Co-ordinated Sciences (0654)

IGCSE • Extended • CAIE

Standard Cheat Sheet

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

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

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.

Acid with a reactive metal

$$Mg(s) + H_2SO_4(aq) \rightarrow MgSO_4(aq) + H_2(g)$$

Used whenever a metal above hydrogen in the reactivity series meets a dilute acid: the products are a salt and hydrogen. The tell-tale observation is bubbles of a gas that gives a squeaky pop with a lit splint. Sulfuric acid supplies two hydrogens itself, so it needs no coefficient with a $2+$ metal. A monoprotic acid does need one: $Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$. The metal is added as a solid, the dilute acid is aqueous, the soluble salt is aqueous and the hydrogen escapes as a gas.

Amphoteric oxide: zinc oxide with an acid and with a base

$$with acid : \text{ZnO(s)} + 2\text{HCl(aq)} \rightarrow \text{ZnCl}_2\text{(aq)} + \text{H}_2\text{O(l)} \cdot with base : \text{ZnO(s)} + 2\text{NaOH(aq)} \rightarrow \text{Na}_2\text{ZnO}_2\text{(aq)} + \text{H}_2\text{O(l)}$$

Used to show amphoteric character in equations: the *pair* is the evidence, because each reaction alone proves only one half. Reacting with hydrochloric acid to give a salt and water is basic behaviour; reacting with sodium hydroxide to give a salt (sodium zincate) and water is acidic behaviour. Aluminium oxide behaves identically: $Al_2O_3(s) + 6HCl(aq) \rightarrow 2AlCl_3(aq) + 3H_2O(l)$ with an acid, and it dissolves in excess sodium hydroxide to give sodium aluminate and water. Note that both reactions give a salt and water, which is why both count.

The ionic equation for a carbonate with an acid

$$CaCO_3(s) + 2H^+(aq) \rightarrow Ca^{2+}(aq) + H_2O(l) + CO_2(g)$$

Used where a question asks for the *ionic* equation of a carbonate neutralising an acid, rather than the full one. Build it from the full equation by writing the acid as its hydrogen ions and cancelling whatever appears unchanged on both sides. With nitric acid the nitrate ion, NO_3^-, is the spectator ion; with hydrochloric acid the chloride ion is. The carbonate stays as $CaCO_3(s)$ because it is an insoluble solid, not free ions in solution. Two hydrogen ions are needed because the calcium ion carries a $2+$ charge.

The preparation equations for the soluble-salt routes

$$metal :\text{Zn(s)} + \text{H}_2\text{SO}_4\text{(aq)} \rightarrow \text{ZnSO}_4\text{(aq)} + \text{H}_2\text{(g)}\cdot carbonate :\text{CuCO}_3\text{(s)} + \text{H}_2\text{SO}_4\text{(aq)} \rightarrow \text{CuSO}_4\text{(aq)} + \text{H}_2\text{O(l)} + \text{CO}_2\text{(g)}\cdot titration :\text{KOH(aq)} + \text{HNO}_3\text{(aq)} \rightarrow \text{KNO}_3\text{(aq)} + \text{H}_2\text{O(l)}$$

Used to write the equation for whichever route a preparation question names. Each is just the matching characteristic reaction of the acid, so the products follow the pattern and only the reactants change. The state symbols mark the route: the metal, base or carbonate is added as (s) and the alkali in the titration route is (aq), which is exactly why the first three can be filtered off in excess and the fourth cannot. The salt is (aq) in every route, because a soluble salt stays in solution until it is crystallised.

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.
- **Insoluble salts by precipitation**: An *insoluble* salt cannot be made by any soluble-salt route, because there is no solution to crystallise. It is made by *precipitation*: mixing two solutions, each supplying one of the ions needed, so the insoluble salt forms at once as a solid. Mixing aqueous lead(II) nitrate with aqueous potassium iodide precipitates lead(II) iodide. The method is four verbs in order: *mix* the two soluble solutions; *filter* to collect the precipitate as the residue, the soluble by-products passing through as the filtrate; *wash* the residue with a little distilled water to rinse away soluble impurities clinging to it; *dry* the washed solid. Both starting solutions must be soluble, which is what makes the ions available to combine.
- **Strong versus weak acids at equal concentration**: A *strong* acid ionises far more fully in water than a *weak* acid, so at the *same concentration* it releases more hydrogen ions and therefore has the *lower pH*. Hydrochloric acid is strong and ethanoic acid is weak, so at equal concentration hydrochloric acid sits redder and lower on the universal indicator scale while ethanoic acid sits orange. The comparison is only valid when the question states that the concentrations are equal, because concentration also moves the pH. Answer such questions by mapping colour to pH first, then attributing the difference to how fully each acid releases its hydrogen ions.
- **Water of crystallisation**: *Water of crystallisation* is water chemically built into the structure of a crystal as it forms, which is what makes a substance *hydrated*. Heating a hydrated salt drives that water off as steam and converts it to the *anhydrous* form; hydrated copper(II) sulfate is blue and anhydrous copper(II) sulfate is white. Heating is continued *until the mass stops falling*, which is the evidence that all the water of crystallisation has gone: while mass is still being lost, water is still leaving. The change is reversible, which is why anhydrous copper(II) sulfate turning white to blue is used as a test for water.
- **Why oxide character changes across a period**: Because oxide character follows the character of the element, it tracks position in the Periodic Table. *Metallic character decreases from left to right across a period*, so the oxides shift in step: basic on the metal side (sodium oxide, magnesium oxide), through *amphoteric* in the middle (aluminium oxide), to acidic on the non-metal side (silicon dioxide, phosphorus and sulfur oxides). Metallic character also increases *down* a group, so the oxides become more basic down a group. The trend explains why the two amphoteric oxides sit where they do: they belong to elements on the metal and non-metal boundary, so they can act as either.

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 $\mathrm{HNO_3}$, because the salt takes two of the non-metal ions: $\mathrm{ZnCO_3(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2O(l) + CO_2(g)}$. 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.

TIP Acid + metal $\rightarrow$ salt + hydrogen only holds for a metal *above hydrogen* in the reactivity series, such as magnesium, zinc or iron. Copper lies below hydrogen and does not react with dilute acids at all, so a question offering copper and dilute sulfuric acid is testing whether you spot the non-reaction. The trap is that copper *compounds* behave normally: copper(II) oxide and copper(II) carbonate both react with dilute acids, because those follow the base and carbonate patterns, which have no reactivity requirement. Check whether the question gives you the *metal* or a *compound* of it before choosing the pattern.

TIP Where an oxide is reported to react with an acid *and* with sodium hydroxide, the reaction with sodium hydroxide is the one that settles the classification. A purely basic oxide *cannot* react with a base, so that second reaction is proof the oxide can also act as an acid, which makes it amphoteric. Reading only the acid reaction leads straight to the standard wrong answer, "it is a basic oxide" or "it is a strong base". Scan the question for a *second* reaction before classifying, and quote it in your answer: the mark is for recognising that reacting with both is what amphoteric means.

2 Atoms, elements and compounds

KEY FORMULAS

Electronic configuration of the first twenty elements

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

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

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

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 ${}^{A}_{Z}\text{X}$. 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: ${}^{23}_{11}\text{Na}$ has $23-11=12$ neutrons.

Electron count in an atom and in an ion

$$\text{atom}:\ \text{electrons} = \text{protons} = Z \qquad \text{ion}:\ \text{electrons} = Z - \text{charge}$$

Use to count electrons in any atom or ion. A neutral atom balances Z protons against Z electrons, which is why it carries no overall charge. Forming an ion moves only electrons, never protons, so subtract the charge: Al^{3+} has $13-3=10$ electrons while keeping its 13 protons.

Ionic formula by charge balance

$$\text{total positive charge} = \text{total negative charge}$$

Use to build any ionic formula from the two ion charges, or to find one charge given the formula and the other. The compound must be electrically neutral overall, so the ratio of ions is forced. Al^{3+} with O^{2-}: two Al^{3+} give $6+$ and three O^{2-} give $6-$, which balance, so aluminium oxide is Al_2O_3.

Number of covalent bonds an atom forms

$$\text{bonds} = 8 - (\text{number of outer-shell electrons})$$

Use to predict how many covalent bonds a non-metal forms before drawing a dot-and-cross diagram. Carbon (4 outer) forms 4, nitrogen (5) forms 3, oxygen (6) forms 2 and chlorine (7) forms 1. Hydrogen is the exception: it needs only 2 electrons to fill its first shell, so it forms 1 bond.

Reading an isotope symbol

$$^{A}_{Z}\mathrm{X}: \ \text{protons} = Z, \quad \text{neutrons} = A - Z, \quad \text{electrons} = Z$$

Use to read every particle count straight off an isotope symbol. For the ion form $^{A}_{Z}\mathrm{X}^{n\pm}$ the nucleus is untouched, so the proton and neutron counts read exactly the same; only the electron count moves, by the charge. A positive charge means electrons were lost, a negative charge means electrons were gained.

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.
- **Conduction and malleability from the electron sea**: *Good electrical and thermal conductivity*: the delocalised electrons are free to move through the lattice, and moving charge is an electric current. The electrons move, not the ions. *Malleable and ductile*: when a force is applied, layers of positive ions slide over one another into new positions and the delocalised electrons move with them, keeping the attraction intact. Because the bonding is non-directional, no specific bond has to break, so the metal changes shape instead of shattering. Contrast the ionic lattice, where sliding a layer brings like charges together and the crystal splits.
- **Diamond and graphite: same element, opposite properties**: *Diamond*: each carbon forms four covalent bonds to four other carbons in a rigid three-dimensional network, so it is extremely hard and does not conduct, because all four outer electrons per carbon are used in bonding. *Graphite*: each carbon forms only three covalent bonds, creating flat layers of hexagonal rings held to each other by weak forces, so the layers slide and graphite is soft and slippery; the fourth outer electron of each carbon is *delocalised* and free to move, so graphite conducts. Both are pure carbon, which is the headline: structure, not composition, sets the properties.
- **Properties of ionic compounds from the lattice**: Reason from the giant lattice every time. *High melting and boiling points*: every ion is held by strong electrostatic forces to many neighbours in every direction, so melting overcomes a vast number of strong forces at once. *Conducts only when molten or dissolved*: conduction needs charged particles free to move, and in the solid the ions are locked in fixed lattice positions, but melting or dissolving frees them. *Brittle*: a blow shifts one layer so that ions of the same charge line up opposite each other, they repel, and the crystal splits.
- **Properties of simple molecular substances**: A simple molecular substance is made of small, separate molecules: strong covalent bonds *inside* each molecule, only weak intermolecular forces *between* them. *Low melting and boiling points* follow, because melting overcomes only the weak forces between molecules, so many of these substances are liquids or gases at room temperature. They *do not conduct electricity in any state*, because the molecules are neutral with no free ions and no free electrons to carry a current.
- **Telling a compound from a mixture**: Two diagnostics settle every classification question. First, *can the proportion vary?* If it can, the substance is a mixture, because a compound is locked to one fixed ratio by its bonding. Second, *did a new substance with new properties form?* If it did, a chemical bond has formed and the substance is a compound. Alloys such as brass and duralumin fail the first test, so they are mixtures, not compounds.
- **The outer shell drives all chemistry**: Atoms react to reach a *full outer shell*, the stable arrangement of a noble gas. Metals, with few outer electrons, tend to lose them; non-metals, with nearly full outer shells, tend to gain or share. Everything about ionic, covalent and metallic bonding is a consequence of that single drive, and it is why the nucleus takes no part in a chemical reaction.

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.

TIP Full marks turn on stating *which* particle carries the charge. In a *metal* the delocalised electrons move while the positive ions stay in their lattice positions. In a *molten or dissolved ionic* compound the ions themselves move, and there are no free electrons. A *simple molecular* substance never conducts, because nothing is free at all. Claiming that metal ions move is the single most common error in this topic.

TIP A positive charge means electrons were *lost*, never that protons were gained. Protons are locked in the nucleus and take no part in ion formation, so a positive ion has exactly the same number of protons as the neutral atom it came from and simply has fewer electrons. Where a question asks what happens to an atom as Al^{3+} forms, the answer is that it loses 3 electrons.

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.
- **A fat is a fixed assembly, not a polymer of many units**: A polysaccharide such as starch is *many* identical glucose units joined in a long chain. A fat, in contrast, is a small fixed assembly of *two different* kinds of unit: one glycerol and three fatty acids. Describing a fat as being "made from smaller molecules" is correct, but writing "many" for the number of units, as if it were a polymer, is not.
- **Benedict's test is semi-quantitative**: As the concentration of reducing sugar rises, the colour on heating with Benedict's solution passes through a sequence: green, then yellow, then orange, then brick-red. The final colour reached, and how quickly it develops, indicate roughly *how much* reducing sugar is present, not merely whether any is present at all.
- **Starch, glycogen and cellulose: one building block, three roles**: All three named polysaccharides are polymers of glucose, yet each plays a different role. *Starch* stores energy in plants; *glycogen* stores energy in animals (and fungi); *cellulose* forms the structural material of plant cell walls. The syllabus point worth stating explicitly is that identical building blocks can produce molecules with completely different functions.
- **The four food tests at a glance**: Each biological molecule has exactly one test: *iodine* for starch, *Benedict's* for reducing sugar, *biuret* for protein, *ethanol then water* for fat. Reading a full panel of results is mechanical: take each test in turn, decide positive or negative from the colour, and list only the molecules whose tests were positive.

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.

TIP An unchanged orange-brown with iodine, or an unchanged blue with Benedict's or biuret, is a completed negative test, not a test that failed to run. On a panel of four results, treat every "no change" colour as evidence of absence and list only the molecules whose tests actually changed colour.

TIP Both biuret and Benedict's solutions start *blue*, which is the classic confusion in a mixed panel. Biuret needs no heating and turns *purple* for protein; Benedict's needs heating and turns *brick-red* for reducing sugar. Check the procedure as well as the final colour before naming the test.

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.

Image size from actual size and magnification

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

The third rearrangement of the magnification formula, used to predict how large a drawing or photograph of a specimen will be at a given magnification.

Micrometres to millimetres

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

Used to convert a length quoted in micrometres back into millimetres, the unit most rulers and drawings use. Divide by 1000, the reverse of the mm-to-µm conversion.

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*.
- **Mitosis makes identical cells for growth and repair**: Mitosis is the cell division that produces new body cells. It gives two new cells, genetically identical to the parent cell and to each other. It happens for two reasons: *growth*, an organism getting bigger by increasing its number of cells, and *repair and replacement*, since worn-out, damaged or dead cells such as skin and blood cells are constantly replaced, so division continues throughout life, not only during childhood.
- **Specialised cells: feature to function**: *Ciliated cell* (lining the airways): tiny hair-like cilia beat to sweep mucus, and trapped particles, along the airway. *Root hair cell*: a long, thin extension into the soil gives a large surface area for absorbing water and mineral ions. *Red blood cell*: a biconcave disc shape gives a large surface area and short diffusion path, and having no nucleus leaves more room for haemoglobin. *Palisade mesophyll cell*: packed with chloroplasts to absorb the most light for photosynthesis.

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.

TIP Two clues decide an unlabelled structure: relative size and shape. *Ribosomes* are the smallest, drawn as many tiny dots scattered through the cytoplasm. *Mitochondria* are oval organelles with a folded inner membrane, usually present in several copies. The *nucleus* is a single, large, rounded structure, typically the most prominent feature in the cell. Reason from the description given, not from a memorised position.

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.
- **Excretion is not egestion**: Excretion removes the waste products of *metabolism*, which the body made itself, and substances in excess of requirements. Egestion removes *undigested food* as faeces from the gut. That material was never absorbed into the body's cells and was never part of metabolism; it simply passed through. Because it is not a metabolic waste, egestion is not excretion.
- **Growth is not reproduction**: Growth makes one existing organism larger: a permanent increase in its own size and dry mass. Reproduction makes new, separate individuals and so increases their *number*. The test is whether the process ends with a bigger organism (growth) or with more organisms (reproduction). Reproduction covers *sexual* reproduction (two parents, gametes joining) and *asexual* reproduction (one parent, genetically identical offspring), so runners and budding count as well as seeds.
- **Respiration is not breathing**: Respiration is *chemical* and takes place inside every living cell, breaking down nutrient molecules such as glucose to release energy for metabolism. Breathing, properly called *ventilation*, is *physical*: the mechanical movement of air into and out of the lungs. Breathing 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.
- **Sensitivity needs a stimulus and a response, not a nervous system**: Every example of sensitivity has two parts: a *stimulus*, the change that is detected, and a *response*, what the organism does in reply. The definition specifies no mechanism, so a nervous system is not required. A plant achieves sensitivity through changes in guard-cell turgor or through uneven growth, so stomata closing as water loss rises is genuine sensitivity.

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.

TIP Where a growth question mentions eating, drinking or a full gut, the added mass is food or water passing through and is later egested or lost, so it is not growth. Apply the two decisive words,

permanent and *dry mass*, and the trap resolves: only a lasting increase in the organism's own living material counts.

TIP For any question asking whether an event is sensitivity, state the change that is detected and the reply that follows. A vague answer such as "it reacts" usually scores nothing, whereas naming both parts secures the mark.

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.

Activation energy of the reverse reaction

$$E_a(\text{reverse}) = E_a(\text{forward}) + |\Delta H|$$

Used to compare the two directions of a reaction on one set of axes. Both directions climb to the same peak, but the reverse of an exothermic reaction starts from the lower products line, so it must climb the forward barrier plus the size of the enthalpy change.

Enthalpy change of the reverse reaction

$$\Delta H(\text{reverse}) = -\Delta H(\text{forward})$$

Used when a question gives the enthalpy change one way and asks for it the other way. The same two energy levels are involved with their roles swapped, so the magnitude is identical and only the sign reverses. An exothermic reaction always has an endothermic reverse.

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.
- **A catalyst lowers the activation energy but never the enthalpy change**: A catalyst speeds a reaction up by providing an alternative pathway with a *lower activation energy*, so a smaller hump has to be climbed and a greater proportion of collisions have enough energy to react. It leaves ΔH *unchanged*, because the reactants and the products are the same chemicals at the same two energy levels. The reaction gets there more easily, not further.
- **Activation energy and enthalpy change are two different distances**: Both are read from the *reactants line*, but they run in different directions. The activation energy runs vertically up to the *peak* of the curve. The enthalpy change runs across to the *products line*. They are not interchangeable, and an E_a question never needs the products energy while a ΔH question never needs the peak.
- **The five features of a fully labelled pathway diagram**: A complete diagram shows: energy on the vertical axis against progress of the reaction on the horizontal axis; a flat *reactants line* and a flat *products line*, products lower for exothermic and higher for endothermic; a *hump* joining them; an E_a *arrow* from the reactants line up to the peak; and a ΔH *arrow* from the reactants line across to the products line, pointing down for exothermic and up for endothermic.

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.

TIP Decide "products up or down?" and draw both flat lines first, then add the hump and the two arrows. Committing to the classification before drawing the curve stops the common error of producing an exothermic shape for an endothermic reaction. Label both arrows separately: reactants to peak is E_a, reactants to products is ΔH.

TIP Where a reaction is unfamiliar, classify it by matching it to an anchor. Combustion and neutralisation are reliably *exothermic*; thermal decomposition and evaporation are reliably *endothermic*. A question that lists several equations and asks which have a products-lower pathway is asking which are exothermic, so pick out the combustions.

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

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

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.

Catalysed decomposition of hydrogen peroxide

$$2\text{H}_2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{O}_2$$

Used as the standard catalysed reaction, sped up by manganese(IV) oxide and followed by collecting the oxygen. Note what the equation does *not* show: the catalyst appears nowhere in it, because it is regenerated and chemically unchanged at the end, so it is neither a reactant nor a product. If it is shown at all it is written above the arrow.

Reduction of iron(III) oxide in the blast furnace

$$\text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2$$

Used to prove a reaction is redox from the equation alone, by tracking where the oxygen goes. The Fe_2O_3 becomes Fe, losing its oxygen, so the iron(III) oxide is reduced; the CO becomes CO_2, gaining that oxygen, so the carbon monoxide is oxidised. Both happen together, which is the definition of redox. The same reading applies to any metal extraction, such as $\text{SnO}_2 + \text{C} \rightarrow \text{Sn} + \text{CO}_2$.

Thermal decomposition of calcium carbonate

$$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$$

Used as the standard example of a thermal decomposition, where a single compound is broken down into simpler substances by heat. Read the shape of the equation rather than memorising the chemicals: one reactant splitting into two products, driven by heating, is a thermal decomposition, and the new substance formed makes it firmly a chemical change.

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.

- **Choosing a method to measure a rate**: A rate is followed by measuring something that changes as the reaction proceeds, recorded at fixed time intervals. Three methods cover almost every case. *Collecting a gas* in a gas syringe reads the volume directly, and suits a reaction whose obvious product is a gas, such as a carbonate with an acid. *Loss of mass* stands the flask on a balance and records the falling mass as gas escapes, and suits a reaction losing a heavy gas such as carbon dioxide. The *disappearing cross* times how long a clouding mixture takes to hide a mark beneath it, and suits sodium thiosulfate with an acid, where sulfur clouds the mixture.
- **Reading a rate graph**: A rate graph plots volume of gas, mass, or amount of product against time, and three readings come off it. The curve is *steepest at the start*, where the rate is fastest, and *flattens* as reactants are used up. Where it becomes *horizontal* the reaction has finished, because a reactant has run out and no more product is being made; a constant final reading is not a sign of a catalyst, a temperature change or a maximum rate. Comparing two curves, the *steeper* one had the faster rate, and the *height at which each levels off* is the total amount of product.
- **State symbols record the state, not the type of change**: The state symbols are (s) solid, (l) liquid, (g) gas and (aq) aqueous, meaning dissolved in water. They are a compact record of what physically happens, and they carry no information about whether a change is chemical: a reaction can produce an (aq) product and still be firmly a chemical change, while $\mathrm{H_2O(l)} \rightarrow \mathrm{H_2O(g)}$ changes only the state symbol and is physical. Where the formula is identical on both sides and only the symbol differs, the change is physical.
- **Why the electron definition is more general**: Every oxygen transfer is also an electron transfer, but not every electron transfer involves oxygen, so the electron definition catches strictly more reactions. Magnesium reacting with chlorine to give $\mathrm{Mg^{2+}}$ and $\mathrm{Cl^-}$ contains no oxygen at all, yet magnesium loses electrons and chlorine gains them, so it is plainly redox. The two definitions never disagree: when a metal oxide loses oxygen, the metal ions are gaining back the electrons they had given to the oxygen, so both descriptions report the same event at different depths. Where a reaction has no oxygen, only the electron definition is available.

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.

TIP Two independent quantities live in a rate graph, and most curve-comparison marks turn on separating them. *Steepness* is the rate, set by the five factors. *Final height* is the total product, set by the amount of reactant. Change surface area, concentration, temperature or add a catalyst and only the steepness changes; change the amount of reactant and only the final height changes. A slower rate does not mean less product, it means the same product takes longer, so a question that keeps the mass of reactant the same is telling you the curves must level off together.

8 Chemistry of the environment

KEY FORMULAS

Formation of the two acid-rain gases

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

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

$$2\mathrm{CO} + 2\mathrm{NO} \rightarrow 2\mathrm{CO_2} + \mathrm{N_2}$$

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 $\mathrm{N_2}$, never as a lone atom N. The catalyst itself is not consumed, so it never appears in the equation.

Calculating a volume from the composition of air

$$V_{\text{gas}} = \frac{\%\text{ by volume}}{100} \times V_{\text{air}}$$

Use to find the volume of any component in a stated volume of clean, dry air, taking nitrogen as 78%, oxygen as 21% and the other gases as 1%. For example, $500\,\mathrm{cm^3}$ of air contains $0.78 \times 500 = 390\,\mathrm{cm^3}$ of nitrogen. The remaining slice follows by subtraction: $100\% - 78\% - 21\% = 1\%$, which is how the combined carbon dioxide and noble gas figure is obtained.

Complete and incomplete combustion of carbon

$$\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2} \text{ and } 2\mathrm{C} + \mathrm{O_2} \rightarrow 2\mathrm{CO}$$

Use the first for a carbon-containing fuel burning in a plentiful supply of oxygen, giving carbon dioxide. Use the second where the oxygen supply is limited, so combustion is *incomplete* and the toxic carbon monoxide forms instead. The same distinction applies to a hydrocarbon: complete combustion of methane is $\mathrm{CH_4} + 2\mathrm{O_2} \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O}$. The amount of oxygen available decides which product forms.

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.
- **Anhydrous and hydrated, and why the tests can be reused**: *Anhydrous* means without water; *hydrated* means the solid has taken water into its structure. The colour belongs to the hydrated form, which is why the change runs white to blue for copper(II) sulfate and blue to pink for cobalt(II) chloride. The change is *reversible* by heating: driving the water off restores the anhydrous colour, so the same solid can be dried and used again. Cobalt(II) chloride is commonly supplied as blue paper for this reason.
- **Strategies to reduce acid rain, and cause against symptom**: Acid rain comes from *sulfur dioxide* and *oxides of nitrogen*, so the strategies target those gases at source. *Remove sulfur dioxide from waste gases* before they leave a power station. *Reduce the sulfur in fuels* before burning. *Fit catalytic converters* to vehicles to convert oxides of nitrogen to nitrogen. Use less fossil fuel overall. Separately, *lime* neutralises an already-acidified lake, but that treats only the *symptom*: it does not stop more acid rain forming. Tackling the cause means stopping the pollutant reaching the air in the first place.
- **Strategies to reduce the effects of climate change**: Because global warming is driven by rising greenhouse gases, the strategies target *carbon dioxide emissions* from burning fossil fuels. Generate electricity from *renewable sources* such as wind turbines and solar panels instead of coal, oil or gas. Reduce fossil-fuel use in transport and improve efficiency. *Plant trees*, which remove carbon dioxide from the air by photosynthesis. *Capture and store* carbon dioxide from power-station waste gases. A sharp point: an electric vehicle only cuts emissions if the electricity itself is generated cleanly, otherwise the carbon dioxide is merely moved to the power station.
- **Why practical chemistry uses distilled water**: Tap water carries *dissolved ions* picked up from the ground and the supply system, including chloride, calcium and sulfate. Those ions can react with the chemicals being tested, giving a false result, or alter the concentration of a solution being prepared. *Distilled water* has been boiled and the steam condensed back to liquid, leaving the dissolved solids behind, so it contains essentially no dissolved ions and cannot interfere. Water can be perfectly safe to drink and still be useless for accurate chemistry.

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.

TIP Each stage is marked on the one job it does, so a vague answer such as "it cleans the water" or "it purifies it" scores nothing. Say that carbon *removes substances causing unpleasant tastes and odours*, that sedimentation and filtration *remove insoluble solids*, and that chlorination *kills harmful microorganisms*. Note also what carbon does not do: it changes only taste and smell, and leaves both the solids and the microbes untouched.

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.

Distance travelled by an impulse

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

The rearrangement used when a question gives an impulse's speed and the time it took and asks for the length of neurone crossed.

Speed comparison between neurones

$$v_{\text{new}} = \frac{v_{\text{old}}}{\text{factor}}$$

Used whenever one neurone's impulse speed is given as a multiple of another's, such as "1.51 times slower". Divide the known speed by the stated factor, and round only at the end, to the significant figures asked for.

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.
- **Adrenaline and fight or flight**: *Adrenaline* is secreted by the adrenal glands when the body is frightened, stressed or excited, preparing it for sudden physical action. Its effects include an increased heart rate, an increased breathing rate, widened pupils and blood diverted to the muscles; the increased breathing rate specifically allows more oxygen to be taken in and delivered to muscles for respiration.
- **Blood glucose control**: When blood glucose is too high, the pancreas releases *insulin*, which causes the liver to convert excess glucose into glycogen for storage, so blood glucose falls back to normal. When blood glucose is too low, the pancreas releases *glucagon*, which causes the liver to convert stored glycogen back into glucose, so blood glucose rises back to normal. The two hormones have opposite effects even though one gland makes both.
- **Endocrine glands and their hormones**: The pancreas secretes *insulin* and *glucagon*; the adrenal glands, one on top of each kidney, secrete *adrenaline*; the testes secrete *testosterone*; the ovaries secrete *oestrogen*. An endocrine gland releases its hormone directly into the blood, with no duct. The two most tested facts are that the pancreas secretes two hormones and that the adrenal glands sit on top of the kidneys.
- **Reflex action defined**: A *reflex action* is a fast, automatic response to a stimulus that does not involve conscious control by the brain. Because the impulse can be processed by the spinal cord alone, the response is quicker than one that waits for the brain, which is why a protective withdrawal happens before the pain is consciously felt.
- **Sense organ versus receptor**: A *sense organ* is a group of receptor cells that responds to a specific stimulus such as light, sound, touch, temperature or chemicals; the *receptor* is the individual cell that detects the stimulus, and the sense organ is the structure built around a population of those cells. A sense organ and a sensory neurone alone cannot produce a coordinated response: the CNS, via a relay neurone and a motor neurone, is still needed to reach an effector.
- **Skin structures for thermoregulation**: The *sweat gland* is a coiled tube deep in the dermis with a duct leading to a pore at the surface. The *hair erector muscle* is a small muscle at the base of a hair follicle that contracts to pull the hair upright, trapping a layer of insulating air. *Arterioles* supplying the skin capillaries widen or narrow to control how much blood reaches the surface; the capillaries themselves cannot change diameter.

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".

TIP For any question asking whether an event is sensitivity or a reflex, state the change that is detected and the reply that follows in full. A vague answer such as "it reacts" scores nothing; naming both parts secures the mark.

TIP Of the glands the syllabus names, only the pancreas secretes a pair of hormones, insulin and glucagon. A question describing a gland "in the abdomen near the stomach, secreting two hormones" is naming the pancreas even before its position is given.

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.
- **Antibody marking and clumping make phagocytosis easier**: When antibodies bind to the antigens on a pathogen, they mark that pathogen and clump several pathogens together. A marked, clumped pathogen is far easier for a phagocyte to recognise and engulf than an unmarked one, so the antibody response and the cellular defence work as one system rather than two separate ones.
- **Hygiene and sanitation measures act on transmission**: Hand washing removes pathogens from hands before they reach the mouth, food or another person. Cleaning and disinfecting surfaces lowers pathogen numbers on objects people touch. Safe disposal of waste and sewage stops pathogens in waste from reaching water and food. Clean drinking water and safe food handling remove routes of indirect transmission. Sterilising equipment kills pathogens on instruments. Every one of these acts by reducing the number of pathogens being passed between people and objects, which is why the body's defences are less likely to be overwhelmed.
- **Memory cells make active immunity long-lasting**: After an infection or a vaccination, some lymphocytes remain in the body as *memory cells*. On a later encounter with the same antigen, memory cells respond much faster and in greater numbers than on the first encounter, so the

pathogen is destroyed before it causes illness. Memory cells, not the first burst of antibodies, are what makes active immunity long-lasting.

- **Vaccination protects the whole population, not only individuals**: When a large majority of a population is vaccinated, most individuals cannot become infected or pass the pathogen on. With far fewer infected people circulating it, the chance the pathogen reaches anyone, including the unvaccinated minority, falls sharply. Widespread vaccination therefore reduces case numbers across a whole population, not only among those directly vaccinated.

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.

TIP An antibody's shape is complementary to only one antigen shape. Antibodies made after a chickenpox infection do not fit the different antigens on an influenza virus, so they give no protection against flu. Having had one transmissible disease never confers protection against an unrelated one.

TIP Apply the body-to-body test to each route on its own. Contaminated food, a droplet in the air, or a shared surface all carry the pathogen, so each of those routes is indirect, even when an infected person was clearly the original source. Only a route with nothing carrying the pathogen between the two bodies is direct.

TIP When the flu virus mutates, the shape of its surface antigens changes. Antibodies and memory cells made against last year's antigen shape no longer fit the new shape, so a new vaccine matched to the current antigens is needed each year. Diseases whose pathogen does not mutate its antigen shape, such as measles, do not need a new vaccine every year.

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.
- **A drug is taken in from outside, unlike a hormone**: The phrase "taken into the body" is the clause that separates a drug from the body's own chemical messengers. A hormone such as adrenaline also modifies chemical reactions, but the body makes adrenaline itself, so adrenaline fails the "taken into the body" test and is not a drug. Caffeine, by contrast, is taken in from a drink, so caffeine is a drug.
- **A drug modifies reactions, unlike a food which supplies energy**: A drug does not have to provide energy or building material, which is what separates it from a food. A glucose sports drink supplies energy and so is a food, not a drug. A statin, by contrast, lowers the rate at which the liver makes cholesterol: it modifies a reaction rather than supplying material for one, so it is a drug.
- **Why an antibiotic can be swallowed safely**: An antibiotic attacks a structure or process the bacterium needs but a human cell does not have, such as the bacterial cell wall or the bacterium's own ribosomes. Because human cells lack these exact targets, the antibiotic can damage the bacteria without poisoning the patient, which is why an antibiotic can be taken as a medicine.

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.

TIP Stopping an antibiotic course as soon as symptoms improve leaves the hardiest, least-affected bacteria alive. Those survivors can then reproduce, increasing the resistant fraction of the population. Completing the full prescribed course removes far more of the non-resistant bacteria before any survivors get the chance to multiply.

TIP Hygiene measures such as handwashing do not change how resistance arises through natural selection; they instead stop resistant bacteria that already exist, such as *MRSA*, from transferring between patients. Restricting antibiotic use and enforcing hygiene are complementary: one lowers how often resistance is selected, the other limits how far an already-resistant strain spreads.

TIP When an antibiotic that once cured infections easily starts to fail, the change is in the bacteria population, not in the chemistry of the drug. Repeated use killed the non-resistant bacteria each time while any resistant individuals survived and reproduced, so the proportion of resistant bacteria has grown. Never describe this as "the antibiotic got weaker" or "the antibiotic made the bacteria resistant": the resistant trait already existed by chance before the antibiotic selected for it.

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 $V_s > V_p$.

Energy in kilowatt-hours and the cost of running an appliance

$$E_{\text{kWh}} = P_{\text{kW}} \times t_{\text{h}}$$

Used for household energy and bills. Energy in kilowatt-hours is the power in *kilowatts* multiplied by the time in *hours*, and the cost is that energy multiplied by the price per kWh. Despite the "kilowatt" in its name the kilowatt-hour is a unit of *energy*, not of power.

Frequency and period of the output

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

Used to find the frequency f in hertz of an alternating e.m.f. from its period T in seconds, where T is read from an e.m.f. against time graph as the time for one complete cycle. Rearranges to $T = \frac{1}{f}$. A period of 0.020 s gives 50 Hz; watch the distractor 0.020 Hz, which is the period misread as a frequency.

Operating current and the choice of fuse

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

Used to find an appliance's normal operating current from its power rating and supply voltage before choosing a fuse. Fit the *smallest standard fuse rated above* that current; the standard ratings are 3 A, 5 A, 13 A and 30 A. A fuse rated below the operating current would blow during ordinary use, and one rated far above would not protect the appliance from a moderate fault.

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.
- **Conventional current and electron flow**: In a metal the current is carried by *delocalised (free) electrons* drifting through a fixed lattice of positive ions. *Conventional current* is defined as flowing from the *positive terminal, through the external circuit, to the negative terminal*. This is the *opposite* direction to the electron drift, a historical convention that is kept and that every rule in this chapter, including the right-hand grip rule and Fleming's left-hand rule, assumes.

- **Diodes, LEDs, thermistors and LDRs**: A *diode* allows current in one direction only, its forward direction. A *light-emitting diode* (LED) does the same and emits light while it is conducting. A *thermistor*'s resistance *falls as its temperature rises*. A *light-dependent resistor* (LDR)'s resistance *falls as the light intensity on it rises*. The last two are the components used to make a circuit respond to its surroundings.
- **How earthing makes a metal case safe**: Earthing connects a metal case, through the earth wire, to earth. If the live wire touches the case, the earth wire gives the fault current a *low-resistance path to earth*, so a very large current flows and *melts the fuse*, disconnecting the appliance and leaving the case safe. With no earth wire the fault current has no such path, stays too small to blow the fuse, and the casing *remains live*, so anyone touching it provides a path for current through their body. A *circuit breaker* does the fuse's job within milliseconds and can be reset rather than replaced.
- **How length and thickness change resistance**: Resistance is *proportional to length*, so a longer wire has a greater resistance. Resistance is *inversely proportional to cross-sectional area*, so a thicker wire has a smaller resistance. When both change at once, treat the two effects as independent factors and multiply them together at the end.
- **Increasing the turning effect of a motor**: The turning effect (couple) on the coil is increased by a *larger current*, *more turns* on the coil, and a *stronger magnetic field*. Each acts independently, so all three together give the largest turning effect. Cooling the coil, reversing the current or shortening the wires do not increase it.
- **Ohm's law and the I against V graph of a metal**: *Ohm's law*: for a metallic conductor *at constant temperature*, the current through it is directly proportional to the p.d. across it. The constant-temperature condition is part of the statement and must be quoted. The graph of I against V is therefore a *straight line through the origin*, and $R = \dfrac{V}{I}$ has the same value at every point on it, so any point on the line may be used to find the resistance.
- **Soft and hard magnetic materials**: A *soft* magnetic material such as soft iron magnetises easily but loses its magnetism as soon as the magnetising field is removed, which is why it is used for electromagnet cores and other temporary magnets. A *hard* magnetic material such as steel is harder to magnetise but retains its magnetism, which is why it is used for permanent magnets. A steel-cored electromagnet fails because it stays magnetised after the current is switched off, when it should release its load.
- **The series voltage rule**: In a series circuit the *sum of the p.d.s across the components equals the e.m.f. of the source*. This follows from conservation of energy: every joule the source gives to a coulomb of charge is delivered back to the components. With three identical lamps across a 6.0 V cell the p.d. splits equally at 2.0 V each, but it is the general rule, not the equal split, that earns the mark.
- **What changes the size and the direction of the force**: The *size* of the force increases if the *current* is increased or the *magnetic field* is made stronger, and it is proportional to the current, so tripling the current gives a force of $3F$. The *direction* is fixed by Fleming's left-hand rule from the directions of the current and the field: reversing *either* the current *or* the field reverses the force, while reversing *both* leaves it unchanged.
- **What reverses the direction of an induced current**: The direction of an induced current depends on the direction of the *relative motion* between magnet and coil and on which *pole* is used. Reversing either one reverses the induced current. A magnet pushed north pole first into a coil deflects a centre-zero galvanometer one way; pulling the same magnet back out of the same end deflects it the *opposite* way, because the field through the coil now changes in the opposite sense.
- **Why a transformer needs a.c., and step-up against step-down**: Primary and secondary coils are wound on a *soft-iron core*. An alternating current in the primary sets up a *continuously changing magnetic field* in the core, which links the secondary and induces an alternating e.m.f. in it. A steady d.c. would give a steady, unchanging field and would induce nothing after switch-on, so a transformer works only with a.c. A *step-up* transformer has more turns on the secondary and raises the voltage; a *step-down* transformer has fewer and lowers it.
- **Why electricity is transmitted at high voltage**: Chain the two equations. For a fixed transmitted power, $P = IV$ means a *high* transmission voltage gives a *small* current. The power wasted heating the cables is $P_{\text{loss}} = I^2R$, which depends on the *square* of the current, so a small current wastes far less energy. Doubling the transmission voltage halves the current and cuts the loss to a *quarter*. A step-up transformer raises the voltage for transmission and a step-down transformer lowers it again for safe use.

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.

TIP $V = IR$ needs the current through *that particular resistor*, which is unknown until the network has been reduced. Collapse every parallel group first, add the series parts to get R_{total}, find the total current from $I = \dfrac{V}{R_{\text{total}}}$, and only then work out how that current divides between the branches. Applying $V = IR$ to a single resistor before this is the commonest mixed-circuit mistake.

TIP Where a graph plots I on the vertical axis against V on the horizontal axis, its *gradient* is $\dfrac{I}{V}$, which is the *reciprocal* of the resistance and not the resistance itself. A line through $V = 6.0$ V, $I = 1.5$ A has gradient 0.25, but the resistance is $\dfrac{6.0}{1.5} = 4.0\ \Omega$. Read which quantity is on which axis, then always divide the p.d. by the current.

13 Electrochemistry

KEY FORMULAS

Cathode half-equation for copper(II) ions

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

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

$$2\mathrm{H}^+ + 2e^- \rightarrow \mathrm{H}_2$$

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

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

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.

Anode half-equation for chloride ions

$$2\mathrm{Cl}^- \rightarrow \mathrm{Cl}_2 + 2e^-$$

Used at an inert anode whenever a concentrated chloride is discharged, as in molten or concentrated aqueous sodium chloride. Oxidation, so the electrons go on the right; chlorine is diatomic, so two chloride ions are needed per molecule.

Cathode half-equation for lead(II) ions

$$\mathrm{Pb}^{2+} + 2e^- \rightarrow \mathrm{Pb}$$

Used for the cathode of molten lead(II) bromide, the standard molten binary compound. The $2+$ charge takes two electrons; one Pb appears on each side and the net charge is zero, matching the neutral atom.

Half-equation for a dissolving copper anode

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

Used at an *active* copper anode, where the metal itself is oxidised in preference to hydroxide, so no oxygen forms. This is an oxidation, so the electrons go on the right; it explains why the anode loses mass and why the blue colour holds constant.

Overall reaction in a hydrogen-oxygen fuel cell

$$2\mathrm{H}_2 + \mathrm{O}_2 \rightarrow 2\mathrm{H}_2\mathrm{O}$$

Used to state what the cell actually does: hydrogen and oxygen combine to give water and nothing else. In words, hydrogen $+$ oxygen $\rightarrow$ water. No carbon is present anywhere, which is why no carbon dioxide can form.

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.

TIP Every half-equation must balance for atoms *and* for charge, and the charge is where marks are lost. Count the electrons against the ion's charge: Cu^{2+} needs two, not one, and $2\mathrm{Na}^+$ needs two, not one. Then check the atoms, remembering that hydrogen, chlorine, bromine and oxygen are diatomic as elements.

TIP Two words decide the anode product: the *ion* present (halide against sulfate or nitrate) and the *concentration* (concentrated against dilute). Always give both in the reason. "Chlorine, because the chloride is concentrated" scores the mark; "chlorine" alone often does not.

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.
- **Activity-against-temperature and activity-against-pH share one shape**: A graph of enzyme activity against temperature and a graph of the same enzyme's activity against pH share the same general shape: a curve that rises to a single peak at the optimum and then falls. Both variables have exactly one optimum at which activity is greatest, so moving away from it in either direction reduces activity, even though the underlying cause of the fall differs (denaturation for temperature, disrupted active-site bonds for pH).
- **An inhibitor in the active site blocks the substrate, not the enzyme's shape**: An inhibitor that binds permanently to an enzyme's active site physically blocks the substrate from entering, so fewer, or no, enzyme-substrate complexes can form and the rate falls, potentially to zero. This differs from denaturation: the enzyme's own shape is unchanged, but the blocked active site is unavailable, showing that reaction rate depends on complexes actually forming, not merely on an intact enzyme existing.
- **Comparing two enzyme curves precisely**: When two enzymes are plotted on the same axes, a full-mark comparison states which reaches the higher peak (greater maximum activity), whose optimum sits at a higher or lower value, and which stays active over a wider or narrower range. A comparison that gives only the range, or only the peak height, earns only part of the available marks; state as many of the three as the graph allows.
- **Metabolism and why a little enzyme goes a long way**: The chemical reactions inside a living organism are together called *metabolism*, and enzymes catalyse essentially all of them. Because each enzyme molecule survives every reaction it catalyses and is released unchanged, a small, fixed mass of enzyme can process a much larger mass of substrate over time; the reaction eventually stops because the substrate runs out, never because the enzyme does.

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.

TIP In any enzyme investigation, temperature, pH and substrate concentration each affect rate independently, so a valid test changes only the *independent* variable, measures one *dependent* variable, and keeps every other factor, including the other two, *controlled*. If two of these differ between trials, the effect of any one factor alone cannot be identified.

TIP Activity falls the further a pH value sits from the optimum, in either direction, so the lowest activity belongs to the value that is furthest away, not necessarily the most acidic or most alkaline value offered. Measure the distance of each option from the optimum first, then rank; do not assume the extreme end of the pH scale is automatically the answer.

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.

Neutralisation of an alkali by an acid

$$\text{NaOH} + \text{HCl} \rightarrow \text{NaCl} + \text{H}_2\text{O}$$

Used as the balanced equation behind a standard acid-base titration, and the source of the mole ratio. Here the ratio is $1 : 1$, so the moles of acid at the end-point equal the moles of alkali. Read the ratio from the equation every time, because a different acid changes it: $\text{H}_2\text{SO}_4 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O}$ needs two moles of alkali per mole of acid.

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 $102\ ^\circ\mathrm{C}$ is not pure water, and the sample with the narrowest melting range is the purest.
- **Tests for anions**: *Carbonate* $\mathrm{CO_3^{2-}}$: add dilute acid, giving effervescence, and the gas turns limewater milky. *Chloride* $\mathrm{Cl^-}$, *bromide* $\mathrm{Br^-}$ and *iodide* $\mathrm{I^-}$: 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.
- **End-point, concordant titres and the rough titration**: The *end-point* is the point at which the indicator just changes colour, showing the two solutions have exactly reacted, and the *titre* is the volume run in from the burette to reach it. A *rough* titration is done first to locate the end-point approximately; near that volume the acid is then added drop by drop with swirling so the colour change is caught and not overshot. *Concordant* titres agree within about $0.10\ \mathrm{cm^3}$, and only these are averaged.
- **Filtrate and distillate are obtained differently**: The *filtrate* is the liquid that passes through the filter paper, separated by *particle size*, with no change of state; the insoluble solid trapped in the paper is the *residue*. The *distillate* is the liquid that has evaporated, passed through the condenser, cooled and been collected, separated by *boiling point* through two changes of state. So distillation separates a dissolved solute from its solvent, which filtration cannot do.
- **Reagent, observation, conclusion**: Every chemical test is marked as three separate things. The *reagent* is what you add, the *observation* is what you see, and the *conclusion* is what it proves. For a carbonate: the reagent is dilute acid, the observation is effervescence and the gas turning limewater milky, and the conclusion is that a carbonate is present. Writing "the gas is carbon dioxide" where an *observation* is asked for scores nothing, because that is the deduction, not the sight.
- **Solute, solvent, solution and saturation**: A *solute* is the substance that dissolves; a *solvent* is the liquid in which it dissolves; a *solution* is the mixture formed once the solute has fully dissolved. A *saturated solution* contains as much dissolved solute as it can hold *at that temperature*, so any extra solute stays as undissolved solid. Those closing words matter: a solvent holds more solute when hotter, so a solution saturated at one temperature is unsaturated at a higher one.
- **The three types of variable in a planned investigation**: The *independent* variable is the one changed, the *dependent* variable is the one measured, and the *control* variables are kept the same throughout. Changing only the independent variable is what makes the test fair, and therefore what makes the result *valid*. A *reliable* result is a separate idea: it is one that repeats closely when the experiment is done again.
- **Why the baseline is pencil and the solvent starts below it**: The baseline is drawn in *pencil* because pencil is carbon, which is insoluble and does not travel up the paper; an ink line would dissolve in the solvent and separate into its own spots, contaminating the chromatogram. The solvent in the tank must start *below* the baseline, or the spots would dissolve straight into the solvent instead of being carried up the paper, so no separation would occur.

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.

TIP The two effects are easy to swap, and they go opposite ways. An impurity *lowers and broadens* the melting point, so quote both effects: the solid melts over a *range* rather than at one value. An impurity *raises* the boiling point. So a measured value *below* the pure melting point and *above* the pure boiling point both point to the same conclusion, that the sample is impure.

TIP Zn^{2+} and Al^{3+} are indistinguishable with sodium hydroxide alone: both give a white precipitate that dissolves in excess to a colourless solution. Only *aqueous ammonia* tells them apart. Zinc hydroxide *dissolves* in excess ammonia to a colourless solution; aluminium hydroxide stays *undissolved*. Ca^{2+} is excluded earlier, because its white precipitate does not dissolve in excess sodium hydroxide.

TIP Every titration calculation runs the same three steps: find the moles of the *known* solution with $n = c \times \dfrac{V}{1000}$, apply the *mole ratio* from the balanced equation, then divide by the volume of the *unknown* in dm^3. The ratio converts moles of one substance into moles of the other, so omitting it only happens to work when the ratio is $1 : 1$. Convert every volume to dm^3 before the final division.

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.

Factor of increase

$$\text{Factor} = \frac{\text{new value}}{\text{old value}}$$

Used to express a rise as a multiple rather than a difference; carbon dioxide rising from 0.04% to about 4% is a factor of 100, a hundredfold increase.

Relative change compared to starting value

$$\text{Relative change} = \frac{\text{change}}{\text{starting value}} \times 100$$

Used to judge which of two changes is bigger in proportion to its own starting value, not just in percentage points; oxygen's fall of 5 percentage points is about 23.8% of its own starting value.

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.
- **Composition of inspired and expired air**: Oxygen falls from about 21% to about 16-17%. Carbon dioxide rises from about 0.04% to about 4%. Nitrogen stays at about 78%. Water vapour rises from a low, variable level to a high, saturated level. Learn the figures exactly; the examiner rewards precise numbers.
- **Five features of an efficient gas exchange surface**: A large surface area lets more gas molecules diffuse across at once; thin walls (a single layer of flattened cells) give a short diffusion distance. A good blood supply carries diffused gas away fast, a moist lining lets gases dissolve before crossing, and good ventilation refreshes the air; these three keep the concentration gradient steep. The first two are about the surface itself; the last three are about maintaining the gradient.
- **Why each gas changes: diffusion, respiration and evaporation**: Oxygen falls because it diffuses from the alveolar air into the blood and is used in aerobic respiration by body cells. Carbon dioxide rises because it is produced by aerobic respiration, carried in the blood to the lungs, and diffuses into the alveoli. Water vapour rises because it evaporates from the moist lining of the airways and alveoli into the passing air. Oxygen and carbon dioxide change through *respiration and diffusion*; water vapour changes through *evaporation*, a separate physical mechanism.

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.

TIP A full answer to "how does breathing change during exercise" states that both the *rate* (breaths per minute) and the *depth* (volume of air per breath) increase. Because total air moved per minute is rate multiplied by depth, an answer naming only rate misses the depth mark.

TIP The rise that triggers faster, deeper breathing is the *carbon dioxide concentration in the blood*, not oxygen, and it is detected by the *brain*, not the lungs. The lungs only carry out the movement the brain commands.

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.
- **Flooding after deforestation**: Tree roots normally absorb rainwater and slow its movement into rivers. Without them, more rainwater runs off the surface instead of being taken up, so rivers receive extra water quickly and their levels rise until they overflow.
- **Hunting is not overharvesting**: *Hunting* is the deliberate killing of individuals, for example poaching rhinos for their horns. *Overharvesting* is removing individuals, often by fishing or collecting, faster than the population can replace them by breeding. The fingerprint of overharvesting is the phrase "faster than the population can replace by breeding".
- **Loss of soil after deforestation**: Tree roots normally bind the soil in place and the canopy shelters it from heavy rain. Once the trees are removed, the exposed soil is no longer held, so rainfall erodes it and washes it away.
- **Two mechanisms raise atmospheric carbon dioxide**: Deforestation raises atmospheric carbon dioxide through two separate mechanisms. Fewer trees means less carbon dioxide is removed by photosynthesis. Burning or decomposing the felled trees releases the carbon stored in the wood back into the atmosphere. Both are required for full marks; quoting only the first mechanism is a half-answer.

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.

TIP Replacing natural forest with a plantation or a single-crop field is still habitat destruction even though the land stays covered in plants. Biodiversity can collapse from dozens of species to one or two while the land remains green.

TIP A seed bank stores the seeds of rare *plants*, never animal material such as DNA, scales or feathers. An option claiming to store animal DNA in a seed bank misapplies the method; the correct answer for a rare mammal is captive breeding instead.

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.

Finding a nutrient's mass from its percentage

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

Used when a percentage by mass and a total portion mass are given and the actual mass of the nutrient is asked for; rearrange the percentage-by-mass formula for the nutrient's mass.

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.

- **Deficiency diseases: keep the two pairings exact**: *Scurvy* is caused by a lack of *vitamin C* and gives swollen, bleeding gums and slow wound healing. *Rickets* is caused by a lack of *vitamin D* (and the calcium it helps absorb) and gives soft, weak bones that bend. Vitamin D is made in the skin in sunlight as well as taken in from oily fish and dairy foods, so low dietary calcium and low sunlight exposure combine to raise rickets risk.
- **Digestive functions grouped by organ**: *Ingestion* occurs at the mouth. *Digestion* occurs in the mouth (amylase), the stomach (protease and acid) and the small intestine (pancreatic and intestinal enzymes). *Absorption* of nutrients occurs mainly in the small intestine; the large intestine absorbs water. *Egestion* of undigested material occurs at the anus. The stomach, pancreas and small intestine wall are the three organs that produce digestive enzymes.
- **Energy needs are not fixed**: The energy a person needs from their diet depends on *age*, *sex* and *level of physical activity*, and on states such as pregnancy. A large, very active person needs more daily energy than a small, inactive one of the same age; the same balanced diet is simply scaled to fit the individual.
- **Surface area and the rate of chemical digestion**: Enzymes can only act on the surface of food they can reach. Physical digestion breaks food into many smaller pieces, which greatly increases the *total surface area* exposed for the same total mass, so more enzyme molecules act at once and chemical digestion proceeds faster.
- **The three digestive enzymes: substrate and products**: *Amylase* (a carbohydrase) acts on starch, producing simple sugars such as maltose. *Protease* acts on protein, producing amino acids. *Lipase* acts on fats and oils, producing fatty acids and glycerol. All three sets of products are small and soluble; all three substrates are large and insoluble.
- **Where lipase acts, and why**: Amylase is secreted by the salivary glands and the pancreas; protease is secreted by the stomach and the pancreas; *lipase is secreted only by the pancreas*. Because lipase has no second source, fat digestion happens almost entirely in the small intestine, where the pancreas releases it.

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.

TIP *Amyl*ase acts on starch (amylum, Latin for starch); *prote*ase acts on protein; *lip*ase acts on lipids (fats). Three enzymes, three substrates, three product sets; never cross the wires between them.

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.
- **Dominant and recessive alleles**: A *dominant* allele is expressed whenever it is present in the genotype, written as a capital letter. A *recessive* allele is only expressed when no dominant allele is present, that is, in the homozygous recessive genotype, written as a small letter. The same letter is used for both alleles of one gene, so the genotype tells you the phenotype directly.
- **Homozygous, heterozygous and pure-breeding**: *Homozygous* means having two identical alleles of a gene, for example DD or dd; a homozygous individual is *pure-breeding*, since crossing it with an identical genotype always reproduces that same genotype. *Heterozygous* means having two different alleles, for example Dd; crossing Dd with Dd produces a mixture of genotypes, so a heterozygous individual is not pure-breeding.
- **Inheritance of sex in humans**: One pair of the 23 human chromosome pairs is the sex chromosomes. A female is *XX*; a male is *XY*. Because the mother is XX, every egg carries an X; because the father is XY, half his sperm carry an X and half carry a Y. An X-carrying sperm fertilising the egg gives XX (female); a Y-carrying sperm gives XY (male). The father's sperm therefore decides the child's sex, and the expected ratio of male to female offspring is 1:1.
- **Why gametes must be haploid**: Body cells are diploid. If gametes were also diploid, fertilisation would double the chromosome number every generation. Meiosis halves the number to produce haploid gametes, so that when two gametes fuse the zygote is restored to the correct diploid number; this is the reason meiosis, not mitosis, produces gametes.

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.

TIP After a chromosome replicates, a cell has the same number of chromosomes but twice as many chromatids, because the two sister chromatids stay joined at one centromere and count as a single chromosome. Questions deliberately test whether the joined pair is counted once or twice; a dog cell with 78 chromosomes still has 78 chromosomes immediately before division, not 156.

TIP State the parental genotypes and phenotypes; write each parent's gametes in circles, one allele per gamete; combine the gametes in a Punnett square, one parent's gametes across the top and the other's down the side; read off the offspring genotypes from the grid; convert to phenotypes using the dominant/recessive rule; state the ratio. Examiners reward this full method, not just the final ratio.

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 $\mathrm{Ca} + 2\mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} + \mathrm{H_2}$. Use the second for a moderately reactive metal heated in steam, for example $\mathrm{Mg} + \mathrm{H_2O} \rightarrow \mathrm{MgO} + \mathrm{H_2}$. 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: $2\mathrm{Mg} + \mathrm{O_2} \rightarrow 2\mathrm{MgO}$. Metals below hydrogen, such as copper, give no reaction with dilute acid.

The balanced displacement equation

$$\mathrm{Mg} + \mathrm{ZnSO_4} \rightarrow \mathrm{MgSO_4} + \mathrm{Zn}$$

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 $\mathrm{Mg^{2+}}$ and sulfate is $\mathrm{SO_4^{2-}}$, so they combine one to one as $\mathrm{MgSO_4}$, never $\mathrm{Mg_2SO_4}$.

The three blast-furnace equations

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

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 $\mathrm{Fe_2O_3}$ plus 3 in $3\mathrm{CO}$, giving the 6 delivered by $3\mathrm{CO_2}$ on the right.

Half-equation for a metal atom forming its ion

$$\mathrm{Mg} \rightarrow \mathrm{Mg^{2+}} + 2e^-$$

Use whenever a question asks what happens to a metal atom during a reaction, or asks for reactivity "in terms of electrons". The number of electrons lost must equal the charge on the ion, so a $2+$ ion requires the loss of exactly two electrons. Zinc behaves identically: $\mathrm{Zn} \rightarrow \mathrm{Zn^{2+}} + 2e^-$. Protons are never lost in an ordinary chemical reaction.

Limestone in the blast furnace: decomposition and slag

$$\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2} \text{ then } \mathrm{CaO} + \mathrm{SiO_2} \rightarrow \mathrm{CaSiO_3}$$

Use for the role of the limestone, which is to remove impurities. In the intense heat it first thermally decomposes to calcium oxide, and the calcium oxide then reacts with the sandy silicon dioxide impurity to form molten slag. The slag is less dense than the molten iron, so it floats on top and is drawn off separately. Distinguish what happens *to the carbonate* (decomposition) from what its product does next.

The cathode half-equation for aluminium

$Al^{3+} + 3e^- \rightarrow Al$

Use for the electrolysis of aluminium oxide. The main ore is bauxite, purified to aluminium oxide and dissolved in molten cryolite to lower its melting point. The aluminium ions gain electrons at the cathode to form aluminium metal. Three electrons are needed because the ion carries a $3+$ charge.

The rusting word equation and the protecting half-equation

$\text{iron} + \text{oxygen} + \text{water} \rightarrow \text{hydrated iron(III) oxide}$ and $Zn \rightarrow Zn^{2+} + 2e^-$

Use the first to state the conditions for rusting; both oxygen and water appear as reactants, which is exactly why removing either one prevents it. Use the second for the zinc that protects iron by galvanising or by bolted-on blocks. State where the electrons go: they flow to the steel, which is why the iron is not the metal losing them.

The two half-equations of a displacement reaction

$Zn \rightarrow Zn^{2+} + 2e^-$ (oxidation) and $Cu^{2+} + 2e^- \rightarrow Cu$ (reduction)$

Use for zinc placed in copper(II) sulfate solution, where the zinc dissolves and copper is deposited. Pair the two halves for a top-band "explain in terms of electrons" mark: the more reactive metal loses electrons and the less reactive metal's ions gain them. Naming both sides earns the reasoning marks that the overall equation alone does not.

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.
- **Barrier methods and how they differ from sacrificial protection**: A *barrier* method (paint, grease or oil, plastic coating) is purely physical: it forms a layer that stops oxygen and water reaching the iron, and without both of them rusting cannot begin. It offers no protection at all where the layer is broken. *Sacrificial protection* is chemical and survives a break, because the more reactive metal corrodes in place of the iron. Zinc is both at once: a barrier while intact, and sacrificial where scratched.
- **Metals form positive ions and basic oxides**: A metal atom has few outer-shell electrons and loses them readily to form a *positive* ion. This single fact drives the whole of metal chemistry, and it is the atomic meaning of reactivity: the more readily an atom gives up its outer electrons, the more reactive the metal. It also fixes the oxide rule. A metal oxide is *basic*, meaning it reacts with an acid to form a salt and water, whereas a non-metal oxide is usually acidic.
- **Reactivity described as ease of electron loss**: The deep description of reactivity is electron loss: a more reactive metal loses its outer electrons more readily to form a positive ion. In a displacement reaction the two halves happen together. The more reactive metal is *oxidised*, losing electrons and dissolving, while the less reactive metal's ions are *reduced*, gaining those electrons and being deposited as the metal. Oxidation is loss of electrons and reduction is gain of electrons.
- **Reading a particle diagram: pure metal against alloy**: A *pure metal* shows one size of circle in a regular pattern. An *alloy* shows two or more different sizes of circle mixed together. That single visual difference is often all a diagram question tests. An alloy is not a compound on a diagram either, because the atoms are simply mixed rather than joined in a fixed ratio.

- **What the reference points carbon and hydrogen are for**: The two non-metals in the series are placed there because each answers a different question. *Hydrogen* decides acid behaviour: zinc lies above hydrogen so it displaces hydrogen from dilute acid and fizzes, while copper lies below it and cannot react. *Carbon* decides extraction: a metal below carbon can have its oxide reduced by carbon, and a metal above carbon cannot. Read off whichever reference point the question is actually about.
- **Why aluminium resists corrosion despite being fairly reactive**: Aluminium sits high in the reactivity series, yet drink cans and aircraft panels do not corrode away. Its surface reacts with oxygen to form a thin, tough layer of aluminium oxide that seals the metal underneath and stops any further attack. The metal is protected by the product of its own reactivity, which is why "corrosion-resistant" and "reactive" are not contradictory here.
- **Why electrolysis extracts aluminium when carbon cannot**: Carbon is *less* reactive than aluminium, so it cannot remove the oxygen from aluminium oxide, and no furnace temperature changes that. Electrolysis does not depend on the reactivity order at all: it uses electrical energy to transfer electrons directly to the aluminium ions. Iron is *below* carbon, so carbon monoxide is reactive enough to strip the oxygen from iron oxide and reduction in a furnace works. The deciding principle is always the position of carbon, not cost.

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.

TIP Where a question stresses that both oxygen and water are present, or that the protecting metal only touches part of the surface, a barrier explanation cannot be the answer. Bolted-on zinc blocks do not seal a hull, so the marks are for the sacrificial mechanism: zinc is more reactive than iron, so it loses electrons and corrodes instead of the steel. Let the scenario tell you which of the two mechanisms is being tested.

TIP A metal is chosen because one property meets the requirement, so identify the requirement first and then name the matching property. An aircraft must be as light as possible, so the answer is *low density*, even though aluminium is also ductile and conducts well. Reactivity decides the answer only when the requirement itself concerns corrosion or chemical attack; otherwise a position in the reactivity series scores nothing.

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.

Efficiency

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

Used to find what fraction of the energy supplied to a device does the intended job. Powers may be substituted in place of energies provided both are per second. No real device reaches 100%, because some input energy always goes to non-useful stores. A reactor releasing 2400 MJ each second and delivering 840 MJ each second electrically is $\frac{840}{2400} \times 100\% = 35\%$ efficient.

Spring constant

$$k = \frac{F}{e}$$

Used to find the stiffness of a spring from the load applied and the *extension* it produces, or rearranged to $F = ke$ and $e = F/k$. The extension e is the loaded length minus the natural unstretched length. The equation holds only up to the limit of proportionality.

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.
- **Floating, sinking and suspension**: Compare the density of the object with the density of the fluid. If the object's density is *greater*, it sinks. If it is *less*, it floats. If the two are *equal*, it stays suspended at any depth. Water has a density of 1.0 g/cm^3, so a wood block of density 0.80 g/cm^3 floats in it while a block of density 1.2 g/cm^3 sinks. Compare the two densities directly; the masses and volumes on their own decide nothing.
- **Mass and weight are different quantities**: *Mass* is the quantity of matter in an object, measured in kilograms, and it is the same everywhere in the universe. *Weight* is the gravitational force acting on that mass, measured in newtons, and it changes with location because it depends on the local gravitational field strength. An 80 kg astronaut still has a mass of 80 kg on the Moon, but her weight falls from $80 \times 9.8 = 784$ N to $80 \times 1.6 = 128$ N. Where a question asks what changes on another planet, the answer is the weight.
- **Power is the rate of transferring energy**: *Power* is the rate of doing work, or equivalently the rate of transferring energy, measured in watts where 1 W = 1 J/s. Two motors that transfer the same energy do not have the same power unless they take the same time. For a fixed amount of energy, power and time are inversely proportional: since $E = Pt$ with E fixed, halving the power doubles the time taken.
- **Terminal velocity**: A falling object accelerates, and as it speeds up the air resistance on it grows. The resultant force, weight minus drag, therefore shrinks, so the acceleration *falls*. Once drag has grown to exactly balance the weight the resultant force is zero, so the acceleration is zero and the object falls at a constant *terminal velocity*. Constant velocity means zero resultant force and zero acceleration, even though the object is still moving fast.
- **The limit of proportionality**: The *limit of proportionality* is the load beyond which the extension is no longer directly proportional to the load. Below it, a load-extension graph is a straight line through the origin and $k = F/e$ applies. Beyond it, the line curves away from the straight line, each extra newton produces more extension than the last, and the spring constant can no longer be used.
- **Turbine and generator: how a power station makes electricity**: Almost every power station follows the same three-step chain: the resource turns a *turbine*, the turbine turns a *generator*, and the generator produces the electricity. Only the first step differs between resources, and most use the resource to boil water into steam that drives the turbine. In a hydroelectric station the falling water's gravitational potential store empties into its kinetic store, that kinetic energy is transferred mechanically to the generator, and the generator outputs it electrically.
- **Wasted energy is dissipated, not destroyed**: *Wasted* energy is energy transferred to stores, usually thermal, that are not useful for the intended job. Calling it wasted does not break conservation: it has not been destroyed, only spread into the surroundings where it is too dilute to use. A heater supplied with 100 J that usefully heats the room and wastes some as sound still accounts for the full 100 J, shared between the useful and wasted stores. State where the energy *went*, never that it was lost.
- **Why a large contact area gives a small pressure**: In $p = F/A$ the force and the area are independent, so spreading the same force over a larger area lowers the pressure in proportion. A hiker of weight 700 N in boots of contact area 0.045 m^2 exerts about 15 600 Pa; snowshoes raise the area to 0.36 m^2, a factor of 8, so the pressure falls to one-eighth and the hiker sinks less into the snow. The weight has not changed. This is why skis, tractor tyres and camel feet are wide, while drawing pins and knife edges are sharp.
- **Work done equals the energy transferred**: Work is done when a force moves an object in the direction of the force, and the work done equals the energy transferred. The two are the same quantity in joules, so a motor doing 3600 J of work on a trolley on a frictionless track transfers 3600 J to its kinetic store. A forklift exerting 900 N over 1.4 m does $900 \times 1.4 = 1260$ J of work, which is also the gravitational potential energy the pallet gains.

EXAM TIPS

TIP An answer in pascals needs the area in m^2. Divide an area in cm^2 by 10 000, not by 100, because the conversion applies to both dimensions: 600 cm^2 $= 0.06$ m^2, giving $p = 840/0.06 =$

$14\,000$ Pa. Dividing by 100 gives an answer 100 times too small. Watch for a force given as a weight in a question that supplies only a mass, and convert that with $W = mg$ first.

TIP The equation $W = mg$ requires the mass in *kilograms*, because g is in N/kg. A rock of mass 250 g weighs $0.25 \times 9.8 = 2.45$ N, not 24.5 N. Divide any mass in grams by 1000 as the first line of working, before substituting. This one conversion accounts for most lost marks on weight calculations.

TIP In $E_k = \frac{1}{2}mv^2$ the square applies to the speed alone, not to the whole product. For a 2.0 kg trolley at 3.0 m/s: square first, $3.0^2 = 9.0$, then $\frac{1}{2} \times 2.0 \times 9.0 = 9.0$ J. Halving first and squaring afterwards gives a different, wrong answer. The same order matters whenever a squared term appears in a substitution.

TIP A single swing of a pendulum is too short to time accurately, because the reaction time at start and stop is a large fraction of the reading. Time *20* complete swings and divide by 20: the same reaction-time error is now spread across 20 readings, so the error in one period is 20 times smaller. State the number timed in the answer. The same reasoning applies to any short repeated event.

TIP The extension is how much *longer* the spring has become, so subtract the natural length from the loaded length first. An unstretched spring 12.0 cm long that stretches to 16.0 cm under a 6.0 N load has an extension of $16.0 - 12.0 = 4.0$ cm, giving $k = 6.0/4.0 = 1.5$ N/cm. Substituting the full 16.0 cm is the classic error and gives 0.375 N/cm.

TIP Only the part of a force acting at right angles to the line from the pivot produces a turning effect, so $M = F \times d$ needs the *perpendicular* distance. Measure from the pivot to the line of action of the force, along a line at right angles to it. A spanner turned by 60 N at a perpendicular distance of 0.24 m from the bolt gives $M = 60 \times 0.24 = 14.4$ N m. Using a slanted distance overstates the moment.

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.

Surface area of a cube

$$\text{SA} = 6s^2$$

The total surface area of a cube of side length s; used to calculate the surface-area-to-volume ratio of a cube-shaped model organism.

Volume of a cube

$$V = s^3$$

The volume of a cube of side length s; paired with the surface-area formula to find a surface-area-to-volume ratio.

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.
- **Contrast with diffusion and osmosis**: Diffusion and osmosis move down a gradient (high to low) and need no energy; active transport moves against a gradient (low to high) and requires energy from respiration. Diffusion moves any particle, osmosis moves water only, and active transport moves the particular ions or molecules a cell needs regardless of the gradient it must cross.
- **Diffusion continues until particles are evenly spread**: Diffusion continues until the particles are evenly spread, at which point *net* movement stops even though the random motion of individual particles never does. Once concentrations are equal, particles are equally likely to cross in either direction, so the two flows cancel.
- **Only water moves by osmosis**: Osmosis is defined specifically and only for *water*; mineral ions, amino acids and other solutes are held back by a partially permeable membrane, and a small non-polar molecule such as oxygen crosses membranes by ordinary diffusion, not osmosis. A *partially permeable membrane* has pores that let small water molecules through but hold back larger solute molecules.
- **Root hair cells take up water by osmosis**: Soil water is usually very dilute and so has a *higher* water potential than the more concentrated cell contents of a root hair cell. Water therefore moves by osmosis from the soil into the root hair cell, from higher to lower water potential, through the partially permeable cell membrane. As soil dries, its water potential falls; once it drops below that of the cells, water no longer enters and the plant wilts.

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.

TIP A cell packed with *mitochondria*, such as a root hair cell or a villus cell, is a strong clue that active transport is one of its main jobs: mitochondria release the energy, from respiration, that drives the carrier proteins moving particles against their gradient.

TIP Raising the temperature speeds up diffusion because particles gain *kinetic energy* and move faster and more often, not because it changes the concentration gradient. The gradient is fixed by the amounts of substance present; temperature acts through particle speed only.

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.

The relative charge of a nucleus

$$\text{relative charge of nucleus} = +Z$$

Use whenever a question gives the composition of a nucleus and asks for its overall relative charge. Only protons carry charge inside the nucleus, each $+1$, while neutrons contribute 0, so the total is simply the proton number with a positive sign. A nucleus of 8 protons and 8 neutrons has relative charge $8 \times (+1) + 8 \times 0 = +8$. The neutrons are irrelevant to charge; they add mass, not charge.

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.
- **Beta emission turns a neutron into a proton**: A beta particle is an electron, yet the nucleus holds no electrons, so the particle must be created at the moment of decay. A *neutron changes into a proton*, and the fast electron produced is ejected as the beta particle. The new proton stays behind. That mechanism explains both bookkeeping rules at once: the nucleon number is unchanged, because a neutron has simply been replaced by a proton and both are nucleons, and the proton number rises by exactly 1, because the count of protons has gone up by one. Sodium-24 (proton number 11) therefore decays to a nucleus of proton number 12, which is magnesium.
- **Ionising power and penetration run opposite ways**: In order of *increasing* ionising power the emissions run gamma, beta, alpha; in order of increasing penetration they run exactly the other way, alpha, beta, gamma. The two orders are opposite for one reason: ionising costs the radiation energy. Alpha is large, slow and doubly charged, so it interacts strongly with the atoms it passes, knocks out many electrons, and gives up all its energy within a very short distance, which is precisely why paper stops it. Gamma has neither charge nor mass, interacts only weakly, loses energy slowly and so travels far. Being the most ionising and being the least penetrating are two descriptions of the same behaviour.
- **Ionising radiation and where background comes from**: Nuclear radiation is described as *ionising* because it carries enough energy to knock electrons out of the atoms and molecules it passes through, leaving charged ions behind. That single property makes it both detectable, since a Geiger-Muller tube registers the ions created inside it, and biologically dangerous, since the same ionisation damages molecules such as DNA. *Background radiation* is the low level of ionising radiation always present around us even with no source nearby. Its sources are mostly *natural*: cosmic rays from space, radioactive rocks and soil such as granite, radon gas in the air, and isotopes in food and drink. A smaller part is *man-made*: medical X-rays, weapons-test fallout and waste from nuclear power.
- **Ionising radiation damages living cells**: Ionising radiation damages living cells in two ways worth naming separately. It can *kill* a cell outright, and it can *damage the DNA* of a cell that survives, causing a mutation that may lead to cancer. The mechanism is the ionisation itself: the radiation knocks electrons out of the molecules inside the cell, breaking them apart. Because the risk grows with the dose received, and any dose carries some risk, precautions aim to keep the dose as low as is practical rather than to reach a supposed safe threshold.
- **The nucleus is positive even when the atom is neutral**: A neutral *atom* has no overall charge only because its Z orbiting electrons, each -1, exactly cancel the $+Z$ of the nucleus. The nucleus on its own holds only protons and neutrons, so it is always positive. A common error is to reason that because the atom is neutral its nucleus must be neutral too. The two are different objects: the cancellation happens across the whole atom, not inside the nucleus.
- **The relative charges and masses of the three particles**: A *proton* has relative charge $+1$ and relative mass 1, and sits in the nucleus. A *neutron* has relative charge 0 and relative mass 1, and sits in the nucleus. An *electron* has relative charge -1 and a relative mass of about $\frac{1}{1836}$, which is treated as negligible, and orbits outside the nucleus. Two consequences follow and are worth holding together: nearly all the mass of an atom is in its nucleus, because only the nucleons have appreciable mass, and the nucleon number counts the protons and neutrons precisely because each has relative mass 1.
- **Time, distance and shielding reduce the dose**: The *dose* is the amount of ionising radiation a person absorbs, and the risk of harm rises with it, so safe handling works by cutting the dose through three levers. *Time*: spend as little time near a source as possible, since dose builds up throughout

the exposure. *Distance*: keep as far away as practical, since the radiation reaching the worker falls off with distance, which is why long-handled tongs are used rather than fingers. *Shielding*: put absorbing material between the source and people, storing sources in lead-lined containers and using lead or thick concrete as a barrier. A question naming any precaution expects the lever it uses and the reason the dose falls.

- **Which emissions change the element**: The proton number identifies the element, so any emission that changes the proton number changes the element. *Alpha* emission removes 2 protons, so Z falls by 2 and the daughter is a different element: polonium-218 ($Z = 84$) becomes a nucleus of $Z = 82$, which is lead. *Beta* emission raises Z by 1, so again the element changes. *Gamma* emission is pure energy, a high-frequency electromagnetic wave carrying no particle away, so both A and Z are unchanged and the element stays the same. Gamma is the only one of the three that leaves the element alone.

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.

TIP Isotopes must share the *proton* number. Two atoms with the same nucleon number 40, one with proton number 18 and one with proton number 20, are not isotopes at all: they are different elements that happen to have equal nucleon numbers. Check Z first and A second in any isotope question. The mirror trap is the word *ion*, which describes a difference in electron number and a net charge, whereas isotopes are neutral atoms differing only in neutrons.

TIP Every reading taken near a source includes the background as well as the source, so a raw reading overstates the activity of the source. Correct it first, then work with the corrected value throughout. A source reading 410 counts/s against a background of 10 counts/s is really 400 counts/s, and only that corrected figure halves cleanly to 200 and 100. Using the raw 410 instead makes the halvings fall on untidy numbers and every half-life read from the data comes out wrong.

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.

Substitution of methane with chlorine

$$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$$

Used for an alkane reacting with chlorine in *ultraviolet light*, the condition that must be quoted. One hydrogen atom of the alkane is replaced by one chlorine atom, giving a halogenoalkane, here chloromethane, together with hydrogen chloride.

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 $\mathrm{C}_n\mathrm{H}_{2n+2}$: 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 $\mathrm{C}_2\mathrm{H}_6$, propane $\mathrm{C}_3\mathrm{H}_8$ and butane $\mathrm{C}_4\mathrm{H}_{10}$. 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, $\mathrm{C}=\mathrm{C}$. 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 ($\mathrm{C}=\mathrm{C}$ 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 $\mathrm{C}=\mathrm{C}$ bond adds the bromine; an *alkane* leaves it orange, because it has no double bond to open. The general formula predicts the result, so $\mathrm{C}_6\mathrm{H}_{12}$ decolourises the bromine and $\mathrm{C}_6\mathrm{H}_{14}$ 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 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, CH_4; petroleum is a mixture of many hydrocarbons of different chain lengths; coal is mostly carbon.
- **Nylon, a polyamide made by condensation**: Nylon is the condensation polymer to know. A monomer carrying an $-\mathrm{NH}_2$ group at each end reacts with a monomer carrying a $-\mathrm{COOH}$ group at each end; a molecule of *water* is lost at every linkage and an *amide linkage*, $-\mathrm{CO}-\mathrm{NH}-$, joins the alternating units. Because that linkage repeats along the chain, nylon is called a *polyamide*.
- **Position numbers locate the double bond**: An alkene with four or more carbon atoms needs a number in its name, because the double bond can sit in more than one place. *But-1-ene* has the $\mathrm{C}=\mathrm{C}$ starting at carbon 1, $\mathrm{CH}_2{=}\mathrm{CHCH}_2\mathrm{CH}_3$; *but-2-ene* has it starting at carbon 2, $\mathrm{CH}_3\mathrm{CH}{=}\mathrm{CHCH}_3$. Ethene and propene need no number because only one position is possible.
- **The alcohols and the two uses of ethanol**: The alcohols are a homologous series whose members carry the $-\mathrm{OH}$ (hydroxyl) functional group and whose names end in *-ol*. The one studied here is ethanol, $\mathrm{C}_2\mathrm{H}_5\mathrm{OH}$. Its two everyday uses each come from a different property: as a *solvent*, because it dissolves many organic substances such as dyes that will not dissolve in water; and as a *fuel*, because its combustion releases a large amount of energy.
- **The carbon-to-carbon double bond**: The alkenes are unsaturated hydrocarbons of general formula $\mathrm{C}_n\mathrm{H}_{2n}$, and their functional group is the carbon-to-carbon double bond, $\mathrm{C}=\mathrm{C}$. That bond is a *double covalent* bond: two shared pairs of electrons between the two carbon atoms, not one pair and not a

transfer of electrons. It is the site that opens up in every addition reaction, which is why alkenes are so much more reactive than alkanes.

- **The four types of formula**: *Molecular formula*: how many of each atom, such as propane C_3H_8. *General formula*: the algebraic pattern for a whole family, such as C_nH_{2n+2}. *Structural formula*: the atoms grouped along the chain, such as $CH_3CH_2CH_3$. *Displayed formula*: every atom and every covalent bond drawn out individually, including the bonds to hydrogen. The word *displayed* is the one being marked whenever a question describes drawing every bond.
- **The fractions and their uses**: Each fraction has a named use, listed here from the top of the column downwards. *Refinery gas*: bottled gas for cooking. *Gasoline* (petrol): fuel for cars. *Naphtha*: feedstock for making chemicals. *Kerosene* (paraffin): fuel for aircraft. *Gas oil* (diesel): fuel for diesel engines. *Bitumen*: surfacing roads. Going up the column the fractions have shorter chains, lower boiling points, and are more flammable and less viscous.

EXAM TIPS

TIP Where a question asks how two of chain length, boiling point and column height are related, remember that a longer chain boils at a higher temperature, so chain length and boiling point never move in opposite directions. Going up the column, temperature, chain length and boiling point all decrease together. Any option that has one rising while another falls can be eliminated without further thought.

TIP Balancing the combustion of an alcohol trips students who treat it as a hydrocarbon. Count the oxygen atoms needed by the products first, then subtract the oxygen the fuel already supplies. For ethanol the products need $(2 \times 2) + 3 = 7$ oxygen atoms, the $-OH$ group supplies 1, so only 6 more are required, which is $3O_2$ and not $3.5O_2$.

TIP These two petroleum processes are a standard discriminator. Fractional distillation only *separates* molecules that are already present, by boiling point, and makes nothing new, so it is a physical change. Cracking *breaks molecules apart* into new, smaller ones using a high temperature and a catalyst, so it is a chemical change. Where a question asks how alkenes are made, the answer is cracking, because distillation cannot make a molecule that was not there.

TIP Repeat-unit questions run in both directions and one rule covers both. Going from monomer to repeat unit, open the $C=C$ into a single bond between the two backbone carbons and *keep every side group*. Going from repeat unit to monomer, put the double bond back between those same two carbons. Losing a side group or leaving a double bond in the repeat unit are the two ways the marks go.

TIP These two terms are tested together and are easily conflated. *Saturated* or *unsaturated* is decided by the type of carbon-to-carbon bond: single bonds only, or a $C=C$ present. *Hydrocarbon* or not is decided by the elements present: hydrogen and carbon only, or something else too. A molecule can pass one test and fail the other, so answer each from its own definition. Ethanol is saturated but is not a hydrocarbon, because it also contains oxygen.

TIP The bonding decides the reaction type, so name the family first. An alkane is saturated and has no double bond, so it reacts by *substitution*: one atom is swapped for another and a small by-product such as HCl is formed. An alkene is unsaturated, so it reacts by *addition*: atoms add across the double bond, everything ends up in one product and there is no by-product.

TIP Where the stem of a name is unfamiliar, the ending still fixes the family completely. An ending of *-ol* means an alcohol containing an $-OH$ group, whatever the rest of the name says; *-ane* means an alkane and *-ene* means an alkene. Read the ending first to fix the family, then work out the structure from the stem.

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.

Energy reaching a level after several transfers

$$E_n = E_0 \times 0.1^n$$

Used for a multi-step calculation where E_0 is the energy at the producer and n is the number of trophic transfers to the level of interest. Apply the 10% figure once for each arrow in the chain, not once for each organism.

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.
- **Consequences of the 10% rule: short chains and efficient producer-eating**: Because roughly 90% of the energy at a level is lost, food chains rarely exceed four or five trophic levels: after several tenfold losses too little energy remains to support a further level. The same loss makes eating producers more efficient than eating meat, since each extra feeding stage inserts another ~90% loss.
- **Food web: many chains interconnected**: Most organisms eat more than one kind of food and are eaten by more than one predator, so many food chains interconnect into a *food web*, a network of

feeding relationships with organisms linked by more than one feeding arrow. A food web is more realistic than a single chain because it shows the alternative routes energy can take.

- **Fossil fuels lock carbon away until burned**: Fossil fuels (coal, oil, natural gas) formed from the incomplete decomposition of dead organisms over millions of years under high pressure and temperature, deep underground where decomposers cannot reach the carbon. This locks the carbon out of the short-term cycle until the fuel is extracted and burned, when *combustion* releases that ancient carbon dioxide on top of the amount already cycling.
- **Three causes of energy loss at each trophic level**: *Respiration* releases energy for movement and warmth, and much of it leaves the body as heat. *Egestion* loses energy in undigested food (faeces) that was never absorbed. *Excretion* loses energy in waste products such as urea, and further energy is used in movement. Only what remains as new biomass is available to the next trophic level.
- **Why energy flow is one-way, not a cycle**: Energy passes from the Sun into producers and then outward through consumers by feeding, and at every step some energy is lost to the surroundings and never recovered. This is why ecologists speak of energy *flow* rather than an energy cycle: unlike carbon, energy makes a single one-way journey and is never recycled back to the start.

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.

TIP In a food *web*, the same organism may sit at different trophic levels along different feeding paths, so it can be both a secondary and a tertiary consumer at once. Always number trophic levels along the specific path a question describes, not by an organism's general reputation as a predator.

TIP Photosynthesis and respiration form a short-term cycle that roughly balances, removing and returning similar amounts of carbon dioxide. Any question about *rising* atmospheric carbon dioxide must look beyond this balance to combustion of fossil fuels, which adds ancient carbon on top of the amount already cycling.

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).

Atom-balance check on the symbol equation

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

Count atoms species by species to confirm or complete a balance: reactant side has 6 carbon, 12 hydrogen (all from $6H_2O$) and 18 oxygen (6×2 from CO_2 plus 6×1 from H_2O); product side matches with 6 carbon, 12 hydrogen and 18 oxygen (6 in glucose, 12 in $6O_2$). Use for "how many atoms" questions and to check a proposed equation balances.

Molecule ratios in the balanced equation

$$6CO_2 : 6H_2O : C_6H_{12}O_6 : 6O_2$$

The fixed whole-number ratio of the balanced symbol equation is 6 carbon dioxide : 6 water : 1 glucose : 6 oxygen. Use to scale up or down (any multiple of the equation still balances) and to convert between the number of molecules of one species and another, e.g. 12 CO_2 molecules make 2 glucose molecules.

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.

- **Adaptations of the leaf for photosynthesis**: Every leaf feature is an adaptation, always feature then reason: *broad and flat* for a large surface area to capture light; *thin* for a short diffusion distance; *palisade cells at the top, full of chloroplasts* for maximum light absorption where light is strongest; *large air spaces in the spongy mesophyll* for a large internal surface and free gas diffusion to every cell; *stomata mostly on the lower surface* to admit carbon dioxide while reducing water loss; *guard cells* that change shape to open and close stomata; and *xylem and phloem* in the veins to supply water and remove sugars.
- **Limiting factors and the plateau**: Three external factors change the rate of photosynthesis: *light intensity*, *carbon dioxide concentration* and *temperature*. Whichever is in shortest supply at a given moment is the *limiting factor* and caps the rate. Raising the limiting factor raises the rate; raising a factor that is not limiting changes nothing, because something else is holding the rate back. A rate-versus-light or rate-versus-carbon-dioxide graph rises while that factor is limiting, then plateaus once another factor becomes limiting.
- **Mineral ions: nitrate and magnesium**: A plant absorbs mineral ions from the soil to make molecules that carbon, hydrogen and oxygen alone cannot supply. *Nitrate ions* are needed to make amino acids, which are joined into proteins; a shortage stunts growth. *Magnesium ions* are needed to make chlorophyll; a shortage means less chlorophyll, so leaves turn yellow (chlorosis) and photosynthesis, and so growth, slows. Keep the pairings exact: nitrate to amino acids and proteins, magnesium to chlorophyll.
- **Uses of the glucose made in photosynthesis**: Glucose is not left as glucose. A plant uses it for *respiration* (broken down to release energy), converts excess to insoluble *starch* for storage, builds *cellulose* for cell walls, converts it to soluble *sucrose* for transport in the phloem, and, together with nitrate ions, uses it to build amino acids and proteins. A rigid woody stem points to cellulose; a sweet fruit points to sucrose.
- **Xylem and phloem carry materials in opposite directions**: The vascular bundle (vein) in a leaf contains two transport tissues. *Xylem* carries water and mineral ions *to* the leaf, from the roots. *Phloem* carries the sugars photosynthesis produces, mainly as sucrose, *away* from the leaf to the rest of the plant. The two tissues move materials in opposite directions relative to the leaf.

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.

TIP When a photosynthesis experiment is criticised for an uncontrolled variable (for example, a sealed bell jar becoming warmer than an open control in the same light), state which variable also differed besides the one being tested, then say how to fix it: keep every other variable the same and vary only the factor under test. Naming the missing control, not just noting "it is a bad experiment", is where the marks are.

TIP A mineral-deficiency question rewards the full chain, not just the endpoint: "less magnesium leads to less chlorophyll, which absorbs less light, which slows photosynthesis, which makes less glucose, which gives poorer growth." Each link is a potential mark, and the answer "yellow leaves, poor growth" alone typically scores less than half.

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.
- **Advantages and disadvantages of sexual reproduction**: Sexual reproduction mixes genes from two parents, so it *produces genetic variation*, the raw material for adapting to a changing environment and the basis on which natural selection acts. The cost is that it is *slower and less certain*: it needs two parents (or at least two gametes), a means of bringing gametes together, and time for offspring to develop from a fertilised egg.

- **Advantages of asexual reproduction to a wild population**: Asexual reproduction is fast, needs only one parent, and needs no mate, no pollinator and no gametes. Identical offspring are well suited to the current environment when conditions are stable and the parent is already successful in them.
- **Controlling the spread of STIs**: The spread of STIs is controlled by using condoms as a barrier during sex, not sharing needles, reducing the number of sexual partners (or abstaining), and testing and treating infected people.
- **Disadvantages of asexual reproduction to a wild population**: There is no genetic variation, so the population cannot adapt if the environment changes. Because the whole population shares one set of genes, a single disease or environmental change that harms one individual can harm every individual.
- **Human fertilisation: definition and location**: Human *fertilisation* is the *fusion of the nucleus of a sperm with the nucleus of an egg*, forming a zygote. It normally happens in the *oviduct*: sperm deposited in the vagina swim through the cervix and uterus into an oviduct, where an egg is travelling towards the uterus.
- **Insect-pollinated versus wind-pollinated flowers**: Insect-pollinated flowers have large, brightly coloured, scented petals, nectar, anthers held inside the flower, and a small sticky stigma inside, because they must *attract and coat an insect*. Wind-pollinated flowers have small, dull petals, no nectar, anthers hanging outside on long filaments, and a large feathery stigma hanging outside, because they must *release pollen into the air and catch it again*.
- **Routes of HIV transmission**: HIV is transmitted by unprotected sexual contact; by contact with infected blood (for example, sharing needles); and from an infected mother to her child (during pregnancy, birth, or breastfeeding).
- **Testosterone and oestrogen at puberty**: *Testosterone*, produced mainly in the testes, brings about *male secondary sexual characteristics* at puberty (for example, facial and body hair, a deepening voice, broadening shoulders). *Oestrogen*, produced mainly in the ovaries, brings about *female secondary sexual characteristics* (breast development, widening hips, the start of the menstrual cycle).
- **The sequence from pollination to a seed and a fruit**: Pollen is transferred from an anther to a stigma (*pollination*); the pollen grain grows a *pollen tube* down through the style towards the ovary; a male nucleus travels down the tube to an ovule and *fuses* with its nucleus (*fertilisation*), forming a zygote; the fertilised ovule develops into a *seed* and the ovary develops into a *fruit*.

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.

Word equation for anaerobic respiration in muscle

$$\text{glucose} \rightarrow \text{lactic acid}$$

Used for anaerobic respiration in human (and other animal) muscle during vigorous exercise, when oxygen cannot be delivered fast enough for aerobic respiration alone to meet demand. There is no oxygen on the left and no carbon dioxide or water on the right, only lactic acid.

Word equation for anaerobic respiration in yeast

$$\text{glucose} \rightarrow \text{ethanol} + \text{carbon dioxide}$$

Used for anaerobic respiration (fermentation) in yeast and some plant cells. Unlike muscle anaerobic respiration, this pathway does release carbon dioxide, which is why a yeast culture in a sealed vessel turns limewater milky.

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.

- **The oxygen debt defined**: The *oxygen debt* is the extra oxygen that must be taken in after exercise to break down the lactic acid that built up during exercise. It arises because vigorous exercise outstrips the oxygen the blood can deliver, forcing the muscles to respire anaerobically and accumulate lactic acid; breaking that lactic acid down again requires oxygen that is only available once the demand on the muscles has dropped.
- **Why anaerobic respiration releases less energy than aerobic respiration**: Aerobic respiration breaks glucose down *completely* to carbon dioxide and water, extracting a large amount of energy. Anaerobic respiration breaks glucose down only *partially*, to lactic acid in muscle or to ethanol and carbon dioxide in yeast, leaving much of the chemical energy still locked in those products. Because so little energy comes from each glucose molecule, a muscle respiring anaerobically must break glucose down very quickly to meet a high energy demand, so glucose is used up fast and lactic acid accumulates rapidly.

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.

TIP Anaerobic respiration in *muscle* produces only lactic acid and uses no oxygen: glucose -> lactic acid. Anaerobic respiration in *yeast* produces ethanol and carbon dioxide: glucose -> ethanol + carbon dioxide. The examiner frequently offers *glucose -> lactic acid + carbon dioxide* or *glucose + oxygen -> lactic acid + water* as wrong options for muscle; neither is correct, since muscle anaerobic respiration adds no carbon dioxide and uses no oxygen.

TIP *Diffusion*, *osmosis*, the *evaporation of sweat*, and the *reflection or absorption of light* are passive or physical events that need no energy input from respiration, even though they sound biological. If an option describes something moving down a concentration gradient or a purely physical process, it is almost certainly not a use of respiration's energy; genuine uses are active processes such as muscle contraction, protein synthesis, cell division, active transport, nerve impulses and maintaining body temperature.

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.

Converting light-years to kilometres

$$d_{\text{km}} = n_{\text{ly}} \times 9.5 \times 10^{12}$$

Used to convert a distance n_{ly} quoted in light-years into kilometres, since one light-year is about 9.5×10^{12} km. Add the powers of ten when multiplying, then write the result in standard form. Benchmarks: the Milky Way is about 1.0×10^5 light-years across and Andromeda is about 2×10^6 light-years away.

Rearranging the orbital-speed equation

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

Used where a question supplies the orbital speed and asks for the period or the radius instead. Both follow from $v = \frac{2\pi r}{T}$ by ordinary rearrangement. Keep r in m, T in s and v in m/s throughout.

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.
- **Nuclear fusion powers the Sun**: A stable star releases energy by *nuclear fusion* in its core: *hydrogen nuclei fuse to form helium nuclei*, releasing a very large amount of energy. The reaction is fusion (small nuclei joining), *not* fission (large nuclei splitting) and not the chemical burning of hydrogen in oxygen, of which there is none in the Sun. Fusion steadily converts hydrogen into helium, so the core's hydrogen proportion falls and its helium proportion rises over billions of years.
- **Red-shift is the evidence for expansion**: Light from almost every distant galaxy is shifted towards the *red*, long-wavelength end of the spectrum, which shows the galaxy is *moving away* from us. Crucially, *more distant galaxies show a greater red-shift*, so they are receding faster. That pattern, everything moving apart with the furthest moving fastest, is exactly what expansion from a single origin produces, and so supports the Big Bang theory.
- **The asteroid belt divides the inner and outer planets**: Most of the Solar System's asteroids lie in the *asteroid belt*, a band between the orbits of Mars and Jupiter. The belt marks a natural boundary: inside it sit the small rocky inner planets, outside it the giant outer planets. An asteroid found beyond Jupiter's orbit still orbits the Sun directly, but it is not a belt member.
- **The minor bodies: dwarf planets, asteroids and moons**: A *dwarf planet* is a round body that orbits the Sun directly but has *not cleared* other similarly sized objects from its orbital region; Pluto is the standard example. An *asteroid* is a small rocky body that orbits the Sun directly. A *moon* is a natural object that orbits a planet rather than the Sun. The phrase "has not cleared its orbital region" is what separates a dwarf planet from the eight planets, which have swept their paths clear.
- **The two endings depend on mass**: All stars share the start (nebula, protostar, stable star), but *mass* alone decides the ending. A star of mass similar to the Sun's becomes a *red giant*, then a *white dwarf*, then a (theoretical) *black dwarf*. A star of mass much greater than the Sun's becomes a *red supergiant*, explodes as a *supernova*, and leaves a *neutron star* or a *black hole*. Only the massive path includes a supernova.

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.

TIP Every "moon or asteroid" question resolves on one test: state *what each one orbits*. A moon orbits a planet, so it orbits the Sun only indirectly. An asteroid orbits the Sun directly. The same test settles the claim that Earth's Moon is a satellite of the Sun: it is not, because it orbits Earth and is carried around the Sun by Earth's own orbit.

TIP Planetary orbital speeds are tens of km/s, Earth's being about 3.0×10^4 m/s. An answer of 3.0×10^7 m/s is a tenth of the speed of light and cannot be right; a slip by a factor of about 10^3, almost

always an unconverted period, has been made. Carry Earth's 30 km/s as the order-of-magnitude anchor.

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.
- **Gas pressure is caused by particles colliding with the container walls**: The pressure of a gas is the combined effect of billions of particle collisions with the walls of the container every second, each collision giving the wall a tiny push. Anything that raises either the *frequency* of the collisions or the *force* of each collision raises the pressure. Every explanation of gas pressure reduces to this one mechanism.
- **Heating and cooling curves: why the flat sections occur**: A heating curve rises, holds constant while the substance melts, rises again, holds constant while it boils, then rises through the gas range; a cooling curve is the mirror image, with plateaus at freezing and condensing. Temperature measures the *average kinetic energy* of the particles, so a constant temperature means their kinetic energy is not changing. The energy still being supplied or removed is instead weakening or forming the *forces of attraction* between the particles, changing their arrangement rather than their speed.
- **Temperature and the rate of diffusion**: Raising the temperature *increases* the rate of diffusion. A higher temperature gives the particles more kinetic energy, so they move faster and spread from high to low concentration more quickly. The effect applies to every gas whatever its relative

molecular mass, and to particles dissolved in a liquid. Particles do not change size with temperature, and the concentration gradient is a separate factor.

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.

TIP These phrases are not decoration; they name the variable being held fixed and therefore the relationship being tested. *At constant pressure*, heating increases the volume. *At constant temperature*, the average particle speed cannot change, so any rise in pressure must come from the collisions becoming more frequent, never from faster particles. Read the fixed condition before deciding the answer.

TIP The mark is awarded for the collision mechanism, not for the observation. An answer that says only "the particles move more" scores nothing. State that the particles collide with the *walls of the container*, and say whether those collisions become more *frequent*, more *forceful*, or both.

TIP A definition that omits *net* describes ordinary particle motion rather than diffusion, and one that omits *random motion* invites the marker to assume an external force is at work. Quote the full wording: the *net* movement of particles from a region of higher *concentration* to a region of lower *concentration*, caused by their *random* motion. Where a question stresses that the liquid was still and unstirred, add that no external force is needed.

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 $0.1 \times 111 = 11.1\ \mathrm{g}$.

Concentration measured by mass

$$\text{concentration}\ (\mathrm{g/dm^3}) = \frac{\text{mass of solute}\ (\mathrm{g})}{\text{volume of solution}\ (\mathrm{dm^3})}$$

Use to find how much solute is dissolved in a given volume of *solution*, and rearrange to $\text{mass} = \text{concentration} \times \text{volume}$. The volume must be in $\mathrm{dm^3}$, so a figure in $\mathrm{cm^3}$ is divided by 1000 first: dissolving $15\ \mathrm{g}$ of potassium nitrate to make $500\ \mathrm{cm^3}$ gives $15 \div 0.500 = 30\ \mathrm{g/dm^3}$. Note that the volume is that of the finished solution, not of the water added.

Deducing a molecular formula from bonding numbers

$$\mathrm{Si}\ (4\ \text{bonds}) + \mathrm{Cl}\ (1\ \text{bond each}) \rightarrow \mathrm{SiCl_4}$$

Use where a question gives the number of covalent bonds each atom forms and asks for the formula of a simple molecular compound. Count the bonds like a jigsaw: the total offered by one type of atom must exactly match the total accepted by the other, with none left over. Silicon forms four bonds and each chlorine accepts one, so four chlorine atoms are needed, giving $\mathrm{SiCl_4}$. Phosphorus (three bonds) with hydrogen (one) gives $\mathrm{PH_3}$ by the same logic.

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.

- **Amount in moles is the hub of every calculation**: No quantity converts directly into another in this chapter; every route passes through *amount in moles*. Mass converts to amount by dividing by the molar mass, a particle count by dividing by the Avogadro constant, and a gas volume at r.t.p. by dividing by 24. Only once a quantity is expressed in moles can the balanced equation's mole ratio carry it across to a different substance, after which the same three relationships convert outwards again. Every stoichiometry question is therefore the same three-step shape: convert in to moles, cross with the ratio, convert out.
- **Ionic equations and spectator ions**: An *ionic equation* shows only the ions that actually take part in the reaction. A *spectator ion* is present but appears unchanged on both sides, so it is left out. Ionic equations are used most often for precipitation and neutralisation: when silver nitrate solution is added to sodium chloride solution, only the silver and chloride ions combine, giving $\mathrm{Ag^+(aq)} + \mathrm{Cl^-(aq)} \rightarrow \mathrm{AgCl(s)}$, while the sodium and nitrate ions are spectators. Both the atoms *and* the total charge must balance on each side.
- **Molecular formula and empirical formula**: A *chemical formula* uses element symbols and subscript numbers to show which atoms, and how many of each, are present. The *molecular formula* gives the *actual* number of atoms of each element in one molecule; the *empirical formula* gives only the simplest whole-number ratio of those atoms. Hydrogen peroxide has molecular formula $\mathrm{H_2O_2}$ but empirical formula HO, so the empirical formula loses the true count. The formula of an element is its bare symbol unless it exists as molecules: the seven diatomic elements are hydrogen, nitrogen, oxygen, fluorine, chlorine, bromine and iodine, written $\mathrm{H_2}$, $\mathrm{N_2}$, $\mathrm{O_2}$, $\mathrm{F_2}$, $\mathrm{Cl_2}$, $\mathrm{Br_2}$ and $\mathrm{I_2}$.
- **Why a relative atomic mass is not a whole number**: A single atom always has a whole-number mass, because it contains a whole number of protons and neutrons. An element, however, is a mixture of *isotopes* of different mass, and A_r is the *weighted average* of those isotope masses, each weighted by its natural abundance. A weighted average of whole numbers need not itself be a whole number, which is why chlorine's A_r is 35.5 and copper's is 63.5. A decimal A_r is evidence of isotopes, not of a fractional particle.
- **Why one mole of different substances has different masses**: One mole of any substance contains the same number of particles, but the particles themselves have different masses, so the samples do not weigh the same. One mole of $\mathrm{H_2}$ has a mass of $2\ \mathrm{g}$ and one mole of $\mathrm{CO_2}$ has a mass of $44\ \mathrm{g}$, yet each contains 6.02×10^{23} molecules, because a $\mathrm{CO_2}$ molecule is far heavier than an $\mathrm{H_2}$ molecule. Read the other way, this is why equal *masses* of two substances are generally *not* equal amounts: $10\ \mathrm{g}$ of neon ($A_r = 20$) and $16\ \mathrm{g}$ of oxygen ($M_r = 32$) are both $0.5\ \mathrm{mol}$, despite the different masses.

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 $\mathrm{2AlCl_3}$ 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.

TIP Two marks are routinely dropped when writing an ionic formula. First, a polyatomic ion needs brackets whenever its subscript exceeds one, so that the subscript multiplies the whole ion: iron(III) sulfate is $\mathrm{Fe_2(SO_4)_3}$, while $\mathrm{FeCl_3}$ needs no bracket because chloride is a single atom. Second, the charge-swap result must always be cancelled: $\mathrm{Mg^{2+}}$ with $\mathrm{O^{2-}}$ swaps to $\mathrm{Mg_2O_2}$, which is not the simplest ratio and scores nothing until it is reduced to MgO.

TIP The arithmetic slip that costs most M_r marks is ignoring a bracket. In $\mathrm{Ca(OH)_2}$ the subscript applies to the whole hydroxide group, so $M_r = 40 + 2 \times (16 + 1) = 74$, not $40 + 16 + 1$. In $\mathrm{Ca(NO_3)_2}$ the subscript multiplies one nitrogen and three oxygens together: $M_r = 40 + 2 \times (14 + 3 \times 16) = 164$. Expand the bracket before adding anything else.

TIP The Avogadro constant links a *number of particles* to an *amount in moles*, and nothing else. It has no relationship to a mass in grams, so a mass must always be converted to moles first: divide by the molar mass, then multiply by 6.02×10^{23}. For $5.4\ \text{g}$ of aluminium ($A_r = 27$), the amount is $5.4 \div 27 = 0.20\ \text{mol}$ and the count is $0.20 \times 6.02 \times 10^{23} = 1.20 \times 10^{23}$ atoms. Multiplying 5.4 by the Avogadro constant directly is the classic wrong answer offered in the options.

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.

Ionic charge and compound formula from group number

$$\text{Group I} \rightarrow 1+,\ \text{Group II} \rightarrow 2+,\ \text{Group VII} \rightarrow 1-$$

Used to deduce the formula of an ionic compound from position alone. A Group I atom loses its single outer electron to give a $1+$ ion, and a Group VII atom gains one electron to give a $1-$ ion. Balance the charges to get the formula: potassium with bromine gives KBr, and magnesium with chlorine gives $\mathrm{MgCl_2}$.

Variable oxidation states of iron

$\mathrm{FeCl_2}$ contains $\mathrm{Fe^{2+}}$ and $\mathrm{FeCl_3}$ contains $\mathrm{Fe^{3+}}$

Used to demonstrate variable oxidation state, the property that most sharply separates a transition metal from a Group I metal. The same element forms ions of different charge under different conditions, so the number of chloride ions needed to balance the charge changes from two to three. A Group I metal, by contrast, only ever forms a $1+$ ion.

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 (Cl_2, Br_2, 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.
- **Transition metals contrasted with Group I metals**: The two metal families are opposites on almost every count. A transition metal is hard, dense and high-melting, acts as a catalyst, forms coloured compounds and shows variable oxidation states. A Group I metal is soft, low in density and low-melting, is not a catalyst, forms white or colourless compounds and forms only a $1+$ ion. Both are metals, so both still conduct electricity and are malleable.
- **Why elements in a group share chemical properties**: Chemical reactions are governed almost entirely by the outer-shell electrons, and every element in a group has the *same number* of them: Group I atoms all have one to lose, Group VII atoms all have seven, one short of a full shell. Going down a group, each successive element has one more filled inner shell, so the outer electrons lie further from the nucleus and are screened from its pull by more inner shells, an effect called *shielding*. That single fact drives every down-a-group trend in the chapter.
- **Why noble gas boiling point increases down the group**: Separate noble-gas atoms are held near one another only by weak intermolecular forces, not by chemical bonds. Going down the group the atoms are larger and carry more electrons, so these weak forces between neighbouring atoms become *stronger*. Stronger forces need more energy to overcome, so the boiling point rises from helium downwards. Unreactivity is set by the full outer shell, which is a separate matter, so a shared unreactivity does not force the boiling points to be equal.
- **Why reactivity decreases down Group VII**: A halogen reacts by *gaining* one electron to complete its outer shell, the mirror image of Group I. Going down the group, the incoming electron would enter a shell further from the nucleus and behind more shielding, so it is attracted less strongly and gained less readily. Reactivity therefore *decreases* down Group VII while it *increases* down Group I: the same reasoning about distance and shielding gives opposite answers because one family loses an electron and the other gains one.
- **Why reactivity increases down Group I**: Every Group I atom has one outer-shell electron, and reactivity is governed by how easily that electron is lost. Going down the group each atom has one more filled inner shell, so the outer electron lies further from the nucleus and is more *shielded* by the inner electrons. Both effects weaken the nuclear hold on it, so it is lost more easily and reactivity rises. The common wrong answers reverse the facts: the number of outer electrons stays at one, proton number *increases* down the group, and atoms get *larger*, not smaller.

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.

TIP Turn "does it react?" into a check on position: displacement occurs only when the added halogen sits *higher* in Group VII than the halogen already in the salt. Higher means more reactive, and the more reactive halogen wins. A halogen can never displace one above it, so bromine added to potassium chloride solution gives no reaction and no colour change.

TIP A phrase such as "on the left-hand side of the table" is coded shorthand for a bundle of properties: metal, few outer-shell electrons, loses them easily, forms a positive ion, forms a *basic* oxide that reacts with acids to give a salt and water. Unpack the whole bundle the moment you read the position. Do not confuse *most metallic* (far left, lowest group number) with *heaviest* or *most protons*, which point to the far right of the same period.

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.

Boyle's law, rearranged

$$P_2 = \frac{P_1V_1}{V_2}$$

Used to find the new pressure of a fixed mass of gas compressed or expanded at constant temperature. Rearrange the same relation to $V_2 = \frac{P_1V_1}{P_2}$ when the new volume is wanted instead.

Pressure at constant volume, rearranged

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

Used to find the new pressure of a fixed mass of gas heated or cooled at constant volume, with both temperatures in kelvin. Rearrange the same relation to $T_2 = T_1 \times \frac{P_2}{P_1}$ when the new temperature is wanted instead.

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.
- **Brownian motion is evidence that particles are real and moving**: Viewed under a microscope, smoke specks in air or pollen grains in water move in continuous, random, jerky paths. They are bombarded from all sides by the surrounding fluid particles, and at any instant the bombardment is slightly *uneven*, so the visible speck is knocked first one way and then another. The particles doing the pushing are much *smaller* than the visible grains, which is why they cannot be seen, yet they move much *faster*, so each collision still carries enough momentum to shove a large, slow grain.

Heating the fluid makes the motion more rapid, because faster molecules strike the grains more energetically and more often.

- **Condensation and solidification release energy**: *Condensation* is a gas turning into a liquid: as the gas cools its particles lose kinetic energy and slow down, and when they are slow enough the attractive forces pull them together. *Solidification* (freezing) is a liquid turning into a solid: the particles lose more energy and the forces lock them into fixed positions in a lattice. Both are the mirror of melting and boiling. Melting and boiling *absorb* energy to break forces; condensation and solidification *release* it as forces re-form. This is why steam at 100 °C burns far more severely than water at 100 °C: the steam must first condense on the skin, releasing that energy into it.
- **Cooling fins maximise all three routes**: Where a vacuum flask blocks every transfer route, cooling fins on a car radiator or a computer chip are designed to maximise them. They are made of *metal*, a good conductor, so energy passes quickly out of the hot component into the fins. They have a *large surface area*, so more of the fin is in contact with the air and the rate of transfer to it rises. They are often *dark and matt*, a good emitter, so they radiate energy away fastest. Each feature targets a different mechanism, and a full-mark answer names all three.
- **The bimetallic strip**: A bimetallic strip is two different metals bonded together along their full length, for example brass bonded to iron. On heating, the brass expands more than the iron, but the two are bonded and must keep the same overall length. The strip resolves this by *bending*, with the metal that expands more forced onto the longer, *outer* curve. This is used in thermostats and fire alarms, where the bending strip makes or breaks a circuit.
- **The Earth's temperature is a balance of radiation absorbed and emitted**: The Earth is not only a receiver: like every object it also emits infrared radiation. Its temperature depends on the *balance* of the two rates. When energy absorbed is greater than energy emitted, the surface warms; this happens during the day, when strong sunlight arrives as well as radiation leaving. When energy emitted is greater than energy absorbed, the surface cools; this happens at night, when there is no incoming sunlight but the surface keeps radiating. If the two rates are equal the temperature stays constant, a dynamic equilibrium.
- **The six changes of state**: *Melting* is solid to liquid; *solidification* (freezing) is liquid to solid; *boiling* and *evaporation* are liquid to gas; *condensation* is gas to liquid; *sublimation* is solid directly to gas; *deposition* is gas directly to solid. A change of state does not change the particles themselves, only their spacing, arrangement and motion. When ice melts to water and then boils to steam, the same $\mathrm{H_2O}$ molecules are present throughout, with larger and larger gaps between them, which is why the volume rises so sharply from liquid to gas.
- **Why a gas compresses easily and a liquid barely does**: Compressibility is decided by *empty space* and by the *forces* that resist closing it. A gas has particles far apart with negligible forces between them, so there is a great deal of empty space to squeeze out and it compresses easily. A liquid has particles already touching, held by much stronger forces, so there is almost nothing left to compress. Particle mass is irrelevant to compressibility.

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.

TIP Heated fluid becomes less dense and can only rise, so it needs cooler, denser fluid above it to rise through. A heat source at the bottom therefore sets up a circulating current, whereas heating from the top leaves the warm, less dense fluid already at the surface and no circulation forms. This is why a room heater is placed near the floor, why a kettle's element sits at the base, and why the cooling compartment of a refrigerator is at the top.

TIP Where a question asks why a metal conducts faster than a non-metal, an answer that says only "metals are better conductors" scores nothing. Both materials pass energy along by lattice vibration; the mark is for the *extra* channel the metal has, namely *free (delocalised) electrons* that gain kinetic energy at the hot end and travel rapidly to the cold end. State that non-metals have no free electrons and rely on the slow vibration mechanism alone.

TIP State the factor and its reason, because the reason usually carries the mark. A higher *temperature*: more particles have enough energy to escape. A larger *surface area*: more particles are exposed at the surface. More *air movement* over the surface, or lower humidity: escaped vapour is carried away instead of returning. A question offering four combinations is testing whether all three factors are pushed in the direction that speeds evaporation up.

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.

Converting cm³ to mm³ before counting

$$1\ \text{cm}^3 = 1000\ \text{mm}^3$$

A sample volume given in cm^3 must be converted to mm^3 before the count-per-mm³ formula can be applied, since the healthy range and the formula are both stated per mm^3.

Rearranging the count formula for total or volume

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

Rearranges the count-per-mm³ formula to find the total number of cells or platelets in a sample of known volume, or the volume of a sample given its total count and its concentration.

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.
- **Coronary heart disease: cause, risk factors, reduction**: *Coronary heart disease (CHD)* develops when the coronary arteries narrow with fatty deposits, cutting the heart muscle's oxygen supply. Risk is raised by smoking, a diet high in saturated fat, inactivity, stress, and being older, male or genetically predisposed. Risk is lowered by not smoking, eating less saturated fat and taking regular exercise, both of which slow fatty build-up and keep the heart and vessels healthy.
- **Haemoglobin binds and releases oxygen**: *Haemoglobin* is the red pigment packed inside red blood cells. In the lungs, where oxygen is plentiful, haemoglobin binds it to form *oxyhaemoglobin*; in the tissues, where oxygen is needed, it releases the oxygen again. This binding and releasing is the mechanism behind the red blood cell's oxygen-transport function.
- **Heart rate rises during exercise**: During exercise the muscles respire faster, using more oxygen and glucose and producing more carbon dioxide. The heart beats *faster* to increase blood flow, so oxygen and glucose are delivered quickly and carbon dioxide is removed. A *resting (baseline)* rate must be recorded first so the size of the rise can be found by comparison.
- **Monitoring heart activity: pulse, stethoscope, ECG**: Heart activity can be checked without electrical equipment by taking the *pulse rate* (the beats felt in an artery near the skin) or by using a *stethoscope* to listen to the sound the *valves* make as they close. An *ECG (electrocardiogram)* gives a more detailed record by tracing the heart's electrical activity, and requires electrical equipment.
- **Plasma transports dissolved substances**: *Plasma* is the liquid part of blood that dissolves and carries substances around the body: nutrients such as glucose and amino acids, mineral ions, the waste product *urea*, hormones, dissolved carbon dioxide and antibodies. The blood cells and platelets are *suspended* in plasma rather than dissolved by it.
- **Platelets and clotting**: *Platelets* are small fragments of cells, not whole cells, whose job is *clotting*. When a vessel is cut, platelets help form a clot that seals the wound. This *prevents further blood loss* and *stops pathogens entering* through the break in the skin; a low platelet count causes prolonged bleeding and a higher risk of infected wounds.
- **The main blood vessels of the heart**: Four large vessels connect the heart to the lungs and body. The *vena cava* carries deoxygenated blood from the body to the right atrium. The *pulmonary artery* carries deoxygenated blood from the right ventricle to the lungs. The *pulmonary vein* carries

oxygenated blood from the lungs to the left atrium. The *aorta* carries oxygenated blood from the left ventricle to the body. The *coronary arteries* carry oxygenated blood from the aorta to the heart muscle.

- **Why double circulation is an advantage**: A double circulation re-pressurises the blood: after the lungs, the blood returns to the heart for a *second* boost in pressure before being sent to the body. It therefore reaches the body organs at *high pressure*, flows *quickly*, and delivers oxygen and nutrients fast enough to support a mammal's high *metabolic rate*. A fish's single circulation has no second boost, so its blood arrives at the body slowly and at low pressure.

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.

TIP If the septum were absent, oxygenated blood returning from the lungs would mix with deoxygenated blood returning from the body inside the heart. The blood pumped out to the body would then carry a *lower* proportion of oxygen, diluted by the deoxygenated supply, never a higher one.

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.
- **A single source can supply multiple sinks at once**: A single source can supply several sinks at once. A photosynthesising leaf, for example, can release sucrose that simultaneously feeds a growing root tip and a developing fruit; the direction of flow at any moment follows demand, not a fixed map of the plant.
- **Osmosis for water, active transport for mineral ions**: Water enters the root hair by *osmosis*, because the soil solution is more dilute than the cell's cytoplasm. Mineral ions, often already more concentrated inside the cell than in the soil, are taken up by *active transport*, which needs energy from respiration, one reason root cells contain many mitochondria.
- **Structure-function: why xylem is dead and phloem needs a companion cell**: A dead, hollow vessel with no cytoplasm gives water a clear, unobstructed channel to flow through, while the lignified wall gives mechanical support. A sieve tube element loses its nucleus and most organelles for the same reason, an unobstructed interior for sap to flow along, but this leaves it unable to carry out ordinary metabolism. Its companion cell, packed with a nucleus, mitochondria and ribosomes, performs that metabolism on its behalf and supplies the energy needed to load sucrose into the phloem.
- **Temperature raises the rate of transpiration**: A higher temperature gives water molecules more energy, so water *evaporates faster* from the mesophyll surfaces inside the leaf. More vapour forms and diffuses out, so the rate of transpiration *increases*.
- **The pathway of water from soil to leaf**: The route a water molecule takes from soil to leaf, in order: *root hair cell -> root cortex cells -> xylem* -> up the stem -> *leaf mesophyll cell*. The cortex is only the short horizontal crossing at the root; the xylem does the long-distance vertical lifting up the stem.

- **Wind speed raises the rate of transpiration**: Moving air blows away the humid layer of water vapour that otherwise collects just outside the stomata. This keeps the air outside the leaf drier than the air inside, maintaining a steep *concentration gradient*, so vapour diffuses out faster and the rate *increases*. In still air the humid layer builds up, the gradient shrinks, and transpiration slows.

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.

TIP Humid air already contains a lot of water vapour, so the vapour concentration outside the leaf is high and close to that inside, making the concentration gradient *shallow* and transpiration *slow*. Dry air gives a *steep* gradient and *fast* transpiration; the fastest transpiration occurs in conditions that are hot, windy and dry.

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.
- **Antibiotic resistance: natural selection in four stages**: 1. A random mutation produces a few bacteria carrying a resistance allele, *before* the antibiotic is ever used. 2. When the antibiotic is applied, non-resistant bacteria are killed but the resistant bacteria survive. 3. The survivors reproduce, passing the resistance allele to their offspring. 4. Over repeated use, each generation contains a higher proportion of resistant bacteria, until the antibiotic no longer works.
- **Bell curve or separate bars: the graph shapes**: Continuous variation, plotted for a large population, gives a smooth, symmetrical bell-shaped curve with a single central peak. Discontinuous variation gives a bar chart of separate columns, one per category, with gaps between them. The decision rule: can the characteristic be measured on a scale, or must it be sorted into named groups? Measured on a scale means continuous and a bell curve; sorted into groups means discontinuous and separate bars.
- **Mutation is the way new alleles are formed**: Mutation is the way in which new alleles are formed. A change to a single base in a gene's sequence does not always destroy the gene's function; many mutations have only a small effect or none at all, but a mutation *can* produce a new allele of that gene. Most new alleles are neutral or harmful; occasionally one is useful in a particular environment, and that rare useful allele is what natural selection can act on.

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.

TIP A full answer to "why do individuals of a species differ" names both causes: genetic causes, the alleles inherited, and environmental causes, the conditions experienced. Identical twins raised in different countries can end up with noticeably different body masses despite identical alleles, because their environmental causes, such as diet, differ; their genetic cause does not.

TIP Mutation is random and unrelated to antibiotic exposure, so a resistance allele must already be present in a few bacteria by chance before the antibiotic is first used; the antibiotic does not rewrite bacterial DNA to order. Reversing this order is the most common wrong answer in antibiotic-resistance questions.

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

The speed of electromagnetic waves in a vacuum

$$c = 3.0 \times 10^8 \text{ m/s\$}$$

Every electromagnetic wave travels through a vacuum at this same speed, whatever its frequency, so a gamma ray and a radio wave cross a vacuum side by side. Combine it with $v = f\lambda$ to convert between the frequency and the

wavelength of any region, and with $t = \frac{\text{distance}}{\text{speed}}$ to find a signal travel time. A gamma ray and a radio wave differ in frequency and wavelength but never in vacuum speed.

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.
- **Describing a wave: amplitude, wavelength, frequency and period**: *Amplitude* is the maximum distance a point on the wave moves from its rest position, measured from the rest line up to a crest, never from crest to trough; the crest-to-trough distance is *twice* the amplitude. *Wavelength* λ is the distance between two nearest points in step with each other, for example crest to crest or compression to compression. *Frequency* f is the number of complete waves passing a point each second, in Hz. *Period* T is the time for one complete wave to pass a point, in s. Frequency and

period are reciprocals, $f = \frac{1}{T}$. Amplitude sets the energy the wave carries and is independent of frequency.

- **Image characteristics by object position**: For a thin converging lens the object distance alone decides the image. Beyond 2F: *real, inverted, diminished*, formed between F and 2F, as in a camera. At 2F: *real, inverted, same size*, formed at 2F on the far side. Between F and 2F: *real, inverted, magnified*, formed beyond 2F, as in a projector. Inside F: *virtual, upright, magnified*, formed on the same side as the object, as in a magnifying glass. Every real image from a single converging lens is inverted, and the only upright image is the virtual one formed inside F.
- **Loudness and pitch**: Two independent properties of the source control two independent properties of the sound. *Loudness* depends on the *amplitude* of the vibration: a larger amplitude gives a louder sound. *Pitch* depends on the *frequency* of the vibration: a higher frequency gives a higher pitch. They can be changed separately. A tuning fork struck harder vibrates with a greater amplitude at the same frequency, so the sound is louder at the same pitch; a siren whose frequency rises while its amplitude holds steady rises in pitch at constant loudness.
- **The image in a plane mirror**: The image formed by a plane mirror is *virtual*, *upright*, the *same size* as the object, *laterally inverted*, and the *same distance* behind the mirror as the object is in front. It is virtual because the reflected rays only *appear* to come from behind the mirror and never actually meet there, so the image cannot be caught on a screen. Laterally inverted means left and right are swapped while the image stays the right way up, which is why text held to a mirror reads backwards.
- **The two conditions for total internal reflection**: Total internal reflection occurs only when *both* conditions hold: the light must be travelling from a *denser* medium towards a *less dense* one, and the angle of incidence must be *greater than the critical angle*. Below the critical angle the ray refracts out with some weak reflection; at the critical angle the refracted ray grazes along the boundary at 90°; above it no light escapes at all and every bit is reflected back into the denser medium, obeying the law of reflection. A ray travelling from air into glass can never be totally internally reflected however large the angle of incidence, because it is entering the denser medium.
- **The two construction rays**: Two standard rays from the top of the object locate the image. The first travels *parallel to the principal axis* and is refracted through the far principal focus F. The second passes *through the centre of the lens* and carries straight on undeviated. Where these two rays actually cross, a *real* image forms, and it can be caught on a screen. Where they diverge after the lens and never cross, trace them backwards as dashed lines to where they appear to meet: that gives a *virtual* image, which cannot be projected.
- **Uses of the regions of the spectrum**: Radio waves: radio and television transmissions, and radar. Microwaves: satellite television, mobile phones and microwave ovens. Infrared: television remote controllers and thermal imaging. Visible light: vision and photography. Ultraviolet: detecting fake bank notes, and sterilising. X-rays: medical scanning and security scanners. Gamma rays: detection and treatment of cancer, and sterilising equipment. The two most confused pairs are microwaves against radio waves for satellite television, and infrared against microwaves for remote controllers.

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.

TIP The single most common error in this topic is forgetting that the sound travels *there and back*. Before substituting, decide which quantity the question gives. If it gives the distance to the reflecting surface, double it to get the path length. If it gives a total there-and-back time and asks for a depth or a distance, halve the result at the end. Writing the path length as $2d$ explicitly, rather than carrying the factor in your head, protects the mark. The same factor of two governs ultrasound depth-sounding and sonar.

TIP When a wave crosses into a new medium its frequency is *unchanged*, because frequency is set by the vibrating source rather than by the medium. This one rule decides a whole family of questions. In $v = f\lambda$ with f fixed, the speed and the wavelength must change *together* and in the same direction. So water waves passing from deep into shallow water slow down, and their

wavelength must therefore shorten. State that the frequency is unchanged explicitly; it is usually a marking point in its own right.
