Co-ordinated Sciences (0654)

IGCSE • Extended • CAIE

Compact Cheat Sheet

The Practice Book
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1 Acids, bases and salts

KEY FORMULAS

Acid with a base: the copper(II) oxide equation

$$H_2SO_4(aq) + CuO(s) \rightarrow CuSO_4(aq) + H_2O(l)$$

Used whenever an acid reacts with a metal oxide or hydroxide: the products are a salt and water, and no gas is released. The state symbols carry marks of their own. A dilute acid is *always* (aq) and never (l); an oxide added as a powder is (s); a soluble salt formed in solution is (aq) and never (s); water formed in solution is (l) and never (g). The same pattern with hydrochloric acid needs two acid molecules: $CuO(s) + 2HCl(aq) \rightarrow CuCl_2(aq) + H_2O(l)$.

The ionic equation for neutralisation

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$$

Used for the reaction of any acid with any alkali in solution. This one equation is the whole chemistry of acid-alkali neutralisation: the hydrogen ion from the acid combines with the hydroxide ion from the alkali to form water. The metal ion from the alkali and the non-metal ion from the acid are *spectator ions*, present unchanged on both sides, so they are cancelled out. For dilute hydrochloric acid with aqueous sodium hydroxide the spectator ions are Na^+ and Cl^-. Because the spectators never appear, the equation is identical for every strong acid with every strong alkali.

The three characteristic reactions of acids

$$acid + metal \rightarrow salt + hydrogen \cdot acid + base \rightarrow salt + water \cdot acid + carbonate \rightarrow salt + water + carbon dioxide$$

Used to predict the products of any reaction of a dilute acid, and to identify the acid from an observation. The three product-patterns are fixed, so naming the second reactant is enough to write the products. Only a metal *above hydrogen* in the reactivity series follows the first pattern, which is why copper does not react with dilute acids. The non-metal part of the salt comes from the acid: hydrochloric gives chlorides, sulfuric gives sulfates, nitric gives nitrates. The metal part comes from the metal, base or carbonate.

KEY CONCEPTS

- **Acid, base and alkali defined**: An *acid* is a source of hydrogen ions, H^+, in aqueous solution. A *base* is an oxide or a hydroxide of a metal, which reacts with an acid to form a salt and water. An *alkali* is a base that is *soluble in water*, dissolving to give a solution containing hydroxide ions, OH^-. The relationship is one-way: every alkali is a base, but not every base is an alkali. Sodium hydroxide is both, because it dissolves; copper(II) oxide and copper(II) hydroxide are bases but *not* alkalis, because they are insoluble. Reacting with an acid to give a salt and water is the property of *all* bases, soluble or not, so that reaction alone never proves a substance is an alkali.
- **Amphoteric oxides: aluminium oxide and zinc oxide**: An *amphoteric oxide reacts with both acids and bases*, in each case producing a salt and water. It behaves as a base towards acids and as an acid towards bases. The syllabus requires exactly two: *aluminium oxide,* Al_2O_3, and *zinc oxide,* ZnO. The test is definitional, so check both reactions: reacting with both is amphoteric; with acids only is basic; with bases only is acidic; with neither is neutral, as for carbon monoxide. One reaction is never enough, because reacting with an acid alone shows only that the oxide is basic.
- **Indicator colours: litmus and methyl orange**: An *indicator* is a substance that is a different colour in acidic and alkaline solutions, so it reports which of the two a solution is. Two must be known exactly. *Litmus*: red in acid, purple when neutral, blue in alkali. *Methyl orange*: red in acid, orange when neutral, yellow in alkali. The two changes worth locking in are "acid turns blue litmus red" and "alkali turns red litmus blue". Litmus does not give a reliable neutral reading, because its purple is hard to judge, which is exactly why universal indicator exists.
- **Metal oxides are basic, non-metal oxides are acidic**: An *oxide* is a compound of an element with oxygen, and its acid-base character follows directly from the character of that element. *Metal oxides are generally basic*: they react with acids to give a salt and water. Examples are CuO, CaO, MgO and Na_2O; the soluble ones dissolve to give alkaline solutions. *Non-metal oxides are generally*

acidic: they react with bases to give a salt and water, and the soluble ones dissolve to give acidic solutions. The two the syllabus names explicitly are SO_2 and CO_2. Classify from the element first, and the justification is half the answer: "basic, because magnesium is a metal and metal oxides are basic".

- **Neutralisation**: *Neutralisation* is the reaction of an acid with a base, including an alkali, to produce a *salt and water*. The class of products is fixed even when the identities are not, so "acid + alkali $\rightarrow$ X + water" always has *salt* as X. Neutralisation is also the name of the reaction type whenever a question describes an acid reacting with a base. Followed with universal indicator, adding alkali to an acid moves the colour *up* the scale in order and gradually, never in one jump: red, orange, yellow, green at pH 7, then blue and purple once the alkali is in excess.
- **The finishing steps, and hydrated versus anhydrous**: Once a pure salt solution has been obtained, the finishing steps are fixed: *evaporate* to concentrate the solution to saturation, *cool slowly* so crystals form, then *filter and dry* the crystals. Do *not* evaporate to dryness. A *hydrated* substance is chemically combined with water, the water of crystallisation built into the crystal structure; an *anhydrous* substance contains no water. Evaporating to dryness drives the water of crystallisation off too and leaves an anhydrous powder, so evaporating only to saturation and cooling slowly is what keeps hydrated crystals hydrated. Hydrated copper(II) sulfate is blue and the anhydrous form is white.
- **The four routes to a soluble salt**: A soluble salt is made from an acid, which supplies the non-metal part, and a second reactant, which supplies the metal part. There are *four routes*, chosen by the second reactant: acid + excess reactive *metal* (zinc with sulfuric acid); acid + excess insoluble *base* (copper(II) oxide with sulfuric acid); acid + excess insoluble *carbonate* (copper(II) carbonate with sulfuric acid); and acid + soluble base, an *alkali*, by *titration* (sodium hydroxide with nitric acid). For the first three the method is identical: add the solid *in excess* so all the acid is used up and none is left to contaminate the salt, then *filter off* the unreacted excess. Excess is impossible with an alkali, because it would stay dissolved and could not be filtered out, which is why route four titrates instead.
- **The pH scale and universal indicator**: The *pH scale* runs 0 to 14 and measures *how* acidic or alkaline a solution is, not merely which. Below 7 is acidic, 7 is neutral, above 7 is alkaline. *Universal indicator* is a mixture of dyes giving a continuous range of colours mapped onto that scale: red at pH 0 to 2 (strongly acidic), through orange and yellow (weakly acidic), green at pH 7 (neutral), blue at pH 9 to 11, and purple at pH 12 to 14 (strongly alkaline). Ranking follows the colour: the redder the solution, the lower the pH and the more acidic; the more purple, the higher the pH and the more alkaline.

EXAM TIPS

TIP The single most common lost mark in this chapter is the coefficient on the acid. Write the salt formula first from the charges, then count backwards to see how many acid molecules are needed. A metal ion carrying a $2+$ charge (Mg, Zn, Cu, Ca) needs *two* molecules of a monoprotic acid such as HCl or HNO_3, because the salt takes two of the non-metal ions: $ZnCO_3(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2O(l) + CO_2(g)$. Sulfuric acid, which supplies two hydrogens itself, usually needs no coefficient with a $2+$ metal. Then check every element on both sides and add the state symbols even when they are not demanded.

TIP Every salt-preparation question is answered by one decision made before you write. Ask whether the second reactant is soluble. If it is *insoluble* (a metal, an insoluble base or a carbonate), use excess-then-filter, and say the excess ensures all the acid reacts and the excess is removed by filtration. If it is *soluble* (an alkali), the method must be *titration*, and you must state that the neutralising volume is found with an indicator and the run then repeated with the same volumes *without* indicator, so the dye does not contaminate the salt. If the salt itself is *insoluble*, neither applies: precipitate it by mixing two solutions. Naming the wrong method loses every method mark that follows, however well the steps are described.

TIP The question gives you a *starting* colour, and only two changes exist: blue litmus in acid turns red, and red litmus in alkali turns blue. Where the starting colour already matches the solution, there is no change to report, and answering "it turns red" for red litmus already sitting in an acid throws the mark away. Read which indicator, which starting colour, and which solution, in that order, before writing anything. The same discipline applies to methyl orange, where red and yellow are the two ends and orange is only the in-between.

2 Atoms, elements and compounds

KEY FORMULAS

Electronic configuration of the first twenty elements

$$\mathrm{Na}\ (Z = 11):\ 2, 8, 1 \qquad \mathrm{Ca}\ (Z = 20):\ 2, 8, 8, 2$$

Use to write the configuration of any of the first twenty elements. Fill shells from the nucleus outwards respecting the maxima 2, then 8, then 8, until the electrons run out; for a neutral atom they total Z. Always check by adding the shells back to Z.

Group and period from the electronic configuration

$$\text{Period} = \text{number of occupied shells} \qquad \text{Group} = \text{number of outer-shell electrons}$$

Use to place any of the first twenty elements in the Periodic Table straight from its configuration, and to predict the ion it forms. Chlorine $(2, 8, 7)$ has three occupied shells and seven outer electrons, so it is in Period 3, Group VII. The two counts are independent: matching shells means the same period, matching outer electrons means the same group.

Ionic charge from the group number

$$\mathrm{I}: 1+ \quad \mathrm{II}: 2+ \quad \mathrm{III}: 3+ \qquad \mathrm{V}: 3- \quad \mathrm{VI}: 2- \quad \mathrm{VII}: 1-$$

Use to predict the charge on any main-group ion before writing a formula. A metal in Groups I to III loses its outer electrons, so the charge equals the group number. A non-metal in Groups V to VII gains electrons to fill its outer shell, so the charge equals the group number minus 8. Every ion formed reaches a noble-gas arrangement.

Proton number, nucleon number and the neutron count

$$A = Z + N \quad \text{so} \quad N = A - Z$$

Use to move between the two counting numbers of any atom, written ${}^{A}_{Z}\mathrm{X}$. Z is the proton number (the element's identity), A is the nucleon number (protons plus neutrons) and N is the neutron count. Given any two, the third follows: ${}^{23}_{11}\mathrm{Na}$ has $23 - 11 = 12$ neutrons.

KEY CONCEPTS

- **Element, compound and mixture defined**: An *element* is a substance made of only one type of atom; it cannot be broken down into anything simpler by a chemical reaction. A *compound* is two or more different elements chemically bonded together in a fixed ratio, with completely different properties from the elements it came from, separable only by chemical means. A *mixture* is two or more substances physically combined with no chemical bonds between them; its proportions can vary, each substance keeps its own properties, and physical methods such as filtering or distillation separate it.
- **Giant covalent structures and their very high melting points**: A *giant covalent structure* is a huge three-dimensional network in which every atom is joined to its neighbours by strong covalent bonds, repeated throughout the whole solid. There are no separate molecules and no weak intermolecular forces holding units together: the covalent bonding is the whole structure. Melting means breaking a colossal number of strong covalent bonds, so melting points are uniformly very high. The examined examples are *diamond*, *graphite* and silicon(IV) oxide, $\mathrm{SiO_2}$.
- **Ions, cations and anions**: An *ion* is a charged atom, or group of atoms, formed when an atom loses or gains electrons to reach a full outer shell. A metal atom has few outer electrons and *loses* them to form a positive ion, a *cation*: sodium $(2, 8, 1)$ loses one electron to become $\mathrm{Na^+}$ $(2, 8)$. A non-metal atom has a nearly full outer shell and *gains* electrons to form a negative ion, an *anion*: chlorine ($2, 8, 7$) gains one to become $\mathrm{Cl^-}$ $(2, 8, 8)$.

- **Isotopes defined**: *Isotopes* are atoms of the same element that have the same number of protons but different numbers of neutrons. Same proton number means the same element and the same number of electrons; different neutron number means a different nucleon number, so a different mass. Chlorine exists as ${}^{35}_{17}\mathrm{Cl}$ and ${}^{37}_{17}\mathrm{Cl}$: both have 17 protons, but 18 and 20 neutrons respectively.
- **Metallic bonding defined**: A metal is a giant lattice of *positive metal ions* surrounded by a sea of *delocalised electrons*. Each metal atom loses its outer electron(s), which become delocalised and free to move throughout the whole structure, leaving positive ions in a regular lattice. *Metallic bonding is the strong electrostatic attraction between the positive metal ions and the delocalised electrons*, acting in all directions. It is neither shared pairs (covalent) nor electron transfer (ionic).
- **Relative charge and relative mass of the subatomic particles**: The *proton* has relative charge $+1$ and relative mass 1, in the nucleus. The *neutron* has relative charge 0 and relative mass 1, in the nucleus. The *electron* has relative charge -1 and relative mass $\frac{1}{2000}$, treated as negligible, in the shells. Two consequences follow: a neutral atom has equal numbers of protons and electrons, so the charges cancel; and the mass of an atom is set by its nucleus alone.
- **The covalent bond: a shared pair of electrons**: A *covalent bond* is a shared pair of electrons between two atoms. It forms between non-metal atoms, which each need to gain electrons: rather than one losing to the other, they share, and each atom counts the shared pair towards its own full outer shell. No ions form, so neither atom carries a charge. A *double* bond is two shared pairs and a *triple* bond is three; outer electrons not used in bonding sit as *lone pairs*.
- **The ionic bond and the giant ionic lattice**: An *ionic bond* is the strong electrostatic force of attraction between oppositely charged ions. It forms when a metal transfers electrons to a non-metal. Because that attraction acts equally in all directions, the ions pack into a *giant ionic lattice*, a regular repeating three-dimensional array in which every cation is surrounded by anions and every anion by cations.
- **The nuclear atom**: Every atom is a tiny, dense *nucleus* surrounded by *electrons* arranged in *shells* (energy levels). The nucleus holds the *protons* and *neutrons*, together called nucleons. Almost all the mass sits in the nucleus; almost all the volume is the near-empty region the electrons occupy. The first shell holds a maximum of 2 electrons, and the second and third hold up to 8 each for the first twenty elements.
- **Why isotopes have identical chemical properties**: Chemical behaviour is decided by the *electrons*, especially the outer-shell electrons that form bonds. Isotopes share a proton number, so they have the same number of electrons in the same electronic configuration, and they therefore react in exactly the same way. Physical properties such as density depend instead on the mass of the atom, which comes from the nucleus, and the differing neutron numbers give differing masses. The one-liner examiners reward: same electrons means same chemistry, different neutrons means different mass.

EXAM TIPS

TIP The classic trap is to reason that covalent bonds are strong, so a simple molecular compound must have a high melting point. That confuses two different forces. The covalent bonds *within* each molecule are strong and stay intact on melting; what actually breaks is the much *weaker intermolecular forces between* separate molecules, which takes little energy. Simple molecular substances therefore have *low* melting and boiling points. Name which force is overcome and the mark follows.

3 Biological molecules

KEY CONCEPTS

- **Carbohydrates are built from glucose**: The building block of carbohydrates is a simple sugar, most importantly *glucose*. Joining many glucose molecules into a long chain produces a large carbohydrate called a *polysaccharide*. *Starch*, the energy store of plants, and *glycogen*, the energy store of animals, are both polysaccharides built entirely from glucose: same building block, different molecule.
- **Nitrogen is the signature of protein**: Nitrogen is the one element that separates protein from the other two families: neither carbohydrates nor fats contain it. If an analysis of a pure biological molecule finds nitrogen, the molecule is a protein, because no other family carries that element. This single fact resolves most "which sample is the protein" questions without further evidence.
- **One glycerol plus three fatty acids builds a fat**: A fat molecule (a *triglyceride*) is built from two kinds of smaller unit: one molecule of *glycerol* and three molecules of *fatty acid*. Glycerol has three attachment points and a fatty acid joins at each one, so the ratio is fixed at one glycerol to three fatty acids, never a variable "many" as in a polysaccharide.
- **Proteins are chains of amino acids**: Proteins are built from *amino acids* joined into a long chain that folds into a specific three-dimensional shape. That folded shape is what lets a protein act as an enzyme, an antibody, a hormone or a structural material. Amino acids, and therefore proteins, always contain nitrogen in addition to carbon, hydrogen and oxygen.
- **The three families and their elements**: Every biological molecule belongs to one of three families and each family has a fixed elemental signature. *Carbohydrates* and *fats* are built from carbon (C), hydrogen (H) and oxygen (O) only. *Proteins* are built from those same three elements plus nitrogen (N). Finding out which elements are present tells you which family a pure molecule belongs to.

EXAM TIPS

TIP Iodine, biuret and the ethanol emulsion test are all added directly to the food sample with no heating. Benedict's solution is the exception: it must be heated, usually in a water bath, before the colour change appears. If a question describes heating a reagent with the food, it is describing Benedict's test for reducing sugar.

TIP State the *starting* colour and the *finishing* colour together, never the finishing colour alone: "orange-brown to blue-black", not "goes dark". Marks are awarded for the precise colour pair, and a vague description of the change loses them even when the correct test has clearly been identified.

4 Cells

KEY FORMULAS

Actual size from magnification

$$\text{actual size} = \frac{\text{image size}}{M}$$

Used whenever a question gives a magnified image and a magnification, and asks for the real size of the specimen. This is a rearrangement of $M = \frac{\text{image size}}{\text{actual size}}$.

Magnification

$$M = \frac{\text{image size}}{\text{actual size}}$$

Used to find how many times larger, or smaller, an image is than the real specimen. Image size and actual size must be in the *same unit* before dividing; M itself has no units, since it is a ratio of two lengths.

Millimetres to micrometres

$$1\ \text{mm} = 1000\ \mu\text{m}$$

Used to convert a measured length into the unit cell sizes are normally quoted in. To go from mm to µm, multiply by 1000; to go from µm to mm, divide by 1000.

KEY CONCEPTS

- **Levels of organisation**: Cells build up into larger working units in a fixed order: *cell* leads to *tissue* (a group of similar cells working together), which leads to *organ* (several tissues working together for a function), which leads to *organ system* (a group of organs working together), which leads to *organism* (a complete living individual). A ribosome is an organelle, smaller than a cell, so it does not belong anywhere on this ladder.
- **Structures shared by every animal and plant cell**: *Cell membrane*: a thin, partially permeable boundary that controls which substances enter and leave the cell. *Cytoplasm*: the watery jelly where most of the cell's chemical reactions occur. *Nucleus*: holds the genetic material (DNA) as chromosomes and controls the cell's activities, including which proteins are made. *Mitochondria*: the site of aerobic respiration, releasing energy for the cell. *Ribosomes*: tiny structures scattered through the cytoplasm; the site of protein synthesis.
- **The three plant-only extras**: A typical animal cell has none of these three structures. *Cell wall*: a rigid outer layer made of cellulose, lying outside the cell membrane, that supports the cell and gives it a fixed shape. *Chloroplasts*: contain chlorophyll and are the site of photosynthesis; present only in cells that receive light. *Permanent vacuole*: a large, fluid-filled sac of cell sap that helps keep the cell firm.
- **What a bacterial cell has and lacks**: A bacterial cell has a cell wall (not cellulose), a cell membrane, cytoplasm, ribosomes, a single circular loop of chromosomal DNA free in the cytoplasm, and often one or more plasmids. It has no nucleus, no mitochondria, no chloroplasts and no permanent vacuole. Its genetic material is not enclosed in a membrane-bound nucleus, so it is described as having *no true nucleus*.

EXAM TIPS

TIP Every cell, animal and plant, has a cell *membrane*; what a typical animal cell lacks is the cell *wall*. Membrane and wall are different structures at different positions in the cell (the wall lies outside the membrane), and only the wall is plant-only. Writing "animal cells have no membrane" scores nothing.

TIP Put image size and actual size in the same unit before applying the magnification formula, so M comes out as a pure number. The safest routine is to do the whole calculation in millimetres and convert the final answer to micrometres only at the end, which keeps the factor of a thousand in one predictable place.

5 Characteristics of living organisms

KEY CONCEPTS

- **Growth, reproduction, excretion and nutrition defined**: *Growth*: a permanent increase in size and dry mass. *Reproduction*: the processes that make more of the same kind of organism. *Excretion*: the removal of the waste products of metabolism and substances in excess of requirements. *Nutrition*: the taking in of materials for energy, growth and development.
- **Metabolism, the source of all seven characteristics**: *Metabolism* is the sum of all the chemical reactions taking place inside the cells of an organism. Each characteristic is an outward sign of metabolism: it releases the energy an organism uses (respiration), builds the new living material an organism adds (growth), and produces the waste an organism must remove (excretion).
- **Movement, respiration and sensitivity defined**: *Movement*: an action by an organism, or part of an organism, that causes a change of position or place. *Respiration*: the chemical reactions in cells that break down nutrient molecules and release energy for metabolism. *Sensitivity*: the ability to detect and respond to changes in the internal or external environment.
- **The seven characteristics of living organisms**: All living organisms carry out seven life processes, remembered by the mnemonic *MRS GREN*: Movement, Respiration, Sensitivity, Growth, Reproduction, Excretion, Nutrition. The seven describe what an organism is *capable* of over its lifetime, not what it must be doing at every instant.
- **What counts as a waste product of metabolism**: Excretion removes waste that the organism's own chemical reactions produced, together with substances in excess of requirements. In a human, *carbon dioxide* from respiration leaves at the lungs, *urea* from breaking down excess protein leaves in urine at the kidneys, and excess water and salts leave in urine and in sweat.

EXAM TIPS

TIP Where a question asks which characteristic is shown by *all* living organisms, excretion is the reliable answer: every organism has metabolism, so every organism produces metabolic waste to remove. Egestion, photosynthesis and plasmolysis are not characteristics of life at all; egestion requires a gut and photosynthesis occurs only in plants and some other organisms.

TIP Marks are lost on paraphrase rather than on recognition, because a paraphrase drops the one word being marked. Growth is a *permanent* increase in size and *dry mass*; excretion removes the waste products of *metabolism*; reproduction makes *more of the same kind* of organism. Reproduce the wording above exactly.

6 Chemical energetics

KEY FORMULAS

Activation energy

$$E_a = E(\text{peak}) - E(\text{reactants})$$

Used to find the energy barrier the reactants must climb before they can react, measured from the reactants line up to the peak of the pathway diagram. The energy of the products is not needed for this calculation.

Enthalpy change

$$\Delta H = E(\text{products}) - E(\text{reactants})$$

Used to find the overall energy change of a reaction from the two flat energy levels on a reaction pathway diagram. Subtract in this order every time. The unit is kJ/mol and the sign carries the classification: negative for exothermic, positive for endothermic.

Enthalpy change from bond energies

$$\Delta H = (\text{energy to break all reactant bonds}) - (\text{energy released making all product bonds})$$

Used when a question supplies bond-breaking and bond-making totals instead of energy levels. It is energy in minus energy out, so a negative result means more energy was released than absorbed and the reaction is exothermic.

KEY CONCEPTS

- **Bond breaking and bond making**: *Breaking bonds takes energy in* and is an endothermic step; *making bonds gives energy out* and is an exothermic step. Every reaction does both, and the balance of the two decides the sign of ΔH. If more energy is released making the product bonds than is absorbed breaking the reactant bonds, the reaction is exothermic; if more is absorbed than released, it is endothermic.
- **Endothermic reactions**: An *endothermic* reaction transfers thermal energy *from* the surroundings into the reacting chemicals. Because that energy is drawn in, the temperature of the mixture *falls* and ΔH is positive. Thermal decomposition and the dissolving of certain salts, such as ammonium salts, are endothermic. A thermal decomposition stops the moment heating stops, because it depends on a continuous supply of thermal energy from outside.
- **Exothermic reactions**: An *exothermic* reaction transfers thermal energy from the reacting chemicals *to* the surroundings. Because that energy flows outward, the temperature of the mixture *rises* and ΔH is negative. Combustion, neutralisation of an acid with an alkali, and a reactive metal reacting with an acid are all exothermic.
- **Reading a reaction pathway diagram**: A reaction pathway diagram plots the energy of the chemicals on the vertical axis against the progress of the reaction on the horizontal axis. One comparison classifies the reaction: if the *products line is lower* than the reactants line the reaction is *exothermic*; if the *products line is higher* it is *endothermic*. The hump between them is the activation energy and never affects the classification.

EXAM TIPS

TIP Where a question gives start and end temperatures, only up against down decides the class. A rise of 1 °C and a rise of 40 °C are both exothermic; a fall of any size is endothermic; no change at all means no net thermal energy was transferred either way. The size of the change matters only when comparing two reactions run in identical volumes of the same solution.

TIP Reversing the subtraction gives the right magnitude with the wrong sign, which flips exothermic and endothermic and scores nothing. Compute $E(\text{products}) - E(\text{reactants})$, then check the

answer against the diagram: a products line drawn lower must give a negative ΔH. Always write the sign; for an enthalpy change the sign *is* the classification, not decoration.

7 Chemical reactions

KEY FORMULAS

Average rate of reaction

$$\text{average rate} = \frac{\text{change in quantity}}{\text{time taken}}$$

Used to find the rate over an interval, given how much gas, mass or product changed and how long it took. The units follow the two quantities, giving cm^3/s, cm^3/min or g/s, so always convert the time to the unit the answer is asked for before dividing. Rearranges to $\text{time} = \frac{\text{change in quantity}}{\text{rate}}$.

Instantaneous rate from the gradient of a tangent

$$\text{rate at a point} = \text{gradient of the tangent} = \frac{\Delta\text{quantity}}{\Delta\text{time}}$$

Used when a question asks for the rate at one particular moment rather than across an interval. Draw a tangent touching the curve at that point, take two widely spaced points on the tangent itself, and divide the rise by the run. A chord through two points on the *curve* gives an average rate instead, so the two must not be confused.

Oxidation and reduction half-equations

$oxidation$:\text{Cu} \rightarrow \text{Cu}^{2+} + 2e^-· $reduction$:\text{Cu}^{2+} + 2e^- \rightarrow \text{Cu}$

Used to label a half-equation as oxidation or reduction by reading which side the electrons sit on. Electrons on the *product* side means they have been lost, so the species is oxidised; electrons on the *reactant* side means they have been gained, so the species is reduced. The number of electrons equals the size of the charge formed, so $\text{Mg} \rightarrow \text{Mg}^{2+} + 2e^-$ loses two and $\text{Cl}_2 + 2e^- \rightarrow 2\text{Cl}^-$ gains two.

KEY CONCEPTS

- **Collision theory**: Collision theory is the model that explains every rate factor. Reacting particles must *collide* before they can react. A collision leads to a reaction only if the particles have energy *greater than or equal to the activation energy*, E_a, the minimum energy needed to break bonds and start the reaction; such a collision is a *successful* collision. The rate depends on the *frequency of successful collisions* per unit time. Anything that raises either the frequency of collisions or the proportion of collisions reaching E_a speeds the reaction up.
- **How a catalyst increases the rate**: A catalyst provides an *alternative reaction pathway with a lower activation energy*. Because E_a is lower, a *greater proportion of the collisions already occurring* have enough energy to succeed, so the rate rises even though the particles' average energy is unchanged. A catalyst does *not* heat the mixture, add energy to the particles, or raise the concentration. Because it is regenerated it is chemically unchanged at the end, so a small amount catalyses a large amount of reaction, it can be recovered and reused, and it does not appear in the balanced equation. Manganese(IV) oxide catalysing the decomposition of hydrogen peroxide is the standard example.
- **Oxidation and reduction in terms of electrons**: The deeper Extended definition is written in electrons: *oxidation is the loss of electrons* and *reduction is the gain of electrons*. The mnemonic is *OIL RIG*: Oxidation Is Loss, Reduction Is Gain. Equivalently, oxidation is an *increase* in oxidation number and reduction a *decrease*. The two definitions agree, because a species that gains oxygen is really losing electrons to it. Electrons are simply the more fundamental bookkeeping, and they identify redox even where no oxygen is present.
- **Oxidation and reduction in terms of oxygen**: In terms of oxygen: *oxidation is the gain of oxygen* and *reduction is the loss of oxygen*. These reactions run through the extraction of metals. In a blast furnace the iron(III) oxide *loses* oxygen and so is reduced, while the carbon monoxide *gains* that oxygen and so is oxidised, both at once, which is what makes it redox. The reversed versions, "oxidation is the loss of oxygen" and "reduction is the gain of oxygen", are the standard distractors.
- **Redox is simultaneous oxidation and reduction**: *Redox* is built from *red*uction and *ox*idation, and the word carries the definition: a redox reaction is one involving *simultaneous* oxidation and

reduction. The two always happen together, so if one substance is oxidised another must be reduced. Neither half can occur alone, because the oxygen or the electrons lost by one species have to be gained by another.

- **Signs of a chemical change, and naming the reaction**: A chemical change is often accompanied by a colour change, a gas given off, a precipitate forming, or an energy change such as heat or light. These are *signs*, not the test, because a physical change can also transfer energy. Common reaction names worth recognising on sight: *thermal decomposition* breaks one compound into simpler substances using heat, as in $\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$; *neutralisation* is an acid reacting with a base; *combustion* is burning in oxygen; *precipitation* forms an insoluble solid from two solutions.
- **The five factors that change the rate**: The *rate of reaction* is how quickly reactants are used up, or products are made, per unit time. Five factors change it, each in a single direction: increasing the *concentration* of a solution increases the rate; increasing the *pressure* of a gas increases the rate; increasing the *surface area* of a solid, by using smaller pieces or a powder, increases the rate; increasing the *temperature* increases the rate; and adding a suitable *catalyst* increases the rate. A *catalyst* is a substance that increases the rate of a reaction and is *chemically unchanged at the end* of the reaction.
- **The new-substance test**: One question separates the two changes: *has a new substance been made?* A *physical change* alters only the state or appearance of a substance, forms no new substance, and can usually be reversed. Melting, boiling, freezing, dissolving and grinding are physical. A *chemical change*, meaning a chemical reaction, produces *at least one new substance* with different properties from the starting materials, and is usually difficult to reverse. Compare the products with the reactants: if the substances after the change are chemically different from those before, the change is chemical.
- **Why concentration, pressure and surface area increase the rate**: These three factors all work the same way, by raising collision *frequency* alone. A higher *concentration* packs more particles into the same volume, so collisions between the reacting particles happen more frequently. A higher gas *pressure* squeezes gas particles closer together, which raises the number of particles per unit volume in the same way. A larger *surface area*, from breaking a solid into smaller pieces, exposes more particles at the surface for the other reactant to hit. None of the three gives any particle more energy, and none changes E_a.
- **Why raising the temperature increases the rate**: Heating gives the particles more *kinetic energy*, so they move faster. This has *two* separate effects: collisions become *more frequent*, and a *greater proportion of collisions reach* E_a, so more of them succeed. Temperature is the only factor that raises the *energy* of collisions rather than just their frequency, which is why both effects must be quoted for full marks. Heating does *not* change the activation energy, which is a fixed property of the reaction, and does *not* push the particles closer together.

EXAM TIPS

TIP *Describe* and *explain* are marked differently. Where a question says describe the effect, naming the factor and its direction earns the mark: "increasing the temperature increases the rate". Where it says explain, that same sentence scores nothing on its own and you must reach for collision theory, reaching the words *frequency of collisions* and, for temperature only, *proportion of collisions with energy at or above* E_a. "More" is not an explanation.

TIP Redox questions are answered one species at a time. Pick the substance the question names, follow either its oxygen or its electrons from the left side of the equation to the right, and apply the definition. Then state what happened to the *other* species, because an answer that reports only one half is incomplete: describing the blast furnace as "reduction" alone misses the carbon monoxide being oxidised, which is exactly the half that makes it redox.

8 Chemistry of the environment

KEY FORMULAS

Formation of the two acid-rain gases

$$S + O_2 \rightarrow SO_2 \text{ and } N_2 + O_2 \rightarrow 2NO$$

Use the first whenever sulfur present as an impurity in a fossil fuel burns, giving the sulfur dioxide that causes acid rain. Use the second inside an engine, where the very high temperature supplies enough energy for the normally unreactive nitrogen of the air to react with oxygen. Both reactants in the second equation come from the *air*, never from the fuel.

The catalytic converter equation

$$2CO + 2NO \rightarrow 2CO_2 + N_2$$

Use for the reaction in a vehicle's exhaust that removes two harmful gases at once: the toxic carbon monoxide is oxidised to carbon dioxide, and the acid-rain gas nitrogen monoxide is reduced to harmless nitrogen. Nitrogen leaves as the molecule N_2, never as a lone atom N. The catalyst itself is not consumed, so it never appears in the equation.

KEY CONCEPTS

- **How greenhouse gases cause global warming**: The marks come from giving the sequence in the right order. Energy from the *Sun* passes through the atmosphere and is *absorbed by the Earth's surface*, warming it. The warmed Earth then *emits* energy back towards space. *Greenhouse gases absorb* some of this emitted energy. They then *re-emit* it *in all directions, including back towards the surface*, causing extra warming. More greenhouse gas traps and returns more of the outgoing energy, so the surface warms further.
- **Testing whether a sample of water is pure**: Purity is judged by a *physical* property, not a colour change: a pure substance has a fixed, sharp boiling point. Pure water boils at *exactly 100 °C* at standard atmospheric pressure and freezes at exactly 0 °C. Dissolving any substance in the water raises the boiling point *above* 100 °C and lowers the freezing point below 0 °C, so a sample boiling at 103 °C contains dissolved substances and is not pure.
- **The adverse effect of each pollutant**: Pairing the wrong effect to a gas is a standard way to lose marks. *Carbon monoxide* is *toxic*, reducing the blood's ability to carry oxygen. *Sulfur dioxide* and *oxides of nitrogen* cause *acid rain*, and the oxides of nitrogen also contribute to breathing problems. *Carbon dioxide* and *methane* are *greenhouse gases* causing global warming. *Particulates* cause respiratory problems. Acid rain damages buildings of limestone and marble, corrodes metals, harms trees, and lowers the pH of lakes and rivers.
- **The common air pollutants and where each one comes from**: State each source precisely. *Carbon dioxide*: complete combustion of carbon-containing fuels, and respiration. *Carbon monoxide*: *incomplete* combustion, where a fuel burns in a limited supply of oxygen. *Sulfur dioxide*: sulfur impurities in fossil fuels burning. *Oxides of nitrogen* (NO and NO_2): nitrogen and oxygen *from the air* reacting at the high temperature inside an engine. *Particulates*: tiny solid particles such as soot from incomplete combustion.
- **The composition of clean, dry air**: Clean, dry air is a *mixture* of almost constant composition by volume: about *78% nitrogen*, about *21% oxygen*, and about *1% other gases*, mainly the noble gas argon together with a small amount of carbon dioxide. Nitrogen and oxygen together account for about 99%, so everything else is the remaining 1%. The word *dry* matters because real air also holds a variable amount of water vapour, which the standard composition leaves out.
- **The four stages of domestic water treatment and the job of each**: Raw water is made safe by a sequence of steps, each doing one specific job. *Sedimentation*: the water stands in large tanks so heavier insoluble solids settle out under gravity. *Filtration*: the water passes through a bed of sand, trapping the remaining insoluble suspended solids. *Carbon*: the water passes over granular carbon, which removes substances causing unpleasant tastes and odours. *Chlorination*: chlorine is added, killing harmful microorganisms and making the water safe to drink.
- **The two chemical tests for the presence of water**: Two anhydrous solids test for water, and both colour changes must be known in the right direction. *Anhydrous copper(II) sulfate* is white and turns

blue when water is added. *Anhydrous cobalt(II) chloride* is blue and turns *pink* when water is added. *Anhydrous* means without water; each solid takes water into its structure to form the coloured hydrated compound. Both changes are positive tests for the *presence* of water.

EXAM TIPS

TIP The discrimination the exam tests most often. Sedimentation, filtration and carbon do *not* kill microorganisms, and chlorination does *not* remove solids. Where stages are labelled P, Q, R and S, never guess from position: match each stage to its job, and the microbe-killing stage is always the one where chlorine is added. Removing chlorination leaves water that looks perfectly clear yet is unsafe, because the microbes survive unseen.

TIP The single most reliable trap in this topic. Distractors offer "nitrogen from the fuel" by analogy with the sulfur impurity, but the nitrogen is drawn in with the *air*. Two conditions are being marked: the reactants are nitrogen *and* oxygen from the air, and the condition is the *high temperature* inside the engine. Quote both. The parallel trap swaps the carbon oxides: carbon *monoxide* comes from *incomplete* combustion, carbon *dioxide* from *complete* combustion.

TIP This is the most common error in the topic. The colour tests detect *water itself*, and salty water, sugary water and pure water all turn anhydrous copper(II) sulfate blue. They prove only that water is present. Purity is proved by boiling point alone. A sample can turn cobalt(II) chloride pink *and* boil at 104 °C, meaning it contains water but is not pure. Where a question asks which observation shows a liquid is *not* pure water, the answer is always the boiling point above 100 °C, never a colour change.

9 Coordination and response

KEY FORMULAS

Impulse speed

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Links the length of a neurone, the time an impulse takes to cross it, and the impulse's speed. Keep distance in metres and speed in metres per second so time comes out in seconds.

Time for an impulse to travel a neurone

$$\text{time} = \frac{\text{distance}}{\text{speed}}$$

The rearrangement used whenever a question gives a neurone's length and the impulse speed and asks how long the impulse takes to arrive.

KEY CONCEPTS

- **Negative feedback**: Homeostatic control works by *negative feedback*: when a factor moves away from its set point, a response is triggered that moves it back towards the set point. The general loop is set point, factor changes, change detected, corrective response, factor returns towards the set point. "Negative" means the response opposes the change, unlike positive feedback, which would amplify it.
- **The central nervous system and its role**: The *central nervous system* (CNS) is the brain and the spinal cord, the part of the nervous system where information is processed and coordinated. The *peripheral nervous system* is the nerves that carry impulses between the CNS and the rest of the body. Together the two parts detect a stimulus, pass it as an electrical impulse, and coordinate a response: *stimulus, receptor, sensory neurone, CNS, motor neurone, effector, response*.
- **The reflex arc sequence**: A *reflex arc* is the pathway an impulse follows during a reflex action: stimulus, receptor, sensory neurone, relay neurone (inside the CNS), motor neurone, effector, response, in that order. The relay neurone's fixed location inside the CNS, usually the spinal cord for a spinal reflex, is the fact most often tested.
- **The three neurones and the direction rule**: A *sensory neurone* carries impulses from a receptor to the CNS. A *relay neurone* lies entirely inside the CNS and connects a sensory neurone to a motor neurone. A *motor neurone* carries impulses from the CNS to an effector. Direction identifies each one: sensory neurones point inward to the CNS, motor neurones point outward to an effector, and the relay neurone never leaves the CNS.
- **What a hormone is**: A *hormone* is a chemical substance, produced by a gland, carried by the blood, that alters the activity of one or more specific target organs. The three load-bearing words are *gland*, *blood* and *target*; reproduce them exactly, since the tempting wrong set, neurone, nerve, effector, describes the nervous system instead.
- **What homeostasis is**: *Homeostasis* is the maintenance of a constant internal environment. The body holds conditions such as body temperature and blood glucose concentration close to a fixed set point even while the outside world changes. Do not confuse it with gas exchange, respiration or a tropism; only "maintenance of a constant internal environment" is homeostasis.

EXAM TIPS

TIP Where a question states an impulse is "X times slower" in one neurone than another, divide the faster speed by X to find the slower speed; do not multiply. "X times faster" is the reverse: multiply. Decide which phrase applies before touching the calculator.

TIP A hormone definition that omits any of *gland*, *blood* or *target* loses the mark tied to that word. State all three explicitly rather than paraphrasing "made somewhere and carried around the body".

10 Diseases and immunity

KEY CONCEPTS

- **Active immunity versus passive immunity**: *Active immunity* is protection produced when a person's own body makes antibodies and memory cells, either after an infection or after vaccination; it is long-lasting. *Passive immunity* is protection gained when ready-made antibodies are received from outside the body, for example across the placenta or in breast milk; it is immediate but short-lived, because no memory cells are made.
- **Antibiotic resistance: mutation, survival, reproduction**: A random change in a bacterium's DNA, a *mutation*, can by chance make that bacterium resistant to an antibiotic. When the antibiotic is used, non-resistant bacteria are killed but resistant ones survive; the survivors reproduce, passing on resistance, so a resistant population builds up. This is natural selection acting on bacteria.
- **Antigens and antibodies: the specificity principle**: Every pathogen carries *antigens*, molecules of a specific shape on its surface that the immune system recognises as foreign. Lymphocytes respond by producing *antibodies*, proteins whose shape is complementary to a particular antigen, so an antibody binds that antigen and no other. Antibodies made against one pathogen's antigens do not fit a different pathogen's antigens.
- **Direct versus indirect transmission: the body-to-body test**: *Direct transmission* is the pathogen passing straight from one body to another, with nothing carrying it in between, such as physical contact or blood-to-blood contact through a wound. *Indirect transmission* is the pathogen travelling via something in between: contaminated food or water, airborne droplets, a contaminated surface, or an animal vector. The decisive test: did the pathogen pass body-to-body, or did something carry it? If food, water, air or a surface was involved, the route is indirect, even if an infected person was the original source.
- **Four pathogen groups, and viruses as a special case**: The syllabus lists four groups of pathogen: *bacteria*, *viruses*, *fungi* and *protoctists*. A virus is not a living cell in its own right, yet it is still a pathogen because it causes disease; it cannot reproduce on its own and must enter a living host cell and use that cell's machinery to make copies of itself.
- **How vaccination works: the four-step sequence**: A vaccine contains a weakened, dead or inactivated form of a pathogen, or its antigens, which keep the same shape as on the active pathogen but cannot cause the full disease. Sequence: (1) the vaccine's antigens enter the body; (2) the antigens are recognised as foreign and stimulate lymphocytes to produce antibodies; (3) memory cells are also produced and remain in the body; (4) if the real pathogen enters later, memory cells trigger a fast, large production of antibodies that destroys it before it causes disease.
- **Pathogen and transmissible disease defined**: A *pathogen* is any organism, or agent such as a virus, that causes disease. A *transmissible disease* (also called communicable or infectious) is the illness a pathogen produces, which can be passed from one host to another. Keep the two separate: the pathogen is the organism, the transmissible disease is the illness it causes and that spreads between hosts.
- **The body's four general defences**: *Mechanical barriers*: the skin forms a physical barrier; hairs and mucus in the nose trap particles; cilia in the airways sweep trapped pathogens away in mucus. *Chemical defence*: stomach acid kills many pathogens in swallowed food and mucus. *Clotting*: when the skin is cut, blood clots to seal the wound and limit further pathogen entry. *Cellular defence*: phagocytes engulf and digest pathogens, a process called phagocytosis.

EXAM TIPS

TIP Antibiotics are drugs that kill bacteria or stop them reproducing; a virus is not a living cell and reproduces inside a host cell's own machinery, so an antibiotic has nothing bacterial to act on. Taking antibiotics for a viral infection such as flu does not help the patient and increases the selection pressure that drives antibiotic resistance elsewhere.

TIP The white blood cell that engulfs and digests pathogens is the *phagocyte*, in the process of *phagocytosis*. Once antibodies have bound to and marked a pathogen, and clumped several pathogens together, phagocytes engulf it more readily. Red blood cells carry oxygen, platelets are involved in clotting, and neither engulfs pathogens.

11 Drugs

KEY CONCEPTS

- **A drug is defined by mechanism, not by harm**: The definition of a drug says nothing about whether it is helpful or harmful. A statin, an antibiotic and a painkiller are all drugs because they modify chemical reactions in the body; a poison is a drug for the same reason. A definition that restricts "drug" to harmful substances only is always the wrong answer.
- **Antibiotic resistance defined**: *Antibiotic resistance* means that some bacteria are able to survive and grow even when an antibiotic that once killed them is present. Resistance is a property of the bacteria, not a weakening of the drug: the antibiotic itself has not changed.
- **Antibiotics kill bacteria but do not affect viruses**: Antibiotics work by attacking structures and processes a bacterium carries out for itself, such as building a cell wall or making proteins on its own ribosomes. A virus has no cell wall, no ribosomes and no metabolism of its own, so there is nothing for an antibiotic to attack. An antibiotic therefore has no effect on a viral illness such as a cold or flu.
- **Antibiotics treat bacterial infections**: An *antibiotic* is a drug used to treat bacterial infections: it either kills bacteria or stops them multiplying, which allows the body's own defences to clear the infection. Penicillin is the standard named example. An antibiotic is not a painkiller, not an antiviral drug and not a food supplement.
- **How resistance develops: the natural-selection chain**: Resistance develops in four linked steps. Variation already exists in a bacterial population, so a few individuals happen to survive the antibiotic. The antibiotic kills the non-resistant majority, leaving the resistant few. The survivors reproduce, and because bacteria divide rapidly they multiply fast. Over time the population becomes mostly resistant, so the antibiotic no longer works well against it.
- **The definition of a drug**: A *drug* is a substance taken into the body that modifies or affects chemical reactions in the body. "Taken into the body" excludes substances the body makes for itself, such as hormones. "Modifies or affects chemical reactions" excludes foods, whose role is to supply energy or building material rather than to change a reaction.

EXAM TIPS

TIP The central measure against resistance is to prescribe an antibiotic only once a bacterial infection is confirmed, never for a viral illness. Every unnecessary course exposes the body's own bacteria to the drug for no benefit, giving resistant survivors another chance to be selected, so avoiding needless prescriptions directly reduces that selection pressure.

12 Electricity and magnetism

KEY FORMULAS

Combined resistance in parallel

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$$

Used to replace resistors connected on separate branches between the same two points by one resistance. The equation gives the *reciprocal*, so invert the sum at the end. The answer must come out smaller than the smallest branch, which is the check that the inversion was done.

Combined resistance in series

$$R_{\text{total}} = R_1 + R_2 + \dots$$

Used to replace resistors connected one after another in a single loop by one resistance. The total is always larger than the largest individual resistor.

Current, charge and time

$$Q = It$$

Used to find the charge Q in coulombs that flows when a current I in amperes passes for a time t in seconds. Rearranges to $I = \frac{Q}{t}$, which is the definition of current as the rate of flow of charge. Convert milliamperes to amperes and minutes to seconds before substituting.

Electrical energy transferred

$$E = IVt$$

Used to find the electrical energy E transferred by a component, in joules when the time t is in seconds. Equivalent to $E = Pt$ once the power is known.

Electrical power

$$P = IV$$

Used to find the power P in watts transferred by a component carrying a current I in amperes across a potential difference V in volts. Rearranges to $I = \frac{P}{V}$, the form used to find an appliance's normal operating current.

Heating effect of a current

$$P = I^2R$$

Used to find the power dissipated as heat in a conductor of resistance R carrying a current I. It is why an overloaded or coiled cable can overheat and start a fire, and why electricity is transmitted at a low current. Note the current is *squared*, so doubling the current quadruples the heating.

Resistance

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

Used to find the resistance R in ohms (Ω) of a component or of a whole circuit from the potential difference V across it in volts and the current I through it in amperes. Rearranges to $V = IR$ and $I = \frac{V}{R}$. A larger resistance means a smaller current for the same p.d.

The ideal transformer power equation

$$I_p V_p = I_s V_s$$

Used for an ideal (100% efficient) transformer, where power in equals power out. Stepping the voltage *up* steps the current *down* by the same factor, and vice versa. Use it whenever a transformer question gives three of the four current and voltage quantities.

The transformer turns-ratio equation

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Used to find any one of the primary voltage, secondary voltage, primary turns or secondary turns when the other three are known. Rearranges to $V_s = V_p \times \frac{N_s}{N_p}$. Check the answer against the type: a *step-down* transformer has fewer secondary turns and must give $V_s < V_p$, while a *step-up* transformer must give $V_s > V_p$.

KEY CONCEPTS

- **Direct current and alternating current**: *Direct current* (d.c.) flows in one direction only and keeps that direction constant with time; a cell supplies d.c. *Alternating current* (a.c.) repeatedly reverses direction many times each second; the mains supplies a.c. Current is measured by an *ammeter connected in series*, because the ammeter must carry the very current it measures.
- **e.m.f. and potential difference defined**: Both are measured in *volts* (V) and both are energy per unit charge. The *electromotive force* (e.m.f.) of a source is the electrical work done by the source in driving unit charge *around a complete circuit*. The *potential difference* (p.d.) across a component is the electrical work done in moving unit charge *between the two ends of that component*. A voltmeter measures p.d. and is connected *in parallel* across the component.
- **Electromagnetic induction and the size of the induced e.m.f.**: When the magnetic field through a coil *changes*, an e.m.f. is induced across the coil; if the coil forms a complete circuit, that e.m.f. drives an induced current. The change can come from moving a magnet or from moving the coil. The induced e.m.f. is larger for *faster* relative movement, a *stronger* magnetic field, and *more turns* on the coil. A stationary magnet gives an unchanging field and induces nothing.
- **How the a.c. generator works and the job of the slip rings**: A coil rotates in a magnetic field, and its sides cut field lines and induce an e.m.f. Each side reverses its direction of motion through the field every half turn, so the e.m.f. *alternates*. *Slip rings* rotate with the coil and fixed *carbon brushes* press against them, keeping the coil connected without the wires twisting. Each ring stays joined to the same coil end throughout, so the connection is never reversed and a genuine alternating output is delivered.
- **The d.c. motor and the split-ring commutator**: A current-carrying coil sits in a magnetic field. Its two long sides carry current in *opposite* directions, so Fleming's left-hand rule gives forces in opposite directions on them, forming a *couple* that turns the coil. A *split-ring commutator* with brushes *reverses the current in the coil every half turn*, at the moment the sides swap over relative to the poles. That keeps the turning effect acting the same way round, so the coil rotates continuously instead of oscillating.
- **The field of a current and the right-hand grip rule**: A current produces a magnetic field. Around a *long straight wire* the field lines are *concentric circles* centred on the wire, in planes perpendicular to it. A *solenoid* produces a field like a bar magnet, with one end an N pole and the other an S pole. The *right-hand grip rule* gives the direction: grip the wire with the right hand, thumb along the conventional current, and the curled fingers show the field. Reversing the current reverses the field; increasing the current strengthens it.
- **The law of electric charges and charging by friction**: There are two kinds of charge, positive and negative, measured in *coulombs* (C). *Like charges repel; unlike charges attract.* Charging by friction

transfers *electrons* only: the material that gains electrons becomes negatively charged and the material that loses them becomes positively charged. Protons never transfer, because electrons are the mobile outer particles.

- **The law of magnetic poles and the test for a magnet**: Every magnet has a north (N) and a south (S) pole. *Like poles repel* (N with N, or S with S) and *unlike poles attract* (N with S). Attraction alone never proves that a bar is a magnet, because a magnet also attracts unmagnetised magnetic materials such as iron, steel, nickel and cobalt. Only *repulsion* is decisive, because only another magnet is pushed away when presented pole-to-like-pole.
- **The motor effect and Fleming's left-hand rule**: A current-carrying conductor in a magnetic field experiences a force, provided the current is not parallel to the field. This is the *motor effect*; if the current is exactly parallel to the field there is no force. *Fleming's left-hand rule* gives the direction: hold the thumb and first two fingers of the *left* hand mutually at right angles, with the *F*irst finger along the *F*ield (N to S), the se*C*ond finger along the *C*urrent (conventional), and the thu*M*b then points along the *M*otion, which is the force.
- **The parallel rules**: A parallel circuit has branches between the same two points, giving more than one path for the current. Every branch has the *same p.d., equal to the supply*, so a branch p.d. is never a share of the supply. The *branch currents add up to the total current* from the source, $I = I_1 + I_2 + \ldots$. The combined resistance is *less than the smallest branch*.
- **The series rules**: A series circuit is a single loop with only one path for the current. The *current is the same everywhere* in the loop. The *p.d.s across the components add up to the e.m.f.* of the source, which follows from conservation of energy. *Resistances add.* A break anywhere stops the current everywhere.
- **Where the ammeter and the voltmeter go**: An *ammeter* is connected *in series* with the component, because it must carry the same current that it measures. A *voltmeter* is connected *in parallel* across the component, because it must sit across the two points whose p.d. it measures. Swapping the two would make each meter read the wrong quantity and disturb the circuit.

EXAM TIPS

TIP Mixing the two energy systems is the commonest way to lose these marks. If a question asks for energy in *joules*, put the power in watts and the time in seconds. If it asks for a bill in *kilowatt-hours*, put the power in kilowatts and the time in hours. Kilowatts and minutes are the two conversions most often forgotten.

TIP The most frequently examined parallel fact is that each branch receives the *full supply p.d.*, not a fraction of it, however many branches there are and whatever their resistances. Two unequal resistors in parallel across a 12 V supply therefore have 12 V across each. Apply $I = \dfrac{V}{R}$ to each branch separately with that same p.d. to find how the current divides; the branch of smaller resistance carries the larger current.

13 Electrochemistry

KEY FORMULAS

Cathode half-equation for copper(II) ions

$$Cu^{2+} + 2e^- \rightarrow Cu$$

Used whenever copper is deposited at the cathode, from copper(II) sulfate or any copper salt. Reduction, so the electrons go on the left; the $2+$ charge takes two electrons and the charges balance to zero.

Cathode half-equation for hydrogen ions

$$2H^+ + 2e^- \rightarrow H_2$$

Used at the cathode of any aqueous solution whose metal is more reactive than hydrogen, such as concentrated sodium chloride or dilute sulfuric acid. Hydrogen gas is diatomic, so two ions and two electrons are needed to build one H_2 molecule.

Electrons in a cathode half-equation

$$M^{n+} + ne^- \rightarrow M$$

The general cathode reduction, used to build any half-equation from the ion's charge alone. The number of electrons equals the size of the positive charge: Ag^+ takes one, Zn^{2+} takes two, Al^{3+} takes three.

KEY CONCEPTS

- **Advantages and disadvantages of fuel cells**: *Advantages*: the only product at the point of use is water, so no carbon dioxide and no oxides of nitrogen are released; and the conversion of chemical energy to electrical energy is efficient, with few moving parts to wear out. *Disadvantages*: most hydrogen is currently manufactured from *fossil fuels* by reacting natural gas with steam, which releases carbon dioxide; and hydrogen is hard to store and transport, needing very high pressure or very low temperature and so heavy, expensive tanks.
- **Copper(II) sulfate: inert electrodes against copper electrodes**: With *inert* electrodes (carbon or platinum), copper is deposited at the cathode and oxygen is released at the anode, and the blue colour *fades* because Cu^{2+} ions are removed and nothing replaces them. With *copper* electrodes the cathode still gains copper, but the anode itself dissolves as Cu^{2+} ions, so the blue colour stays *constant* and the anode loses exactly the mass the cathode gains. This is the basis of copper purification and electroplating.
- **Electron transfer at the electrodes**: At the *cathode*, positive cations gain electrons, which is *reduction*. At the *anode*, negative anions lose electrons, which is *oxidation*. Two mnemonics fix all four facts: *OIL RIG* (Oxidation Is Loss, Reduction Is Gain of electrons) and *AN OX / RED CAT* (oxidation at the anode, reduction at the cathode).
- **Preferential discharge at an inert anode**: At an inert anode the non-metal anion competes with OH^-. If a *concentrated halide* (Cl^-, Br^-, I^-) is present, the halogen is discharged. Otherwise, meaning a *dilute* halide or an ion such as sulfate SO_4^{2-} or nitrate NO_3^-, hydroxide is discharged and oxygen is released. Two things decide the product: which ion is present and at what concentration.
- **Preferential discharge at the cathode of an aqueous solution**: An aqueous solution also contains H^+ and OH^- from the water, so two cations compete at the cathode. If the metal is *more reactive than hydrogen* (K, Na, Ca, Mg, Al, Zn, Fe), hydrogen is discharged and its gas bubbles off while the metal ion stays in solution. If the metal is *less reactive than hydrogen* (Cu, Ag), the metal is discharged and deposited.
- **Products of a molten binary compound**: A *binary* compound contains two elements, a metal and a non-metal. With no water present the rule is clean: the *metal* is deposited at the cathode and the *non-metal* is released at the anode. Molten lead(II) bromide gives lead and orange-brown bromine vapour; molten sodium chloride gives sodium and greenish-yellow chlorine. The products change; the pattern does not.

- **The hydrogen-oxygen fuel cell**: A *hydrogen-oxygen fuel cell* converts the chemical energy of hydrogen and oxygen *directly* into electrical energy, without first burning the gases to make heat. Hydrogen is fed to one electrode and oxygen or air to the other, and the electrons flowing round the external circuit are the electricity. The only chemical product is *water*. Unlike a battery it stores no reactants of its own, so it never goes flat: it runs for as long as the gases keep flowing in.
- **The parts of an electrolytic cell**: The *anode* is the positive electrode, joined to the positive terminal of the power supply. The *cathode* is the negative electrode, joined to the negative terminal. The *electrolyte* is the molten or aqueous ionic compound that is decomposed; it is not an electrode. Positive *cat*ions migrate to the *cat*hode and negative *an*ions migrate to the *an*ode, because opposite charges attract.
- **What electrolysis is**: *Electrolysis* is the decomposition of an ionic compound, when molten or in aqueous solution, by the passage of an electric current. Three words carry the marks. *Decomposition*: the compound is broken down into simpler substances, a chemical change and not merely dissolving. *Ionic compound*: the substance must be made of ions, because the ions carry the charge and react at the electrodes. *Molten or aqueous*: the ions must be free to move.

EXAM TIPS

TIP Where a question asks how the current is carried, answering only "by electrons" scores nothing, because the mark is for spotting that the carrier changes at the electrodes. Charge is carried by *electrons* in the external metal wires and by *migrating ions* inside the electrolyte. State both halves.

14 Enzymes

KEY CONCEPTS

- **Enzymes are protein catalysts that are not used up**: An *enzyme* is a protein that acts as a *biological catalyst*: it speeds up a chemical reaction taking place inside a living organism and is not permanently changed or used up by that reaction, so the same molecule catalyses reaction after reaction. Enzymes catalyse the *metabolic reactions* that together make up an organism's *metabolism*, which is why this small chapter underpins digestion, respiration and every other process examined elsewhere in the syllabus.
- **Optimum pH and the fall away from it**: Every enzyme has an *optimum pH* at which its activity is greatest, and this is not always pH 7: the stomach protease works best around pH 2, matching its acidic surroundings. Moving the pH away from the optimum in either direction disrupts the bonds holding the active site's precise shape, so the substrate fits less well, fewer enzyme-substrate complexes form, and activity falls; far enough from the optimum the enzyme denatures completely.
- **Specificity: one active-site shape, one substrate**: Because an active site has one definite shape, an enzyme normally binds only a substrate whose shape is complementary to it, a property called *specificity*. A wrongly shaped molecule cannot form an enzyme-substrate complex, so no reaction occurs however suitable the temperature and pH. This is why a cell needs thousands of different enzymes rather than a handful of general-purpose ones: each distinct reaction, even on a single molecule such as glucose, needs its own specific enzyme.
- **Temperature has two opposite effects either side of the optimum**: Below the *optimum temperature*, raising the temperature gives enzyme and substrate molecules more kinetic energy, so they move faster and collide more frequently; more frequent successful collisions form more enzyme-substrate complexes per second, so the rate rises. Above the optimum, the extra heat makes the enzyme vibrate so violently that the bonds holding the active site's shape break: the enzyme is *denatured*, the substrate no longer fits, and the rate falls sharply towards zero.
- **The active site, substrate and enzyme-substrate complex**: The *substrate* is the molecule an enzyme acts on; the *product* is what the reaction forms. Only a small region of the enzyme, the *active site*, does the catalysis: its shape is *complementary* to the substrate, so the two bind to form an *enzyme-substrate complex*. Once the reaction is complete the product no longer fits the active site and is released, leaving the enzyme unchanged and ready to bind again. This is the *lock-and-key model*: the active site is the lock, the substrate is the key.

EXAM TIPS

TIP A denatured enzyme has an active site whose shape has changed irreversibly, so warming or cooling it back does not restore activity. An enzyme merely slowed by low temperature is unchanged and recovers fully once warmed. Never describe heat as "killing" an enzyme: enzymes are molecules, not organisms, and the correct exam term is always *denatured*.

TIP The *optimum temperature* is the single temperature at which an enzyme's activity peaks, not the highest temperature at which the enzyme shows any activity at all. Activity can still occur, at a reduced rate, above the optimum until denaturation is complete, so "optimum" and "highest temperature survived" are two different ideas that a careful answer keeps separate.

15 Experimental techniques and chemical analysis

KEY FORMULAS

Moles from concentration and a volume in cubic centimetres

$$n = c \times \frac{V}{1000}$$

Used to convert a burette or pipette volume into moles, where c is the concentration in mol/dm^3 and V is the volume in cm^3. The division by 1000 converts cm^3 into dm^3, because concentration is measured per dm^3. Rearranges to $c = \frac{n}{V}$ with V in dm^3.

The R_f value

$$R_f = \frac{\text{distance moved by the substance}}{\text{distance moved by the solvent}}$$

Used to identify a substance from a chromatogram, since the same substance gives the same R_f in the same solvent. Both distances are measured from the *baseline*, and the substance distance is measured to the *centre* of its spot. The value has no units, because the units of the two distances cancel, and always lies between 0 and 1.

Titre from the two burette readings

$$\text{titre} = \text{final burette reading} - \text{initial burette reading}$$

Used to find the volume actually run in from the burette, which is never read straight off the scale because the burette rarely starts at zero. Both readings are taken to $0.05\ \text{cm}^3$. Average only the *concordant* titres, those agreeing within about $0.10\ \text{cm}^3$, and discard any anomalous value first.

KEY CONCEPTS

- **Choosing a separation technique**: The technique follows from what is being separated. *Filtration* removes an insoluble solid from a liquid, leaving the *residue* in the paper and the *filtrate* passing through. *Crystallisation* obtains a pure soluble solid from its solution. *Simple distillation* obtains the solvent from a solution, such as pure water from sea water. *Fractional distillation* separates miscible liquids with close boiling points. A *separating funnel* separates immiscible liquids, which settle into layers.
- **Choosing the apparatus that measures a volume**: Each instrument is chosen for the *kind* of volume needed. A *pipette* delivers one fixed accurate volume, such as $25.0\ \text{cm}^3$. A *burette* delivers a variable volume from a tap, read to the nearest $0.05\ \text{cm}^3$, so it is used whenever the volume must be both adjustable and accurate. A *measuring cylinder* reads only to about $1\ \text{cm}^3$ and is used when the exact volume does not matter. A *gas syringe* measures the volume of a gas given off in a reaction.
- **Flame tests**: A flame test identifies certain metal cations by the colour they give to a Bunsen flame; a *clean* wire is dipped in the sample and held in the edge of a blue flame. *Lithium* red, *sodium* yellow, *potassium* lilac, *copper(II)* blue-green, *calcium* orange-red.
- **How paper chromatography separates a mixture**: The mixture is spotted onto a *pencil* baseline near the bottom of the paper, and the solvent in the tank must start *below* that baseline, or the spots would dissolve straight into it instead of travelling. As the solvent rises it carries each substance a different distance, because each dissolves in the solvent to a different extent and is attracted to the paper to a different extent. *One spot means a pure substance; several spots mean a mixture.*
- **Purity from melting and boiling points**: A *pure substance* melts at one sharp fixed temperature and boils at one sharp fixed temperature, rather than over a range. An impurity *lowers and broadens* the melting point, so an impure solid melts over a range instead of at one value, and *raises* the boiling point above the pure value. So sea water boiling at $102\ ^\circ\text{C}$ is not pure water, and the sample with the narrowest melting range is the purest.
- **Tests for anions**: *Carbonate* CO_3^{2-}: add dilute acid, giving effervescence, and the gas turns limewater milky. *Chloride* Cl^-, *bromide* Br^- and *iodide* I^-: add dilute nitric acid then aqueous silver

nitrate, giving a *white*, *cream* and *yellow* precipitate respectively. *Sulfate* $\mathrm{SO_4^{2-}}$: add dilute nitric acid then aqueous barium nitrate, giving a white precipitate. *Nitrate* $\mathrm{NO_3^-}$: add aqueous sodium hydroxide and aluminium foil and warm, giving ammonia, which turns damp red litmus blue.

- **Tests for aqueous cations with sodium hydroxide and ammonia**: Add each reagent *drop by drop, then in excess*; the identity follows from the precipitate colour and whether it dissolves in excess. With aqueous sodium hydroxide: $\mathrm{Cu^{2+}}$ light blue, insoluble in excess; $\mathrm{Fe^{2+}}$ green, insoluble; $\mathrm{Fe^{3+}}$ red-brown, insoluble; $\mathrm{Zn^{2+}}$ white, *dissolves* in excess; $\mathrm{Al^{3+}}$ white, *dissolves* in excess; $\mathrm{Ca^{2+}}$ white, insoluble. With aqueous ammonia the results match except that $\mathrm{Cu^{2+}}$ dissolves in excess to a deep blue solution, $\mathrm{Zn^{2+}}$ dissolves, $\mathrm{Al^{3+}}$ does *not*, and $\mathrm{Ca^{2+}}$ gives no precipitate.
- **Tests for the five gases**: *Hydrogen*: a *lighted* splint gives a squeaky pop. *Oxygen*: a *glowing* splint relights. *Carbon dioxide*: bubbled through limewater, it turns the limewater milky. *Chlorine*: turns damp litmus paper red and then bleaches it white. *Ammonia*: turns damp *red* litmus paper blue, because it is alkaline.
- **The acid-base titration method**: The *alkali* is measured into the conical flask with a pipette, one fixed accurate volume, and the indicator is added to it. The *acid* is run in from the burette, swirling continuously so it mixes evenly as it enters. A white tile under the flask makes the colour change easy to see. With phenolphthalein the *end-point* is pink to colourless, the point at which the indicator just changes colour and the two solutions have exactly reacted.

EXAM TIPS

TIP The classic trap in gas tests is swapping the two splints, which loses the mark even when the right gas is named. The *glowing* splint *relights* for oxygen; the *lighted* splint gives the *squeaky pop* for hydrogen. State the splint and its result together, since the examiner marks the pair.

TIP The solvent carries the substance, so the substance can never travel further than the solvent front: the numerator is always the smaller distance. Any answer above 1 means the two distances have been divided the wrong way round, so invert it. Convert both distances to the *same unit* before dividing, since a spot is often quoted in mm while the solvent front is quoted in cm.

16 Gas exchange in humans

KEY FORMULAS

Decrease in oxygen percentage

$$\text{Decrease in } O_2\% = \text{Inspired } O_2\% - \text{Expired } O_2\%$$

Used to calculate how far the oxygen percentage falls between inspired and expired air; inspired 21% minus expired 16% gives a fall of 5%.

Increase in carbon dioxide percentage

$$\text{Increase in } CO_2\% = \text{Expired } CO_2\% - \text{Inspired } CO_2\%$$

Used to calculate the rise in carbon dioxide percentage between inspired and expired air; expired 4.00% minus inspired 0.04% gives a rise of 3.96%.

Total volume of air moved per minute

$$V = \text{breathing rate} \times \text{volume per breath}$$

Used to find the total volume of air ventilated each minute; multiply the number of breaths per minute by the volume of air taken in with each breath.

KEY CONCEPTS

- **Breathing, gas exchange and respiration are three different processes**: *Breathing* (ventilation) is the mechanical movement of air into and out of the lungs. *Gas exchange* is the diffusion of oxygen and carbon dioxide across the alveolar surface. *Respiration* is the chemical release of energy from nutrient molecules inside every living cell. The three are separate processes and must not be treated as synonyms.
- **Protecting the airways: goblet cells and ciliated cells**: *Goblet cells* in the lining of the trachea and bronchi secrete sticky *mucus*, which traps dust, particles and pathogens. *Ciliated cells* alongside them carry beating *cilia* that sweep the trapped mucus upwards toward the throat, where it is swallowed or coughed out. This "mucus escalator" protects the delicate alveoli from damage and infection.
- **The pathway of air from mouth to alveoli**: Air passes from the nose or mouth to the *larynx* (the voice box, at the top of the windpipe), then the *trachea* (the single wide windpipe, held open by rings of cartilage), which divides into two *bronchi* (one per lung), which branch into narrower *bronchioles*, ending at the *alveoli*, the tiny thin-walled air sacs where gas exchange happens.
- **The pump: ribs, intercostal muscles and diaphragm**: The *ribs* form a protective cage around the lungs. The *intercostal muscles* are the thin muscles between neighbouring ribs that move the rib cage during breathing. The *diaphragm* is the wide, dome-shaped sheet of muscle across the base of the chest cavity; it flattens on contraction to help draw air in.

EXAM TIPS

TIP Nitrogen stays at about 78% in both inspired and expired air, because it is neither used nor produced by the body. Where a question asks which gas does *not* change, nitrogen is the answer. Do not be misled by the small absolute size of the carbon dioxide change: 0.04% to about 4% is roughly a hundredfold *relative* rise, even though the percentage-point change looks small next to oxygen's.

TIP On a labelled diagram, "the single central tube at the top, before it divides" is always the *trachea*; "one of the two tubes after the division, entering a lung" is a *bronchus*; "a fine branch inside the lung" is a *bronchiole*; and "the dome-shaped sheet of muscle at the base of the chest" is the *diaphragm*. Confusing the larynx (the voice box, singular, at the very top) with a bronchus is the most common slip.

17 Human influences on ecosystems

KEY CONCEPTS

- **Biodiversity counts species, not individuals or mass**: *Biodiversity* is the number of different species that live in an area. It is not population size, the number of individual organisms, and not biomass, their total mass. A field of ten thousand wheat plants has a huge population but a biodiversity of one.
- **Endangered and extinct defined**: A species is *endangered* when its numbers have fallen so low that it is at risk of dying out completely. A species is *extinct* when no individuals remain anywhere. The distinction matters: an endangered species can still be raised by conservation action; an extinct species cannot.
- **Six reasons for endangerment or extinction**: The syllabus lists six reasons an organism becomes endangered or extinct: climate change, habitat destruction, hunting, overharvesting, pollution, and introduced species. Identify which one, or more than one, a scenario shows by matching its exact wording rather than a general impression.
- **The five undesirable effects of deforestation**: Clearing large areas of forest causes reduced biodiversity, extinction of species that cannot survive elsewhere, loss of soil through erosion, increased flooding, and an increase in atmospheric carbon dioxide. At Extended level each effect must be *explained* through its mechanism, not merely listed.
- **The four permitted conservation methods**: Conservation is limited to four syllabus methods: monitoring and protecting species and habitats; education, to change human behaviour towards a species; captive breeding programmes, to raise numbers before release to the wild; and seed banks, storing the seeds of rare plants so the species can be regrown later.
- **The three-part definition of an ecosystem**: An *ecosystem* is a unit containing the community of organisms and their environment, interacting together. The *community* is every population of organism present; the *environment* is the non-living surroundings (water, air, soil, minerals, sunlight); *interacting* means energy and nutrients pass between the two. Omitting either the non-living half or the interaction reduces the answer to a mere list.
- **Three reasons for habitat destruction**: Humans destroy habitats under three headings: increased area for housing, crop production and livestock production; extraction of natural resources such as mining, quarrying and drilling; and freshwater and marine pollution from untreated sewage and chemical waste. An option that protects or restores a habitat is never a reason for destroying one.

EXAM TIPS

TIP An "explain" instruction at Extended level rewards the causal chain, not the bare fact. Convert every stated effect into "X happens *because* Y": for example "soil is lost because roots no longer bind it and rain washes the exposed soil away" scores, while "soil is lost" alone often does not.

18 Human nutrition

KEY FORMULAS

Comparing nutrient percentages at equal total mass

$$\text{if total mass}_1 = \text{total mass}_2\text{, then } \%_1 > \%_2 \iff \text{mass}_1 > \text{mass}_2$$

Used when two portions of equal total mass are compared; because the denominator is the same for both, the portion with the higher percentage by mass always contains the greater actual mass of that nutrient.

Percentage of a nutrient by mass

$$\text{percentage by mass} = \frac{\text{mass of nutrient}}{\text{total mass}} \times 100$$

Used whenever a question gives the mass of one nutrient in a stated portion mass and asks for its percentage by mass; divide the nutrient's mass by the total mass and multiply by 100.

KEY CONCEPTS

- **Chemical digestion: large insoluble to small soluble**: *Chemical digestion* is the breakdown of large, insoluble molecules into small, soluble molecules, carried out by enzymes that break the chemical bonds inside the large food molecules. Starch becomes sugar, protein becomes amino acids, fat becomes fatty acids and glycerol.
- **Physical digestion: smaller pieces, no chemical change**: *Physical (mechanical) digestion* is the breakdown of food into smaller pieces without any chemical change to the food molecules. Chewing and churning change only the size of the pieces; every starch, protein or fat molecule inside is still the same molecule afterwards.
- **The alimentary canal in order**: Food travels, in order, through the *mouth* (chewed, mixed with saliva), the *oesophagus* (a muscular tube pushing food to the stomach), the *stomach* (a J-shaped muscular sac that churns food with acid and enzymes), the *small intestine* (a long, coiled tube where digestion is completed and nutrients are absorbed), and the *large intestine* (absorbs water; stores undigested food before it is egested through the anus).
- **The four associated organs**: *Salivary glands* secrete saliva, containing amylase, into the mouth. The *liver* makes bile. The *gall bladder* stores and concentrates bile, releasing it into the small intestine. The *pancreas* secretes digestive enzymes and an alkaline fluid into the small intestine. None of these organs is part of the tube food passes through.
- **The seven components of a balanced diet**: *Carbohydrates* supply energy; *fats and oils* are a concentrated energy store and insulation; *protein* is for growth and repair; *vitamins* (for example C and D) are needed in small amounts for health; *mineral ions* (for example calcium for bones and iron for haemoglobin) support specific functions; *fibre* gives bulk that keeps food moving through the gut; *water* is the solvent for reactions and transport.
- **The test that separates physical from chemical digestion**: Ask whether a molecule has been changed into a *different* molecule. If no, the change is physical (only the size of the pieces changed); if yes, the change is chemical (bonds inside the molecule were broken). This single test resolves almost every "which type of digestion is this" question.
- **What a balanced diet means**: A *balanced diet* contains all the nutrient types the body needs (carbohydrates, fats and oils, proteins, vitamins, mineral ions, fibre and water), in amounts and proportions correct for that individual. Both parts of the definition must be present, every nutrient type and quantities suited to the person; a diet is not balanced merely because it is plentiful or because it follows one fixed recipe.

EXAM TIPS

TIP The definition of chemical digestion turns on two properties changing together: size (large to small) and solubility (insoluble to soluble). A molecule could in principle shrink without becoming soluble, so both properties, not just one, must be stated to pin down what chemical digestion produces.

TIP The *liver* makes bile but no enzymes; the *pancreas* makes enzymes (and an alkaline fluid) but no bile; the *gall bladder* makes nothing at all, it only stores and concentrates the bile the liver has already made. Confusing these three costs marks on almost every paper that tests this chapter.

TIP A question about a nutrient asks for either its *dietary source* (where it comes from) or its *importance* (what the body uses it for), and sometimes both. Answering the wrong half, or only one half when two are asked for, is the commonest way to lose these marks.

19 Inheritance

KEY CONCEPTS

- **Chromosome, gene and allele: the three nested terms**: A *chromosome* is a length of DNA, found in the nucleus, that carries genetic information. A *gene* is a length of DNA that codes for a particular protein; a single chromosome carries many genes. An *allele* is an alternative form of a gene, for example a red-flower allele and a white-flower allele of the same flower-colour gene. The relationship runs from largest to smallest: chromosome, then many genes, then each gene's alleles.
- **Genotype versus phenotype**: *Genotype* is the genetic make-up of an organism, written as its alleles, for example *Tt*. *Phenotype* is the observable features of an organism, for example *tall*. A quick check: the genotype uses letters; the phenotype uses a description you could see or measure.
- **Haploid and diploid: the halving-and-doubling rule**: A *diploid* nucleus contains two sets of chromosomes, arranged in matching pairs; body cells are diploid, and a human body cell has 46 chromosomes in 23 pairs. A *haploid* nucleus contains a single set, with no pairs; gametes are haploid, with 23 chromosomes in a human. The rule connecting them is fixed: the haploid number is half the diploid number, so halve a body-cell number to find a gamete's, or double a gamete's number to find a body cell's.
- **Meiosis: products and role**: *Meiosis* is the reduction division that produces gametes. From one diploid parent cell it makes four daughter nuclei, each haploid (half the parent's chromosome number) and each genetically different from the others. Halving the chromosome number means fertilisation, which fuses two gametes, restores the full diploid number in the zygote.
- **Mitosis: products and role**: *Mitosis* is nuclear division producing two daughter nuclei that are genetically identical to each other and to the parent nucleus, keeping the parent's chromosome number. It is the division used for growth, for repair of damaged tissue, and for replacing worn-out cells.
- **Sister chromatids: replication without a change in chromosome count**: Before a cell divides, by either mitosis or meiosis, each chromosome is replicated to form two identical sister chromatids joined at a centromere. Replication copies the DNA but does not change the chromosome *count*: a chromosome with two chromatids still counts as one chromosome. Only when the chromatids separate, during division, does the chromosome number of each new cell become fixed.
- **What inheritance means**: *Inheritance* is the transmission of genetic information from one generation to the next. Monohybrid inheritance is the inheritance of a single characteristic controlled by one gene, and almost every mark in it depends on using the vocabulary below exactly rather than approximately.

EXAM TIPS

TIP Gene and allele are the most confused pair of terms in this chapter. Every organism has the flower-colour gene; the red-flower and white-flower forms are its alleles. If a question asks for the alternative *forms* of a characteristic, the answer is allele, not gene; if it asks for the section of DNA responsible for the characteristic, the answer is gene, not allele.

TIP If two parents show no sign of a condition yet produce an affected child, the allele responsible must be recessive: each parent was a hidden, heterozygous carrier. An individual showing a recessive phenotype must be homozygous recessive, because a single dominant allele would have masked it; fix these individuals' genotypes first in any pedigree question, then work outwards.

TIP Sort any process by the pairing *identical and same number* against *different and halved number*. Healing a wound, a root growing longer and making new skin cells are all identical, same-number outcomes, so all are mitosis. Making sperm, making pollen or making egg cells are all different, halved-number outcomes, so all are meiosis.

20 Metals

KEY FORMULAS

General equations for a metal with water and with steam

$$\text{metal} + \text{water} \rightarrow \text{metal hydroxide} + \text{hydrogen} \quad \text{and} \quad \text{metal} + \text{steam} \rightarrow \text{metal oxide} + \text{hydrogen}$$

Use the first for a very reactive metal in cold water, for example $Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2$. Use the second for a moderately reactive metal heated in steam, for example $Mg + H_2O \rightarrow MgO + H_2$. Note that cold water gives a *hydroxide* while steam gives an *oxide*.

General reactions of a metal with oxygen and with dilute acid

$$\text{metal} + \text{oxygen} \rightarrow \text{metal oxide} \quad \text{and} \quad \text{metal} + \text{acid} \rightarrow \text{salt} + \text{hydrogen}$$

Use for any metal burning or oxidising in air, and for any metal above hydrogen in the reactivity series added to a dilute acid. A worked case is magnesium burning: $2Mg + O_2 \rightarrow 2MgO$. Metals below hydrogen, such as copper, give no reaction with dilute acid.

The balanced displacement equation

$$Mg + ZnSO_4 \rightarrow MgSO_4 + Zn$$

Use whenever a more reactive metal is added to a solution of a less reactive metal's salt. The more reactive metal takes the anion and the less reactive metal is released. Check the formula of the new salt from the ion charges: magnesium forms Mg^{2+} and sulfate is SO_4^{2-}, so they combine one to one as $MgSO_4$, never Mg_2SO_4.

The three blast-furnace equations

$$C + O_2 \rightarrow CO_2, \text{ then } CO_2 + C \rightarrow 2CO, \text{ then } Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

Use as a set for the extraction of iron. Coke burns in the hot air blast to release heat, the carbon dioxide is reduced by more hot coke to carbon monoxide, and the carbon monoxide reduces the iron(III) oxide to molten iron. State that *carbon monoxide is the reducing agent*. The third equation balances because the left has 3 oxygen in Fe_2O_3 plus 3 in $3CO$, giving the 6 delivered by $3CO_2$ on the right.

KEY CONCEPTS

- **An alloy is a mixture, not a compound**: An *alloy* is a mixture of a metal with one or more other elements, usually other metals but sometimes a non-metal such as carbon. Its atoms are simply mixed together and are not chemically joined in a fixed ratio, so the proportions can be varied and no new substance is formed. That is precisely why an alloy is classed as a mixture rather than a compound.
- **Choosing a metal: the standard property to use links**: Every "why is this metal used" question is answered by matching one property to the design requirement. *Copper*: an excellent electrical conductor and ductile, so it is used for electrical wiring. *Aluminium*: low density, a good conductor and corrosion-resistant, so it is used for aircraft bodies, overhead power cables and drink cans. *Iron and steel*: strong and cheap, so they are used for structural girders, car bodies and tools. *Gold*: very unreactive and attractive, so it is used for jewellery and electrical contacts.
- **Deducing the order of reactivity from displacement**: In a *displacement reaction* a more reactive metal takes the place of a less reactive metal in a solution of the less reactive metal's compound. The rule is that a metal displaces any metal less reactive than itself, so the number of other metals each one displaces ranks them directly. Rate evidence works the same way: the more vigorous the fizzing with acid or water, the more reactive the metal.
- **How each band of the series reacts with water, steam and acid**: *Very reactive* metals (potassium, sodium, calcium) react with cold water, giving a metal hydroxide and hydrogen. *Moderately reactive* metals (magnesium, zinc, iron) react little or not at all with cold water but react

with steam and with dilute acid, giving hydrogen. *Unreactive* metals (copper, silver, gold) react with none of them. A metal above hydrogen displaces hydrogen from a dilute acid and fizzes; a metal below hydrogen does not react with dilute acid at all.

- **Metallic bonding and the sea of delocalised electrons**: A metal is a giant lattice of positive metal ions surrounded by a sea of *delocalised electrons*, the outer-shell electrons that are no longer attached to any one atom and are free to move. *Metallic bonding* is the strong electrostatic attraction between that lattice of positive ions and the electron sea. Nearly every physical property of a metal follows from this one model.
- **Ores, native metals and the three extraction routes**: The most reactive metals (potassium down to aluminium) are extracted by *electrolysis*. Metals below carbon are extracted by *reduction with carbon*, because carbon is more reactive than they are and removes the oxygen from their oxides; iron comes from hematite, which is iron(III) oxide. The least reactive metals, gold and silver, are found *native*, as the free element rather than combined in a compound, and need little or no chemical extraction. Aluminium comes from bauxite, which is purified to aluminium oxide.
- **Reactivity decides the extraction method, and carbon is the pivot**: An *ore* is a rock or mineral containing a metal compound from which the metal can be extracted. A more reactive metal forms a more stable compound and holds its combined elements more tightly, so it is *harder* to extract. The deciding fact is the position of carbon: a metal *below* carbon (zinc, iron, copper) is extracted by reduction with carbon, and a metal *above* carbon (aluminium and everything higher) must be extracted by electrolysis.
- **Rusting requires both oxygen and water**: *Corrosion* is the gradual reaction of a metal with substances in its environment; for iron and steel the process is *rusting*, which forms hydrated iron(III) oxide. Rusting requires *both* oxygen (from the air) and water. Remove either one and rusting stops. Barrier methods (painting, greasing or oiling, coating with plastic) work by keeping both away from the iron surface.
- **Sacrificial protection and galvanising**: *Sacrificial protection* attaches a *more* reactive metal to the iron so that it corrodes in its place. Being more reactive, zinc loses electrons more readily than iron, so it is oxidised in preference to the iron. *Galvanising* is coating steel with zinc: while intact the zinc is a barrier, but even where the coating is scratched the exposed steel still does not rust, because the protection does not depend on the coating staying intact. Zinc or magnesium blocks protect ship hulls and underground pipes the same way and are replaced when consumed.
- **The named alloys and the elements they contain**: *Steel*: iron with a small amount of carbon, hard and strong, used for girders, car bodies and tools. *Brass*: copper and zinc. *Bronze*: copper and tin. *Duralumin*: aluminium and copper, which keeps aluminium's low density but is stronger, so it is used for aircraft body panels. *Solder*: historically tin and lead, with a low melting point for joining electrical components.
- **The physical properties of a metal and the reason for each**: Metals conduct electricity and heat well because the delocalised electrons are free to move and carry charge and thermal energy. They are *malleable* (hammered into shape) and *ductile* (drawn into wire) because layers of identical atoms slide over one another without the metallic bonding breaking. They are shiny when freshly cut, sonorous, dense, and generally high melting because strong metallic bonding acts throughout the whole lattice. Typical non-metals are the opposite: poor conductors, brittle and dull.
- **The reactivity series in order**: The *reactivity series* lists metals in order of how readily they react, most reactive at the top: potassium, sodium, calcium, magnesium, aluminium, (carbon), zinc, iron, (hydrogen), copper, silver, gold. Carbon and hydrogen are not metals but are included as reference points, because a metal's position relative to each one decides how it behaves with acid and how it is extracted.
- **Why an alloy is harder and stronger than a pure metal**: In a *pure metal* every atom is the same size, so the atoms form regular layers that slide over one another easily when a force is applied, and the metal is relatively soft. In an *alloy*, atoms of a different size are mixed in among the original atoms and distort the regular layers, so the layers can no longer slide easily and the metal is harder and stronger. The greater the size difference and the more foreign atoms present, the harder the alloy.

EXAM TIPS

TIP Distractors offer "a compound of copper and zinc" or "a mixture of a compound of copper and a compound of zinc". Both are wrong. Brass is made by mixing the two *elements*; neither metal is present as a compound, and the two are not chemically combined with each other. Read every option for the words *mixture* and *element* together before choosing.

TIP Questions deliberately probe the boundary between the two. Calcium and sodium react readily with *cold water*; magnesium barely reacts with cold water but reacts rapidly when heated in *steam*. Where a question says a metal reacts with steam but only very slowly with cold water, the answer is magnesium. Treat the two tests as separate points of the series and never lump them together.

21 Motion, forces and energy

KEY FORMULAS

Acceleration

$$a = \frac{\Delta v}{t}$$

Used to find acceleration from the change in speed and the time taken for that change. The unit is m/s^2. A negative value is a deceleration, meaning the object is slowing down.

Average speed

$$v = \frac{s}{t}$$

Used to find average speed from the total distance travelled and the total time taken, or rearranged to $s = vt$ and $t = s/v$. It gives the average over the whole journey, not the speed at any one instant.

Change in gravitational potential energy

$$\Delta E_p = mgh$$

Used to find the energy transferred when a mass is raised or lowered, where h is the *vertical* height gained and g the gravitational field strength in N/kg. Only the vertical height counts, so a load pushed up a ramp gains the same ΔE_p as one lifted straight up to the same height.

Density

$$\rho = \frac{m}{V}$$

Used to find the density of a substance from its mass and volume, or rearranged to $m = \rho V$ and $V = m/\rho$. Report it in g/cm^3 when the mass is in grams and the volume in cm^3, or in kg/m^3 when both are in base units. Never mix the two.

Kinetic energy

$$E_k = \tfrac{1}{2}mv^2$$

Used to find the energy of a moving object of mass m travelling at speed v. Because the speed is *squared*, doubling the speed quadruples the kinetic energy. Square the speed before halving.

Mechanical work

$$W = Fd$$

Used to find the work done when a force moves an object through a distance *in the direction of the force*, or rearranged to $F = W/d$. It is measured in joules, and 1 J = 1 N m. The work done equals the energy transferred.

Moment of a force

$$M = F \times d$$

Used to find the turning effect of a force about a pivot, where d is the *perpendicular* distance from the pivot to the line of the force. The unit is the newton metre (N m). The same force applied further from the pivot produces a larger moment, which is why a door opens more easily when pushed at its edge.

Newton's second law

$$F = ma$$

Used to link the *resultant* force on an object to the acceleration it produces, or rearranged to $a = F/m$ and $m = F/a$. The F is always the resultant, so combine the forces first and substitute that single value, never one individual force.

Power

$$P = \frac{E}{t}$$

Used to find the rate at which energy is transferred, or equivalently $P = W/t$, the rate of doing work. It is measured in watts, and 1 W = 1 J/s. Rearranges to $E = Pt$ and $t = E/P$. Convert any time given in minutes to seconds before substituting.

Pressure

$$p = \frac{F}{A}$$

Used to find the pressure a force exerts over a contact area, or rearranged to $F = pA$ and $A = F/p$. It is measured in pascals, and 1 Pa = 1 N/m^2. The area must be in m^2 for the answer to be in pascals.

Speed from a kinetic energy store

$$v = \sqrt{\frac{2E_k}{m}}$$

Used to find the speed of an object from its kinetic energy and mass, by rearranging $E_k = \frac{1}{2}mv^2$. For an object falling freely through a height h, all the gravitational potential energy lost becomes kinetic energy, so $mgh = \frac{1}{2}mv^2$ and the mass cancels to give the special case $v = \sqrt{2gh}$.

Weight from mass

$$W = mg$$

Used to find the weight in newtons from a mass in kilograms and the gravitational field strength g in N/kg, or rearranged to $g = W/m$. At the Earth's surface $g \approx 9.8$ N/kg. Convert any mass given in grams to kilograms before substituting.

KEY CONCEPTS

- **Centre of gravity**: The *centre of gravity* is the single point at which the entire weight of an object can be taken to act. For a uniform, symmetrical object it lies at the geometric centre. In any diagram the weight is drawn as one arrow acting vertically downwards from this point, however the object is oriented.
- **Energy stores and the four transfer pathways**: Energy is held in *stores*: kinetic, gravitational potential, elastic (strain), chemical, thermal (internal) and nuclear. It moves between them by four *pathways*: mechanically (a force doing work), electrically (a current), by heating, and by radiation. Radiation is the only pathway that crosses a vacuum, which is how energy reaches the Earth from the Sun. Name the store and the pathway separately: a torch battery holds a *chemical* store, transferred *electrically* to the lamp, which then transfers energy to the surroundings by *radiation* and by *heating*.

- **Finding the centre of gravity of a lamina by suspension**: Suspend the flat sheet freely from a pin through a hole near one corner, so it can swing. Hang a plumb line from the same pin and mark the vertical line it traces on the sheet. Repeat from a second hole. The centre of gravity is the point where the two lines *cross*. The method works because a freely suspended object always hangs with its centre of gravity directly below the point of suspension. A third hole gives a check.
- **Gradient and area on motion graphs**: On a *distance-time* graph the gradient is the speed: a straight line means constant speed and a horizontal line means the object is stationary. On a *speed-time* graph the gradient is the acceleration and the area between the line and the time axis is the distance travelled. Read the axes first, because the same straight line means constant speed on one graph and constant acceleration on the other.
- **Measuring the density of an irregular solid by displacement**: The volume of an irregular solid cannot be measured with a ruler, so it is found by *displacement*. Find the mass on a balance. Part-fill a measuring cylinder with water, read the level, lower the solid in until it is fully submerged and read the new level. The volume of the solid is the *rise* in level, the difference between the two readings, not the final reading. Then apply $\rho = m/V$.
- **Resultant force and Newton's first law**: The *resultant* force is the single force with the same effect as all the forces acting together. Along a line, add forces pointing the same way and subtract those pointing in opposite directions; the resultant acts in the direction of the larger force. Newton's first law states that when the resultant force is zero the object stays at rest or continues at constant velocity in a straight line. A resultant force can change an object's speed, its direction, or its shape.
- **Scalar and vector quantities**: A *scalar* has magnitude only. A *vector* has both magnitude and direction, so two vectors acting in opposite directions can cancel. Scalars: distance, speed, mass, time, energy, temperature. Vectors: displacement, velocity, acceleration, force, weight, gravitational field strength. Weight is a vector because it acts towards the planet, while the mass it acts on is a scalar.
- **Stability: a low centre of gravity and a wide base**: An object topples once its centre of gravity passes *beyond the edge of its base*. Two design features make that harder: a *low* centre of gravity and a *wide* base. Both increase the angle the object must be tilted through before the centre of gravity crosses the edge, so both increase stability. A racing car with a low, wide chassis is therefore more stable than a tall, narrow SUV of the same mass.
- **The energy resources that do not rely on the Sun**: Exactly three resources do *not* rely on radiation from the Sun: *nuclear* (energy from splitting large nuclei such as uranium), *tidal* (energy from the Moon's gravitational pull on the oceans) and *geothermal* (energy from heat in underground rocks). Every other resource traces back to the Sun. Learn this list of three, because the question is nearly always asked in this direction.
- **The principle of conservation of energy**: Energy cannot be created or destroyed, only transferred from one store to another. The total energy always stays the same. Every energy question is therefore a bookkeeping exercise: the energy leaving one store must appear, in full, across the stores it fills. Where a measured value falls short of the prediction, the shortfall has gone to another store, usually thermal, rather than disappearing.
- **The principle of moments**: For a body balanced about a pivot, the total *clockwise* moment about that pivot equals the total *anticlockwise* moment. Set the two sums equal and solve for the unknown. Where several forces act on one side, add all their moments before equating. The heavier of two balanced objects always sits closer to the pivot, which is a quick check on any answer.

22 Movement into and out of cells

KEY FORMULAS

Percentage change in mass

$$\text{percentage change in mass} = \frac{\text{final mass} - \text{initial mass}}{\text{initial mass}} \times 100$$

Used to compare tissue samples of different starting sizes in the osmosis practical; a positive value means the tissue gained water, a negative value means it lost water.

Surface-area-to-volume ratio

$$\text{SA:V} = \frac{\text{SA}}{V}$$

Used to judge whether diffusion alone can supply an organism's cells; a larger ratio means more surface area is available per unit of volume that must be supplied. For a cube this simplifies to $\text{SA:V} = 6/s$, so the ratio falls as the organism gets larger.

KEY CONCEPTS

- **Active transport defined**: *Active transport* is the movement of particles through a cell membrane from a region of their *lower* concentration to a region of their *higher* concentration, that is *against* a concentration gradient, using *energy from respiration*. Unlike diffusion and osmosis, active transport must be paid for because it moves particles the "wrong" way.
- **Diffusion defined**: *Diffusion* is the net movement of particles from a region of their higher concentration to a region of their lower concentration, that is *down* a concentration gradient, as a result of the *random* motion of the particles. A statement of diffusion is only correct if both halves agree: high to low concentration *and* down the gradient; reversing either half describes active transport instead.
- **Four factors that change the rate of diffusion**: The rate of diffusion rises with a larger *surface area* (more room for particles to cross at once), a higher *temperature* (particles have more kinetic energy and move faster), a steeper *concentration gradient* (a bigger difference drives faster net movement) and a shorter *distance* (less barrier to cross). Whether diffusion happens at all is decided by the gradient; how fast is decided by these four factors.
- **Osmosis defined, water-potential form**: *Osmosis* is the net movement of water molecules from a region of higher water potential to a region of lower water potential, through a *partially permeable membrane*. A statement of osmosis is only correct if it moves *water* (not solute), from *higher* to *lower* water potential, and needs *no energy*.
- **Turgid, flaccid and plasmolysed defined**: *Turgid*: a plant cell in a dilute solution takes in water by osmosis, the vacuole swells, and the wall pushes back with *turgor pressure*, making the cell firm. *Flaccid*: in a solution of equal or slightly lower water potential the cell loses some water and becomes soft. *Plasmolysed*: in a strongly concentrated solution the cell loses so much water that the cytoplasm and cell membrane pull away from the cell wall; the wall itself does not move.
- **Water potential rules**: *Water potential* measures the tendency of water to leave a solution. Pure water has the *highest* water potential; adding solute *lowers* it. So a dilute solution has a higher water potential and a concentrated solution has a lower water potential. Osmosis moves water from the side with the higher water potential to the side with the lower.

EXAM TIPS

TIP A correct statement of active transport must have *both* features together: movement against the gradient (lower to higher concentration) *and* energy from respiration. A statement with only one of the two, or with the direction reversed, describes diffusion or osmosis instead.

TIP For any "cell placed in a solution" question, write the reasoning in order: compare water potentials, state which way water moves by osmosis, then state the effect on the cell (turgid,

flaccid or plasmolysed). Marks are awarded for each link in the chain, so never jump straight to the final state without stating the water-potential comparison first.

TIP The direction of net movement *is* the direction of the gradient: if particles move from region P to region Q, then P is the higher concentration and Q is the lower, and the movement runs down the gradient from P to Q. Read a stated direction of movement as telling you which side is more concentrated, never the reverse.

23 Nuclear physics

KEY FORMULAS

Alpha decay

$$^{A}_{Z}\text{X} \rightarrow \, ^{A-4}_{Z-2}\text{Y} + \, ^{4}_{2}\alpha$$

Use for any alpha emission. The alpha particle carries away 2 protons and 2 neutrons, so the nucleon number falls by 4, the proton number falls by 2, and the daughter Y is a different element. Balance by conserving both totals across the arrow: $^{238}_{92}\text{U} \rightarrow \, ^{234}_{90}\text{Th} + \, ^{4}_{2}\alpha$, where $234 + 4 = 238$ on top and $90 + 2 = 92$ underneath. Use the resulting proton number to name the daughter from the periodic table.

Beta decay

$$^{A}_{Z}\text{X} \rightarrow \, ^{A}_{Z+1}\text{Y} + \, ^{0}_{-1}\beta$$

Use for any beta emission, the most frequently examined equation in this chapter. A neutron changes into a proton, so the nucleon number is unchanged while the proton number rises by 1. Balance both totals as usual, remembering that the beta particle carries 0 on top and -1 underneath: in $^{14}_{6}\text{C} \rightarrow \, ^{A}_{Z}\text{N} + \, ^{0}_{-1}\text{e}$ the top gives $14 = A + 0$, so $A = 14$, and the bottom gives $6 = Z + (-1)$, so $Z = 7$.

Corrected count rate

$$\text{corrected count rate} = \text{total count rate} - \text{background count rate}$$

Use before any calculation about a source, because every detector reading taken near a source also picks up the background radiation that is always present. Subtracting the background isolates the source alone. A total of 45 counts/s against a background of 9 counts/s gives $45 - 9 = 36$ counts/s. Any half-life read from uncorrected data will come out wrong.

Count rate

$$\text{count rate} = \frac{\text{number of counts}}{\text{time}}$$

Use whenever a Geiger-Muller tube and counter give a number of counts over a stated time. Each burst of ionisation inside the tube registers as one count. Divide, never multiply: 180 counts in 60 s gives $180 \div 60 = 3$ counts/s, and the classic error is to multiply and report $10\,800$. Check which time unit the question wants, counts per second or counts per minute.

Fraction remaining after n half-lives

$$\text{fraction remaining} = \left(\frac{1}{2}\right)^{n}$$

Use for any question giving a whole number of half-lives, where $n = \text{time} \div \text{half-life}$. It applies equally to mass, activity, count rate and number of undecayed nuclei, because all four are proportional to one another. A 240 g sample with a half-life of 5 minutes leaves $240 \times \left(\frac{1}{2}\right)^{2} = 60$ g after 10 minutes. Where the fraction is given instead, read n off it: one sixteenth is $\left(\frac{1}{2}\right)^{4}$, so 4 half-lives have passed.

Nuclide notation

$$^{A}_{Z}\text{X}$$

Use to read or write any nucleus. The nucleon number A sits on top, the proton number Z sits underneath, and X is the chemical symbol. Read it in both directions: from $^{24}_{12}\text{Mg}$ you know there are 12 protons and $24 - 12 = 12$

neutrons, and from 12 protons and 12 neutrons you write $^{24}_{12}\mathrm{Mg}$. The larger number is always the nucleon number and always goes on top.

Number of neutrons in a nucleus

$$\text{number of neutrons} = A - Z$$

Use whenever a question supplies a nucleon number A and a proton number Z and asks for neutrons. The nucleon number counts protons plus neutrons and the proton number counts protons alone, so the difference is the neutron count. For gold-197, $197 - 79 = 118$. The distractors offered are almost always Z and A themselves, so read carefully: the question wants the difference between the two totals, not either total.

The alpha and beta particles in nuclide notation

$^{4}_{2}\alpha$ and $^{0}_{-1}\beta$

Use these two symbols in every decay equation. An alpha particle is a helium nucleus, 2 protons and 2 neutrons, so its nucleon number is 4 and its proton number is 2; it may also be written $^{4}_{2}\mathrm{He}$. A beta particle is a fast-moving electron, so its nucleon number is 0, because an electron is not a nucleon, and its charge is -1; it may also be written $^{0}_{-1}\mathrm{e}$. Gamma carries neither mass nor charge and so contributes nothing to either total.

KEY CONCEPTS

- **Decay is random and spontaneous**: *Radioactive decay* is the process by which an unstable nucleus emits radiation and becomes more stable. It is *spontaneous*: it happens of its own accord, driven only by instability inside the nucleus, and is not affected by external conditions such as temperature, pressure or chemical state. Heating or compressing a source leaves its decay rate unchanged, and that is a favourite trap. It is also *random*: which individual nucleus decays next, and exactly when, cannot be predicted, only the probability of a decay in a given time. Averaged over the enormous number of nuclei in a sample, those random events still give a steady and predictable rate.
- **Fission splits, fusion joins**: *Nuclear fission* is a large, unstable nucleus such as uranium-235 splitting into two smaller nuclei, usually after absorbing a neutron. It is the process used in a nuclear reactor. *Nuclear fusion* is two small nuclei joining to form a larger nucleus, the process that powers the Sun and other stars. Both release energy, so asking which one releases energy never separates them. The discriminator is direction: fission splits, fusion joins.
- **Isotopes**: *Isotopes* are atoms of the same element, and so with the same proton number Z, that have different numbers of neutrons and therefore different nucleon numbers A. Carbon-12 ($^{12}_{6}\mathrm{C}$, 6 neutrons) and carbon-14 ($^{14}_{6}\mathrm{C}$, 8 neutrons) are isotopes because both have 6 protons. Because Z is unchanged, isotopes have the same number and arrangement of electrons and are chemically identical. They differ only in mass and, sometimes, in nuclear stability.
- **Match the radiation to the job**: The source chosen for a job is decided by the *penetration* of its radiation. *Sterilising* medical equipment sealed inside packaging uses gamma, because only gamma passes through the packaging to kill the bacteria inside without the package being opened. *Thickness monitoring* uses the radiation that the material absorbs only partly, so that the detected count rate changes when the thickness changes: beta for thin foil, gamma for thick steel. *Smoke detectors* use alpha. Medical tracers and diagnosis are further everyday uses.
- **Nature, charge and penetration of the three emissions**: *Alpha* is a helium nucleus of 2 protons and 2 neutrons, relative charge $+2$, stopped by paper or a few cm of air. *Beta* is a fast-moving electron, relative charge -1, stopped by a few mm of aluminium. *Gamma* is a high-frequency electromagnetic wave, relative charge 0, reduced only by thick lead or concrete. Learn each emission as that set of properties: nature, relative charge, and what stops it. An absorber test then identifies an emission by which barrier removes it.
- **What half-life means**: The *half-life* of a radioactive isotope is the average time taken for half of the undecayed nuclei in a sample to decay. Equivalently it is the time for the activity, or count rate, to fall to half its value, because count rate is proportional to the number of undecayed nuclei. It is not the time for *all* the nuclei to decay: each halving removes only half of what remains, so in principle

undecayed nuclei always remain and that time never arrives. Half-life is a fixed property of the isotope, so every successive halving takes the same time.

- **What the nucleus contains**: The nucleus is the tiny, dense central region of an atom. It contains *protons* and *neutrons*, which taken together are called *nucleons*. The *electrons* orbit outside the nucleus and are not nucleons. Listing electrons as a nuclear particle is a routinely lost mark: where a question asks what is found inside the nucleus, the answer is always protons and neutrons.

EXAM TIPS

TIP Almost every half-life calculation is settled by halving repeatedly rather than by any formula. Write the chain from the starting value down to the final value and count the arrows: $800 \rightarrow 400 \rightarrow 200 \rightarrow 100 \rightarrow 50$ is 4 halvings, so if that took 60 minutes the half-life is $60 \div 4 = 15$ minutes. Where the data come from a detector, subtract the background *first*, or every halving will be counted from the wrong starting value.

TIP A gauge works only when a change in thickness changes the detector reading, so the radiation must be *partly* absorbed by the material. Radiation stopped completely gives no signal at any thickness, and radiation passing straight through gives the same signal at every thickness. For thin aluminium foil the answer is therefore beta: alpha would be stopped by the first trace of metal and gamma would pass almost unchanged. For thick steel the same reasoning gives gamma, because beta would be absorbed completely.

TIP Where a question shows a parent and a daughter nucleus and asks which particle was emitted, compare the two pairs of numbers rather than recalling any rule. A fall of 4 in the nucleon number together with a fall of 2 in the proton number is an *alpha* particle. No change in the nucleon number with a rise of 1 in the proton number is a *beta* particle. No change in either is *gamma*. The same comparison names the particle at every step of a decay chain.

24 Organic chemistry

KEY FORMULAS

Addition polymerisation of ethene

$$n\,CH_2{=}CH_2 \rightarrow -[CH_2{-}CH_2]_n-$$

Used to write the formation of poly(ethene) from its monomer ethene, where n represents a large number of monomer molecules joining together. The $C=C$ double bonds open into single bonds and link up, and poly(ethene) is the only product. Ethane cannot be used because it is saturated and has no double bond to open.

Addition reactions of ethene

$$C_2H_4 + H_2 \rightarrow C_2H_6 \qquad C_2H_4 + H_2O \rightarrow C_2H_5OH$$

Used for the two addition reactions of ethene on the syllabus: hydrogen adds over a catalyst to give ethane, and steam adds over a catalyst at high temperature and pressure to give ethanol, which is the industrial route to ethanol. In each the double bond becomes a single bond, each carbon gains a new atom, and there is no by-product.

Complete combustion of an alkane

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

Used whenever an alkane burns in a plentiful supply of oxygen: every carbon becomes carbon dioxide and every hydrogen becomes water. Balance the carbon first, then the hydrogen, then the oxygen last.

Complete combustion of ethanol

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

Used when ethanol burns in a plentiful supply of oxygen, giving carbon dioxide and water only. Just $3O_2$ is needed because ethanol supplies one of the seven oxygen atoms itself, from its $-OH$ group.

General formulas of the alkanes and the alkenes

$$C_nH_{2n+2}\ (\text{alkane}) \qquad C_nH_{2n}\ (\text{alkene})$$

Used to write the molecular formula of any member of either series from its number of carbon atoms n, and to classify an unknown hydrocarbon by testing its hydrogen count against both formulas.

KEY CONCEPTS

- **Addition and condensation polymerisation compared**: *Addition* polymerisation joins many unsaturated monomers, each with a $C=C$ double bond, and forms *no other product*. *Condensation* polymerisation joins monomers that each carry two functional groups and *releases a small molecule*, such as water, at every linkage. The single most reliable difference to quote is that addition makes only the polymer, whereas condensation also makes a small molecule.
- **Alkanes are saturated hydrocarbons**: The alkanes are saturated hydrocarbons of general formula C_nH_{2n+2}: every carbon-to-carbon bond is a single covalent bond and every carbon uses all four of its bonds. The first four are methane CH_4, ethane C_2H_6, propane C_3H_8 and butane C_4H_{10}. They are relatively unreactive because their bonds are strong and non-polar and there is no double bond to open.
- **Cracking large alkanes into smaller, more useful molecules**: *Cracking* breaks large alkane molecules into smaller, more useful ones, including the alkenes that plastics are made from. The conditions are a *high temperature* and a *catalyst*, and the products are a mixture of smaller alkanes and alkenes. Atoms are conserved, so an unknown product can be found by subtraction.

- **Fractional distillation separates petroleum by boiling point**: Petroleum is separated into *fractions*, groups of hydrocarbons with similar boiling points, in a column that is hot at the bottom and cool at the top. The vapour rises and cools, and each hydrocarbon condenses where the temperature falls below its boiling point. Going *up* the column, boiling point, chain length and temperature all decrease, so refinery gas collects at the top and bitumen at the bottom.
- **Hydrocarbon, saturated and unsaturated defined**: *Hydrocarbon*: a compound containing hydrogen and carbon *only*, with no other element present. *Saturated*: a compound whose carbon atoms are joined to one another by single covalent bonds only. *Unsaturated*: a compound containing at least one carbon-to-carbon double bond, $\mathrm{C=C}$. Saturation describes the *bonding*; hydrocarbon describes the *elements present*.
- **Polymers, monomers and repeat units**: A *polymer* is a very large molecule built from many small repeating units, called *monomers*, joined by covalent bonds. The *repeat unit* is the smallest section that repeats along the finished chain. In *addition polymerisation* many unsaturated monomers join into one chain and no other product is formed.
- **Stems and endings: reading an organic name**: An organic name is a stem plus an ending. The *stem* counts the carbon atoms: meth- is 1, eth- is 2, prop- is 3, but- is 4. The *ending* names the family: *-ane* is an alkane (single bonds only), *-ene* is an alkene ($\mathrm{C=C}$ double bond), *-ol* is an alcohol ($-\mathrm{OH}$ group). So propane is a three-carbon alkane and ethanol is a two-carbon alcohol.
- **The bromine test for unsaturation**: The test that distinguishes a saturated from an unsaturated hydrocarbon. Shake the hydrocarbon with orange *aqueous bromine*: an *alkene* decolourises it from orange to colourless, because its $\mathrm{C=C}$ bond adds the bromine; an *alkane* leaves it orange, because it has no double bond to open. The general formula predicts the result, so $\mathrm{C_6H_{12}}$ decolourises the bromine and $\mathrm{C_6H_{14}}$ does not.
- **The homologous series and its four characteristics**: A *homologous series* is a family of compounds that share the same general formula, share the same functional group and so have similar chemical properties, differ from the next member by a $\mathrm{CH_2}$ unit, and show a gradual trend in physical properties such as boiling point along the series. The alkanes and the alkenes are the two series used most.
- **The three fossil fuels and their main constituents**: A *fuel* releases energy when it burns. The three *fossil fuels*, formed over millions of years from the buried remains of dead organisms, are *coal*, *petroleum* (crude oil) and *natural gas*. Natural gas is mostly a single hydrocarbon, methane, $\mathrm{CH_4}$; petroleum is a mixture of many hydrocarbons of different chain lengths; coal is mostly carbon.

25 Organisms and their environment

KEY FORMULAS

Energy transfer efficiency between trophic levels

$$\text{Energy transferred} = \text{Energy available} \times 0.1$$

Used whenever a question asks how much energy passes from one trophic level to the next. Roughly *10%* of the energy at one level is transferred to the level above; the rest is lost as heat, in egestion, in excretion and in movement.

Percentage of energy lost at each transfer

$$\text{Energy lost} = \text{Energy available} \times 0.9$$

The complement of the 10% rule. Used to state or estimate how much energy fails to reach the next trophic level; about *90%* is lost rather than passed on.

KEY CONCEPTS

- **Producer, consumer, herbivore, carnivore and decomposer defined**: *Producer*: an organism that makes its own organic nutrients from simple inorganic molecules, usually using light energy in photosynthesis. *Consumer*: an organism that gets its energy by feeding on other organisms. *Herbivore*: a consumer that eats plants. *Carnivore*: a consumer that eats other animals. *Decomposer*: a bacterium or fungus that gets its energy from dead or waste organic material, releasing simple inorganic molecules back into the environment.
- **The arrow in a food chain shows the direction of energy flow**: An arrow points from the organism that is eaten to the organism that eats it, in the direction energy flows. To build a chain, find the producer first, then follow "is eaten by" links outward until reaching an organism nothing eats.
- **The carbon cycle: how carbon moves between the air and living organisms**: The *carbon cycle* describes how carbon moves between the atmosphere (as carbon dioxide) and living organisms, and back again. *Photosynthesis* is the only major process removing carbon dioxide from the air, fixing it into glucose in producers. *Respiration* (in producers, consumers and decomposers), *decomposition* and *combustion* all return carbon dioxide to the atmosphere.
- **The Sun as principal energy source; photosynthesis converts light to chemical energy**: The Sun is the *principal source of energy* for almost all living organisms. Only *producers* (green plants and algae) capture it directly: photosynthesis converts light energy into chemical energy stored in glucose and other organic molecules, the form energy must take before it can be passed along a food chain by feeding.
- **Trophic levels counted from the producer**: A *trophic level* is the position an organism occupies in a food chain, counted from the producer as level 1. The primary consumer is level 2, the secondary consumer level 3, the tertiary consumer level 4. Always count from the producer, not from whichever organism a question mentions first.

EXAM TIPS

TIP A consumer's class is fixed by what it feeds on *in that chain*, never by its size or how impressive a predator it appears to be. A small animal feeding directly on a producer is a primary consumer even if a much larger animal shares its habitat.

TIP A food chain of four organisms has only *three* arrows between them, so the 10% figure is applied three times, not four. Before calculating, count the arrows in the chain, not the boxes.

26 Plant nutrition

KEY FORMULAS

Balanced symbol equation for photosynthesis

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

The whole-number-balanced form of the word equation. Use to choose the correct symbol equation among near-misses (wrong gas released, missing coefficients, reversed direction) and as the base for any atom-counting or molecule-ratio question.

Word equation for photosynthesis

$$\text{carbon dioxide} + \text{water} \xrightarrow{\text{light energy}} \text{glucose} + \text{oxygen}$$

States the reactants (carbon dioxide, water) and products (glucose, oxygen) of photosynthesis. Light energy and chlorophyll are written over the arrow because they drive the reaction without being consumed as matter. Use to identify the correct reactants and products, and to reject the reverse equation (respiration).

KEY CONCEPTS

- **Chlorophyll absorbs and transfers light energy**: Chlorophyll is the green pigment inside *chloroplasts*. It absorbs light energy and *transfers* it into chemical energy stored in the glucose that is made. Chlorophyll is not a reactant, is not consumed, and does not "make" or "release" energy; it is the light-capturing machinery.
- **Definition of photosynthesis**: Photosynthesis is the process by which plants synthesise carbohydrates from the raw materials carbon dioxide and water, using energy from light. A full-mark answer names all three parts: the *raw materials* (carbon dioxide and water), the *product* (a carbohydrate, ultimately glucose) and the *energy source* (light). Missing any one part loses marks.
- **Destarching before a photosynthesis test**: Before testing whether a factor is needed for photosynthesis, a plant is left in the dark for 24 to 48 hours to *destarch* it: with no light it cannot photosynthesise, so it uses up any starch already present. Any starch detected after the experiment must then have been made *during* the test, giving a clean result. The standard leaf-starch test is boil in water, boil in ethanol to remove the chlorophyll, then add iodine solution; starch present turns blue-black, starch absent stays yellow-brown.
- **Leaf cross-section, top to bottom**: A leaf's structure runs, from the top: *waxy cuticle* (waterproof, reduces water loss), *upper epidermis* (transparent, chloroplast-free, lets light through), *palisade mesophyll* (tall cells packed with chloroplasts, the main site of photosynthesis), *spongy mesophyll* (loosely packed cells with large air spaces for gas diffusion), *lower epidermis* (holds most of the *stomata*), and a *vascular bundle* (vein) carrying xylem and phloem. Each layer is an adaptation for capturing light and exchanging gases.

EXAM TIPS

TIP A leaf-structure mark is almost always for feature *plus* function, never the feature alone: "large air spaces, so gases diffuse freely to every cell", not just "large air spaces". Naming a structure without its function typically scores only half the available marks.

27 Reproduction

KEY CONCEPTS

- **Defining a sexually transmitted infection**: A *sexually transmitted infection (STI)* is *an infection caused by a pathogen that is transmitted between people through sexual contact.*
- **Definition of sexual reproduction**: *Sexual reproduction is a process involving the fusion of the nuclei of two gametes (sex cells) to form a zygote, and the production of offspring that are genetically different from each other.* The contrast with asexual reproduction is exact: two gametes instead of one parent's cell, fusion instead of no fusion, varied offspring instead of clones.
- **Egg cell adaptations**: An egg is built to *provision*. *Food (energy) stores* in its cytoplasm nourish the early embryo after fertilisation, and its *jelly coat* changes at fertilisation to stop any further sperm entering. An egg is much *larger* than a sperm and produced in far *smaller numbers*.
- **Fertilisation: the fusion of nuclei**: *Fertilisation occurs when a pollen nucleus fuses with a nucleus in an ovule*, inside the ovary. Pollination *moves* pollen to the stigma; fertilisation *fuses* nuclei inside the ovary. They are different events, at different places, at different times.
- **Flower structure: stamen and carpel**: A flower's male parts form the *stamen*: *anther* (produces and releases pollen grains, which carry the male gametes) plus *filament* (the stalk that holds the anther up). Its female parts form the *carpel*: *stigma* (sticky surface that receives pollen) plus *style* (connects the stigma to the ovary) plus *ovary* (contains the *ovules*; each ovule contains a female gamete and becomes a seed after fertilisation).
- **Gametes and zygotes: haploid versus diploid**: A *gamete* is a sex cell; a gamete nucleus is *haploid*, containing a single set of chromosomes. A *zygote* is the cell formed when two gamete nuclei fuse at fertilisation; a zygote nucleus is *diploid*, containing two sets of chromosomes.
- **HIV: the pathogen and its link to AIDS**: *HIV* (human immunodeficiency virus) is a *pathogen*, specifically a *virus*, that causes an STI. Untreated HIV infection progressively damages the immune system and *may lead to AIDS* (acquired immune deficiency syndrome).
- **Pollination: the transfer of pollen**: *Pollination is the transfer of pollen grains from an anther to a stigma.* It is defined narrowly as the transfer step only, nothing more: not the pollen tube growing, not any fusion of nuclei.
- **Sperm cell adaptations**: A sperm is built to *travel*. Its *flagellum* (tail) beats to swim it towards the egg; *mitochondria* in the mid-piece release energy by respiration to power the tail; the *acrosome*, a cap on the tip of the head, contains enzymes that digest through the egg's outer layer so the sperm can enter. Sperm are very *small* and produced in very *large numbers*.
- **The definition of a species**: A species is *a group of organisms that can reproduce to produce fertile offspring.* The word *fertile* carries the definition: two organisms may look alike and even mate, but if their offspring cannot themselves reproduce, the two organisms belong to different species.
- **The human female reproductive system**: *Ovaries* produce egg cells and the hormone oestrogen, usually releasing one egg about every month. *Oviducts* carry an egg from an ovary towards the uterus and are the usual site of fertilisation. The *uterus* is a muscular organ in which a fertilised egg implants and develops. The *cervix* is the narrow lower part of the uterus, opening into the *vagina*, which receives the penis and semen during mating and is the birth canal.
- **The human male reproductive system**: *Testes* produce sperm cells and the hormone testosterone. The *scrotum* holds the testes outside the main body, slightly cooler than body temperature, which sperm production requires. *Sperm ducts* carry sperm from the testes towards the urethra. The *prostate gland* adds fluid to sperm to make *semen*. The *urethra* carries semen (and, separately, urine) through the *penis* out of the body.
- **The two features that define asexual reproduction**: *Asexual reproduction is a process resulting in the production of genetically identical offspring from one parent.* Two features must be quoted together: there is only *one* parent, and there is *no fusion of gametes*.
- **Why asexual offspring are genetic clones**: Because no genes are mixed in from a second parent, every offspring is a genetic copy, a *clone*, of the parent. This is the direct consequence of the "one parent, no gamete fusion" definition, not a separate fact to memorise.

EXAM TIPS

TIP Learn *binary fission* in bacteria (one cell divides into two identical cells), *budding* in yeast (a small outgrowth grows and separates from the parent), *runners* in plants such as the strawberry (a horizontal stem roots to form an identical new plant), and *taking cuttings* (a gardener's

technique producing a plant identical to the parent). Exam questions often show an unfamiliar organism and ask for a classification against the two-feature test.

TIP The anther *makes* pollen; the stigma *receives* it. They sit on opposite teams (male stamen, female carpel). A second trap: *stamen* and *carpel* name the whole male and female structures, while *anther/filament* and *stigma/style/ovary* name their parts, so read a question carefully to see whether it asks for the whole or a part.

TIP If a body cell is diploid with $2n$ chromosomes, each gamete is haploid with n. Fertilisation adds two haploid sets, $n + n = 2n$, restoring the diploid number in the zygote. Halving happens when gametes are made; doubling happens at fertilisation. Given a gamete number, double it for the zygote; given a body-cell number, halve it for the gamete.

TIP Anchor every sperm-versus-egg question on this single sentence: the small, numerous sperm is adapted to *move*; the large, few egg is adapted to *provision*. A question that swaps the flagellum onto the egg or the food stores onto the sperm has swapped the two roles and is wrong.

TIP A pathogen counts as sexually transmitted if sexual contact is *one* of its routes; it need not be the *only* route. HIV also spreads through infected blood and from mother to child, and that does not stop it being an STI.

28 Respiration

KEY FORMULAS

Balanced symbol equation for aerobic respiration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Used in calculations that scale between the molecules of glucose, oxygen, carbon dioxide and water in aerobic respiration, following the fixed 1 : 6 : 6 : 6 ratio; multiply a quantity of glucose by 6 to find carbon dioxide, oxygen or water, and divide by 6 to convert any of those three back to glucose.

Word equation for aerobic respiration

$$\text{glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water}$$

Used to summarise aerobic respiration: glucose reacts with oxygen and energy is released as it goes, though energy is not a substance and so does not appear in the equation itself. Glucose and oxygen are the reactants; carbon dioxide and water are the products.

KEY CONCEPTS

- **Aerobic respiration: definition and site**: *Aerobic respiration* is the chemical reactions in cells that use *oxygen* to break down *nutrient molecules* to release *energy*. All three features, oxygen use, breakdown of nutrient molecules, and the release of energy, must be present for a complete definition; omitting oxygen use is the most common way to lose the mark, since it is the one feature that separates aerobic from anaerobic respiration. Most aerobic respiration takes place in the *mitochondria*, so a cell with a high energy demand, such as a muscle cell, contains very many of them.
- **Anaerobic respiration: definition**: *Anaerobic respiration* is the chemical reactions in cells that break down nutrient molecules to release energy *without using oxygen*. The defining phrase is the absence of oxygen: because glucose is only partially broken down without oxygen, anaerobic respiration releases much less energy per glucose molecule than aerobic respiration. The product depends on the organism: *lactic acid* in human muscle, or *ethanol and carbon dioxide* in yeast and some plant cells (fermentation).
- **Respiration is not breathing**: *Respiration* is the chemical release of energy from nutrient molecules inside every living cell; it takes place continuously, whether or not the organism is visibly active. *Breathing*, properly called *ventilation*, is the mechanical movement of air into and out of the lungs and only supplies the oxygen that aerobic respiration uses. An organism with no lungs, such as a plant or a bacterium, still respires in every cell.
- **Uses of the energy released by respiration**: Living organisms use the energy released by respiration for *muscle contraction*, *protein synthesis*, *cell division*, *growth*, *active transport* against a concentration gradient, the *passage of nerve impulses*, and *maintaining a constant body temperature* in mammals and birds. Each of these is an active process that would not occur without an input of energy.

EXAM TIPS

TIP Where a question offers *carbon dioxide + water -> glucose + oxygen* as an option for aerobic respiration, reject it: that is the reverse reaction, photosynthesis, not respiration. Aerobic respiration always has glucose and oxygen as reactants and carbon dioxide and water as products, never the other way round.

29 Space physics

KEY FORMULAS

Orbital speed

$$v = \frac{2\pi r}{T}$$

Used to find the speed of any body in a circular orbit, where r is the orbital radius in m, T is the orbital period in s and v is the orbital speed in m/s. The quantity $2\pi r$ is the circumference of the orbit, the distance covered in one complete orbit.

Time for light to travel a distance

$$t = \frac{d}{c}$$

Used to find the time light takes to cross an astronomical distance d, where $c = 3.0 \times 10^8$ m/s is the speed of light. Rearranges to $d = ct$. Light takes about 8.3 minutes to travel from the Sun to Earth, and over four years from the next nearest star.

KEY CONCEPTS

- **Galaxy, the Milky Way and the Universe**: A *galaxy* is a huge collection of billions of stars, together with gas and dust, held together by *gravity*. The Sun is one ordinary star in the galaxy called the *Milky Way*. The *Universe* is everything that exists: all of the billions of galaxies and all the space between them. In order of increasing size: star, Solar System, galaxy, Universe.
- **Nebula, protostar, stable star**: Every star begins the same way. A *nebula*, a vast cloud of gas (mostly hydrogen) and dust, is pulled together by *gravity*. The matter clumps and heats into a hot spinning ball called a *protostar*. Once its core is hot and dense enough for *nuclear fusion* to begin, the outward push of the released energy balances the inward pull of gravity and it becomes a *stable star*.
- **Orbital speed decreases with distance from the Sun**: Because the Sun's gravitational field strength falls with distance, a planet further from the Sun is held by a weaker pull and travels more slowly along its orbit. So as orbital radius increases, orbital speed *decreases*: Mercury races around the Sun and Neptune crawls. Earth's orbital speed is about 3.0×10^4 m/s, roughly 30 km/s.
- **The Big Bang theory and the age of the Universe**: The *Big Bang theory* states that the Universe began from a *single point of extremely high temperature and density* and has been *expanding and cooling ever since*. The best current estimate for the age of the Universe is about *13.8 billion years*. Watch the unit in the distractors: 13.8 million years and 13.8 thousand years are both far too small.
- **The eight planets in order**: In order of increasing distance from the Sun: *Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune*. The *asteroid belt* lies between the orbits of Mars and Jupiter, that is between the fourth and fifth planets. Write the full ordered list out before reading off whichever positions a question asks for.
- **The structure of the Solar System**: The *Solar System* is the Sun together with everything held in orbit around it by the Sun's gravity. At its centre is one star, the Sun. *Planets*, *dwarf planets* and *asteroids* orbit the Sun *directly*. *Moons* orbit a planet, so they orbit the Sun only *indirectly*. The hierarchy to memorise: the Sun is a star; planets and minor planets orbit the Sun; moons orbit planets.
- **The Sun as a medium-sized star**: The Sun is a *medium-sized star*, made mostly of the two lightest elements, *hydrogen* and *helium*. It radiates most of its energy in the *infrared*, *visible* and *ultraviolet* regions of the electromagnetic spectrum, with the peak in the visible. Heavier elements such as oxygen, carbon and iron are present only in tiny amounts.
- **The Sun's mass and gravity govern every orbit**: The Sun holds about 99.8% of the mass of the Solar System, far more than all the planets, moons and asteroids combined. The *gravitational attraction of the Sun* supplies the inward force that curves each planet's path into a closed orbit. The Sun's *gravitational field strength decreases with distance*, so a planet further out is held by a weaker pull.

EXAM TIPS

TIP Where a period is quoted in hours or days, convert it to seconds before substituting into $v = \dfrac{2\pi r}{T}$. A period of 7.7 hours is $7.7 \times 3600 = 27\,720$ s. Using the raw 7.7 makes T about 3600 times too small, so the calculated speed comes out about 3600 times too large. This single omission is the most common cause of a wrong orbital speed.

30 States of matter

KEY CONCEPTS

- **Diffusion defined by kinetic particle theory**: *Diffusion* is the net movement of particles from a region of higher concentration to a region of lower concentration, caused by the random motion of the particles. It is a *net* movement: particles travel in all directions, but more leave the crowded region than enter it. It needs no stirring and no external force, which is what separates it from being blown or mechanically mixed. It is fastest in gases, slower in liquids and negligible in solids.
- **Particle arrangement, separation and motion in the three states**: *Kinetic particle theory*: all matter is made of tiny particles that are constantly moving, and the state depends on the arrangement, separation and motion of those particles. *Solid*: regular repeating arrangement, touching, vibrating about fixed positions. *Liquid*: irregular arrangement, touching but with slightly larger gaps, sliding past one another. *Gas*: random arrangement, far apart, moving quickly in all directions.
- **Predicting the state of a substance from its melting and boiling points**: Below its melting point a pure substance is a *solid*; between the melting and boiling points it is a *liquid*; above its boiling point it is a *gas*. Place the given temperature on a number line between the two fixed points and read off the region it falls in. Take care with negative values: -40 °C is warmer than -95 °C, so a substance melting at -95 °C has already melted at -40 °C.
- **Relative molecular mass and the rate of diffusion**: At the same temperature, a gas with a *smaller* relative molecular mass (M_r) diffuses *faster* than a gas with a larger relative molecular mass. The reason is that at a given temperature all gas particles have the same average kinetic energy, and kinetic energy depends on both mass and speed, so the lighter particles must move faster. Ranking gases by rate of diffusion is therefore ranking them by M_r, smallest first.
- **The effect of temperature and pressure on the volume of a gas**: Heating a gas at constant pressure *increases* its volume: the particles gain kinetic energy, move faster and spread further apart, so the gas expands. Increasing the pressure on a gas at constant temperature *decreases* its volume, because the same number of particles is forced into a smaller space. A solid or a liquid barely responds to either change, because its particles are already touching.
- **The six changes of state**: *Melting* is solid to liquid and *freezing* is liquid to solid. *Evaporating* or *boiling* is liquid to gas and *condensing* is gas to liquid. *Sublimation* is solid straight to gas, shown by solid carbon dioxide, and *deposition* is gas straight to solid. Heating drives a substance towards the gas state as its particles gain energy; cooling drives it towards the solid state as they lose energy.
- **The three states and their distinguishing properties**: A *solid* has a fixed shape and a fixed volume, cannot flow and cannot be compressed. A *liquid* has a fixed volume but no fixed shape; it flows and takes the shape of its container, and it can barely be compressed. A *gas* has neither a fixed shape nor a fixed volume; it flows, fills its container completely and is easily compressed. Only a gas can be compressed easily, because only a gas has large empty spaces between its particles.
- **What happens to the particles when a solid melts**: Melting supplies the energy that frees the particles from their fixed positions. Their *motion* changes from vibrating about fixed positions to moving around and past one another randomly, which is why a liquid can flow. Their *separation* changes only slightly: they move a little further apart but are *still touching*. The large separation with big gaps belongs to a gas, not to a liquid.

EXAM TIPS

TIP Where a question asks which state has the most widely separated particles, the answer is the *gas*. The ranking is fixed: a solid's particles are packed together and touching, a liquid's are touching but slightly further apart, and a gas's are far apart with large gaps between them. The same ranking explains why only a gas has a very low density and why only a gas compresses easily.

31 Stoichiometry

KEY FORMULAS

Amount and number of particles

$$\text{number of particles} = n \times 6.02 \times 10^{23}$$

Use to turn an amount in moles into a count of atoms, molecules or ions, and divide by the Avogadro constant to go back the other way. To reach a particle count from a mass, chain the two relationships: $\text{particles} = \frac{m}{M} \times 6.02 \times 10^{23}$. For $5.4\ \text{g}$ of aluminium ($A_r = 27$) the amount is $0.20\ \text{mol}$, giving 1.20×10^{23} atoms.

Amount, mass and molar mass

$$n = \frac{m}{M}$$

Use to convert between a mass that can be weighed and an amount in moles. n is the amount in mol, m the mass in g, and M the *molar mass* in g/mol, which is numerically equal to the A_r or M_r. It rearranges to $m = n \times M$ and $M = m \div n$. This is the most used relationship in the chapter.

Reacting masses by proportion

$$\text{mass of product} = \text{mass of reactant} \times \frac{M_r \text{ of product}}{M_r \text{ of reactant}}$$

Use where the balanced equation puts the reactant and product in a $1 : 1$ ratio, so the masses scale directly as the formula masses and no mole step is needed. For $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$, with M_r values 100 and 56, making 7 tonnes of CaO needs $7 \times \frac{100}{56} = 12.5$ tonnes of CaCO_3. Check the ratio first; if it is not $1 : 1$, work through moles instead.

Relative molecular mass and relative formula mass

$$M_r = \sum A_r \text{ of every atom shown in the formula}$$

Use to find the mass of one formula unit, which is also the molar mass in g/mol. Add the A_r of every atom the formula shows, respecting subscripts: $M_r(\text{H}_2\text{SO}_4) = (2 \times 1) + 32 + (4 \times 16) = 98$. Applied to an ionic compound the same sum is called the *relative formula mass*; the arithmetic is identical.

The charge-swap method for an ionic formula

$$\text{Al}^{3+} \text{ with } \text{O}^{2-} \;\rightarrow\; \text{Al}_2\text{O}_3 \quad \text{since} \quad 2 \times (3+) = 6+ \text{ balances } 3 \times (2-) = 6-$$

Use to deduce the formula of any ionic compound from the charges on its two ions. The size of each ion's charge becomes the subscript of the other ion, so the two totals cancel. Always reduce the result to the simplest whole-number ratio: Mg^{2+} with O^{2-} swaps to Mg_2O_2, which must be cancelled to MgO.

The molar gas volume at r.t.p.

$$n = \frac{V}{24} \qquad V = n \times 24$$

Use for any gas at *room temperature and pressure*, where one mole of *any* gas occupies $24\ \text{dm}^3$ and V is the volume in dm^3. The value is the same whatever the gas, because equal volumes of gases at the same temperature and pressure contain equal numbers of molecules. The figure 24 holds only at r.t.p.

The mole ratio from a balanced equation

$$n(\mathrm{B}) = n(\mathrm{A}) \times \frac{\text{coefficient of B}}{\text{coefficient of A}}$$

Use as the bridge of every stoichiometry calculation: convert what you are given into moles, cross to the other substance with this ratio, then convert out to whatever the question asks for. In $2\mathrm{HCl} + \mathrm{CaCO_3} \rightarrow \mathrm{CaCl_2} + \mathrm{CO_2} + \mathrm{H_2O}$ the ratio of HCl to $\mathrm{CaCl_2}$ is $2:1$, so $0.2\ \mathrm{mol}$ of acid gives $0.1\ \mathrm{mol}$ of $\mathrm{CaCl_2}$, a mass of $0.1 \times 111 = 11.1\ \mathrm{g}$.

KEY CONCEPTS

- **A balanced symbol equation conserves atoms**: A *word equation* names the reactants on the left and the products on the right, joined by an arrow meaning "react to form". A *symbol equation* replaces the names with formulas and must be *balanced*: the same number of atoms of each element on both sides, because atoms are never created or destroyed in a reaction. Balance by writing every correct formula first, then adjusting only the large numbers in front, checking each element in turn and leaving oxygen and hydrogen until last.
- **One mole and the Avogadro constant**: *One mole* of a substance is the amount containing as many particles (atoms, molecules or ions) as the *Avogadro constant*, 6.02×10^{23} per mole. The mole is a unit of *amount*, never of mass or volume: one mole of any substance holds the same number of particles whatever the substance, even though one mole of different substances has different masses. The Avogadro constant is a *count of particles per mole*; it is not a mass, and it is not the $24\ \mathrm{dm^3}$ molar gas volume.
- **Relative atomic mass defined**: *Relative atomic mass*, A_r, is the average mass of the atoms of an element compared with *one twelfth of the mass of one atom of carbon-12*. It has no units, because it is a ratio of two masses and the units cancel. The standard is the detail being marked, so quote it in full: one twelfth of the mass of one *atom* of carbon-12, not one twelfth of a *mole* of carbon-12 and not the mass of one whole carbon-12 atom.
- **State symbols and what each one means**: A *state symbol* is written in brackets after each formula to show the physical state: (s) solid, (l) pure liquid, (g) gas, and (aq) aqueous, meaning dissolved in water. The distinction actually being marked is (l) against (aq): (l) is reserved for a *pure* liquid, so a dilute acid or any other solution is (aq) and never (l). A metal or an insoluble precipitate is (s), and steam is (g).
- **The formula of an ionic compound is electrically neutral**: An ionic compound is built from positive and negative ions, and its formula must be *electrically neutral overall*: the total positive charge exactly cancels the total negative charge. Write the two ions with their charges, choose the smallest whole numbers of each ion that make the charges balance, then write those numbers as subscripts. A polyatomic ion such as $\mathrm{SO_4^{2-}}$ or $\mathrm{NO_3^-}$ is enclosed in brackets before any subscript greater than one.

EXAM TIPS

TIP A *coefficient* is the large number in front of a formula and may be changed freely to balance an equation. A *subscript* belongs to the formula itself and must never be changed, because changing it changes the substance: turning $\mathrm{H_2O}$ into $\mathrm{H_2O_2}$ replaces water with hydrogen peroxide. Remember that a coefficient multiplies every atom in the formula it precedes, so $2\mathrm{AlCl_3}$ supplies two aluminium atoms and six chlorine atoms.

TIP The commonest slip in this chapter is leaving a volume in $\mathrm{cm^3}$. Both the molar gas volume and a concentration are defined per $\mathrm{dm^3}$, and $1\ \mathrm{dm^3} = 1000\ \mathrm{cm^3}$, so divide by 1000 before either is used. Collecting $50\ \mathrm{cm^3}$ of carbon dioxide at r.t.p. is $0.050\ \mathrm{dm^3}$, giving $0.050 \div 24 = 0.0021\ \mathrm{mol}$, not $50 \div 24$. Skipping the conversion overstates the amount by a factor of 1000.

32 The Periodic Table

KEY FORMULAS

Alkali metal with cold water

$$2\mathrm{Na} + 2\mathrm{H_2O} \rightarrow 2\mathrm{NaOH} + \mathrm{H_2}$$

Used for any Group I metal with cold water, in the general form alkali metal + water $\rightarrow$ metal hydroxide + hydrogen. Swap in the metal for lithium, $2\mathrm{Li} + 2\mathrm{H_2O} \rightarrow 2\mathrm{LiOH} + \mathrm{H_2}$, or potassium, $2\mathrm{K} + 2\mathrm{H_2O} \rightarrow 2\mathrm{KOH} + \mathrm{H_2}$. The two products are always the metal hydroxide and hydrogen, never an oxide.

Halogen displacement from a halide

$$\mathrm{Cl_2} + 2\mathrm{KBr} \rightarrow 2\mathrm{KCl} + \mathrm{Br_2}$$

Used when a more reactive halogen meets a solution of a less reactive halide: the more reactive halogen displaces the less reactive one. Chlorine bubbled through colourless potassium bromide solution turns it orange-brown as free bromine is displaced. Two formula units of the halide are needed to balance, because the halogen is diatomic and supplies two atoms.

Position and electronic structure

$$\text{group number} = \text{number of outer-shell electrons and period number} = \text{number of occupied electron shells}$$

Used to convert an element's position in the table into its electron arrangement, and back again. Read the two numbers off the table and the chemistry follows, because reactions are governed by the outer-shell electrons.

KEY CONCEPTS

- **Characteristic properties of the transition elements**: The transition elements form the central block between Group II and Group III. Four properties characterise them: *high density* and *high melting points*; *catalytic activity*, as with iron in the manufacture of ammonia and manganese(IV) oxide in the decomposition of hydrogen peroxide; *coloured compounds*, with copper compounds typically blue or green; and *variable oxidation states*, iron forming both $\mathrm{Fe^{2+}}$ and $\mathrm{Fe^{3+}}$.
- **How the Periodic Table is arranged**: The elements are placed in one continuous sequence in order of increasing *proton number*, one proton at a time with no gaps. The horizontal rows are *periods*: the period number equals the number of occupied electron shells. The vertical columns are *groups*: for the main groups, the group number equals the number of outer-shell electrons. Metals occupy the left and centre, and non-metals are confined to the top right, separated from the metals by a rough diagonal staircase.
- **Metallic character across a period**: Across any period, from left to right, the number of outer-shell electrons rises from one to eight and the elements change from *metallic* to *non-metallic* in character. Metallic character is how readily an atom loses its outer-shell electrons, so it is greatest at the far left, where the group number is lowest. The oxides change in step: metal oxides on the left are *basic*, non-metal oxides on the right are *acidic*.
- **The alkali metals: physical properties and storage**: Group I is the family of *alkali metals* (lithium, sodium, potassium and below), named for the alkaline hydroxide solutions they form with water. Unlike everyday metals they have *low density*, so lithium, sodium and potassium float on water, and they are *soft* enough to cut with a knife, exposing a shiny surface that tarnishes within seconds as it reacts with oxygen. Their melting points are low for metals. Because they react readily with both air and water they are stored under oil.
- **The halogens: appearance and trends down Group VII**: Group VII, the *halogens*, are reactive non-metals that exist as *diatomic* molecules ($\mathrm{Cl_2}$, $\mathrm{Br_2}$, $\mathrm{I_2}$); every atom has seven outer-shell electrons, one short of a full shell. Down the group the colour becomes *darker* and the density, melting point and boiling point all *increase*, so the state at r.t.p. passes from gas (pale yellow-green chlorine) through liquid (red-brown bromine) to solid (grey-black iodine). Reactivity *decreases* down the group, the opposite direction to Group I.

- **The noble gases: full outer shell**: Group VIII, also labelled Group 0, holds the *noble gases* (helium, neon, argon and below). Each atom has a *full outer shell*, two electrons for helium and eight for the rest, which is a very stable arrangement, so the atoms have no tendency to gain, lose or share electrons and are *unreactive*. Having no driving force to bond, they exist as single separate atoms (*monatomic*), and all are colourless gases at room temperature.
- **Trends down Group I**: Going down Group I, *density increases*, *melting point decreases* because the atoms become larger and the metallic bonding holding the solid together weakens, and *reactivity increases* because the outer electron is lost more easily. Because all three trends are smooth, an unknown value can be estimated by interpolation and the behaviour of a lower element predicted by extrapolation.

EXAM TIPS

TIP Two observations together fix an unknown substance as a Group I metal: it *floats* on water, so its density is very low, and it reacts with *cold* water to release *hydrogen*, so it is highly reactive. No other family satisfies both. Magnesium and zinc are far denser and react with cold water only slowly or not at all, and a non-metal such as iodine does neither.

33 Thermal physics

KEY FORMULAS

Boyle's law, pressure and volume at constant temperature

$$P_1V_1 = P_2V_2$$

Used for a fixed mass of gas held at constant temperature, such as gas in a syringe whose plunger is pushed in slowly. The pressure is inversely proportional to the volume, so halving the volume doubles the pressure.

Celsius to absolute temperature

$$T(\mathrm{K}) = \theta(^\circ\mathrm{C}) + 273$$

Used to convert a Celsius temperature to kelvin before substituting into either gas law. The kelvin scale is measured from absolute zero, which is why only kelvin temperatures give a constant ratio P/T.

Pressure and absolute temperature at constant volume

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Used for a fixed mass of gas held at constant volume, such as gas sealed in a rigid cylinder. The pressure is directly proportional to the absolute temperature, so doubling the kelvin temperature doubles the pressure. Both temperatures must be in kelvin.

KEY CONCEPTS

- **Boiling is not evaporation**: Two discriminators separate them, and a question will test one or both. *Where*: boiling occurs throughout the liquid, forming bubbles, whereas evaporation occurs only at the surface. *At what temperature*: boiling occurs only at the fixed boiling point, whereas evaporation occurs at any temperature below it. Boiling is also rapid where evaporation is usually slow.
- **Convection currents are driven by density changes**: Convection is the transfer of thermal energy through a *fluid* (a liquid or a gas) by the bulk movement of the fluid itself. It cannot occur in a solid, whose particles cannot flow. When part of a fluid is heated it *expands and becomes less dense*, so it rises; cooler, denser fluid sinks to take its place, is heated in turn, and also rises. This continuous circulation is a *convection current*.
- **Evaporation cools the liquid left behind**: Evaporation is a liquid turning into a gas *at its surface*, at any temperature below the boiling point. The particles have a spread of energies, and only the *most energetic* surface particles have enough energy to break free of the attractive forces and escape. Because it is always the fastest particles that leave, the average kinetic energy of the particles remaining falls, so the liquid cools. This is why sweat cools the skin.
- **Gas pressure is caused by collisions with the walls**: Gas particles move rapidly in all directions and collide with the container walls. Each collision exerts a small outward force on the wall, and the enormous number of collisions every second adds up to a steady pressure, the force per unit area. Two changes raise the pressure: the particles hitting the walls *more often*, and each hit being *harder*.
- **Gases expand most, solids expand least**: Heating gives the particles kinetic energy, so on average they move slightly further apart and the substance expands. For the same temperature rise the order is *gases* > *liquids* > *solids*. A gas expands most because its particles are already far apart with negligible forces, so extra motion lets them spread out freely. A solid expands least because strong bonds hold its particles in place and they can only vibrate with a slightly larger amplitude.
- **Solids, liquids and gases in the particle model**: Three quantities describe every state: *spacing*, *arrangement* and *motion*. In a *solid* the particles are close together in a regular, repeating lattice, held by strong forces, and vibrate about fixed positions; it has a fixed shape and fixed volume. In a *liquid* the particles are close together but irregularly arranged, with slightly weaker forces, and slide past one another; it has a fixed volume but takes the shape of its container. In a *gas* the particles are far apart and randomly arranged, with negligible forces, moving rapidly in all directions; it has neither a fixed shape nor a fixed volume.

- **Surface colour and texture decide emission and absorption**: *Dull (matt) black* surfaces are the best emitters and the best absorbers of thermal radiation. *Shiny (polished) white or silver* surfaces are the worst emitters and worst absorbers, and the best reflectors. One rule captures it: a good absorber is also a good emitter. This is why refrigerator cooling pipes and radiators are dark, while vacuum flasks and petrol tanks are silvered.
- **Temperature measures the average kinetic energy of the particles**: Heating a substance transfers energy to its particles and makes them move faster, so the *average kinetic energy of the particles increases as the temperature rises*. In a gas the particles travel at higher speeds between collisions, in a liquid they slide past one another more vigorously, and in a solid they vibrate with a larger amplitude about their fixed positions.
- **Temperature stays constant during a change of state**: While a pure solid melts or a pure liquid boils, the temperature stays constant even though energy is still supplied. The energy is used to *overcome the forces of attraction* between the particles, not to increase their average kinetic energy, and temperature tracks the average kinetic energy. On a heating curve this is a flat, horizontal plateau: one at the melting point and one at the boiling point. For pure water at standard atmospheric pressure these are 0 °C and 100 °C.
- **The two mechanisms of conduction**: Conduction is the transfer of thermal energy through a material *without the material itself moving*, and it is the main mechanism in solids. Two processes carry the energy. *Lattice vibration*: particles at the hot end gain kinetic energy, vibrate more strongly, collide with their neighbours and pass the vibration along; this is slow and is the only mechanism non-metals have. *Free electrons*: metals contain delocalised electrons that gain kinetic energy at the hot end and travel rapidly to the cold end. Metals have both mechanisms and are excellent conductors; non-metals such as wood, plastic and air have only the slow one and are insulators.
- **The vacuum flask blocks all three routes**: A vacuum flask is designed to minimise every route by which thermal energy could leave a hot drink or enter a cold one. The *vacuum* between the double walls stops conduction and convection across the gap, because there are almost no particles to carry the energy. The *silvered walls* reduce radiation across the gap, because shiny surfaces are poor emitters. The *stopper* stops convection carrying warm air out of the open top. Radiation is the one mechanism a vacuum cannot block, which is exactly why the walls are silvered.
- **Thermal radiation needs no medium**: Thermal radiation is energy transferred as infrared *electromagnetic waves*. Unlike conduction and convection, which both need particles to carry the energy, radiation needs no medium and travels through a vacuum. It is therefore the only mechanism that can cross the vacuum of space, which is how the Sun's energy reaches the Earth. Every object emits thermal radiation, and the hotter it is the more it emits.

EXAM TIPS

TIP Where a question says "in terms of the particles", never answer in terms of heat. Name the particles and then state their *spacing*, their *arrangement* and their *motion*, together with the forces between them. Marks in this chapter are awarded for those words, not for a general description of something becoming hotter.

TIP The commonest lost mark in this topic is substituting a Celsius value into $\frac{P_1}{T_1} = \frac{P_2}{T_2}$. Add 273 to every Celsius temperature first. Heating a gas from 27 °C to 327 °C multiplies the pressure by $\frac{600}{300} = 2$, not by $\frac{327}{27} \approx 12$. Boyle's law needs no conversion, because volume has no arbitrary zero.

34 Transport in animals

KEY FORMULAS

Count of cells or platelets per mm³

$$\text{count per mm}^3 = \frac{\text{total number counted}}{\text{sample volume in mm}^3}$$

Used to convert a total cell or platelet count from a blood sample into a concentration that can be compared with a healthy range, which is always stated per mm^3.

Percentage increase in heart rate

$$\text{percentage increase} = \frac{\text{change in value}}{\text{original value}} \times 100\%$$

Used to quantify a rise in heart rate with exercise. The "change in value" is the exercise rate minus the resting rate; the "original value" is always the *resting (baseline)* rate, never the exercise rate.

KEY CONCEPTS

- **Arteries: thick, muscular, elastic wall**: *Arteries* carry blood away from the heart at *high pressure*. Their walls are *thick, muscular and elastic* and the *lumen* (central space) is relatively small. The thick elastic wall withstands the high pressure without bursting and recoils to help keep the blood moving.
- **Capillaries: a wall one cell thick**: *Capillaries* are the tiny vessels linking arteries to veins, reaching almost every cell. Their walls are only *one cell thick*, giving the shortest possible *diffusion distance* so that oxygen, glucose, carbon dioxide and wastes are exchanged rapidly between the blood and body cells.
- **Circulatory system defined**: A *circulatory system* is a system of blood vessels with a *pump* (the heart) and *valves* that keep blood flowing in one direction around the body. All three parts, vessels, pump and valves, are required by the definition; the valves are the part most often left out, and without them the pump's pressure would push blood backwards as easily as forwards.
- **Coronary arteries supply the heart muscle**: The heart muscle cannot take oxygen from the blood passing through its own chambers, so it has a dedicated supply. The *coronary arteries* branch off the aorta and run over the surface of the heart, delivering oxygenated blood to the heart muscle itself.
- **Double circulation in a mammal**: A mammal has a *double circulation*: blood passes through the heart *twice* per complete circuit. In the *pulmonary circuit* the right side of the heart pumps deoxygenated blood to the lungs and oxygenated blood returns to the left side. In the *systemic circuit* the left side pumps that oxygenated blood to the body and deoxygenated blood returns to the right side. The *septum*, a muscular wall down the middle of the heart, keeps the two supplies separate.
- **One-way valves keep blood flowing forwards**: Valves sit between the atria and ventricles and at the base of the major arteries leaving the heart. As a chamber contracts, rising pressure pushes blood forwards through the next valve; once the blood is through, the valve *shuts* to stop it flowing back into the chamber it just left. This keeps blood moving in a single direction.
- **Phagocytes and lymphocytes**: Two types of white blood cell defend the body. *Phagocytes* carry out *phagocytosis*: they engulf and digest pathogens directly, and have a smaller, lobed or irregularly shaped nucleus. *Lymphocytes* produce *antibodies*, proteins that target specific pathogens, and have a large, round nucleus filling most of the cell.
- **Red blood cell structure**: A *red blood cell* is a *biconcave disc* with *no nucleus*, packed with the red pigment *haemoglobin*. The biconcave shape gives a large surface area and a short diffusion path; the absence of a nucleus leaves more room for haemoglobin. Together these adaptations make oxygen transport efficient.
- **Single circulation in a fish**: A fish has a *single circulation*: blood passes through the heart only once per complete circuit of the body. The route is heart to *gills* (where it is oxygenated) to *body organs* (where oxygen is delivered) and back to the heart. Because the blood is forced through the narrow gill capillaries, it loses pressure there and arrives at the body organs slowly and at low pressure.

- **The four chambers of the heart**: The heart has four chambers. The two upper chambers, the *atria* (left and right), *receive* blood returning to the heart. The two lower chambers, the *ventricles* (left and right), *pump* blood out. Deoxygenated blood passes right atrium, right ventricle, then to the lungs; oxygenated blood returns to the left atrium, left ventricle, then out to the body.
- **The four components of blood**: Blood has four components: *red blood cells*, *white blood cells*, *platelets* and *plasma*. Plasma is the straw-coloured liquid that carries the cells and platelets, and the dissolved substances, around the body.
- **The left ventricle wall is thicker than the right**: The *left* ventricle wall is noticeably thicker than the right ventricle wall. The left side must pump blood all the way around the whole body (the systemic circuit), a much larger pressure task, while the right side only has to pump blood the short distance to the nearby lungs (the pulmonary circuit).
- **Veins: thin wall, wide lumen, valves**: *Veins* carry blood back to the heart at *low pressure*. Their walls are *thin*, the lumen is *wide*, and *valves* are spaced along their length to stop the low-pressure blood flowing backwards. Arteries carry no such valves, because their high-pressure blood only flows forwards.

EXAM TIPS

TIP In a percentage-increase question the denominator is always the *resting* heart rate, recorded *before* exercise begins, because a percentage increase is measured against the starting value. Dividing by the exercise (final) rate instead is the single most common error in this calculation and gives a smaller, wrong answer.

TIP A vessel is classified an artery or a vein by the *direction* blood flows, never by whether the blood is oxygenated. The pulmonary artery carries *deoxygenated* blood but is still an artery because it carries blood *away* from the heart; the pulmonary vein carries *oxygenated* blood but is still a vein because it carries blood *back* to the heart.

35 Transport in plants

KEY CONCEPTS

- **Guard cells control the stomatal pore**: Each stoma is flanked by a pair of curved *guard cells* that change shape to open or close the pore. When the guard cells are turgid the pore opens; when they lose water and become flaccid the pore closes. By controlling the size of the pore, guard cells control the rate at which water vapour diffuses out of the leaf.
- **Phloem: cargo, direction and cell type**: *Phloem* transports *dissolved food substances*, sucrose and amino acids. Movement can be in *either direction*, up or down, depending on where the plant currently needs the food. Phloem is made of *living* cells: *sieve tube elements* joined end to end, each supported by a *companion cell*.
- **Root hair cell: sole job is absorption**: Water and mineral ions enter a plant almost entirely through *root hair cells*, epidermal cells near the root tip drawn out into a long, thin projection into the soil. Their single job is absorption of water and mineral ions from the soil solution, not photosynthesis, sucrose transport or mechanical support.
- **Source and sink are roles, not fixed identities**: A *source* is any part of the plant that releases sucrose or amino acids into the phloem, for example a photosynthesising leaf. A *sink* is any part that receives and uses or stores them, for example a growing root tip or a developing fruit. Source and sink are *roles, not fixed identities*: the same organ can be a sink at one time and a source at another, depending on whether it is currently receiving or releasing food.
- **Translocation defined: sucrose and amino acids, source to sink**: *Translocation* is the movement of *sucrose and amino acids* through the phloem, from regions where they are made or stored, *sources*, to regions where they are used or stored, *sinks*. The substances are sucrose and amino acids, not glucose, starch, water or mineral ions; the tissue is the phloem; the direction can be up or down, unlike the always-upward xylem.
- **Transpiration defined: evaporation then diffusion**: *Transpiration* is the loss of water vapour from the leaves, and other above-ground parts, of a plant. It is a two-stage process: water *evaporates* from the wet surfaces of the mesophyll cells inside the leaf, forming water vapour in the leaf's internal air spaces; that vapour then *diffuses* out of the leaf through the *stomata* into the drier air outside.
- **Two adaptations of a root hair cell**: Two adaptations do the work. A *very large surface area*: the long, thin hair shape enormously increases the area of membrane in contact with the soil water, speeding up absorption. A *thin cell surface membrane* in close contact with the soil solution, keeping the diffusion and osmosis distances short.
- **Xylem: cargo, direction and cell type**: *Xylem* transports *water and dissolved mineral ions*. Movement is one-way: *upward*, from the roots to the stem and leaves. Xylem vessels are long, hollow tubes of *dead* cells joined end to end, with no cytoplasm or cell contents inside, and their walls are strengthened with *lignin*, which also lets the xylem support the plant.

EXAM TIPS

TIP Keep translocation and transpiration firmly apart despite the shared *trans-* prefix: transpiration is water vapour lost from leaves by evaporation and diffusion through the stomata; translocation is food, sucrose and amino acids, moved through the phloem between sources and sinks. Only translocation can move either up or down.

TIP Everything about transpiration rate reduces to one master idea: transpiration is fast when water vapour leaves the leaf quickly, and water vapour leaves quickly when it evaporates quickly inside the leaf and there is a steep *concentration gradient* of water vapour between the inside and the outside of the leaf. Explain every factor, temperature, wind speed or humidity, by naming which of these two levers it pulls.

TIP The examiner's favourite trap is the pairing of substance with tissue. Nitrate ions are minerals absorbed from the soil, so they travel in the *xylem*, not the phloem, even though the plant later uses that nitrogen to build amino acids, the phloem's cargo. Test every claim against cargo first: water and mineral ions mean xylem; sucrose and amino acids mean phloem.

TIP For the same number of cells, more surface area always means a faster rate of absorption of water and mineral ions, never a slower one. Longer root hairs, or more root hairs per unit area,

both increase the total absorbing surface; do not accept an option that reverses this principle.

36 Variation and selection

KEY CONCEPTS

- **Continuous variation: a range between two extremes**: *Continuous variation* produces a range of phenotypes between two extremes, with every value in between possible, such as height or body mass. It is measured on a scale rather than sorted into named groups, and it is usually controlled by many genes acting together, often together with an environmental influence.
- **Discontinuous variation: a limited number of distinct categories**: *Discontinuous variation* produces a limited number of distinct phenotypes with no intermediates, such as ABO blood group (A, B, AB or O). It is counted into named groups rather than measured on a scale, and it is usually controlled by a single gene, or very few genes, with little environmental influence.
- **Mutation: a random change in the DNA base sequence**: A *mutation* is a genetic change: a change in the base sequence of DNA, most commonly one base swapped for a different base. A mutation is a random event; it is not caused deliberately and is not produced to order by whatever the organism happens to need. Mutations occur naturally at a low rate, but the rate is increased by *mutagens* such as certain chemicals and ionising radiation.
- **Natural selection: the five-step chain**: 1. *Genetic variation*: mutation ultimately produces genetic variation within a population. 2. *Overproduction*: organisms produce more offspring than the environment can support. 3. *Struggle for survival*: competition for limited resources means not all offspring survive. 4. *Survival of the better adapted*: individuals whose alleles make them better suited to the environment have a greater chance of surviving and reproducing. 5. *Inheritance*: survivors pass on their alleles, so advantageous alleles become more common over time. The chain must stay in this order.
- **Selective breeding: the three-step process**: *Selective breeding* (artificial selection) is the human-directed version of natural selection. 1. Humans *select* individuals showing a desired feature. 2. Those individuals are *crossed* to produce the next generation. 3. The offspring showing the desired feature are *selected* to be the next generation's parents. Repeating this over generations makes the desired alleles more common.
- **Variation defined: differences within one species**: *Variation* is the differences between individuals of the same species. The differences between two different species, such as a cat and a dog, are not variation; variation is what you see comparing members of one species with each other. Variation has two ultimate causes: *genetic causes*, the alleles an individual inherits, and *environmental causes*, the conditions an individual experiences such as diet or sunlight. Only genetic variation is passed on to offspring and can be acted on by selection over generations.

EXAM TIPS

TIP Mutation is the only process that can produce a genuinely new allele; selection, natural or artificial, only sorts the variation mutation has already supplied and cannot invent an allele that was never there. Whenever a question asks how a *new* characteristic first appeared in a population, the first cause is always a mutation, never the selecting agent.

TIP Natural selection and selective breeding share one mechanism: both increase the frequency of alleles already present in a population; neither creates a new allele. They differ only in the *selecting agent*: the environment selects in natural selection, a human selects in selective breeding.

37 Waves

KEY FORMULAS

Refractive index from the angles

$$n = \frac{\sin i}{\sin r}$$

Refractive index n has no unit and is always greater than 1, because a material always slows light down. Here i is the angle of incidence in air and r is the angle of refraction in the material. Use it to find n from a measured pair of angles, or rearrange as $\sin r = \frac{\sin i}{n}$ to find the angle of refraction. Equivalently n is the ratio of the speeds of the wave in the two regions.

Speed of sound from an echo

$$\text{speed} = \frac{2d}{t}$$

An echo is sound reflected from a hard surface. The sound travels to the surface and back, so the path length is *twice* the distance d to the surface, and t is the time for the echo to return. This is the standard method for determining the speed of sound in air from a measurement of distance and time; it gives about 340 m/s. Rearranged as $d = \frac{\text{speed} \times t}{2}$ it gives the depth found from a reflected ultrasound pulse.

The critical angle

$$\sin c = \frac{1}{n}$$

The critical angle c is the angle of incidence, measured *in the denser medium*, at which the refracted ray travels along the boundary at 90° to the normal. Above c all the light is totally internally reflected. Use it to find c from n, or n from c. A smaller refractive index gives a *larger* critical angle. For ordinary glass, $n = 1.5$ gives $c = 42^\circ$, a value worth memorising.

The law of reflection

$$i = r$$

The angle of incidence i equals the angle of reflection r. Both are measured between the ray and the *normal*, the construction line drawn at 90° to the surface at the point where the ray strikes, never between the ray and the mirror surface. Use it for every plane-mirror calculation, including total internal reflection.

The wave equation

$$v = f\lambda$$

The single most used equation in this chapter. Wave speed v in m/s, frequency f in Hz and wavelength λ in m. Use it in any question that supplies two of the three quantities, rearranged as $f = v/\lambda$ or $\lambda = v/f$. Where a question gives the number of waves and a time instead of a frequency, find f first from $f = \frac{\text{number of waves}}{\text{time}}$, or from the period using $f = \frac{1}{T}$.

KEY CONCEPTS

- **Dispersion and the order of the visible spectrum**: *Dispersion* is the spreading of white light into its separate colours by refraction, as at a glass prism, producing a *spectrum*. White light is a mixture of frequencies, and each colour is refracted by a different amount, so the colours leave the prism travelling in different directions. The seven colours in order are red, orange, yellow, green, blue,

indigo, violet. Red has the lowest frequency and the longest wavelength and is refracted *least*; violet has the highest frequency and the shortest wavelength and is refracted *most*.

- **Principal axis, principal focus and focal length**: A thin converging lens refracts a beam arriving parallel to the *principal axis* so that it meets at a single point, the *principal focus* F, on that axis. The distance from the lens to F is the *focal length*, fixed by the curvature of the lens and its material. There is a principal focus on each side of the lens, and twice the focal length is marked as 2F. Rays reaching the lens from a distant object may be assumed parallel.
- **Sound is a longitudinal wave that needs a medium**: Sound is produced by a *vibrating source* and travels as a longitudinal wave, a series of *compressions*, regions of higher pressure where the particles are closer together, and *rarefactions*, regions of lower pressure where the particles are spread further apart. Because the vibration is passed on from particle to particle, sound needs a material medium and cannot travel through a vacuum, which contains no particles to carry it. In general sound travels faster in solids than in liquids, and faster in liquids than in gases.
- **The audible range and ultrasound**: The approximate range of frequencies audible to a healthy human ear is 20 Hz to 20 kHz, that is 20 Hz to $20\,000$ Hz. *Ultrasound* is defined as sound with a frequency higher than 20 kHz, which is above the upper limit of human hearing. The boundary is the definition itself, so 20 kHz is the lowest frequency that counts as ultrasound. Ultrasound is used for pre-natal scanning, for cleaning delicate equipment and for sonar depth-sounding.
- **The seven regions of the electromagnetic spectrum**: In order of *increasing frequency* and *decreasing wavelength*: radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays. All electromagnetic waves are transverse, all transfer energy, and all travel through a vacuum at the same high speed of 3.0×10^8 m/s regardless of frequency. They differ only in frequency and wavelength. Reading the list backwards gives the order of increasing wavelength.
- **Waves transfer energy, not matter**: A wave is a disturbance, produced by a vibrating source, that transfers energy from one place to another *without transferring matter*. Each point of the medium repeats its neighbour's motion a moment later, so the pattern travels outward while the particles themselves stay put. A cork on a pond bobs in place as ripples pass and is never carried to the shore. In a *transverse* wave the vibration is at right angles to the direction of energy transfer, giving crests and troughs; electromagnetic radiation, water waves and seismic S-waves are transverse. In a *longitudinal* wave the vibration is parallel to the direction of energy transfer, giving compressions and rarefactions; sound and seismic P-waves are longitudinal.
- **What virtual means**: A *virtual* image is one the light only *appears* to come from: the rays never actually meet there, so the image cannot be caught on a screen. A plane mirror always forms a virtual image, because the reflected rays diverge and only their backward extensions meet behind the mirror, where no light ever reaches. A *real* image is the opposite: the rays genuinely cross and it can be projected onto a screen, as a converging lens does for an object beyond F. The test is always the same, ask whether the rays truly meet or only seem to.
- **Which way light bends at a boundary**: Refraction is the change in direction of light as it crosses a boundary between two transparent media, caused by a change in its *speed*. Entering an optically denser medium, such as air into glass, light slows down and bends *towards* the normal. Leaving a denser medium for a less dense one, such as water into air, light speeds up and bends *away* from the normal. A ray meeting the boundary along the normal, at an angle of incidence of 0°, changes speed but not direction.

EXAM TIPS

TIP X-rays are asked about more often than any other region. Fix three facts: they lie between *ultraviolet* and *gamma rays*, so they are the second highest in frequency; their hospital use is *medical scanning*, imaging bone and detecting fractures, and they are also used in security scanners; their hazard is *mutation or damage to cells in the body*, because their high frequency carries enough energy to penetrate deeply. Do not confuse the hospital uses: X-rays *image* the body, whereas gamma rays *treat* cancer and sterilise equipment.

Generated 2026/07/17