Gravitational field strength: the force per unit mass. $g = W / m$ (N/kg).

Weight $W = mg$. On Earth g is approximately 9.8 N/kg; on the Moon it is about one sixth of this. Mass does not change from place to place, but weight does. Mass is measured with a balance; weight with a force meter (newton meter). Two objects can be compared by mass on a beam balance, because the gravitational field strength is the same for both. The gravitational field strength (in N/kg) is numerically equal to the acceleration of free fall (in m/s^2).

4.2 Density

Density: mass per unit volume. $\rho = m / V$ (kg/m^3 or g/cm^3).

$1 \text{ g/cm}^3 = 1,000 \text{ kg/m}^3$. The density of pure water is about $1,000 \text{ kg/m}^3$. An object floats in a liquid if its density is less than that of the liquid, and sinks if it is greater. One liquid floats on another liquid it does not mix with if it is less dense.

Measuring density: for a regular solid, measure its dimensions with a ruler or calipers and calculate the volume; find mass on a balance. For an irregular solid, use displacement: lower it into a measuring cylinder of water and the rise in level equals its volume. For a liquid, find the mass of an empty measuring cylinder, add a known volume of liquid, find the new mass, and subtract.

Worked example: a stone of mass 156 g is lowered into a measuring cylinder and the water level rises from 50 cm^3 to 110 cm^3 .

Volume = 110 minus 50 = 60 cm^3 .

Density = $156 / 60 = 2.6 \text{ g/cm}^3 = 2,600 \text{ kg/m}^3$.

5. Turning effect of forces

5.1 Moments

Moment of a force: the product of the force and the perpendicular distance from the pivot to the line of action of the force. $\text{moment} = F \times d \text{ (N m)}$.

Principle of moments: when an object is in equilibrium, the sum of the clockwise moments about any point is equal to the sum of the anticlockwise moments about that same point.

For an object to be in equilibrium there must be no resultant force and no resultant moment. Everyday uses of moments include spanners (a longer handle gives a larger moment for the same force), door handles placed far from the hinge, wheelbarrows, and see-saws.

Worked example: a uniform metre rule is pivoted at its centre. A 3.0 N weight hangs 20 cm to the left of the pivot. Where must a 2.0 N weight hang to balance it?

Anticlockwise moment = $3.0 \times 0.20 = 0.60 \text{ N m}$.

Clockwise moment = $2.0 \times d = 0.60$, so $d = 0.30 \text{ m}$, that is 30 cm to the right of the pivot.

5.2 Centre of gravity and stability

Centre of gravity: the point through which the whole weight of an object appears to act.

For a uniform regular object the centre of gravity is at its geometric centre. To find the centre of gravity of an irregular flat sheet (lamina): hang it from a pin through one hole so it swings freely, hang a plumb line from the same pin and draw the vertical line; repeat from a second hole. The centre of gravity is where the lines cross.

An object is **stable** if, when tilted slightly, the line of action of its weight still passes through its base, so the moment of the weight returns it to its original position. It topples when the line of action of the weight falls outside the base. Stability is increased by a **lower centre of gravity** and a **wider base**, as in racing cars and table lamps with heavy bases.

5.3 Springs and load-extension graphs

Forces can stretch springs and other materials. Extension = stretched length minus original length.

Hooke's law: the extension of a spring is directly proportional to the load applied, provided the limit of proportionality is not exceeded. $F = kx$, where k is the spring constant (N/m) and x the extension (m).

Limit of proportionality: the point beyond which extension is no longer directly proportional to load.

A load-extension graph for a spring is a straight line through the origin up to the limit of proportionality, then curves. The spring constant is the gradient of the straight part when force is on the vertical axis.

6. Pressure

6.1 Pressure on solids

Pressure: the force acting per unit area, at right angles to the surface. $p = F / A$. The unit is the pascal (Pa), where $1 \text{ Pa} = 1 \text{ N/m}^2$.

A large area reduces pressure: snowshoes, wide tractor tyres and the broad foundations of buildings spread the force. A small area increases pressure: knives, needles and drawing pins concentrate the force.

Worked example: a box of weight 600 N rests on a face measuring 0.50 m by 0.40 m.

Area = $0.50 \times 0.40 = 0.20 \text{ m}^2$.

Pressure = $600 / 0.20 = 3,000 \text{ Pa}$.

6.2 Pressure in liquids

Pressure in a liquid increases with depth and with the density of the liquid, and acts equally in all directions at a given depth. It does not depend on the shape of the container.

Pressure change in a liquid: $\Delta p = \rho g \Delta h$, where ρ is the density of the liquid (kg/m^3), g the gravitational field strength (N/kg) and Δh the change in depth (m).

Dams are built thicker at the bottom because the water pressure is greatest there. Water spurts further from a hole near the bottom of a tall container than from a hole near the top.

Worked example: calculate the pressure due to water at a depth of 5.0 m (density of water $1,000 \text{ kg/m}^3$, $g = 9.8 \text{ N/kg}$).

$\Delta p = 1,000 \times 9.8 \times 5.0 = 49,000 \text{ Pa} = 49 \text{ kPa}$. The total pressure is this plus atmospheric pressure acting on the surface.

6.3 Atmospheric pressure and the manometer

The atmosphere exerts pressure because of the weight of the air above. Atmospheric pressure is about $1.0 \times 10^5 \text{ Pa}$ at sea level and decreases with height. A **mercury barometer** is a long tube filled with mercury, inverted in a dish of mercury; the vertical height of the mercury column (about 760 mm at sea level) measures atmospheric pressure. The space above the column is a vacuum. Tilting the tube

does not change the vertical height.

A **manometer** is a U-tube containing liquid, used to measure the pressure of a gas supply. One side is connected to the gas and the other is open to the atmosphere. The difference in liquid levels h shows how much the gas pressure exceeds atmospheric pressure: excess pressure = ρgh .

6.4 Hydraulic systems

Liquids are almost incompressible and transmit pressure equally throughout. In a hydraulic jack or car brake, a small force on a small piston produces a pressure which acts on a larger piston to produce a larger force. Since pressure is the same: $F_1 / A_1 = F_2 / A_2$.

6.5 Gas pressure and volume

Gas molecules move randomly and collide with the walls of their container. Each collision exerts a tiny force; the total force per unit area is the gas pressure. For a fixed mass of gas at constant temperature, decreasing the volume means the molecules hit the walls more often, so the pressure increases.

Boyle's law: for a fixed mass of gas at constant temperature, pressure is inversely proportional to volume. $pV = \text{constant}$, or $p_1V_1 = p_2V_2$.

Worked example: a gas at 100 kPa occupies 300 cm^3 . It is compressed slowly at constant temperature to 120 cm^3 .

$$p_2 = p_1V_1 / V_2 = 100 \times 300 / 120 = 250 \text{ kPa}.$$

7. Energy, work and power

7.1 Energy stores and transfers

Energy is stored in several forms: kinetic, gravitational potential, chemical, elastic (strain), nuclear, electrostatic and internal (thermal). Energy is transferred between stores by forces doing work (mechanical working), by electric currents (electrical working), by heating, and by waves (electromagnetic, sound and other waves).

Principle of conservation of energy: energy cannot be created or destroyed; it can only be transferred from one store to another. The total energy of a closed system remains constant.

7.2 Kinetic and gravitational potential energy

Kinetic energy: $E_k = \frac{1}{2}mv^2$ (J).

Change in gravitational potential energy: $\Delta E_p = mg\Delta h$ (J).

Worked example: a ball of mass 0.20 kg is dropped from a height of 5.0 m. Ignoring air resistance, find its speed just before it hits the ground ($g = 9.8 \text{ N/kg}$).

Loss of gravitational potential energy = $mg\Delta h = 0.20 \times 9.8 \times 5.0 = 9.8 \text{ J}$.

This becomes kinetic energy: $\frac{1}{2} \times 0.20 \times v^2 = 9.8$, so $v^2 = 98$ and $v = 9.9 \text{ m/s}$.

Note that the mass cancels: $v = \sqrt{2gh}$ for any falling object without air resistance.

7.3 Work

Work done: the product of the force and the distance moved in the direction of the force. $W = Fd = \Delta E$ (J). Work done is equal to the energy transferred.

1 joule is the work done when a force of 1 N moves its point of application 1 m in the direction of the force. No work is done if there is no movement in the direction of the force (for example, holding a heavy bag stationary).

7.4 Power and efficiency

Power: the work done per unit time, or the energy transferred per unit time. $P = W / t = \Delta E / t$. The unit is the watt (W), where 1 W = 1 J/s.

Efficiency = useful energy output / total energy input $\times 100\%$ = useful power output / total power input $\times 100\%$.

Worked example: a motor lifts a 50 kg load through 12 m in 20 s. The electrical input power is 400 W.

Useful work = $mgh = 50 \times 9.8 \times 12 = 5,880$ J.

Useful power output = $5,880 / 20 = 294$ W.

Efficiency = $294 / 400 \times 100\% = 74\%$ (to 2 significant figures). The rest is wasted, mostly as thermal energy and sound.

Sankey diagrams show energy transfers: arrow widths are proportional to the energy, with the useful output going straight on and wasted energy branching off.

7.5 Energy resources

Resource	Renewable?	Advantages	Disadvantages
Fossil fuels (coal, oil, gas)	No	Reliable, high energy density, power output easily controlled	Release carbon dioxide (climate change) and other pollutants; will run out
Nuclear fission	No	No carbon dioxide during operation; large reliable output	Radioactive waste; high cost; risk of accidents
Hydroelectric	Yes	Reliable; output can be changed quickly; no fuel cost	Floods land; needs suitable rivers and valleys; high building cost
Wind	Yes	No fuel cost; no pollution in use	Unreliable (depends on wind); noise and visual impact
Solar (photovoltaic cells and solar panels)	Yes	No fuel cost; useful in remote places	No output at night; reduced in cloudy weather; large area needed
Geothermal	Yes	Reliable	Only in certain volcanic regions

Tidal and wave	Yes	Tides are predictable	Few suitable sites; may harm habitats
Biofuels	Yes	Crops can be regrown	Use land that could grow food

The Sun is the original source of energy for most resources: fossil fuels, biofuels, wind, waves and hydroelectric power. The exceptions are geothermal, nuclear and tidal energy. In the Sun, energy is released by **nuclear fusion** of light nuclei such as hydrogen.

8. Thermal physics

8.1 Kinetic particle model of matter

State	Arrangement	Motion	Properties
Solid	Particles close together in a regular pattern	Vibrate about fixed positions	Fixed shape and volume
Liquid	Particles close together, irregular	Move around each other	Fixed volume, takes the shape of its container
Gas	Particles far apart, random	Move quickly and randomly in all directions	No fixed shape or volume; easily compressed

Brownian motion is the random, jerky movement of small visible particles (such as smoke particles in air seen through a microscope) caused by collisions with the much smaller, fast-moving, invisible molecules of the air. It is evidence for the kinetic particle model.

The temperature of a substance is related to the average kinetic energy of its particles. At **absolute zero** (0 K, or minus 273 °C), the particles have the least possible kinetic energy. To convert: temperature in K = temperature in °C + 273.

8.2 Evaporation

Evaporation happens at the surface of a liquid at any temperature. The more energetic molecules escape from the surface, leaving behind molecules with a lower average kinetic energy, so the liquid cools. Evaporation is faster at a higher temperature, with a larger surface area, and with a draught of air passing over the surface. Sweating cools the body by evaporation.

Boiling, by contrast, happens throughout the liquid at one fixed temperature (the boiling point), and bubbles form inside the liquid.

8.3 Thermal expansion

When heated, solids, liquids and gases expand because their particles move or vibrate more and take up more space. For the same temperature rise, gases expand most and solids least. Applications and problems: gaps in railway tracks and bridges allow for expansion; overhead cables sag in summer; the liquid in a thermometer expands up the tube; bimetallic strips bend when heated, because one metal expands more than the other, and are used in thermostats.

8.4 Specific heat capacity

Specific heat capacity: the energy required per unit mass per unit temperature increase. $c = \Delta E /$

($m\Delta\theta$), so $\Delta E = mc\Delta\theta$ (unit J/(kg °C)).

Thermal capacity (heat capacity): the energy needed to raise the temperature of an object by 1 °C.

Water has a high specific heat capacity, about 4,200 J/(kg °C), which is why it is used in central heating systems and why coastal climates are milder.

Worked example: a 2.0 kW kettle heats 1.5 kg of water from 20 °C to 100 °C. Take c for water as 4,200 J/(kg °C) and assume no heat is lost.

Energy needed = $mc\Delta\theta = 1.5 \times 4,200 \times 80 = 504,000$ J.

Time = energy / power = $504,000 / 2,000 = 252$ s, about 4.2 minutes.

Experiment: heat a metal block with an electric immersion heater. Measure the energy supplied (from a joulemeter, or as power $\times$ time) and the temperature rise with a thermometer. Calculate $c = E / (m\Delta\theta)$. Insulating the block reduces heat loss; the value obtained is usually too high because some energy is lost to the surroundings.

8.5 Melting, boiling and latent heat

During melting and boiling, energy is supplied but the temperature stays constant, because the energy is used to break the bonds between particles rather than to increase their kinetic energy. A heating curve (temperature against time) has flat sections at the melting point and boiling point.

Specific latent heat of fusion: the energy required to change unit mass of a substance from solid to liquid without any change in temperature.

Specific latent heat of vaporisation: the energy required to change unit mass of a substance from liquid to gas without any change in temperature.

$E = mL$, with L in J/kg.

The specific latent heat of vaporisation is much larger than that of fusion because, in boiling, the particles must be separated completely and must push back the atmosphere as the gas expands. The values for water (approximately 3.3×10^5 J/kg for fusion and 2.3×10^6 J/kg for vaporisation) are usually given in the question.

Worked example: how much energy is needed to melt 0.40 kg of ice at 0 °C? (specific latent heat of fusion = 3.3×10^5 J/kg)

$E = mL = 0.40 \times 3.3 \times 10^5 = 1.32 \times 10^5$ J, about 1.3×10^5 J.

8.6 Thermal energy transfer

Conduction is the transfer of thermal energy through a material without the material itself moving. In all solids, vibrating particles pass energy to neighbouring particles. In metals, free (delocalised) electrons also carry energy quickly through the lattice, which is why metals are good conductors. Non-metals, liquids and gases are poor conductors (insulators); trapped air is an excellent insulator.

Convection is the transfer of thermal energy in a fluid (liquid or gas) by the movement of the fluid itself. Heated fluid expands, becomes less dense and rises; cooler, denser fluid sinks to take its place, setting up a **convection current**. This is why heaters are placed low in a room and the freezer compartment of a fridge is at the top.

Thermal radiation is the transfer of energy by infrared electromagnetic waves. It needs no medium and can travel through a vacuum. All objects emit infrared radiation; hotter objects emit more. Dull black surfaces are the best absorbers and emitters; shiny silver or white surfaces are the worst absorbers and emitters and the best reflectors. The rate of emission also increases with surface area.

Consequences: a vacuum flask reduces conduction and convection with its vacuum, and radiation with its silvered walls. Houses are insulated with loft insulation and cavity wall foam, which trap air. Solar water heaters have black panels to absorb radiation.

9. General properties of waves

9.1 What a wave is

Waves transfer energy from one place to another without transferring matter. The particles of the medium only oscillate about fixed positions.

Transverse wave: a wave in which the oscillations are perpendicular to the direction of travel of the wave (energy transfer). Examples: electromagnetic waves, waves on a string, ripples on water, seismic S-waves.

Longitudinal wave: a wave in which the oscillations are parallel to the direction of travel of the wave. Examples: sound waves, seismic P-waves.

Longitudinal waves consist of **compressions** (regions where particles are close together, higher pressure) and **rarefactions** (regions where particles are spread out, lower pressure).

9.2 Describing a wave

Amplitude: the maximum displacement of a particle from its rest position.

Wavelength (λ): the distance between two consecutive points on a wave that are in phase, for example from crest to crest.

Frequency (f): the number of complete waves passing a point per second, measured in hertz (Hz).

Period (T): the time for one complete oscillation. $T = 1 / f$.

Wave speed: $v = f\lambda$.

On a displacement-distance graph you can read wavelength and amplitude; on a displacement-time graph you can read the period and amplitude.

Worked example: a water wave has a frequency of 4.0 Hz and a wavelength of 0.25 m.

Speed = $f\lambda = 4.0 \times 0.25 = 1.0$ m/s.

Period = $1 / f = 1 / 4.0 = 0.25$ s.

9.3 Reflection, refraction and diffraction (ripple tank)

A ripple tank shows wave behaviour using water waves, with straight wavefronts drawn as parallel lines one wavelength apart.

- **Reflection:** waves bounce off a barrier; the angle of reflection equals the angle of incidence. Wavelength, frequency and speed are unchanged.

- **Refraction:** waves passing from deep to shallow water slow down. The frequency stays the same, so the wavelength decreases and the wavefronts are drawn closer together. If the waves meet the boundary at an angle, they change direction, bending towards the normal on entering shallow water.
- **Diffraction:** waves spread out as they pass through a gap or round an edge. The wavelength does not change. Diffraction is most noticeable when the gap is about the same size as the wavelength; a gap much wider than the wavelength gives very little spreading.

10. Light

10.1 Reflection of light

Law of reflection: the angle of incidence equals the angle of reflection. Both angles are measured from the normal, the line drawn perpendicular to the surface at the point where the ray hits it.

The image in a plane mirror is: the same size as the object, upright, laterally inverted, the same distance behind the mirror as the object is in front, and **virtual** (it cannot be formed on a screen because light rays do not actually pass through it). To locate the image in a ray diagram, draw two rays from the object, reflect them, and extend the reflected rays backwards behind the mirror with dashed lines until they meet.

10.2 Refraction of light

When light passes from air into glass at an angle, it slows down and bends towards the normal. When it leaves glass into air, it speeds up and bends away from the normal. A ray travelling along the normal does not change direction.

Refractive index: $n = \sin i / \sin r$, where i is the angle of incidence in air and r is the angle of refraction in the material. Also $n = \text{speed of light in a vacuum (or air)} / \text{speed of light in the material}$.

Worked example: a ray enters a glass block at an angle of incidence of 40° . The refractive index of the glass is 1.5.

$\sin r = \sin 40^\circ / 1.5 = 0.643 / 1.5 = 0.429$, so $r = 25^\circ$ (to 2 significant figures).

10.3 Total internal reflection

Critical angle: the angle of incidence in the denser medium for which the angle of refraction is 90° .

$$n = 1 / \sin c$$

Total internal reflection: occurs when light travelling in a denser medium meets the boundary with a less dense medium at an angle of incidence greater than the critical angle; all the light is reflected back inside the denser medium.

For glass with $n = 1.5$, $\sin c = 1 / 1.5 = 0.667$, so $c = 42^\circ$. Uses: **optical fibres** carry light (and so data)

along thin glass fibres by repeated total internal reflection, used in telecommunications and in endoscopes for seeing inside the body; prisms in periscopes and binoculars turn light through 90° or 180° .

10.4 Converging lenses

A converging (convex) lens refracts parallel rays so that they meet at the **principal focus** (focal point) F. The **focal length** f is the distance from the centre of the lens to the principal focus. A thicker, more curved lens has a shorter focal length.

To draw a ray diagram, use two of these three rays from the top of the object:

1. A ray parallel to the principal axis, which refracts through F on the far side.
2. A ray through the optical centre of the lens, which passes straight through undeviated.
3. A ray through F on the near side, which leaves the lens parallel to the principal axis.

Object position	Image	Use
Further than 2F	Real, inverted, diminished, between F and 2F	Camera, eye
At 2F	Real, inverted, same size, at 2F	Photocopier at same size
Between F and 2F	Real, inverted, enlarged, beyond 2F	Projector
Closer than F	Virtual, upright, enlarged, same side as object	Magnifying glass

Linear magnification = image height / object height. A **real** image is formed where rays actually meet and can be projected onto a screen; a **virtual** image is where rays only appear to come from. Short sight (images formed in front of the retina) is corrected with diverging lenses; long sight (images would form behind the retina) is corrected with converging lenses.

10.5 Dispersion

When white light passes through a glass prism, it is split into a spectrum of colours because each colour has a different refractive index in glass (violet is refracted most, red least). The order is red, orange, yellow, green, blue, indigo, violet. This splitting is called **dispersion**. Light of a single frequency is called **monochromatic**.

11. The electromagnetic spectrum

11.1 Properties shared by all electromagnetic waves

- They are transverse waves.
- They can travel through a vacuum.
- They all travel at the same speed in a vacuum, 3.0×10^8 m/s, approximately the same in air.
- They obey $v = f\lambda$, so the higher the frequency, the shorter the wavelength.
- They transfer energy and can be reflected, refracted and diffracted.

11.2 The regions in order

In order of increasing frequency (decreasing wavelength): radio waves, microwaves, infrared, visible

light, ultraviolet, X-rays, gamma rays.

Region	Typical uses	Hazards
Radio waves	Radio and television broadcasting, astronomy, radio frequency identification (RFID)	Generally regarded as low risk
Microwaves	Satellite television, mobile phones, microwave ovens, Wi-Fi	Internal heating of body tissue
Infrared	Remote controls, thermal imaging, electric grills, optical fibre communication, intruder alarms	Skin burns
Visible light	Vision, photography, illumination	Very bright light can damage the eyes
Ultraviolet	Security marking (fluorescence), detecting fake bank notes, sterilising water	Damage to surface cells and eyes, skin cancer
X-rays	Medical imaging, security scanners at airports	Mutation or damage to cells (ionising), cancer
Gamma rays	Sterilising food and medical equipment, detecting and treating cancer	Mutation or damage to cells (ionising), cancer

Worked example: a radio station broadcasts at a frequency of 100 MHz. Calculate the wavelength.

$$\lambda = v / f = 3.0 \times 10^8 / (100 \times 10^6) = 3.0 \text{ m.}$$

12. Sound

12.1 Production and transmission

Sound is produced by vibrating sources and travels as a longitudinal wave of compressions and rarefactions. It needs a medium (solid, liquid or gas) and cannot travel through a vacuum. This is shown by a bell in a sealed jar: as the air is pumped out, the sound fades even though the hammer can still be seen striking the bell.

Sound travels fastest in solids, slower in liquids and slowest in gases. The speed of sound in air is about 330 to 350 m/s, depending on temperature; in water it is roughly 1,500 m/s.

12.2 Pitch, loudness and range of hearing

- **Pitch** depends on frequency: higher frequency gives a higher pitch.
- **Loudness** depends on amplitude: larger amplitude gives a louder sound.
- The range of human hearing is approximately 20 Hz to 20,000 Hz (20 kHz).

Ultrasound: sound with a frequency higher than 20 kHz.

Uses of ultrasound include pre-natal scanning, non-destructive testing of materials for cracks, and sonar for measuring the depth of the sea. The pulses reflect from boundaries between different materials, and the time for the echo gives the distance.

12.3 Echoes and measuring the speed of sound

An echo is a reflected sound wave. Because the sound travels to the reflector and back, the distance to the reflector = speed $\times$ time / 2.

Method: two observers stand a measured distance apart, for example 400 m, in an open field. One fires a starting pistol or bangs two blocks together; the other starts a stopwatch on seeing the flash or movement and stops it on hearing the sound. Speed = distance / time. Repeat several times and average, and swap positions to cancel the effect of wind.

Worked example: a ship sends an ultrasound pulse to the sea bed and receives the echo 0.80 s later. The speed of sound in sea water is 1,500 m/s.
Total distance travelled = $1,500 \times 0.80 = 1,200$ m.
Depth = $1,200 / 2 = 600$ m.

13. Static and current electricity

13.1 Electric charge

There are two types of charge, positive and negative. Like charges repel; unlike charges attract. Charge is measured in coulombs (C). Insulators such as polythene and acrylic can be charged by friction: rubbing transfers electrons from one material to the other. The material that gains electrons becomes negatively charged; the one that loses electrons becomes positively charged. Only electrons move; positive charges (protons) stay fixed in the nuclei.

Conductors (such as metals) allow charge to flow because they contain free electrons. **Insulators** (such as plastic, rubber and glass) do not. A charged conductor can be discharged by connecting it to earth.

Induction: a charged rod brought near a neutral conductor attracts opposite charge to the near side and repels like charge to the far side. Earthing the far side and then removing the earth before the rod is taken away leaves the conductor with a charge opposite to the rod. A charged rod also attracts small uncharged objects such as bits of paper, because it induces opposite charge on the near side.

13.2 Electric fields

Electric field: a region in which an electric charge experiences a force.

The direction of an electric field at a point is the direction of the force on a small positive charge placed there. Field lines point away from a positive charge and towards a negative charge. Between two parallel plates with opposite charges, the field lines are parallel and evenly spaced from the positive plate to the negative plate, showing a uniform field.

Uses of electrostatics include photocopiers, electrostatic paint spraying and dust precipitators in chimneys. Dangers include sparks when refuelling aircraft or vehicles, which is why fuel tankers are earthed, and lightning.

13.3 Current

Electric current: the rate of flow of charge. $I = Q / t$, current in amperes (A), charge in coulombs

(C), time in seconds (s).

In metals, current is a flow of free electrons. By convention, **conventional current** flows from the positive terminal of a supply around the circuit to the negative terminal, opposite to the direction of electron flow. Current is measured with an **ammeter connected in series**. Direct current (d.c.) flows in one direction only; alternating current (a.c.) repeatedly reverses direction.

13.4 Electromotive force and potential difference

Electromotive force (e.m.f.): the electrical work done by a source in moving a unit charge around a complete circuit. Measured in volts (V).

Potential difference (p.d.): the work done by a unit charge passing through a component. Measured in volts (V).

$$1 \text{ V} = 1 \text{ J/C.}$$

P.d. is measured with a **voltmeter connected in parallel** across the component. Energy transferred = charge $\times$ p.d., $W = QV$.

13.5 Resistance

Resistance: the ratio of the potential difference across a component to the current in it. $R = V / I$. The unit is the ohm (Ω).

For a metallic wire at constant temperature: resistance is directly proportional to length and inversely proportional to cross-sectional area. A long thin wire has a higher resistance than a short thick one of the same material.

Current-voltage (I-V) graphs:

- **Ohmic resistor (metal wire at constant temperature):** a straight line through the origin; current is directly proportional to p.d. and resistance is constant.
- **Filament lamp:** a curve whose gradient decreases as p.d. increases; as the filament gets hotter, its resistance increases.
- **Semiconductor diode:** almost no current in the reverse direction; current flows in the forward direction once the p.d. exceeds a small value. A diode lets current flow in one direction only and is used to rectify a.c. into d.c.

Worked example: a current of 0.25 A flows through a resistor when the p.d. across it is 6.0 V.

$$R = V / I = 6.0 / 0.25 = 24 \Omega.$$

$$\text{Charge passing in 2.0 minutes} = It = 0.25 \times 120 = 30 \text{ C.}$$

13.6 Electrical power and energy

Electrical power: $P = IV$ (W). Also $P = I^2R$ and $P = V^2 / R$.

Electrical energy: $E = IVt$ (J).

14. Electric circuits

14.1 Circuit symbols

You should be able to draw and interpret the symbols for: cell, battery, power supply (d.c. and a.c.), switch, fixed resistor, variable resistor, thermistor, light-dependent resistor (LDR), lamp, ammeter, voltmeter, fuse, diode, light-emitting diode (LED), relay coil, transformer, heater, motor and generator.

14.2 Series circuits

- The current is the same at every point.
- The e.m.f. of the supply is shared between the components: $V = V_1 + V_2 + \dots$
- The combined resistance is the sum of the individual resistances: $R = R_1 + R_2 + \dots$
- If one component fails, the whole circuit stops.

14.3 Parallel circuits

- The p.d. across each branch is the same as the supply p.d.
- The current from the source is the sum of the currents in the separate branches: $I = I_1 + I_2 + \dots$
- For two resistors in parallel: $1/R = 1/R_1 + 1/R_2$.
- The combined resistance of two resistors in parallel is less than either resistor alone.
- Each branch can be switched independently, and one failing does not stop the others, which is why household lights are wired in parallel.

Worked example: a 12 V supply is connected to a 4.0 Ω resistor in series with a parallel combination of two 6.0 Ω resistors.

Parallel combination: $1/R = 1/6.0 + 1/6.0 = 2/6.0$, so $R = 3.0 \Omega$.

Total resistance = 4.0 + 3.0 = 7.0 Ω .

Current from the supply = $12 / 7.0 = 1.7 \text{ A}$ (1.71 A).

P.d. across the 4.0 Ω resistor = $1.71 \times 4.0 = 6.9 \text{ V}$; p.d. across the parallel pair = 12 minus 6.9 = 5.1 V.

Current in each 6.0 Ω resistor = $5.1 / 6.0 = 0.86 \text{ A}$, which is half the supply current, as expected for two equal branches.

14.4 Potential dividers and sensors

Two resistors in series across a supply share the p.d. in the ratio of their resistances: $V_1 / V_2 = R_1 / R_2$. The output voltage taken across one resistor can be varied using a variable resistor.

- A **thermistor** (negative temperature coefficient type) has a resistance that decreases as temperature increases.
- A **light-dependent resistor** has a resistance that decreases as light intensity increases.

Placing a thermistor or LDR in a potential divider gives an output voltage that changes with temperature or light level. This can switch on a relay, which then controls a separate circuit such as a heater, a fan or a street light.

Worked example: an LDR and a 2.0 k Ω resistor are in series across a 9.0 V supply. In darkness the LDR has a resistance of 10 k Ω .

Total resistance = 12 k Ω . P.d. across the LDR = $9.0 \times 10 / 12 = 7.5 \text{ V}$. In bright light the LDR resistance falls, so its share of the p.d. falls.

15. Practical electricity

15.1 Uses and cost of electricity

Electricity is used for heating (kettles, irons, heaters), lighting, and driving motors. The energy used by appliances is billed in **kilowatt-hours** (kWh). 1 kWh is the energy transferred by a 1 kW appliance in 1 hour, equal to 3.6×10^6 J.

Worked example: a 2.5 kW heater is used for 4 hours a day for 30 days. Electricity costs Rs 50 per kWh (use the price given in your question).

Energy = $2.5 \times 4 \times 30 = 300$ kWh.

Cost = $300 \times 50 = \text{Rs } 15,000$.

15.2 Hazards

Dangers in the home include damaged insulation (exposed live wires), overheating of cables carrying too much current, overloaded sockets and adaptors, and damp conditions (water conducts and can create a path to the user).

15.3 Safety features

A mains plug or appliance cable has three wires: **live** (carries the alternating p.d.), **neutral** (completes the circuit) and **earth** (a safety wire). Check the colour code used in your country.

- **Fuse:** a thin wire in the live line that melts if the current exceeds its rating, breaking the circuit. Choose a rating slightly above the normal working current: for a current of 4.3 A, use a 5 A fuse rather than 3 A or 13 A.
- **Circuit breaker:** an automatic switch that trips (opens) when the current is too large; it can be reset and acts faster than a fuse.
- **Earthing:** the metal case of an appliance is connected to the earth wire. If the live wire touches the case, a large current flows to earth, which blows the fuse or trips the breaker and makes the appliance safe.
- **Double insulation:** appliances with a non-conducting (plastic) case do not need an earth wire.
- Switches and fuses are placed in the **live** wire so that, when they are open, the appliance is disconnected from the high p.d.

Worked example (choosing a fuse): a 230 V kettle is rated at 2.3 kW. Current = $P / V = 2,300 / 230 = 10$ A. A 13 A fuse is suitable; a 5 A fuse would melt in normal use.

16. Magnetism and electromagnetism

16.1 Magnets and magnetic fields

Magnets have a north pole and a south pole. Like poles repel; unlike poles attract. Magnetic materials (iron, steel, nickel, cobalt) are attracted by magnets. Magnetic materials can be magnetised by induction when placed near a magnet.

Magnetic field: a region in which a magnetic pole experiences a force.

The direction of a magnetic field at a point is the direction of the force on the north pole of a magnet placed there. Field lines run from north to south outside a magnet; the field is strongest where the lines are closest together, near the poles. The pattern is plotted with iron filings or with a small plotting compass moved step by step around the magnet.

Soft iron is easily magnetised and easily loses its magnetism, so it is used for temporary magnets such as the cores of electromagnets and transformers. **Steel** is harder to magnetise but keeps its magnetism, so it is used for permanent magnets.

16.2 Magnetic effect of a current

A current in a wire produces a magnetic field around it.

- **Straight wire:** concentric circles around the wire, closer together near the wire. The direction is given by the right-hand grip rule: grip the wire with the right thumb pointing along the conventional current, and the fingers curl in the direction of the field.
- **Solenoid (coil):** the field inside is strong and nearly uniform; outside it resembles that of a bar magnet.

The field of a solenoid is made stronger by increasing the current, increasing the number of turns, and inserting a soft iron core. Reversing the current reverses the field. An **electromagnet** can be switched on and off and is used in scrap-yard cranes, relays, electric bells and circuit breakers.

A **relay** is a switch operated by an electromagnet: a small current in the coil attracts an iron armature which closes contacts in a second circuit carrying a large current.

16.3 Force on a current-carrying conductor

A wire carrying a current in a magnetic field experiences a force, because the field of the current interacts with the external field. The force is largest when the wire is perpendicular to the field and zero when it is parallel. Reversing either the current or the field reverses the force.

Fleming's left-hand rule: with the thumb, first finger and second finger of the left hand held at right angles to each other, the First finger points along the magnetic Field (north to south), the seCond finger along the conventional Current, and the thuMb gives the direction of the force (Motion).

A beam of charged particles moving through a magnetic field is also deflected; the direction follows the same rule, remembering that electrons moving one way are equivalent to conventional current in the opposite direction.

16.4 The d.c. motor

A coil carrying a current sits between the poles of a magnet. The two sides of the coil carry current in opposite directions, so they experience forces in opposite directions, producing a turning effect. A **split-ring commutator** reverses the current in the coil every half turn, when the coil passes the vertical, so the coil keeps turning in the same direction. Carbon brushes press against the commutator to make contact. The turning effect is increased by increasing the current, the number of turns, or the strength of the magnetic field.

17. Electromagnetic induction

17.1 Inducing an e.m.f.

When a conductor cuts magnetic field lines, or when the magnetic field through a coil changes, an e.m.f. is induced across the conductor. If the conductor is part of a complete circuit, a current flows. Moving a magnet into a coil connected to a sensitive galvanometer makes the needle deflect; holding the magnet still gives no reading; pulling it out gives a deflection the other way.

The induced e.m.f. is increased by moving the magnet or conductor faster, using a stronger magnet, and using more turns on the coil.

Faraday's law (as needed for O Level): the size of the induced e.m.f. is proportional to the rate of change of the magnetic field linking the circuit (the rate at which field lines are cut).

Lenz's law: the direction of an induced e.m.f. is such that it opposes the change producing it.

Example of Lenz's law: when the north pole of a magnet is pushed into a coil, the induced current makes the near end of the coil a north pole, which repels the approaching magnet. Work must be done to push the magnet in, and this work becomes electrical energy, so energy is conserved.

17.2 The a.c. generator

A coil rotates in a magnetic field. As it turns, the sides of the coil cut field lines and an alternating e.m.f. is induced. **Slip rings** and brushes connect the coil to the external circuit without the wires twisting. The output e.m.f. against time is a sine-shaped curve: it is maximum when the plane of the coil is parallel to the field lines (sides cutting the lines fastest) and zero when the plane of the coil is perpendicular to the field lines (sides moving along the lines). Rotating faster increases both the peak e.m.f. and the frequency.

17.3 Transformers

A transformer has a primary coil and a secondary coil wound on a laminated soft iron core. An alternating current in the primary coil produces a changing magnetic field in the core, which induces an alternating e.m.f. in the secondary coil. Transformers do not work with steady d.c., because the field would not change.

Transformer equation: $V_p / V_s = N_p / N_s$

For a 100% efficient transformer: $I_p V_p = I_s V_s$

A **step-up** transformer has more turns on the secondary and increases the voltage; a **step-down** transformer has fewer turns on the secondary and decreases it.

Why electricity is transmitted at high voltage: for a given power $P = IV$, a higher voltage means a smaller current. The power wasted as heat in the cables is $I^2 R$, so a smaller current greatly reduces energy loss, and thinner, cheaper cables can be used. Step-up transformers raise the voltage at the power station and step-down transformers lower it before it reaches homes.

Worked example: a transformer steps 230 V down to 11.5 V. The primary coil has 2,000 turns.

$N_s = N_p \times V_s / V_p = 2,000 \times 11.5 / 230 = 100$ turns.

If the secondary current is 2.0 A and the transformer is 100% efficient, $I_p = I_s V_s / V_p = 2.0 \times 11.5 / 230 = 0.10$ A.

18. Radioactivity

18.1 The nuclear atom

An atom has a tiny, dense, positively charged nucleus containing protons and neutrons (nucleons), surrounded by negatively charged electrons. The **alpha particle scattering experiment** provided the evidence: when alpha particles were fired at thin gold foil, most passed straight through (the atom is mostly empty space), a few were deflected (the nucleus is positively charged) and a very small number bounced back (the nucleus is very small and contains most of the mass).

Proton number (atomic number) Z: the number of protons in the nucleus.

Nucleon number (mass number) A: the total number of protons and neutrons in the nucleus.

Isotopes: atoms of the same element with the same number of protons but different numbers of neutrons.

A nuclide is written ${}^A_ZX$, for example ${}^{14}_6\text{C}$ has 6 protons and 14 minus 6 = 8 neutrons.

18.2 Background radiation and detection

Background radiation is ionising radiation present all the time. Sources include radon gas from rocks and soil, cosmic rays from space, food and drink, building materials, and medical sources. Radiation can be detected with a Geiger-Müller tube connected to a counter (count rate in counts per second or per minute). When measuring the activity of a source, subtract the background count rate.

18.3 Alpha, beta and gamma radiation

Property	Alpha (α)	Beta (β)	Gamma (γ)
Nature	Helium nucleus (2 protons, 2 neutrons)	Fast-moving electron from the nucleus	Electromagnetic radiation
Charge	+2	minus 1	0
Ionising effect	Strongly ionising	Moderately ionising	Weakly ionising
Penetration	Stopped by paper or a few cm of air	Stopped by a few mm of aluminium	Reduced by several cm of lead or thick concrete
Deflection in electric and magnetic fields	Deflected (slightly, as it is massive)	Deflected more, in the opposite direction to alpha	Not deflected

Radioactive decay is **random** (you cannot predict which nucleus will decay next or when) and **spontaneous** (it is not affected by temperature, pressure or chemical changes). A count rate measured with a detector fluctuates for this reason.

18.4 Decay equations

In all decay equations, nucleon number and proton number are both conserved.

- **Alpha decay:** the nucleus loses 2 protons and 2 neutrons. Nucleon number falls by 4, proton number falls by 2. Example: ${}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^4_2\text{He}$.
- **Beta decay:** a neutron changes into a proton and an electron, and the electron is emitted.

Nucleon number unchanged, proton number increases by 1. Example: $^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_{-1}\text{e}$.

- **Gamma emission:** the nucleus loses energy; nucleon number and proton number do not change.

18.5 Half-life

Half-life: the time taken for half the nuclei of a particular isotope in a sample to decay.

After each half-life, the activity (and the number of undecayed nuclei) halves. A decay curve of count rate against time falls steeply at first then levels off, never quite reaching zero. To find the half-life from the graph, read the time for the count rate to fall from any value to half that value (after subtracting background).

Worked example: a sample has an activity of 800 counts per minute (background already subtracted) and a half-life of 6 hours. What is its activity after 24 hours?

Number of half-lives = $24 / 6 = 4$.

$800 \rightarrow 400 \rightarrow 200 \rightarrow 100 \rightarrow 50$ counts per minute.

18.6 Uses and safety

- **Smoke alarms:** an alpha source ionises the air so a small current flows; smoke absorbs the alpha particles, the current falls, and the alarm sounds. Alpha is used because it is strongly ionising but has a short range.
- **Thickness control:** beta radiation passes through paper or thin metal sheets; the count rate on the far side changes if the thickness changes, and the rollers are adjusted.
- **Sterilising and cancer treatment:** gamma rays kill bacteria on medical equipment and food, and can destroy cancer cells.
- **Tracers:** a gamma or beta emitter with a short half-life can be injected or added to a pipe to follow its path and find blockages or leaks.
- **Radiocarbon dating:** the proportion of carbon-14 remaining in dead organic material shows how long ago it died.

Ionising radiation can damage cells, cause mutations and cancer. Safety precautions: handle sources with tongs, keep them at a distance and pointing away from the body, limit exposure time, store them in lead-lined boxes, and use shielding. Workers wear dosimeter badges to monitor exposure.

18.7 Fission and fusion

Nuclear fission is the splitting of a large nucleus, such as uranium-235, into two smaller nuclei after it absorbs a neutron, releasing energy and further neutrons which can cause a chain reaction. This is the process used in nuclear power stations. **Nuclear fusion** is the joining of two light nuclei, such as hydrogen isotopes, to form a heavier nucleus, releasing energy. Fusion is the energy source of the Sun and other stars.

19. Space physics

19.1 The Earth, the Moon and the Sun

- **Day and night:** the Earth spins on its axis once in approximately 24 hours. The half of the Earth facing the Sun has day; the other half has night. This also makes the Sun appear to rise in the east and set in the west.
- **Year:** the Earth orbits the Sun once in approximately 365 days.
- **Seasons:** the Earth's axis is tilted (by about 23.5°) relative to the plane of its orbit, and the tilt always points the same way in space. The hemisphere tilted towards the Sun receives more direct sunlight (more energy per square metre) and longer days, so it has summer; six months later it is tilted away and has winter. Seasons are caused by the tilt, not by changes in the Earth's distance from the Sun.
- **Phases of the Moon:** the Moon orbits the Earth approximately once a month. It does not give out its own light; we see it because it reflects sunlight. Half of the Moon is always lit, but as it orbits we see different amounts of the lit half: new moon (lit side facing away from us), crescent, half moon, gibbous, full moon (lit side facing us), then back again.

19.2 The Solar System

The Solar System is the Sun and everything that orbits it: eight planets, dwarf planets such as Pluto, moons that orbit planets, and smaller bodies such as asteroids and comets. In order from the Sun the planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune. The four inner planets are small and rocky; the four outer planets are much larger and made mostly of gases (the gas giants).

The Solar System formed from a rotating cloud of gas and dust. Most of it collected at the centre to form the Sun; the rest clumped together (accretion) to form the planets, rocky near the hot Sun and gaseous further out where it was colder.

The Sun's gravitational attraction, acting towards the Sun, keeps the planets in orbit. Planets and moons move in approximately circular orbits, while comets move in very elongated (elliptical) orbits. In an elliptical orbit an object moves fastest when it is closest to the Sun and slowest when it is furthest away.

The gravitational field strength at the surface of a planet or moon depends on its mass and size: g is about 9.8 N/kg on Earth but about one sixth of this on the Moon. An object's mass is the same everywhere but its weight differs. The gravitational field of the Sun (or of a planet) becomes weaker with increasing distance from it. As a result, planets further from the Sun have a weaker gravitational pull acting on them, a lower orbital speed, a longer orbital period and a lower surface temperature.

Orbital speed: $v = 2\pi r / T$, where r is the average radius of the orbit (m) and T is the orbital period (s).

Worked example: the Earth orbits the Sun at an average radius of $1.5 \times 10^{11} \text{ m}$ in 365 days. Calculate its average orbital speed.

$$T = 365 \times 24 \times 3,600 = 3.15 \times 10^7 \text{ s.}$$

$$v = 2\pi r / T = 2 \times 3.14 \times 1.5 \times 10^{11} / 3.15 \times 10^7 = 3.0 \times 10^4 \text{ m/s, that is about 30 km/s.}$$

19.3 The Sun as a star

The Sun is a medium-sized star. It consists mostly of hydrogen and helium. Its energy is released by **nuclear fusion** in its core, where hydrogen nuclei join to form helium. The Sun radiates most of its energy as infrared, visible light and ultraviolet radiation.

19.4 The life cycle of stars

1. A star forms from an interstellar cloud of gas and dust (a **nebula**) containing hydrogen. Gravity pulls the material together.
2. The collapsing cloud becomes a **protostar**. Its temperature rises as gravitational potential energy is transferred to internal energy.
3. When the core is hot enough, hydrogen nuclei fuse into helium and the star becomes a **stable star**. It stays stable for a long time because the inward pull of gravity is balanced by the outward pressure from the hot core.
4. When most of the hydrogen in the core has been used, the star expands. A star of similar mass to the Sun becomes a **red giant**; a much more massive star becomes a **red supergiant**.
5. A red giant loses its outer layers as a **planetary nebula**, leaving a small, hot, dense core called a **white dwarf**.
6. A red supergiant explodes as a **supernova**, forming a nebula and leaving behind either a **neutron star** or, for the most massive stars, a **black hole**.

The nebula left by a supernova contains hydrogen and heavier elements and may later form new stars with orbiting planets.

19.5 Galaxies and the Universe

A galaxy is a very large group of stars held together by gravity. The Sun is one of many billions of stars in our galaxy, the **Milky Way**, and the Milky Way is one of many billions of galaxies that make up the Universe.

Light-year: the distance travelled by light in a vacuum in one year. 1 light-year is about 9.5×10^{15} m.

The diameter of the Milky Way is about 100,000 light-years.

Redshift: the increase in the observed wavelength of electromagnetic radiation emitted from stars and galaxies that are moving away from the observer.

Light from distant galaxies is redshifted, so they are moving away from us. The further away a galaxy is, the greater its redshift and the faster it is moving away. This shows that the Universe is expanding, which supports the **Big Bang theory**: the Universe began from a single point and has been expanding ever since.

A second piece of evidence is the **cosmic microwave background radiation (CMBR)**: microwave radiation of a specific frequency observed from all directions in space. It was produced shortly after the Universe was formed and its wavelength has been stretched into the microwave region as the Universe expanded.

Hubble constant: $H_0 = v / d$, the ratio of the speed at which a galaxy is moving away from the Earth to its distance from the Earth. The current estimate is about 2.2×10^{-18} per second. The age of the Universe is estimated as $d / v = 1 / H_0$.

Worked example: estimate the age of the Universe, taking $H_0 = 2.2 \times 10^{-18}$ per second.

Age = $1 / H_0 = 1 / 2.2 \times 10^{-18} = 4.5 \times 10^{17}$ s.

One year = 3.15×10^7 s, so age = $4.5 \times 10^{17} / 3.15 \times 10^7 = 1.4 \times 10^{10}$ years, about 14 billion years.

Quick check

1. A micrometer screw gauge has a zero error of +0.02 mm. It gives a reading of 0.58 mm for the diameter of a wire. State the correct diameter and explain why measuring the diameter at several places along the wire improves the result. [3]
2. A cyclist accelerates uniformly from 2.0 m/s to 8.0 m/s in 4.0 s, then brakes uniformly to rest in a further 2.0 s. (a) Calculate the acceleration in the first 4.0 s. (b) Calculate the total distance travelled. [5]
3. A skydiver jumps from a plane. Describe and explain how the skydiver's speed changes from the moment of jumping until terminal velocity is reached. [4]
4. A 0.050 kg ball moving at 12 m/s hits a wall and rebounds at 8.0 m/s in the opposite direction. The ball is in contact with the wall for 0.020 s. Calculate (a) the change in momentum and (b) the average force on the ball. [4]
5. A block of metal measures 2.0 cm × 3.0 cm × 5.0 cm and has a mass of 237 g. Calculate its density in kg/m³. [3]
6. A uniform plank of weight 200 N and length 4.0 m rests on a pivot 1.0 m from its left end. What downward force must be applied at the left end to keep the plank horizontal? [4]
7. A diver is 12 m below the surface of a lake. The density of water is 1,000 kg/m³, $g = 9.8$ N/kg and atmospheric pressure is 1.0×10^5 Pa. Calculate the total pressure on the diver. [3]
8. A crane lifts a 400 kg load at a steady speed through 15 m in 30 s. (a) Calculate the gain in gravitational potential energy. (b) Calculate the useful output power. [4]
9. Calculate the energy needed to heat 0.50 kg of water from 25 °C to 100 °C and then boil away 0.10 kg of it. Take the specific heat capacity of water as 4,200 J/(kg °C) and the specific latent heat of vaporisation as 2.3×10^6 J/kg. [4]
10. Explain, in terms of particles, why evaporation causes cooling. [3]
11. Light travels from glass of refractive index 1.6 into air. (a) Calculate the critical angle. (b) State what happens to a ray that meets the glass-air surface at an angle of incidence of 45°. [4]
12. An object 2.0 cm tall is placed 15 cm from a converging lens of focal length 10 cm. Describe the image formed and state one optical instrument that uses this arrangement. [3]
13. Two resistors of 3.0 Ω and 6.0 Ω are connected in parallel across a 6.0 V battery. Calculate (a) the combined resistance, (b) the current from the battery and (c) the power dissipated in the 3.0 Ω resistor. [5]
14. A transformer has 4,000 turns on its primary coil and 200 turns on its secondary coil. The primary is connected to a 240 V a.c. supply. (a) Calculate the secondary voltage. (b) Explain why the transformer would not work on a 240 V d.c. supply. [4]
15. Thorium-232 ($^{232}_{90}\text{Th}$) decays by alpha emission to radium. (a) Write the decay equation. (b) A sample of a different isotope has a count rate of 960 counts per minute, falling to 120 counts per minute after 15 days (background subtracted). Calculate its half-life. [5]

16. The Moon orbits the Earth at an average radius of 3.8×10^8 m with a period of 27.3 days. (a) Calculate the average orbital speed of the Moon. (b) The Moon does not emit light. Explain why we see the Moon go through phases during each orbit. [5]
17. (a) Describe what happens to a star much more massive than the Sun after it has used up most of the hydrogen in its core. (b) Explain how the light from distant galaxies and the cosmic microwave background radiation support the Big Bang theory. [6]

1. Correct diameter = reading minus zero error = 0.58 minus $0.02 = 0.56$ mm. The wire may not be perfectly uniform or perfectly round, so taking readings at several places (and in different directions) and averaging reduces the effect of these variations and of random errors.

2. (a) $a = (v \text{ minus } u) / t = (8.0 \text{ minus } 2.0) / 4.0 = 1.5 \text{ m/s}^2$. (b) Use areas under the speed-time graph. First 4.0 s: a trapezium, distance = $\frac{1}{2} \times (2.0 + 8.0) \times 4.0 = 20$ m. Braking: a triangle, distance = $\frac{1}{2} \times 8.0 \times 2.0 = 8.0$ m. Total distance = $20 + 8.0 = 28$ m.

3. At first the only force is weight (air resistance is zero at zero speed), so the skydiver accelerates at g , about 9.8 m/s^2 . As speed increases, air resistance increases, so the resultant force (weight minus air resistance) decreases, and the acceleration decreases: speed still increases, but more slowly. Eventually air resistance equals weight, the resultant force is zero, the acceleration is zero, and the skydiver falls at a constant terminal velocity.

4. Take the initial direction as positive. (a) Initial momentum = $0.050 \times 12 = 0.60 \text{ kg m/s}$. Final momentum = $0.050 \times (\text{minus } 8.0) = \text{minus } 0.40 \text{ kg m/s}$. Change in momentum = $\text{minus } 0.40 \text{ minus } 0.60 = \text{minus } 1.0 \text{ kg m/s}$, so the magnitude is 1.0 kg m/s directed away from the wall. (b) Force = change in momentum / time = $1.0 / 0.020 = 50 \text{ N}$, directed away from the wall.

5. Volume = $2.0 \times 3.0 \times 5.0 = 30 \text{ cm}^3$. Density = $237 / 30 = 7.9 \text{ g/cm}^3$. Multiply by 1,000: density = $7,900 \text{ kg/m}^3$.

6. The weight of a uniform plank acts at its centre, 2.0 m from the left end, which is 2.0 minus 1.0 = 1.0 m to the right of the pivot. Clockwise moment of the weight = $200 \times 1.0 = 200 \text{ N m}$. The force F at the left end is 1.0 m to the left of the pivot, giving an anticlockwise moment $F \times 1.0$. Principle of moments: $F \times 1.0 = 200$, so $F = 200 \text{ N}$.

7. Pressure due to water = $pgh = 1,000 \times 9.8 \times 12 = 117,600 \text{ Pa} = 1.18 \times 10^5 \text{ Pa}$. Total pressure = $1.18 \times 10^5 + 1.0 \times 10^5 = 2.2 \times 10^5 \text{ Pa}$ (to 2 significant figures).

8. (a) $\Delta E_p = mg\Delta h = 400 \times 9.8 \times 15 = 58,800 \text{ J}$ (about $5.9 \times 10^4 \text{ J}$). (b) Power = energy / time = $58,800 / 30 = 1,960 \text{ W}$, about 2.0 kW.

9. Heating: $E_1 = mc\Delta\theta = 0.50 \times 4,200 \times 75 = 157,500 \text{ J}$. Boiling: $E_2 = mL = 0.10 \times 2.3 \times 10^6 = 230,000 \text{ J}$. Total = $157,500 + 230,000 = 387,500 \text{ J}$, about $3.9 \times 10^5 \text{ J}$.

10. The molecules of a liquid have a range of kinetic energies. Only the most energetic molecules near the surface have enough energy to overcome the attractions of other molecules and escape. When they leave, the average kinetic energy of the molecules remaining in the liquid falls. Since temperature depends on the average kinetic energy of the particles, the temperature of the liquid falls.

11. (a) $\sin c = 1 / n = 1 / 1.6 = 0.625$, so $c = 39^\circ$ (to 2 significant figures). (b) 45° is greater than the critical angle, so the ray is totally internally reflected: no light leaves the glass, and the ray reflects back into the glass with an angle of reflection of 45° .

12. The object is between F (10 cm) and 2F (20 cm). The image is real, inverted and enlarged, formed beyond 2F on the other side of the lens (it can be shown by ray diagram to be at 30 cm from the lens and 4.0 cm tall). This arrangement is used in a projector.

13. (a) $1/R = 1/3.0 + 1/6.0 = 2/6.0 + 1/6.0 = 3/6.0$, so $R = 2.0 \Omega$. (b) $I = V / R = 6.0 / 2.0 = 3.0 \text{ A}$. (c) The p.d. across each parallel branch is 6.0 V. Power in the 3.0Ω resistor = $V^2 / R = 6.0^2 / 3.0 = 12 \text{ W}$. (Check: current in it = $6.0 / 3.0 = 2.0 \text{ A}$, and $P = IV = 2.0 \times 6.0 = 12 \text{ W}$.)

14. (a) $V_s = V_p \times N_s / N_p = 240 \times 200 / 4,000 = 12 \text{ V}$. (b) A transformer relies on electromagnetic induction, which needs a changing magnetic field in the core. A steady d.c. in the primary produces a constant magnetic field, so no e.m.f. is induced in the secondary (except briefly when the supply is switched on or off).

15. (a) In alpha decay the nucleon number falls by 4 and the proton number falls by 2: ${}^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^4_2\text{He}$. Check: $232 = 228 + 4$ and $90 = 88 + 2$. (b) $960 \rightarrow 480 \rightarrow 240 \rightarrow 120$ counts per minute is three halvings, so 15 days = 3 half-lives. Half-life = $15 / 3 = 5$ days.

16. (a) $T = 27.3 \times 24 \times 3,600 = 2.36 \times 10^6 \text{ s}$. $v = 2\pi r / T = 2 \times 3.14 \times 3.8 \times 10^8 / 2.36 \times 10^6 = 1.0 \times 10^3 \text{ m/s}$, about 1 km/s. (b) We see the Moon because it reflects sunlight. The half of the Moon facing the Sun is always lit. As the Moon orbits the Earth, the angle between the Sun, Earth and Moon changes, so we see different amounts of the lit half: none at new moon (lit half facing away from the Earth), all of it at full moon (lit half facing the Earth), and crescent, half and gibbous shapes in between.

17. (a) The star expands to become a red supergiant. It then explodes as a supernova, throwing out a nebula of gas and dust containing hydrogen and heavier elements, and leaves behind either a neutron star or, if the star is massive enough, a black hole. (b) Light from distant galaxies is redshifted: its observed wavelength is longer than when it was emitted, so the galaxies are moving away from us. More distant galaxies have greater redshift, so they are moving away faster. This shows the Universe is expanding, which is consistent with it having started from a single point (the Big Bang). The cosmic microwave background radiation is microwave radiation observed from all directions in space. It is explained as radiation produced shortly after the Universe formed, whose wavelength has been stretched into the microwave region as the Universe expanded.