3 Subject content

Sections 3.1.1 to 3.1.7 of the Physical chemistry content, sections 3.2.1 to 3.2.3 of the Inorganic chemistry content and sections 3.3.1 to 3.3.6 of the Organic chemistry content are designed to be covered in the first year of the A-level and are also the AS subject content. So you can teach AS and A-level together.

Each section begins with an overview, which puts the topic into a broader chemical context and encourages understanding of the place of each topic within the subject. The overviews are intended to encourage an overarching approach to both the teaching and learning of topic areas. As such, they will not be directly assessed.

These specifications are presented in a two-column format. The left-hand column contains the specification content that all students must cover, and that can be assessed in the written papers. The right-hand column exemplifies the opportunities for skills to be developed throughout the course. As such, knowledge of individual experiments on the right-hand side is **not** assumed knowledge for the assessment.

The codes in the right-hand column refer to the skills in the relevant appendices. **MS** refers to the Mathematical skills, **AT** refers to the Apparatus and techniques and **PS** refers to the Practical skills.

3.1 Physical chemistry

3.1.1 Atomic structure

The chemical properties of elements depend on their atomic structure and in particular on the arrangement of electrons around the nucleus. The arrangement of electrons in orbitals is linked to the way in which elements are organised in the Periodic Table. Chemists can measure the mass of atoms and molecules to a high degree of accuracy in a mass spectrometer. The principles of operation of a modern mass spectrometer are studied.

3.1.1.1 Fundamental particles

Content	Opportunities for skills development
Appreciate that knowledge and understanding of atomic structure has evolved over time.	
Protons, neutrons and electrons: relative charge and relative mass.	
An atom consists of a nucleus containing protons and neutrons surrounded by electrons.	

3.1.1.2 Mass number and isotopes

Content	Opportunities for skills development
Mass number (A) and atomic (proton) number (Z).	MS 1.1
 Students should be able to: determine the number of fundamental particles in atoms and ions using mass number, atomic number and charge explain the existence of isotopes. 	Students report calculations to an appropriate number of significant figures, given raw data quoted to varying numbers of significant figures.
The principles of a simple time of flight (TOF) mass	MS 1.2
spectrometer, limited to ionisation, acceleration to give all ions constant kinetic energy, ion drift, ion detection, data analysis.	Students calculate weighted means eg calculation of an atomic mass based on supplied isotopic abundances.
The mass spectrometer gives accurate information	MS 3.1
about relative isotopic mass and also about the relative abundance of isotopes.	Students interpret and analyse
Mass spectrometry can be used to identify elements.	spectra.
Mass spectrometry can be used to determine relative molecular mass.	
Students should be able to:	
 interpret simple mass spectra of elements 	
 calculate relative atomic mass from isotopic abundance, limited to mononuclear ions. 	

3.1.1.3 Electron configuration

Content	Opportunities for skills development
Electron configurations of atoms and ions up to $Z = 36$ in terms of shells and sub-shells (orbitals) s, p and d.	
Ionisation energies.	
Students should be able to:	
define first ionisation energy	
 write equations for first and successive ionisation energies 	
 explain how first and successive ionisation energies in Period 3 (Na–Ar) and in Group 2 (Be–Ba) give evidence for electron configuration in sub-shells and in shells. 	

3.1.2 Amount of substance

When chemists measure out an amount of a substance, they use an amount in moles. The mole is a useful quantity because one mole of a substance always contains the same number of entities of the substance. An amount in moles can be measured out by mass in grams, by volume in dm³ of a solution of known concentration and by volume in dm³ of a gas.

3.1.2.1 Relative atomic mass and relative molecular mass

Content	Opportunities for skills development
Relative atomic mass and relative molecular mass in terms of $^{\rm 12}{\rm C}.$	
The term relative formula mass will be used for ionic compounds.	
Students should be able to:	
 define relative atomic mass (A_r) 	
• define relative molecular mass (M_r) .	

3.1.2.2 The mole and the Avogadro constant

Content	Opportunities for skills development
The Avogadro constant as the number of particles in a	MS 0.1
mole.	Students carry out calculations using
The mole as applied to electrons, atoms, molecules, ions, formulas and equations.	numbers in standard and ordinary form eg using the Avogadro constant.
The concentration of a substance in solution, measured in mol dm^{-3}	MS 0.4
	Students carry out calculations using
Students should be able to carry out calculations:	the Avogadro constant.
 using the Avogadro constant 	MS 1.1
• using mass of substance, M_r , and amount in moles	
• using concentration, volume and amount of substance in a solution.	Students report calculations to an appropriate number of significant
Students will not be expected to recall the value of the	varying numbers of significant figures.
Avogadio constant.	Students understand that calculated
	results can only be reported to
	measurement.

3.1.2.3 The ideal gas equation

Content	Opportunities for skills development
The ideal gas equation $pV = nRT$ with the variables in SI units	AT a, b and k
units.	PS 3.2
Students should be able to use the equation in calculations.	Students could be asked to find the M_r of a volatile liquid.
Students will not be expected to recall the value of the gas constant, <i>R</i> .	MS 0.0
	Students understand that the correct units need to be in $pV = nRT$.
	MS 2.2, 2.3 and 2.4
	Students carry out calculations with the ideal gas equation, including rearranging the ideal gas equation to find unknown quantities.

3.1.2.4 Empirical and molecular formula

Content	Opportunities for skills development
Empirical formula is the simplest whole number ratio of	AT a and k
atoms of each element in a compound.	PS 2.3 and 3.3
Molecular formula is the actual number of atoms of each element in a compound.	Students could be asked to find the empirical formula of a metal oxide.
The relationship between empirical formula and molecular formula.	
Students should be able to:	
 calculate empirical formula from data giving composition by mass or percentage by mass 	
 calculate molecular formula from the empirical formula and relative molecular mass. 	

3.1.2.5 Balanced equations and associated calculations

Content	Opportunities for skills development
Equations (full and ionic).	AT a, d, e, f and k
Percentage atom economy is:	PS 4.1
$\frac{\circ cu}{su} \frac{ss \circ s}{\circ cu} \frac{s \circ o uct}{ss \circ s} \frac{\circ uct}{ct \circ ts} \times$ Economic, ethical and environmental advantages for society and for industry of developing chemical processes with a high stars account.	 Students could be asked to find: the concentration of ethanoic acid in vinegar the mass of calcium carbonate in an
 Students should be able to: write balanced equations for reactions studied balance equations for unfamiliar reactions when reactants and products are specified. 	indigestion tablet • the M_r of MHCO ₃ • the M_r of succinic acid • the mass of aspirin in an aspirin tablet
 Students should be able to use balanced equations to calculate: masses volumes of gases percentage vields 	 the yield for the conversion of magnesium to magnesium oxide the <i>M</i>_r of a hydrated salt (eg magnesium sulfate) by heating to constant mass.
percentage atom economies	AT a and k
 concentrations and volumes for reactions in solutions. 	Students could be asked to find the percentage conversion of a Group 2 carbonate to its oxide by heat.
	AT d, e, f and k
	Students could be asked to determine the number of moles of water of crystallisation in a hydrated salt by titration.
	MS 0.2
	Students construct and/or balance equations using ratios.
	Students calculate percentage yields and atom economies of reactions.
	MS 1.2 and 1.3
	Students select appropriate titration data (ie identify outliers) in order to calculate mean titres.
	Students determine uncertainty when two burette readings are used to calculate a titre value.
Required practical 1	
Make up a volumetric solution and carry out a simple acid-base titration.	

3.1.3 Bonding

The physical and chemical properties of compounds depend on the ways in which the compounds are held together by chemical bonds and by intermolecular forces. Theories of bonding explain how atoms or ions are held together in these structures. Materials scientists use knowledge of structure and bonding to engineer new materials with desirable properties. These new materials may offer new applications in a range of different modern technologies.

3.1.3.1 Ionic bonding

Content	Opportunities for skills development
Ionic bonding involves electrostatic attraction between oppositely charged ions in a lattice.	
The formulas of compound ions eg sulfate, hydroxide, nitrate, carbonate and ammonium.	
Students should be able to:	
 predict the charge on a simple ion using the position of the element in the Periodic Table 	
 construct formulas for ionic compounds. 	

3.1.3.2 Nature of covalent and dative covalent bonds

Content	Opportunities for skills development
A single covalent bond contains a shared pair of electrons.	
Multiple bonds contain multiple pairs of electrons.	
A co-ordinate (dative covalent) bond contains a shared pair of electrons with both electrons supplied by one atom.	
Students should be able to represent:	
 a covalent bond using a line 	
 a co-ordinate bond using an arrow. 	

3.1.3.3 Metallic bonding

Content	Opportunities for skills development
Metallic bonding involves attraction between delocalised	
electrons and positive ions arranged in a lattice.	

3.1.3.4 Bonding and physical properties

Content	Opportunities for skills development
The four types of crystal structure:	AT a, b, h and k
• ionic	PS 1.1
metallic	
 macromolecular (giant covalent) 	Students could be asked to find
molecular.	by experiment (eq to test solubility,
The structures of the following crystals as examples of these four types of crystal structure:	conductivity and ease of melting).
diamond	
graphite	
• ice	
iodine	
magnesium	
sodium chloride.	
Students should be able to:	
 relate the melting point and conductivity of materials to the type of structure and the bonding present 	
 explain the energy changes associated with changes of state 	
 draw diagrams to represent these structures involving specified numbers of particles. 	

3.1.3.5 Shapes of simple molecules and ions

Content	Opportunities for skills development
Bonding pairs and lone (non-bonding) pairs of electrons as charge clouds that repel each other.	MS 0.3 and 4.1 Students could be given familiar and
Pairs of electrons in the outer shell of atoms arrange themselves as far apart as possible to minimise repulsion.	unfamiliar examples of species and asked to deduce the shape according
Lone pair-lone pair repulsion is greater than lone pair-bond pair repulsion, which is greater than bond pair-bond pair repulsion.	to valence shell electron pair repulsio (VSEPR) principles.
The effect of electron pair repulsion on bond angles.	
Students should be able to explain the shapes of, and bond angles in, simple molecules and ions with up to six electron pairs (including lone pairs of electrons) surrounding the central atom.	

3.1.3.6 Bond polarity

Content	Opportunities for skills development
Electronegativity as the power of an atom to attract the pair of electrons in a covalent bond.	
The electron distribution in a covalent bond between elements with different electronegativities will be unsymmetrical. This produces a polar covalent bond, and may cause a molecule to have a permanent dipole.	
Students should be able to:	
 use partial charges to show that a bond is polar 	
 explain why some molecules with polar bonds do not have a permanent dipole. 	

3.1.3.7 Forces between molecules

Content	Opportunities for skills development
Forces between molecules:	AT d and k
 permanent dipole-dipole forces 	PS 1.2
 induced dipole–dipole (van der Waals, dispersion, London) forces 	Students could try to deflect jets
 hydrogen bonding. 	to investigate the presence of
The melting and boiling points of molecular substances are influenced by the strength of these intermolecular forces.	different types and relative size of intermolecular forces.
The importance of hydrogen bonding in the low density of ice and the anomalous boiling points of compounds.	
Students should be able to:	
 explain the existence of these forces between familiar and unfamiliar molecules 	
 explain how melting and boiling points are influenced by these intermolecular forces. 	

3.1.4 Energetics

The enthalpy change in a chemical reaction can be measured accurately. It is important to know this value for chemical reactions that are used as a source of heat energy in applications such as domestic boilers and internal combustion engines.

3.1.4.1 Enthalpy change

Content	Opportunities for skills development
Reactions can be endothermic or exothermic.	
Enthalpy change (ΔH) is the heat energy change measured under conditions of constant pressure.	
Standard enthalpy changes refer to standard conditions ie 100 kPa and a stated temperature (eg $\Delta H_{_{298}}^{}$ $^{\Theta}$).	
Students should be able to:	
• define standard enthalpy of combustion ($\Delta_c H^{\Theta}$)	
• define standard enthalpy of formation ($\Delta_{e}H^{\Theta}$).	

3.1.4.2 Calorimetry

Content	Opportunities for skills development
The heat change, q , in a reaction is given by the equation	MS 0.0 and 1.1
$q = mc\Delta I$ where <i>m</i> is the mass of the substance that has a temperature change ΔT and a specific heat capacity <i>c</i> .	Students understand that the correct units need to be used in $q = mc \Delta T$
 Students should be able to: use this equation to calculate the molar enthalpy change for a reaction 	Students report calculations to an appropriate number of significant figures, given raw data quoted to varying numbers of significant figures.
 use this equation in related calculations. 	Students understand that calculated
Students will not be expected to recall the value of the specific heat capacity, c , of a substance.	results can only be reported to the limits of the least accurate measurement.
Required practical 2	AT a and k
Measurement of an enthalpy change.	PS 2.4, 3.1, 3.2, 3.3 and 4.1
	Students could be asked to find ΔH for a reaction by calorimetry. Examples of reactions could include:
	dissolution of potassium chloride
	dissolution of sodium carbonate
	neutralising NaOH with HCI
	 displacement reaction between CuSO₄ + Zn
	combustion of alcohols.

3.1.4.3 Applications of Hess's law

Content	Opportunities for skills development
Hess's law.	MS 2.4
Students should be able to use Hess's law to perform calculations, including calculation of enthalpy changes for	Students carry out Hess's law calculations.
reactions from enthalpies of combustion or from enthalpies of formation.	AT a and k
	PS 2.4, 3.2 and 4.1
	Students could be asked to find ΔH for a reaction using Hess's law and calorimetry, then present data in appropriate ways. Examples of reactions could include:
	 thermal decomposition of NaHCO₃
	 hydration of MgSO₄
	 hydration of CuSO₄

3.1.4.4 Bond enthalpies

Content	Opportunities for skills development
Mean bond enthalpy.	MS 1.2
 Students should be able to: define the term mean bond enthalpy use mean bond enthalpies to calculate an approximate value of Δ<i>H</i> for reactions in the gaseous phase explain why values from mean bond enthalpy calculations differ from those determined using Hess's law. 	Students understand that bond enthalpies are mean values across a range of compounds containing that bond.

3.1.5 Kinetics

The study of kinetics enables chemists to determine how a change in conditions affects the speed of a chemical reaction. Whilst the reactivity of chemicals is a significant factor in how fast chemical reactions proceed, there are variables that can be manipulated in order to speed them up or slow them down.

3.1.5.1 Collision theory

Content	Opportunities for skills development
Reactions can only occur when collisions take place between particles having sufficient energy.	
This energy is called the activation energy.	
Students should be able to:	
define the term activation energy	
• explain why most collisions do not lead to a reaction.	

3.1.5.2 Maxwell-Boltzmann distribution

Content	Opportunities for skills development
Maxwell–Boltzmann distribution of molecular energies in gases.	
Students should be able to draw and interpret distribution curves for different temperatures.	

3.1.5.3 Effect of temperature on reaction rate

Content	Opportunities for skills development
Meaning of the term rate of reaction.	AT a, b, k and I
The qualitative effect of temperature changes on the rate of reaction.	PS 2.4 and 3.1 Students could investigate the effect
Students should be able to use the Maxwell–Boltzmann distribution to explain why a small temperature increase can lead to a large increase in rate.	of temperature on the rate of reaction of sodium thiosulfate and hydrochloric acid by an initial rate method.
	Research opportunity
	Students could investigate how knowledge and understanding of the factors that affect the rate of chemical reaction have changed methods of storage and cooking of food.
Required practical 3	
Investigation of how the rate of a reaction changes with temperature.	

3.1.5.4 Effect of concentration and pressure

Content	Opportunities for skills development
The qualitative effect of changes in concentration on collision frequency.	AT a, e, k and i Students could investigate the effect
The qualitative effect of a change in the pressure of a gas on collision frequency.	of changing the concentration of acid on the rate of a reaction of calcium
Students should be able to explain how a change in concentration or a change in pressure influences the rate of a reaction.	carbonate and hydrochloric acid by a continuous monitoring method.

3.1.5.5 Catalysts

Content	Opportunities for skills development
A catalyst is a substance that increases the rate of a chemical reaction without being changed in chemical composition or amount.	
Catalysts work by providing an alternative reaction route of lower activation energy.	
Students should be able to use a Maxwell–Boltzmann distribution to help explain how a catalyst increases the rate of a reaction involving a gas.	

3.1.6 Chemical equilibria, Le Chatelier's principle and K_{c}

In contrast with kinetics, which is a study of how quickly reactions occur, a study of equilibria indicates how far reactions will go. Le Chatelier's principle can be used to predict the effects of changes in temperature, pressure and concentration on the yield of a reversible reaction. This has important consequences for many industrial processes. The further study of the equilibrium constant, K_c , considers how the mathematical expression for the equilibrium constant enables us to calculate how an equilibrium yield will be influenced by the concentration of reactants and products.

3.1.6.1 Chemical equilibria and Le Chatelier's principle

Content	Opportunities for skills development
Many chemical reactions are reversible.	PS 1.1
 In a reversible reaction at equilibrium: forward and reverse reactions proceed at equal rates the concentrations of reactants and products remain constant. 	Students could carry out test-tube equilibrium shifts to show the effect of concentration and temperature (eg $Cu(H_2O)_6^{2+}$ with concentrated HCI).
Le Chatelier's principle.	
Le Chatelier's principle can be used to predict the effects of changes in temperature, pressure and concentration on the position of equilibrium in homogeneous reactions.	
A catalyst does not affect the position of equilibrium.	
Students should be able to:	
 use Le Chatelier's principle to predict qualitatively the effect of changes in temperature, pressure and concentration on the position of equilibrium 	
• explain why, for a reversible reaction used in an industrial process, a compromise temperature and pressure may be used.	

3.1.6.2 Equilibrium constant $K_{\rm c}$ for homogeneous systems

Content	Opportunities for skills development
The equilibrium constant K_c is deduced from the equation for a reversible reaction.	MS 0.3
The concentration, in mol dm ⁻³ , of a species X involved in the expression for K_c is represented by [X]	changing experimental parameters on a measurable value eg how the value
The value of the equilibrium constant is not affected either by changes in concentration or addition of a catalyst.	given different specified conditions.
Students should be able to:	MS 1.1
 construct an expression for K_c for a homogeneous system in equilibrium 	Students report calculations to an appropriate number of significant
 calculate a value for K_c from the equilibrium concentrations for a homogeneous system at constant 	figures, given raw data quoted to varying numbers of significant figures.
 perform calculations involving K 	Students understand that calculated results can only be reported to
 predict the qualitative effects of changes of temperature on the value of K_c 	the limits of the least accurate measurement.
	MS 2.2 and 2.3
	Students calculate the concentration of a reagent at equilibrium.
	Students calculate the value of an equilibrium constant $K_{\rm c}$
	PS 2.3
	Students could determine the equilibrium constant, K_c , for the reaction of ethanol with ethanoic acid in the presence of a strong acid catalyst to ethyl ethanoate.

3.1.7 Oxidation, reduction and redox equations

Redox reactions involve a transfer of electrons from the reducing agent to the oxidising agent. The change in the oxidation state of an element in a compound or ion is used to identify the element that has been oxidised or reduced in a given reaction. Separate half-equations are written for the oxidation or reduction processes. These half-equations can then be combined to give an overall equation for any redox reaction.

Content	Opportunities for skills development
Oxidation is the process of electron loss and oxidising agents are electron acceptors.	
Reduction is the process of electron gain and reducing agents are electron donors.	
The rules for assigning oxidation states.	
Students should be able to:	
 work out the oxidation state of an element in a compound or ion from the formula 	
 write half-equations identifying the oxidation and reduction processes in redox reactions 	
 combine half-equations to give an overall redox equation. 	

3.1.8 Thermodynamics (A-level only)

The further study of thermodynamics builds on the Energetics section and is important in understanding the stability of compounds and why chemical reactions occur. Enthalpy change is linked with entropy change enabling the free-energy change to be calculated.

3.1.8.1 Born-Haber cycles (A-level only)

Content	Opportunities for skills development
Lattice enthalpy can be defined as either enthalpy of lattice dissociation or enthalpy of lattice formation.	
 Born–Haber cycles are used to calculate lattice enthalpies using the following data: enthalpy of formation ionisation energy enthalpy of atomisation bond enthalpy electron affinity. 	
 Students should be able to: define each of the above terms and lattice enthalpy construct Born–Haber cycles to calculate lattice enthalpies using these enthalpy changes construct Born–Haber cycles to calculate one of the other enthalpy changes compare lattice enthalpies from Born–Haber cycles with those from calculations based on a perfect ionic model to provide evidence for covalent character in ionic compounds. 	
Cycles are used to calculate enthalpies of solution for ionic compounds from lattice enthalpies and enthalpies of hydration.	
 Students should be able to: define the term enthalpy of hydration perform calculations of an enthalpy change using these cycles. 	

3.1.8.2 Gibbs free-energy change, ΔG , and entropy change, ΔS (A-level only)

Opportunities for skills development
AT a, b and k
PS 3.2
Students could be asked to find $\triangle S$ for
vaporization of water using a kettle.
MS 2.2, 2.3 and 2.4
Students rearrange the equation $\Delta G = \Delta H - T \Delta S$ to find unknown values.
MS 3.3
Students determine ΔS and ΔH from a graph of ΔG versus <i>T</i> .

3.1.9 Rate equations (A-level only)

In rate equations, the mathematical relationship between rate of reaction and concentration gives information about the mechanism of a reaction that may occur in several steps.

3.1.9.1 Rate equations (A-level only)

Content	Opportunities for skills development
The rate of a chemical reaction is related to the	MS 0.0 and 2.4
Concentration of reactants by a rate equation of the form: $P_{\text{oto}} = k[\Lambda]^m [P]^n$	Students use given rate data and
	some of the data to calculate the
where <i>m</i> and <i>n</i> are the orders of reaction with respect to reactants A and B and <i>k</i> is the rate constant.	rate constant including units. Rate equations could be given and students
The orders <i>m</i> and <i>n</i> are restricted to the values 0, 1, and 2.	asked to calculate rate constant or rate.
The rate constant k varies with temperature as shown by the equation:	MS 3.3 and 3.4
$k = Ae^{-E_{a}/RT}$	Students use a graph of
where A is a constant, known as the Arrhenius constant, E_{a} is the activation energy and T is the temperature in K.	rate constant of a zero-order reaction by determination of the gradient.
Students should be able to:	
define the terms order of reaction and rate constant	
 perform calculations using the rate equation 	
 explain the qualitative effect of changes in temperature on the rate constant k 	
• perform calculations using the equation $k = Ae^{-E_a/RT}$	
• understand that the equation $k = Ae^{-E_a/RT}$ can be rearranged into the form $\ln k = -E_a/RT + \ln A$ and know how to use this rearranged equation with experimental data to plot a straight line graph with slope $-E_a/R$	
These equations and the gas constant, <i>R</i> , will be given when required.	

3.1.9.2 Determination of rate equation (A-level only)	
Content	Opportunities for skills development
The rate equation is an experimentally determined	AT a, b, k and l
relationship.	PS 2.4 and 3.1
The orders with respect to reactants can provide information about the mechanism of a reaction.	Students could determine the order of reaction for a reactant in the iodine
Students should be able to:	clock reaction.
 use concentration-time graphs to deduce the rate of a reaction 	MS 3.1
 use initial concentration-time data to deduce the initial rate of a reaction 	Students could be given data to plot and interpret in terms of order with
 use rate-concentration data or graphs to deduce the order (0, 1 or 2) with respect to a reactant 	respect to a reactant. Alternatively, students could just be given
 derive the rate equation for a reaction from the orders with respect to each of the reactants 	appropriate graphs and asked to derive order(s).
• use the orders with respect to reactants to provide	MS 3.3 and 3.4
information about the rate determining/limiting step of a reaction.	Students calculate the rate constant of a zero-order reaction by determining the gradient of a concentration-time graph.
	MS 3.5
	Students plot concentration-time graphs from collected or supplied data and draw an appropriate best-fit curve.
	Students draw tangents to such curves to deduce rates at different times.
Required practical 7	
Measuring the rate of reaction:	
by an initial rate method	
 by a continuous monitoring method. 	

tion (A lovel only) . . . • _

3.1.10 Equilibrium constant K_p for homogeneous systems (A-level only) The further study of equilibria considers how the mathematical expression for the equilibrium constant K_p enables us to calculate how an equilibrium yield will be influenced by the partial pressures of reactants and products. This has important consequences for many industrial processes.

Content	Opportunities for skills development
The equilibrium constant K_p is deduced from the equation for a reversible reaction occurring in the gas phase.	MS 1.1 Students report calculations to an
K_{p} is the equilibrium constant calculated from partial pressures for a system at constant temperature.	appropriate number of significant figures, given raw data quoted to varying numbers of significant figures.
Students should be able to:	
 derive partial pressure from mole fraction and total pressure 	Students understand that calculated results can only be reported to
 construct an expression for K_p for a homogeneous system in equilibrium 	measurement.
• perform calculations involving K_{p}	MS 2.2 and 2.3
 predict the qualitative effects of changes in temperature and pressure on the position of equilibrium 	Students calculate the partial
 predict the qualitative effects of changes in temperature on the value of K_a 	equilibrium.
 understand that, whilst a catalyst can affect the rate of attainment of an equilibrium, it does not affect the value of the equilibrium constant. 	Students calculate the value of an equilibrium constant K_{p}

3.1.11 Electrode potentials and electrochemical cells (A-level only)

Redox reactions take place in electrochemical cells where electrons are transferred from the reducing agent to the oxidising agent indirectly via an external circuit. A potential difference is created that can drive an electric current to do work. Electrochemical cells have very important commercial applications as a portable supply of electricity to power electronic devices such as mobile phones, tablets and laptops. On a larger scale, they can provide energy to power a vehicle.

3.1.11.1 Electrode potentials and cells (A-level only)

Content	Opportunities for skills development
IUPAC convention for writing half-equations for electrode	AT j and k
	PS 1.1
The conventional representation of cells.	Students could make simple cells
Cells are used to measure electrode potentials by reference to the standard hydrogen electrode.	and use them to measure unknown electrode potentials.
The importance of the conditions when measuring the	AT a, b, j and k
electrode potential, E (Nernst equation not required).	PS 2.1 and 2.4
Standard electrode potential, E^{Θ} , refers to conditions of 298 K, 100 kPa and 1.00 mol dm ⁻³ solution of ions.	Students could be asked to plan and carry out an experiment to investigate
Standard electrode potentials can be listed as an electrochemical series.	the effect of changing conditions, such as concentration or temperature, in a
Students should be able to:	voltaic cell such as Zn Zn2+ Cu2+ Cu
• use E^{Θ} values to predict the direction of simple redox	AT j and k
reactions	PS 2.2
 write and apply the conventional representation of a cell. 	Students could use E^{Θ} values to
·····	predict the direction of simple redox reactions, then test these predictions by simple test-tube reactions.
Required practical 8	
Measuring the EMF of an electrochemical cell.	

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Content	Opportunities for skills development
Electrochemical cells can be used as a commercial source	Research opportunity
The simplified electrode reactions in a lithium cells	Students could investigate how
The simplined electrode reactions in a lithium cell.	electrochemical cells has evolved from
Positive electrode: $Li^+ + CoO_2 + e^- \rightarrow Li^+[CoO_2]^-$	the first voltaic battery.
Negative electrode: $Li \rightarrow Li^+ + e^-$	
Cells can be non-rechargeable (irreversible), rechargeable or fuel cells.	
Fuel cells are used to generate an electric current and do not need to be electrically recharged.	
The electrode reactions in an alkaline hydrogen-oxygen fuel cell.	
The benefits and risks to society associated with using these cells.	
Students should be able to:	
• use given electrode data to deduce the reactions	
deduce the EME of a cell	
 explain how the electrode reactions can be used to generate an electric current. 	

3.1.11.2 Commercial applications of electrochemical cells (A-level only)

3.1.12 Acids and bases (A-level only)

Acids and bases are important in domestic, environmental and industrial contexts. Acidity in aqueous solutions is caused by hydrogen ions and a logarithmic scale, pH, has been devised to measure acidity. Buffer solutions, which can be made from partially neutralised weak acids, resist changes in pH and find many important industrial and biological applications.

3.1.12.1 Brønsted-Lowry acid-base equilibria in aqueous solution (A-level only)

Content	Opportunities for skills development
An acid is a proton donor.	
A base is a proton acceptor.	
Acid-base equilibria involve the transfer of protons.	

3.1.12.2 Definition and determination of pH (A-level only)

Content	Opportunities for skills development
The concentration of hydrogen ions in aqueous solution covers a very wide range. Therefore, a logarithmic scale, the pH scale, is used as a measure of hydrogen ion	MS 0.4 Students carry out pH calculations.
concentration.	MS 2.5
$pH = -log_{10}[H^+]$	Students could be given concentration
Students should be able to:	values and asked to calculate pH or
 convert concentration of hydrogen ions into pH and vice versa 	vice versa.
 calculate the pH of a solution of a strong acid from its concentration. 	

3.1.12.3 The ionic product of water, K_{w} (A-level only)

Content	Opportunities for skills development
Water is slightly dissociated.	MS 0.1
$K_{\rm w}$ is derived from the equilibrium constant for this dissociation.	Students use an appropriate number of decimal places in pH calculations.
$K_{\rm w} = [{\rm H}^+][{\rm O}{\rm H}^-]$	Students understand standard form
The value of $K_{\rm w}$ varies with temperature.	limited to) $K_{\rm w}$
Students should be able to use K_w to calculate the pH of a strong base from its concentration.	MS 2.2
	Students use $K_{W} = [H^+][OH^-]$ to find the pH of strong bases.

3.1.12.4 Weak acids and bases K_{a} for weak acids (A-level only)

Content	Opportunities for skills development
Weak acids and weak bases dissociate only slightly in aqueous solution.	MS 0.0
$K_{\rm a}$ is the dissociation constant for a weak acid.	and give appropriate units.
$pK_{a} = -\log_{10}K_{a}$	MS 0.1
 Students should be able to: construct an expression for K_a perform calculations relating the pH of a weak acid 	Students understand standard form when applied to areas such as (but not limited to) $K_{\rm a}$
to the concentration of the acid and the dissociation constant K	AT a, c, d, e, f and k
• convert K_a into p K_a and vice versa.	PS 2.3
	Students could calculate K_a of a weak acid by measuring the pH at half neutralisation.

3.1.12.5 pH curves, titrations and indicators (A-level only)

Content	Opportunities for skills development
Titrations of acids with bases.	MS 3.2
Students should be able to perform calculations for these titrations based on experimental results.	AT a, c, d and k
	PS 3.2 and 4.1
Typical pH curves for acid–base titrations in all combinations of weak and strong monoprotic acids and bases.	Students could plot pH curves to show how pH changes during reactions.
Students should be able to:	
 sketch and explain the shapes of typical pH curves 	
 use pH curves to select an appropriate indicator. 	
Required practical 9	
Investigate how pH changes when a weak acid reacts with a strong base and when a strong acid reacts with a weak base.	

3.1.12.6 Buffer action (A-level only)

Content	Opportunities for skills development
A buffer solution maintains an approximately constant pH,	AT a, c, e and k
despite dilution or addition of small amounts of acid or base.	PS 1.1
Acidic buffer solutions contain a weak acid and the salt of that weak acid.	Students could be asked to prepare and test a buffer solution with a specific pH value.
Basic buffer solutions contain a weak base and the salt of that weak base.	MS 0.4
Applications of buffer solutions.	Students make appropriate mathematical approximations in buffer
Students should be able to:	calculations.
explain qualitatively the action of acidic and basic buffers	
 calculate the pH of acidic buffer solutions. 	

3.2 Inorganic chemistry

3.2.1 Periodicity

The Periodic Table provides chemists with a structured organisation of the known chemical elements from which they can make sense of their physical and chemical properties. The historical development of the Periodic Table and models of atomic structure provide good examples of how scientific ideas and explanations develop over time.

3.2.1.1 Classification

Content	Opportunities for skills development
An element is classified as s, p, d or f block according to its position in the Periodic Table, which is determined by its proton number.	

3.2.1.2 Physical properties of Period 3 elements

Content	Opportunities for skills development
The trends in atomic radius, first ionisation energy and melting point of the elements Na-Ar	
The reasons for these trends in terms of the structure of and bonding in the elements.	
Students should be able to:	
 explain the trends in atomic radius and first ionisation energy 	
• explain the melting point of the elements in terms of their structure and bonding.	

3.2.2 Group 2, the alkaline earth metals

The elements in Group 2 are called the alkaline earth metals. The trends in the solubilities of the hydroxides and the sulfates of these elements are linked to their use. Barium sulfate, magnesium hydroxide and magnesium sulfate have applications in medicines whilst calcium hydroxide is used in agriculture to change soil pH, which is essential for good crop production and maintaining the food supply.

Content	Opportunities for skills development
The trends in atomic radius, first ionisation energy and	AT c and k
melting point of the elements Mg-Ba	PS 2.2
 Students should be able to: explain the trends in atomic radius and first ionisation energy explain the melting point of the elements in terms of their 	Students could test the reactions of Mg–Ba with water and Mg with steam and record their results.
structure and bonding.	AT d and k
The reactions of the elements Mg–Ba with water.	PS 2.2
The use of magnesium in the extraction of titanium from ${\rm TiCl}_{_{\! 4}}$	Students could test the solubility of Group 2 hydroxides by mixing
The relative solubilities of the hydroxides of the elements Mg–Ba in water.	sodium hydroxide and record their results.
$Mg(OH)_2$ is sparingly soluble.	Students could test the solubility of
The use of $Mg(OH)_2$ in medicine and of Ca(OH)_2 in agriculture.	Group 2 sulfates by mixing solutions of soluble Group 2 salts with sulfuric acid and record their results.
The use of CaO or ${\rm CaCO}_{\rm _3}$ to remove ${\rm SO}_{\rm _2}$ from flue gases.	Students could test for sulfate ions
The relative solubilities of the sulfates of the elements Mg–Ba in water.	using acidified barium chloride and record their results.
$BaSO_4$ is insoluble.	Research opportunity
The use of acidified BaCl ₂ solution to test for sulfate ions.	Students could investigate the use of $BaSO_4$ in medicine.
The use of $BaSO_4$ in medicine.	
Students should be able to explain why BaCl ₂ solution is used to test for sulfate ions and why it is acidified.	

3.2.3 Group 7(17), the halogens

The halogens in Group 7 are very reactive non-metals. Trends in their physical properties are examined and explained. Fluorine is too dangerous to be used in a school laboratory but the reactions of chlorine are studied. Challenges in studying the properties of elements in this group include explaining the trends in ability of the halogens to behave as oxidising agents and the halide ions to behave as reducing agents.

3.2.3.1 Trends in properties

Content	Opportunities for skills development
The trends in electronegativity and boiling point of the	AT d and k
halogens.	PS 2.2
 Students should be able to: explain the trend in electronegativity explain the trend in the boiling point of the elements in terms of their structure and bonding. 	Students could carry out test-tube reactions of solutions of the halogens (Cl_2, Br_2, I_2) with solutions containing their halide ions (eg KCl, KBr, Kl).
The trend in oxidising ability of the halogens down the group, including displacement reactions of halide ions in aqueous solution.	Students could record observations from reactions of NaCl, NaBr and Nal with concentrated sulfuric acid.
The trend in reducing ability of the halide ions, including the reactions of solid sodium halides with concentrated sulfuric acid.	Students could carry out tests for halide ions using acidified silver nitrate, including the use of ammonia to
The use of acidified silver nitrate solution to identify and distinguish between halide ions.	distinguish the silver halides formed.
The trend in solubility of the silver halides in ammonia.	
Students should be able to explain why:	
 silver nitrate solution is used to identify halide ions 	
 the silver nitrate solution is acidified 	
 ammonia solution is added. 	

Content	Opportunities for skills development
The reaction of chlorine with water to form chloride ions	Research opportunity
	Students could investigate the
and oxygen.	chlorine.
Appreciate that society assesses the advantages and disadvantages when deciding if chemicals should be added to water supplies.	Students could investigate the addition of sodium fluoride to water supplies.
The use of chlorine in water treatment.	
Appreciate that the benefits to health of water treatment by chlorine outweigh its toxic effects.	
The reaction of chlorine with cold, dilute, aqueous NaOH and uses of the solution formed.	
Required practical 4	
Carry out simple test-tube reactions to identify:	
• cations – Group 2, NH ₄ ⁺	
 anions – Group 7 (halide ions), OH⁻, CO₃²⁻, SO₄²⁻ 	

3.2.4 Properties of Period 3 elements and their oxides (A-level only)

The reactions of the Period 3 elements with oxygen are considered. The pH of the solutions formed when the oxides react with water illustrates further trends in properties across this period. Explanations of these reactions offer opportunities to develop an in-depth understanding of how and why these reactions occur.

Content	Opportunities for skills development
The reactions of Na and Mg with water.	AT a, c and k
The trends in the reactions of the elements Na, Mg, Al, Si, P	PS 2.2
AI_2O_3 , SiO_2 , P_4O_{10} , SO_2 and SO_3	Students could carry out reactions of elements with oxygen and test the pH
The trend in the melting point of the highest oxides of the elements Na-S	of the resulting oxides.
The reactions of the oxides of the elements Na–S with water, limited to Na ₂ O, MgO, Al ₂ O ₃ , SiO ₂ , P ₄ O ₁₀ , SO ₂ and SO ₃ , and the pH of the solutions formed.	
The structures of the acids and the anions formed when P_4O_{10} , SO_2 and SO_3 react with water.	
Students should be able to:	
• explain the trend in the melting point of the oxides of the elements Na–S in terms of their structure and bonding	
 explain the trends in the reactions of the oxides with water in terms of the type of bonding present in each oxide 	
 write equations for the reactions that occur between the oxides of the elements Na–S and given acids and bases. 	

3.2.5 Transition metals (A-level only)

The 3d block contains 10 elements, all of which are metals. Unlike the metals in Groups 1 and 2, the transition metals Ti to Cu form coloured compounds and compounds where the transition metal exists in different oxidation states. Some of these metals are familiar as catalysts. The properties of these elements are studied in this section with opportunities for a wide range of practical investigations.

3.2.5.1 General properties of transition metals (A-level only)

Content	Opportunities for skills development
Transition metal characteristics of elements Ti–Cu arise from an incomplete d sub-level in atoms or ions.	
 The characteristic properties include: complex formation formation of coloured ions variable oxidation state catalytic activity. 	
A ligand is a molecule or ion that forms a co-ordinate bond with a transition metal by donating a pair of electrons.	
A complex is a central metal atom or ion surrounded by ligands.	
Co-ordination number is number of co-ordinate bonds to the central metal atom or ion.	

3.2.5.2 Substitution reactions (A-level only)

Content	Opportunities for skills development
H_2O , NH_3 and CI^- can act as monodentate ligands.	AT d and k
The ligands NH_3 and H_2O are similar in size and are uncharged.	PS 1.2
Exchange of the ligands NH_3 and H_2O occurs without change of co-ordination number (eg Co ²⁺ and Cu ²⁺).	reactions of complexes with monodentate, bidentate and
Substitution may be incomplete (eg the formation of $[Cu(NH_3)_4(H_2O)_2]^{2+}$).	of substitution.
The Cl ⁻ ligand is larger than the uncharged ligands NH _a and	AT d and k
H_2O	PS 2.2
Exchange of the ligand H_2^{0} by Cl^{-} can involve a change of co-ordination number (eg Co ²⁺ , Cu ²⁺ and Fe ³⁺).	Students could carry out test-tube reactions of solutions of metal aqua
Ligands can be bidentate (eg $H_2NCH_2CH_2NH_2$ and $C_2O_4^{-2}$).	hydrochloric acid.
Ligands can be multidentate (eg EDTA4-).	
Haem is an iron(II) complex with a multidentate ligand.	
Oxygen forms a co-ordinate bond to Fe(II) in haemoglobin, enabling oxygen to be transported in the blood.	
Carbon monoxide is toxic because it replaces oxygen co-ordinately bonded to Fe(II) in haemoglobin.	
Bidentate and multidentate ligands replace monodentate ligands from complexes. This is called the chelate effect.	
Students should be able to explain the chelate effect, in terms of the balance between the entropy and enthalpy change in these reactions.	

3.2.5.3 Shapes of complex ions (A-level only)

Content	Opportunities for skills development
Transition metal ions commonly form octahedral complexes with small ligands (eq. H.O. and NH.)	MS 4.1 and 4.2
Octahedral complexes can display <i>cis</i> – <i>trans</i> isomerism (a	Students understand and draw the shape of complex ions.
special case of $E-Z$ isomerism) with monodentate ligands and optical isomerism with bidentate ligands.	MS 4.3
Transition metal ions commonly form tetrahedral complexes with larger ligands (eg Cl ⁻).	Students understand the origin of <i>cis-trans</i> and optical isomerism.
Square planar complexes are also formed and can display <i>cis-trans</i> isomerism.	Students draw <i>cis–trans</i> and optical isomers.
Cisplatin is the <i>cis</i> isomer.	Students describe the types of stereoisomerism shown by molecules/
Ag ⁺ forms the linear complex $[Ag(NH_3)_2]^+$ as used in Tollens' reagent.	complexes.

3.2.5.4 Formation of coloured ions (A-level only)

Content	Opportunities for skills development
Transition metal ions can be identified by their colour.	PS 3.1 and 3.2
Colour arises when some of the wavelengths of visible light are absorbed and the remaining wavelengths of light are transmitted or reflected.	Students could determine the concentration of a solution of copper(II) ions by colorimetry.
d electrons move from the ground state to an excited state when light is absorbed.	MS 3.1 and 3.2
The energy difference between the ground state and the excited state of the d electrons is given by:	of a solution from a graph of absorption versus concentration.
$\Delta E = hv = hc/\lambda$	AT a, e and k
Changes in oxidation state, co-ordination number and ligand alter ΔE and this leads to a change in colour.	Students could determine the concentration of a coloured complex
The absorption of visible light is used in spectroscopy.	ion by colorimetry.
A simple colorimeter can be used to determine the concentration of coloured ions in solution.	

3.2.5.5 Variable oxidation states (A-level only)	
Content	Opportunities for skills development
Transition elements show variable oxidation states.	AT d and k
Vanadium species in oxidation states IV, III and II are formed by the reduction of vanadate(V) ions by zinc in acidic solution.	PS 1.2
	Students could reduce vanadate(V) with zinc in acidic solution.
The redox potential for a transition metal ion changing from a higher to a lower oxidation state is influenced by pH and	AT b, d and k
by the ligand.	PS 4.1
The reduction of $[Ag(NH_{3})_{2}]^{+}$ (Tollens' reagent) to metallic silver is used to distinguish between aldehydes and ketones.	Students could carry out test-tube reactions of Tollens' reagent to distinguish aldehydes and ketones.
The redox titrations of Fe ²⁺ and $C_2^{}O_4^{}^{2-}$ with $MnO_4^{}^{-}$	AT a, d, e and k
Students should be able to perform calculations for these titrations and similar redox reactions	PS 2.3, 3.2 and 3.3
	Students could carry out redox titrations.
	Examples include, finding:
	the mass of iron in an iron tablet
	 the percentage of iron in steel
	 the M_r of hydrated ammonium iron(II) sulfate
	• the M_r of ethanedioic acid
	• the concentration of H_2O_2 in hair bleach.

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3.2.5.6 Catalysts (A-level only)

Content	Opportunities for skills development
Transition metals and their compounds can act as	AT d and k
heterogeneous and homogeneous catalysts.	PS 4.1
A heterogeneous catalyst is in a different phase from the reactants and the reaction occurs at active sites on the surface.	Students could investigate Mn ²⁺ as the autocatalyst in the reaction between ethanedioic acid and acidified
The use of a support medium to maximise the surface area of a heterogeneous catalyst and minimise the cost.	potassium manganate(VII).
$\rm V_2O_5$ acts as a heterogeneous catalyst in the Contact process.	
Fe is used as a heterogeneous catalyst in the Haber process.	
Heterogeneous catalysts can become poisoned by impurities that block the active sites and consequently have reduced efficiency; this has a cost implication.	
A homogeneous catalyst is in the same phase as the reactants.	
When catalysts and reactants are in the same phase, the reaction proceeds through an intermediate species.	
Students should be able to:	
 explain the importance of variable oxidation states in catalysis 	
 explain, with the aid of equations, how V₂O₅ acts as a catalyst in the Contact process 	
- explain, with the aid of equations, how Fe^{2+} ions catalyse the reaction between I^ and $S_2O_8^{\ 2-}$	
- explain, with the aid of equations, how Mn^{2+} ions autocatalyse the reaction between $C_2O_4^{2-}$ and MnO_4^{-}	

3.2.6 Reactions of ions in aqueous solution (A-level only)

The reactions of transition metal ions in aqueous solution provide a practical opportunity for students to show and to understand how transition metal ions can be identified by test-tube reactions in the laboratory.

Content	Opportunities for skills development
In aqueous solution, the following metal-aqua ions are formed:	AT d and K
$[M(H_2O)_6]^{2+}$, limited to M = Fe and Cu	PS 1.2 Students could carry out test-tube
$[M(H_2O)_6]^{3+}$, limited to M = Al and Fe The acidity of $[M(H_2O)_6]^{3+}$ is greater than that of $[M(H_2O)_6]^{2+}$	reactions of metal-aqua ions with NaOH, NH ₃ and Na ₂ CO ₃
Some metal hydroxides show amphoteric character by dissolving in both acids and bases (eg hydroxides of Al ³⁺).	AT d and k PS 2.2
 Students should be able to: explain, in terms of the charge/size ratio of the metal ion, why the acidity of [M(H₂O)₆]³⁺ is greater than that of [M(H₂O)₆]²⁺ describe and explain the simple test-tube reactions of: M²⁺(aq) ions, limited to M = Fe and Cu, and of M³⁺(aq) ions, limited to M = Al and Fe, with the bases OH⁻, NH₃ and CO₃²⁻ 	Students could carry out test-tube reactions to identify the positive and negative ions in this specification. PS 1.1 Students could identify unknown substances using reagents.
Required practical 11	
Carry out simple test-tube reactions to identify transition metal ions in aqueous solution.	

3.3 Organic chemistry

3.3.1 Introduction to organic chemistry

Organic chemistry is the study of the millions of covalent compounds of the element carbon.

These structurally diverse compounds vary from naturally occurring petroleum fuels to DNA and the molecules in living systems. Organic compounds also demonstrate human ingenuity in the vast range of synthetic materials created by chemists. Many of these compounds are used as drugs, medicines and plastics.

Organic compounds are named using the International Union of Pure and Applied Chemistry (IUPAC) system and the structure or formula of molecules can be represented in various different ways. Organic mechanisms are studied, which enable reactions to be explained.

In the search for sustainable chemistry, for safer agrochemicals and for new materials to match the desire for new technology, chemistry plays the dominant role.

3.3.1.1 Nomenclature

Content	Opportunities for skills development
Organic compounds can be represented by:	
empirical formula	
molecular formula	
general formula	
structural formula	
displayed formula	
skeletal formula.	
The characteristics of a homologous series, a series of compounds containing the same functional group.	
IUPAC rules for nomenclature.	
Students should be able to:	
 draw structural, displayed and skeletal formulas for given organic compounds 	
 apply IUPAC rules for nomenclature to name organic compounds limited to chains and rings with up to six carbon atoms each 	
• apply IUPAC rules for nomenclature to draw the structure of an organic compound from the IUPAC name limited to chains and rings with up to six carbon atoms each.	

3.3.1.2 Reaction mechanisms

Content	Opportunities for skills development
Reactions of organic compounds can be explained using mechanisms.	
 Free-radical mechanisms: the unpaired electron in a radical is represented by a dot the use of curly arrows is not required for radical mechanisms. 	
Students should be able to write balanced equations for the steps in a free-radical mechanism.	
 Other mechanisms: the formation of a covalent bond is shown by a curly arrow that starts from a lone electron pair or from another covalent bond the breaking of a covalent bond is shown by a curly arrow starting from the bond. 	
Students should be able to outline mechanisms by drawing the structures of the species involved and curly arrows to represent the movement of electron pairs.	

3.3.1.3 Isomerism

Content	Opportunities for skills development
Structural isomerism.	MS 4.2
Stereoisomerism.	Students could be given the
E-Z isomerism is a form of stereoisomerism and occurs as a result of restricted rotation about the planar carbon-carbon double bond.	structure of one isomer and asked to draw further isomers. Various representations could be used to give the opportunity to identify those that
Cahn–Ingold–Prelog (CIP) priority rules.	are isomeric.
Students should be able to:	MS 4.1, 4.2 and 4.3
define the term structural isomer	Students understand the origin of $E-Z$
draw the structures of chain, position and functional	isomerism.
group isomers	Students draw different forms of
 define the term stereoisomer 	isomers.
 draw the structural formulas of E and Z isomers 	
• apply the CIP priority rules to <i>E</i> and <i>Z</i> isomers.	

3.3.2 Alkanes

Alkanes are the main constituent of crude oil, which is an important raw material for the chemical industry. Alkanes are also used as fuels and the environmental consequences of this use are considered in this section.

3.3.2.1 Fractional distillation of crude oil

Content	Opportunities for skills development
Alkanes are saturated hydrocarbons.	AT a, d and k
Petroleum is a mixture consisting mainly of alkane hydrocarbons that can be separated by fractional distillation.	PS 1.2 Fractional distillation of a crude oil substitute.

3.3.2.2 Modification of alkanes by cracking

Content	Opportunities for skills development
Cracking involves breaking C–C bonds in alkanes.	
Thermal cracking takes place at high pressure and high temperature and produces a high percentage of alkenes (mechanism not required).	
Catalytic cracking takes place at a slight pressure, high temperature and in the presence of a zeolite catalyst and is used mainly to produce motor fuels and aromatic hydrocarbons (mechanism not required).	
Students should be able to explain the economic reasons for cracking alkanes.	

3.3.2.3 Combustion of alkanes

Content	Opportunities for skills development
Alkanes are used as fuels.	
Combustion of alkanes and other organic compounds can be complete or incomplete.	
The internal combustion engine produces a number of pollutants including NO _x , CO, carbon and unburned hydrocarbons.	
These gaseous pollutants from internal combustion engines can be removed using catalytic converters.	
Combustion of hydrocarbons containing sulfur leads to sulfur dioxide that causes air pollution.	
Students should be able to explain why sulfur dioxide can be removed from flue gases using calcium oxide or calcium carbonate.	

3.3.2.4 Chlorination of alkanes

Content	Opportunities for skills development
The reaction of methane with chlorine.	
Students should be able to explain this reaction as a free-radical substitution mechanism involving initiation, propagation and termination steps.	

3.3.3 Halogenoalkanes

Halogenoalkanes are much more reactive than alkanes. They have many uses, including as refrigerants, as solvents and in pharmaceuticals. The use of some halogenoalkanes has been restricted due to the effect of chlorofluorocarbons (CFCs) on the atmosphere.

3.3.3.1 Nucleophilic substitution

Content	Opportunities for skills development
Halogenoalkanes contain polar bonds.	AT a, b and k
Halogenoalkanes undergo substitution reactions with the nucleophiles OH ⁻ , CN ⁻ and $\rm NH_3$	PS 4.1 Students could follow instructions
Students should be able to:	when carrying out test-tube hydrolysis
 outline the nucleophilic substitution mechanisms of these reactions 	of halogenoalkanes to show their relative rates of reaction.
 explain why the carbon-halogen bond enthalpy influences the rate of reaction 	AT d, g and k
	Students could prepare a chloroalkane, purifying the product using a separating funnel and distillation.

3.3.3.2 Elimination

Content	Opportunities for skills development
The concurrent substitution and elimination reactions of a halogenoalkane (eg 2-bromopropane with potassium hydroxide).	
Students should be able to:	
 explain the role of the reagent as both nucleophile and base 	
 outline the mechanisms of these reactions. 	

3.3.3.3 Ozone depletion

Content	Opportunities for skills development
Ozone, formed naturally in the upper atmosphere, is beneficial because it absorbs ultraviolet radiation.	Research opportunity Students could investigate the role
Chlorine atoms are formed in the upper atmosphere when ultraviolet radiation causes C–Cl bonds in chlorofluorocarbons (CFCs) to break.	of chemists in the introduction of legislation to ban the use of CFCs and in finding replacements.
Chlorine atoms catalyse the decomposition of ozone and contribute to the hole in the ozone layer.	
Appreciate that results of research by different groups in the scientific community provided evidence for legislation to ban the use of CFCs as solvents and refrigerants. Chemists have now developed alternative chlorine-free compounds.	
Students should be able to use equations, such as the following, to explain how chlorine atoms catalyse decomposition of ozone:	
$CI \bullet + O_3 \rightarrow CIO \bullet + O_2$ and $CIO \bullet + O_3 \rightarrow 2O_2 + CI \bullet$	

3.3.4 Alkenes

In alkenes, the high electron density of the carbon–carbon double bond leads to attack on these molecules by electrophiles. This section also covers the mechanism of addition to the double bond and introduces addition polymers, which are commercially important and have many uses in modern society.

3.3.4.1 Structure, bonding and reactivity

Content	Opportunities for skills development
Alkenes are unsaturated hydrocarbons.	
Bonding in alkenes involves a double covalent bond, a centre of high electron density.	

3.3.4.2 Addition reactions of alkenes

Content	Opportunities for skills development
Electrophilic addition reactions of alkenes with HBr, H_2SO_4	AT d and k
and Br ₂	PS 4.1
The use of bromine to test for unsaturation.	Students could test organic
The formation of major and minor products in addition reactions of unsymmetrical alkenes.	compounds for unsaturation using bromine water and record their
Students should be able to:	observations.
 outline the mechanisms for these reactions 	
• explain the formation of major and minor products by reference to the relative stabilities of primary, secondary and tertiary carbocation intermediates.	

3.3.4.3 Addition polymers

Content	Opportunities for skills development
Addition polymers are formed from alkenes and substituted alkenes.	AT k
	PS 1.2
The repeating unit of addition polymers.	Making poly(phenylethene) from
IUPAC rules for naming addition polymers.	phenylethene.
Addition polymers are unreactive.	
Appreciate that knowledge and understanding of the production and properties of polymers has developed over time.	
Typical uses of poly(chloroethene), commonly known as PVC, and how its properties can be modified using a plasticiser.	
Students should be able to:	
 draw the repeating unit from a monomer structure 	
 draw the repeating unit from a section of the polymer chain 	
 draw the structure of the monomer from a section of the polymer 	
 explain why addition polymers are unreactive 	
 explain the nature of intermolecular forces between molecules of polyalkenes. 	

3.3.5 Alcohols

Alcohols have many scientific, medicinal and industrial uses. Ethanol is one such alcohol and it is produced using different methods, which are considered in this section. Ethanol can be used as a biofuel.

3.3.5.1 Alcohol production

Content	Opportunities for skills development
Alcohols are produced industrially by hydration of alkenes	AT a, d and k
in the presence of an acid catalyst.	PS 1.2
Ethanol is produced industrially by fermentation of glucose. The conditions for this process.	Students could produce ethanol by fermentation, followed by purification
Ethanol produced industrially by fermentation is separated by fractional distillation and can then be used as a biofuel.	by fractional distillation.
Students should be able to:	
 explain the meaning of the term biofuel 	
 justify the conditions used in the production of ethanol by fermentation of glucose 	
 write equations to support the statement that ethanol produced by fermentation is a carbon-neutral fuel and give reasons why this statement is not valid 	
 outline the mechanism for the formation of an alcohol by the reaction of an alkene with steam in the presence of an acid catalyst 	
 discuss the environmental (including ethical) issues linked to decision making about biofuel use. 	

3.3.5.2 Oxidation of alcohols

Content	Opportunities for skills development
Alcohols are classified as primary, secondary and tertiary.	AT b, d and k
Primary alcohols can be oxidised to aldehydes which can be further oxidised to carboxylic acids.	Students could carry out the preparation of an aldehyde by the
Secondary alcohols can be oxidised to ketones.	oxidation of a primary alconol.
Tertiary alcohols are not easily oxidised.	Students could carry out the preparation of a carboxylic acid by the
Acidified potassium dichromate(VI) is a suitable oxidising agent.	oxidation of a primary alcohol.
Students should be able to:	
 write equations for these oxidation reactions (equations showing [O] as oxidant are acceptable) 	
 explain how the method used to oxidise a primary alcohol determines whether an aldehyde or carboxylic acid is obtained 	
• use chemical tests to distinguish between aldehydes and ketones including Fehling's solution and Tollens' reagent.	

3.3.5.3 Elimination

Content	Opportunities for skills development
Alkenes can be formed from alcohols by acid-catalysed elimination reactions.	AT b, d, g and k PS 4.1
Alkenes produced by this method can be used to produce addition polymers without using monomers derived from crude oil.	Students could carry out the preparation of cyclohexene from cyclohexanol, including purification
Students should be able to outline the mechanism for the elimination of water from alcohols.	using a separating funnel and by distillation.
Required practical 5	
Distillation of a product from a reaction.	

3.3.6 Organic analysis

Our understanding of organic molecules, their structure and the way they react, has been enhanced by organic analysis. This section considers some of the analytical techniques used by chemists, including test-tube reactions and spectroscopic techniques.

3.3.6.1 Identification of functional groups by test-tube reactions

Content	Opportunities for skills development
The reactions of functional groups listed in the specification.	AT b, d and k
Students should be able to identify the functional groups using reactions in the specification.	PS 2.2, 2.3 and 4.1
	Students could carry out test-tube reactions in the specification to distinguish alcohols, aldehydes, alkenes and carboxylic acids.
Required practical 6	
Tests for alcohol, aldehyde, alkene and carboxylic acid.	

3.3.6.2 Mass spectrometry

Content	Opportunities for skills development
Mass spectrometry can be used to determine the molecular formula of a compound.	
Students should be able to use precise atomic masses and the precise molecular mass to determine the molecular formula of a compound.	

3.3.6.3 Infrared spectroscopy

Content	Opportunities for skills development
Bonds in a molecule absorb infrared radiation at characteristic wavenumbers.	Students should be able to use data in the Chemistry Data Sheet or Booklet to suggest possible structures for molecules.
'Fingerprinting' allows identification of a molecule by comparison of spectra.	
Students should be able to:	
 use infrared spectra and the Chemistry Data Sheet or Booklet to identify particular bonds, and therefore functional groups, and also to identify impurities. 	
The link between absorption of infrared radiation by bonds in CO_2 , methane and water vapour and global warming.	

3.3.7 Optical isomerism (A-level only)

Compounds that contain an asymmetric carbon atom form stereoisomers that differ in their effect on plane polarised light. This type of isomerism is called optical isomerism.

Content	Opportunities for skills development
Optical isomerism is a form of stereoisomerism and occurs as a result of chirality in molecules, limited to molecules with a single chiral centre. An asymmetric carbon atom is chiral and gives rise to optical isomers (enantiomers), which exist as non super- imposable mirror images and differ in their effect on plane polarised light.	MS 4.1, 4.2 and 4.3 Students could be asked to recognise the presence of a chiral centre in a given structure in 2D or 3D forms. They could also be asked to draw the 3D representation of chiral centres in various species.
A mixture of equal amounts of enantiomers is called a racemic mixture (racemate).	Students understand the origin of optical isomerism.
Students should be able to:	AT a and k
 draw the structural formulas and displayed formulas of enantiomers 	PS 1.2
 understand how racemic mixtures (racemates) are formed and why they are optically inactive. 	Passing polarised light through a solution of sucrose.

3.3.8 Aldehydes and ketones (A-level only)

Aldehydes, ketones, carboxylic acids and their derivatives all contain the carbonyl group which is attacked by nucleophiles. This section includes the addition reactions of aldehydes and ketones.

Content	Opportunities for skills development
Aldehydes are readily oxidised to carboxylic acids.	AT b, d and k
Chemical tests to distinguish between aldehydes and ketones including Fehling's solution and Tollens' reagent.	PS 2.2 Students could carry out test-tube
Aldehydes can be reduced to primary alcohols, and ketones to secondary alcohols, using $NaBH_4$ in aqueous solution. These reduction reactions are examples of nucleophilic addition.	reactions of Tollens' reagent and Fehling's solution to distinguish aldehydes and ketones.
The nucleophilic addition reactions of carbonyl compounds with KCN, followed by dilute acid, to produce hydroxynitriles.	
Aldehydes and unsymmetrical ketones form mixtures of enantiomers when they react with KCN followed by dilute acid.	
The hazards of using KCN.	
Students should be able to:	
 write overall equations for reduction reactions using [H] as the reductant 	
 outline the nucleophilic addition mechanism for reduction reactions with NaBH₄ (the nucleophile should be shown as H⁻) 	
 write overall equations for the formation of hydroxynitriles using HCN 	
 outline the nucleophilic addition mechanism for the reaction with KCN followed by dilute acid 	
 explain why nucleophilic addition reactions of KCN, followed by dilute acid, can produce a mixture of enantiomers. 	

3.3.9 Carboxylic acids and derivatives (A-level only)

Carboxylic acids are weak acids but strong enough to liberate carbon dioxide from carbonates. Esters occur naturally in vegetable oils and animal fats. Important products obtained from esters include biodiesel, soap and glycerol.

3.3.9.1 Carboxylic acids and esters (A-level only)

Content	Opportunities for skills development
The structures of:	AT b, d, g and k
carboxylic acids	PS 4.1
• esters.	Students could make esters by
Carboxylic acids are weak acids but will liberate CO_2 from carbonates.	reacting alcohols with carboxylic acids, purifying the product using a
Carboxylic acids and alcohols react, in the presence of an	separating funnel and by distillation.
acid catalyst, to give esters.	AT b, d, g, h and k
Common uses of esters (eg in solvents, plasticisers, perfumes and food flavourings).	Students could identify an ester by measuring its boiling point, followed by
Vegetable oils and animal fats are esters of propane-1,2,3-triol (glycerol).	hydrolysis to form the carboxylic acid, which is purified by recrystallisation, and determine its melting point.
Esters can be hydrolysed in acid or alkaline conditions to form alcohols and carboxylic acids or salts of carboxylic	AT b, c, d and k
acids.	Students could make soap.
Vegetable oils and animal fats can be hydrolysed in alkaline	AT b and k
acids) and glycerol.	Students could make biodiesel.
Biodiesel is a mixture of methyl esters of long-chain carboxylic acids.	
Biodiesel is produced by reacting vegetable oils with methanol in the presence of a catalyst.	

3.3.9.2 Acylation (A-level only)

Content	Opportunities for skills development
The structures of:	AT d and k
acid anhydrides	PS 2.2
acyl chloridesamides.	Students could record observations from reaction of ethanoyl chloride and
The nucleophilic addition–elimination reactions of water, alcohols, ammonia and primary amines with acyl chlorides	ethanoic anhydride with water, ethanol, ammonia and phenylamine.
	AT b, d, g and h
The industrial advantages of ethanoic anhydride over ethanoyl chloride in the manufacture of the drug aspirin.	PS 2.1, 2.3 and 4.1
Students should be able to outline the mechanism of nucleophilic addition–elimination reactions of acyl chlorides with water, alcohols, ammonia and primary amines.	Students could carry out the preparation of aspirin, purification by recrystallisation and determination of its melting point.
	Students could carry out the purification of impure benzoic acid and determination of its melting point.
Required practical 10	
Preparation of:	
 a pure organic solid and test of its purity 	
a pure organic liquid.	

3.3.10 Aromatic chemistry (A-level only)

Aromatic chemistry takes benzene as an example of this type of molecule and looks at the structure of the benzene ring and its substitution reactions.

3.3.10.1 Bonding (A-level only)

Content	Opportunities for skills development
The nature of the bonding in a benzene ring, limited to planar structure and bond length intermediate between single and double.	
Delocalisation of p electrons makes benzene more stable than the theoretical molecule cyclohexa-1,3,5-triene.	
Students should be able to:	
 use thermochemical evidence from enthalpies of hydrogenation to account for this extra stability 	
• explain why substitution reactions occur in preference to addition reactions.	

3.3.10.2 Electrophilic substitution (A-level only)

Content	Opportunities for skills development
Electrophilic attack on benzene rings results in substitution,	AT b, d, g and h
limited to monosubstitutions.	PS 2.1, 2.3 and 4.1
Nitration is an important step in synthesis, including the manufacture of explosives and formation of amines.	Students could carry out the preparation of methyl 3-nitrobenzoate
Friedel–Crafts acylation reactions are also important steps in synthesis.	by nitration of methyl benzoate, purification by recrystallisation and
Students should be able to outline the electrophilic substitution mechanisms of:	determination of melting point.
 nitration, including the generation of the nitronium ion 	
 acylation using AICl₃ as a catalyst. 	

3.3.11 Amines (A-level only)

Amines are compounds based on ammonia where hydrogen atoms have been replaced by alkyl or aryl groups. This section includes their reactions as nucleophiles.

3.3.11.1 Preparation (A-level only)

Content	Opportunities for skills development
Primary aliphatic amines can be prepared by the reaction of ammonia with halogenoalkanes and by the reduction of nitriles.	
Aromatic amines, prepared by the reduction of nitro compounds, are used in the manufacture of dyes.	

3.3.11.2 Base properties (A-level only)

Content	Opportunities for skills development
Amines are weak bases.	
The difference in base strength between ammonia, primary aliphatic and primary aromatic amines.	
Students should be able to explain the difference in base strength in terms of the availability of the lone pair of electrons on the N atom.	

3.3.11.3 Nucleophilic properties (A-level only)

Content	Opportunities for skills development
Amines are nucleophiles.	
The nucleophilic substitution reactions of ammonia and amines with halogenoalkanes to form primary, secondary, tertiary amines and quaternary ammonium salts.	
The use of quaternary ammonium salts as cationic surfactants.	
The nucleophilic addition–elimination reactions of ammonia and primary amines with acyl chlorides and acid anhydrides.	
Students should be able to outline the mechanisms of:	
 these nucleophilic substitution reactions 	
 the nucleophilic addition–elimination reactions of ammonia and primary amines with acyl chlorides. 	

3.3.12 Polymers (A-level only)

The study of polymers is extended to include condensation polymers. The ways in which condensation polymers are formed are studied, together with their properties and typical uses. Problems associated with the reuse or disposal of both addition and condensation polymers are considered.

3.3.12.1 Condensation polymers (A-level only)

Content	Opportunities for skills development
Condensation polymers are formed by reactions between:	AT k
 dicarboxylic acids and diamines 	PS 1.2
acids and diaminesamino acids.	Making nylon 6,6
The repeating units in polyesters (eg Terylene) and polyamides (eg nylon 6,6 and Kevlar) and the linkages between these repeating units.	
Typical uses of these polymers.	
Students should be able to:	
 draw the repeating unit from monomer structure(s) 	
 draw the repeating unit from a section of the polymer chain 	
• draw the structure(s) of the monomer(s) from a section of the polymer	
 explain the nature of the intermolecular forces between molecules of condensation polymers. 	

3.3.12.2 Biodegradability and disposal of polymers (A-level only)

Content	Opportunities for skills development
Polyalkenes are chemically inert and non-biodegradable.	Research opportunity
Polyesters and polyamides can be broken down by hydrolysis and are biodegradable.	Students could research problems associated with the disposal of
The advantages and disadvantages of different methods of disposal of polymers, including recycling.	different polymers.
Students should be able to explain why polyesters and polyamides can be hydrolysed but polyalkenes cannot.	

3.3.13 Amino acids, proteins and DNA (A-level only)

Amino acids, proteins and DNA are the molecules of life. In this section, the structure and bonding in these molecules and the way they interact is studied. Drug action is also considered.

3.3.13.1 Amino acids (A-level only)

Content	Opportunities for skills development
Amino acids have both acidic and basic properties, including the formation of zwitterions.	
Students should be able to draw the structures of amino acids as zwitterions and the ions formed from amino acids:	
in acid solution	
in alkaline solution.	

3.3.13.2 Proteins (A-level only)

Content	Opportunities for skills development
Proteins are sequences of amino acids joined by peptide links.	
The importance of hydrogen bonding and sulfur-sulfur bonds in proteins.	
The primary, secondary (α -helix and β -pleated sheets) and tertiary structure of proteins.	
Hydrolysis of the peptide link produces the constituent amino acids.	
Amino acids can be separated and identified by thin-layer chromatography.	
Amino acids can be located on a chromatogram using developing agents such as ninhydrin or ultraviolet light and identified by their R_f values.	
Students should be able to:	
 draw the structure of a peptide formed from up to three amino acids 	
 draw the structure of the amino acids formed by hydrolysis of a peptide 	
 identify primary, secondary and tertiary structures in diagrams 	
• explain how these structures are maintained by hydrogen bonding and S–S bonds	
 calculate R, values from a chromatogram. 	

3.3.13.3 Enzymes (A-level only)

Content	Opportunities for skills development
Enzymes are proteins.	
The action of enzymes as catalysts, including the concept of a stereospecific active site that binds to a substrate molecule.	
The principle of a drug acting as an enzyme inhibitor by blocking the active site.	
Computers can be used to help design such drugs.	
Students should be able to explain why a stereospecific active site can only bond to one enantiomeric form of a substrate or drug.	

3.3.13.4 DNA (A-level only)

Content	Opportunities for skills development
The structures of the phosphate ion, 2-deoxyribose (a pentose sugar) and the four bases adenine, cytosine, guanine and thymine are given in the Chemistry Data Booklet.	
A nucleotide is made up from a phosphate ion bonded to 2-deoxyribose which is in turn bonded to one of the four bases adenine, cytosine, guanine and thymine.	
A single strand of DNA (deoxyribonucleic acid) is a polymer of nucleotides linked by covalent bonds between the phosphate group of one nucleotide and the 2-deoxyribose of another nucleotide. This results in a sugar-phosphate- sugar-phosphate polymer chain with bases attached to the sugars in the chain.	
DNA exists as two complementary strands arranged in the form of a double helix.	
Students should be able to explain how hydrogen bonding between base pairs leads to the two complementary strands of DNA.	

3.3.13.5 Action of anticancer drugs (A-level only)

Content	Opportunities for skills development
The Pt(II) complex cisplatin is used as an anticancer drug.	
Cisplatin prevents DNA replication in cancer cells by a ligand replacement reaction with DNA in which a bond is formed between platinum and a nitrogen atom on guanine.	
Appreciate that society needs to assess the balance between the benefits and the adverse effects of drugs, such as the anticancer drug cisplatin.	
Students should be able to:	
 explain why cisplatin prevents DNA replication 	
 explain why such drugs can have adverse effects. 	

3.3.14 Organic synthesis (A-level only)

The formation of new organic compounds by multi-step syntheses using reactions included in the specification is covered in this section.

Content	Opportunities for skills development
The synthesis of an organic compound can involve several steps.	
Students should be able to:	
 explain why chemists aim to design processes that do not require a solvent and that use non-hazardous starting materials 	
 explain why chemists aim to design production methods with fewer steps that have a high percentage atom economy 	
• use reactions in this specification to devise a synthesis, with up to four steps, for an organic compound.	

3.3.15 Nuclear magnetic resonance spectroscopy (A-level only)

Chemists use a variety of techniques to deduce the structure of compounds. In this section, nuclear magnetic resonance spectroscopy is added to mass spectrometry and infrared spectroscopy as an analytical technique. The emphasis is on the use of analytical data to solve problems rather than on spectroscopic theory.

Content	Opportunities for skills development
Appreciation that scientists have developed a range of analytical techniques which together enable the structures of new compounds to be confirmed.	Students should be able to use data in the Chemistry Data Booklet to suggest possible structures for molecules.
Nuclear magnetic resonance (NMR) gives information about the position of ¹³ C or ¹ H atoms in a molecule.	
¹³ C NMR gives simpler spectra than ¹ H NMR.	
The use of the δ scale for recording chemical shift.	
Chemical shift depends on the molecular environment.	
Integrated spectra indicate the relative numbers of ¹ H atoms in different environments.	
$^1\mathrm{H}$ NMR spectra are obtained using samples dissolved in deuterated solvents or CCl_4	
The use of tetramethylsilane (TMS) as a standard.	
Students should be able to:	
 explain why TMS is a suitable substance to use as a standard 	
 use ¹H NMR and ¹³C NMR spectra and chemical shift data from the Chemistry Data Booklet to suggest possible structures or part structures for molecules 	
 use integration data from ¹H NMR spectra to determine the relative numbers of equivalent protons in the molecule 	
 use the n+1 rule to deduce the spin-spin splitting patterns of adjacent, non-equivalent protons, limited to doublet, triplet and quartet formation in aliphatic compounds. 	

3.3.16 Chromatography (A-level only)

Chromatography provides an important method of separating and identifying components in a mixture. Different types of chromatography are used depending on the composition of mixture to be separated.

Content	Opportunities for skills development
Chromatography can be used to separate and identify the components in a mixture.	AT a, i and k
	PS 1.2, 3.2 and 4.1
Types of chromatography include:	Students could use thin-layer
 thin-layer chromatography (ILC) – a plate is coated with a solid and a solvent moves up the plate 	chromatography to identify analgesics.
 column chromatography (CC) – a column is packed with a solid and a solvent moves down the column 	Students could use thin-layer chromatography to identify transition
 gas chromatography (GC) – a column is packed with a solid or with a solid coated by a liquid, and a gas is passed through the column under pressure at high temperature. 	metal ions in a solution.
Separation depends on the balance between solubility in the moving phase and retention by the stationary phase.	
Retention times and ${\rm R}_{\rm f}$ values are used to identify different substances.	
The use of mass spectrometry to analyse the components separated by GC.	
Students should be able to:	
 calculate R_f values from a chromatogram 	
 compare retention times and R_f values with standards to identify different substances. 	
Required practical 12	
Separation of species by thin-layer chromatography.	