Core topics

Essential idea: Materials science involves understanding the properties of a material, and then applying those properties to desired structures.

A.1 Materials science introduction

Nature of science:

Improvements in technology—different materials were used for different purposes before the development of a scientific understanding of their properties. (1.8)

Patterns in science—history has characterized civilizations by the materials they used: Stone Age, Bronze Age and Iron Age. There are various ways of classifying materials according to desired patterns. (3.1)

Understandings:

- Materials are classified based on their uses, properties, or bonding and structure.
- The properties of a material based on the degree of covalent, ionic or metallic character in a compound can be deduced from its position on a bonding triangle.
- Composites are mixtures in which materials are composed of two distinct phases, a reinforcing phase that is embedded in a matrix phase.

Applications and skills:

- Use of bond triangle diagrams for binary compounds from electronegativity data.
- Evaluation of various ways of classifying materials.
- Relating physical characteristics (melting point, permeability, conductivity, elasticity, brittleness) of a material to its bonding and structures (packing arrangements, electron mobility, ability of atoms to slide relative to one another).

International-mindedness:

- What materials were used by ancient civilizations, such as the Aztecs, Romans, and Chinese? Even though these ancient civilizations were located in geographically diverse locations, the materials they used were similar.

Theory of knowledge:

- Although it is convenient to classify materials into categories no single classification is “perfect”. How do we evaluate the different classification systems we use in the different areas of knowledge? How does our need to categorize the world help and hinder the pursuit of knowledge?

Utilization:

Syllabus and cross-curricular links:
Topic 4.2—the role of electronegativity in bonding types

A.1 Materials science introduction	
Guidance: • Permeability to moisture should be considered with respect to bonding and simple packing arrangements. • Consider properties of metals, polymers and ceramics in terms of metallic, covalent, and ionic bonding. • See section 29 of the data booklet for a triangular bonding diagram.	**Aims:** • **Aims 1** and **3**: Investigation of tetrahedra of structure and bonding types and where covalent networks and polymers fit on these diagrams. • **Aim 6**: Experiments could include investigating the stretching of rubber bands under different chemical environments, or properties of metals, polymers, ceramics, or composites, making thin concrete slabs from various ratios of cement, gravel, and sand and investigating the breaking strength upon drying.

Essential idea: Metals can be extracted from their ores and alloyed for desired characteristics. ICP-MS/OES Spectroscopy ionizes metals and uses mass and emission spectra for analysis.

A.2 Metals and inductively coupled plasma (ICP) spectroscopy

Nature of science:

Development of new instruments and techniques—ICP spectroscopy, developed from an understanding of scientific principles, can be used to identify and quantify trace amounts of metals. (1.8)

Details of data—with the discovery that trace amounts of certain materials can greatly enhance a metal's performance, alloying was initially more of an art than a science. (3.1)

Understandings:

- Reduction by coke (carbon), a more reactive metal, or electrolysis are means of obtaining some metals from their ores.
- The relationship between charge and the number of moles of electrons is given by Faraday's constant, *F*.
- Alloys are homogeneous mixtures of metals with other metals or non-metals.
- Diamagnetic and paramagnetic compounds differ in electron spin pairing and their behaviour in magnetic fields.
- Trace amounts of metals can be identified and quantified by ionizing them with argon gas plasma in Inductively Coupled Plasma (ICP) Spectroscopy using Mass Spectroscopy ICP-MS and Optical Emission Spectroscopy ICP-OES.

Applications and skills:

- Deduction of redox equations for the reduction of metals.
- Relating the method of extraction to the position of a metal on the activity series.
- Explanation of the production of aluminium by the electrolysis of alumina in molten cryolite
- Explanation of how alloying alters properties of metals.

International-mindedness:

- The use of rare earth metals, or exotic minerals, has grown dramatically. They are used in green technology, medicines, lasers, weapons technology and elsewhere. They are expensive to obtain but growing in demand. What happens if rare earth reserves are controlled only by a few countries but are used by many countries?

Theory of knowledge:

- What factors/outcomes should be used to determine how time, money, and effort is spent on scientific research? Who decides which knowledge is to be pursued?

Utilization:

Syllabus and cross-curricular links:
Topics 2.1 and 12.1—mass spectrometry
Topic 2.2—emission spectra
Topic 9.1—oxidation and reduction

Aims:

- **Aim 6**: Experiments could include calculating the Faraday constant via electrolysis of aqueous copper sulfate, solving for the concentration of a nickel or copper solution using Beer's law and spectrophotometry. Analysis of alloy composition labs could also be conducted such as colorimetric determination of manganese in a paper clip or gravimetric analysis of silver or copper in a coin.

A.2 Metals and inductively coupled plasma (ICP) spectroscopy	
• Solving stoichiometric problems using Faraday's constant based on mass deposits in electrolysis. • Discussion of paramagnetism and diamagnetism in relation to electron structure of metals. • Explanation of the plasma state and its production in ICP- MS/OES. • Identify metals and abundances from simple data and calibration curves provided from ICP-MS and ICP-OES. • Explanation of the separation and quantification of metallic ions by MS and OES. • Uses of ICP-MS and ICP-OES. **Guidance:** • Faraday's constant is given in the data booklet in section 2. • Details of operating parts of ICP-MS and ICP-OES instruments will not be assessed. • Only analysis of metals should be covered. • The importance of calibration should be covered.	• **Aim 7**: Animations involving ICP could be used. • **Aim 7**: Simulations and virtual experiments could be used to investigate semiconductors.

Essential idea: Catalysts work by providing an alternate reaction pathway for the reaction. Catalysts always increase the rate of the reaction and are left unchanged at the end of the reaction.

A.3 Catalysts

Nature of science:

Use of models—catalysts were used to increase reaction rates before the development of an understanding of how they work. This led to models that are constantly being tested and improved. (1.10)

Understandings:

- Reactants adsorb onto heterogeneous catalysts at active sites and the products desorb.
- Homogeneous catalysts chemically combine with the reactants to form a temporary activated complex or a reaction intermediate.
- Transition metal catalytic properties depend on the adsorption/absorption properties of the metal and the variable oxidation states.
- Zeolites act as selective catalysts because of their cage structure.
- Catalytic particles are nearly always nanoparticles that have large surface areas per unit mass.

Applications and skills:

- Explanation of factors involved in choosing a catalyst for a process.
- Description of how metals work as heterogeneous catalysts.
- Description of the benefits of nanocatalysts in industry.

Guidance:

- Consider catalytic properties such as selectivity for only the desired product, efficiency, ability to work in mild/severe conditions, environmental impact and impurities.
- The use of carbon nanocatalysts should be covered.

International-mindedness:

- Palladium, platinum and rhodium are common catalysts that are used in catalytic converters. Because of the value of these metals, catalytic converter thefts are on the rise.

Theory of knowledge:

- Some materials used as effective catalysts are toxic and harmful to the environment. Is environmental degradation justified in the pursuit of knowledge?

Utilization:

Syllabus and cross-curricular links:
Topics 6.1 and 16.1—reaction mechanisms
Topic 10.2—esterification and hydrogenation reactions
Topic 16.2—activation energy
Option B.10—hydrogenation of fats

Aims:

- **Aims 1** and **3**: Investigate various catalysts for both the benefits and risks.
- **Aim 6**: Experiments could include investigating the decomposition of potassium sodium tartrate with cobalt chloride and the decomposition of hydrogen peroxide with manganese (IV) oxide.
- **Aim 6**: An ion exchange using zeolite could be explored.
- **Aim 7**: Virtual experiments and simulations involving nanoparticles as catalysts could be done here.

Essential idea: Liquid crystals are fluids that have physical properties which are dependent on molecular orientation relative to some fixed axis in the material.

A.4 Liquid crystals

Nature of science

Serendipity and scientific discoveries—Friedrich Reinitzer accidently discovered flowing liquid crystals in 1888 while experimenting on cholesterol. (1.4)

Understandings:

- Liquid crystals are fluids that have physical properties (electrical, optical and elasticity) that are dependent on molecular orientation to some fixed axis in the material.
- Thermotropic liquid-crystal materials are pure substances that show liquid-crystal behaviour over a temperature range.
- Lyotropic liquid crystals are solutions that show the liquid-crystal state over a (certain) range of concentrations.
- Nematic liquid crystal phase is characterized by rod shaped molecules which are randomly distributed but on average align in the same direction.

Applications and skills:

- Discussion of the properties needed for a substance to be used in liquid-crystal displays (LCD).
- Explanation of liquid-crystal behaviour on a molecular level.

Guidance:

- Properties needed for liquid crystals include: chemically stable, a phase which is stable over a suitable temperature range, polar so they can change orientation when an electric field is applied, and rapid switching speed.
- Soap and water is an example of lyotropic liquid crystals and the biphenyl nitriles are examples of thermotropic liquid crystals.
- Liquid crystal behaviour should be limited to the biphenyl nitriles.
- Smectics and other liquid crystals types need not be discussed.

International-mindedness:

- The production of many electronic goods is concentrated in areas of the world where the working conditions may not be ideal. Should there be internationally set labour standards for all workers? What implications would this have on the cost of consumer goods?

Theory of knowledge:

- Developments in technology mean that we can store more and more information available on an increasingly smaller scale. Does this mean that we can access more knowledge?

Utilization:

Syllabus and cross-curricular links:
Topic 20.3—chirality and stereoisomers

Aims:

- **Aim 6**: Experiments could include investigating a thermotropic liquid crystal and the temperature range which affects these crystals.
- **Aim 7**: Computer animations could be used to investigate thermotropic liquid crystals.

Essential idea: Polymers are made up of repeating monomer units which can be manipulated in various ways to give structures with desired properties.

A.5 Polymers

Nature of science:

Advances in technology—as a result of advances in technology (X-ray diffraction, scanning tunnelling electron microscopes, etc), scientists have been able to understand what occurs on the molecular level and manipulate matter in new ways. This allows new polymers to be developed. (3.7)

Theories can be superseded—Staudinger's proposal of macromolecules made of many repeating units was integral in the development of polymer science. (1.9)

Ethics and risk assessment—polymer development and use has grown quicker than an understanding of the risks involved, such as recycling or possible carcinogenic properties. (4.5)

Understandings:

- Thermoplastics soften when heated and harden when cooled.
- A thermosetting polymer is a prepolymer in a soft solid or viscous state that changes irreversibly into a hardened thermoset by curing.
- Elastomers are flexible and can be deformed under force but will return to nearly their original shape once the stress is released.
- High density polyethene (HDPE) has no branching allowing chains to be packed together.
- Low density polyethene (LDPE) has some branching and is more flexible.
- Plasticizers added to a polymer increase the flexibility by weakening the intermolecular forces between the polymer chains.
- Atom economy is a measure of efficiency applied in green chemistry.
- Isotactic addition polymers have substituents on the same side.
- Atactic addition polymers have the substituents randomly placed.

Applications and skills:

- Description of the use of plasticizers in polyvinyl chloride and volatile hydrocarbons in the formation of expanded polystyrene.

International-mindedness:

- Plastics were virtually unheard of prior to the second world war. How has the introduction of plastics affected the world economically, socially and environmentally?

Utilization:

Syllabus and cross-curricular links:
Topics 10.2 and 20.1—addition and condensation reactions

Aims:

- **Aim 6**: Physical properties of high and low density polyethene could be investigated or synthesis of a polyester, polyamide or other polymer could be quantitatively performed to measure atom efficiency.

A.5 Polymers	
• Solving problems and evaluating atom economy in synthesis reactions. • Description of how the properties of polymers depend on their structural features. • Description of ways of modifying the properties of polymers, including LDPE and HDPE. • Deduction of structures of polymers formed from polymerizing 2-methylpropene. **Guidance:** • The equation for percent atom economy is provided in the data booklet in section 1. • Consider only polystyrene foams as examples of polymer property manipulation.	

Essential idea: Chemical techniques position atoms in molecules using chemical reactions whilst physical techniques allow atoms/molecules to be manipulated and positioned to specific requirements.

A.6 Nanotechnology

Nature of science:

Improvements in apparatus—high power electron microscopes have allowed for the study of positioning of atoms. (1.8)

The need to regard theories as uncertain—the role of trial and error in the development of nanotubes and their associated theories. (2.2)

"The principles of physics, as far as I can see, do not speak against the possibility of manoeuvring things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big."
— Richard Feynman, Nobel Prize winner in Physics

Understandings:

- Molecular self-assembly is the bottom-up assembly of nanoparticles and can occur by selectively attaching molecules to specific surfaces. Self-assembly can also occur spontaneously in solution.
- Possible methods of producing nanotubes are arc discharge, chemical vapour deposition (CVD) and high pressure carbon monoxide (HIPCO).
- Arc discharge involves either vaporizing the surface of one of the carbon electrodes, or discharging an arc through metal electrodes submersed in a hydrocarbon solvent, which forms a small rod-shaped deposit on the anode.

Applications and skills:

- Distinguishing between physical and chemical techniques in manipulating atoms to form molecules.
- Description of the structure and properties of carbon nanotubes.
- Explanation of why an inert gas, and not oxygen, is necessary for CVD preparation of carbon nanotubes.
- Explanation of the production of carbon from hydrocarbon solvents in arc discharge by oxidation at the anode.
- Deduction of equations for the production of carbon atoms from HIPCO.

International-mindedness:

- Some studies have shown that inhaling nanoparticle dust can be as harmful as asbestos. Should nanotechnology be regulated or will this hinder research?
- International collaboration in space exploration is growing. Would a carbon nanotube space elevator be feasible, or wanted? What are the implications?

Theory of knowledge:

- The use of the scanning tunnelling microscope has allowed us to "see" individual atoms, which was previously thought to be unattainable. How do these advances in technology change our view of what knowledge is attainable?
- Some people are concerned about the possible implication of nanotechnology. How do we evaluate the possible consequences of future developments in this area? Is the knowledge we need publicly available or do we rely on the authority of experts?

Utilization:

- Protein synthesis in cells is a form of nanotechnology with ribosomes acting as molecular assemblers.

Syllabus and cross-curricular links:
Topics 4.3—molecular polarity

A.6 Nanotechnology	
• Discussion of some implications and applications of nanotechnology. • Explanation of why nanotubes are strong and good conductors of electricity. **Guidance:** • Possible implications of nanotechnology include uncertainty as to toxicity levels on a nanoscale, unknown health risks with new materials, concern that human defence systems are not effective against particles on the nanoscale, responsibilities of the industries and governments involved in this research. • Conductivity of graphene and fullerenes can be explained in terms of delocalization of electrons. An explanation based on hybridization is not required.	**Aims:** • **Aims 1**, **8** and **9**: Investigate the theoretical and large scale manufacturing of nanotechnology products and their implications. Examples could include sporting equipment, medicinal products, construction, environmental cleaning, robotics, weaponry or other theoretical commercial uses. • **Aims 7**, **8** and **9**: Animations, simulations, and videos of nanotube manufacture and uses should be used.

Essential idea: Although materials science generates many useful new products there are challenges associated with recycling of and high levels of toxicity of some of these materials.

A.7 Environmental impact—plastics

Nature of science:

Risks and problems—scientific research often proceeds with perceived benefits in mind, but the risks and implications also need to be considered. (4.8)

Understandings:

- Plastics do not degrade easily because of their strong covalent bonds.
- Burning of polyvinyl chloride releases dioxins, HCl gas and incomplete hydrocarbon combustion products.
- Dioxins contain unsaturated six-member heterocyclic rings with two oxygen atoms, usually in positions 1 and 4.
- Chlorinated dioxins are hormone disrupting, leading to cellular and genetic damage.
- Plastics require more processing to be recycled than other materials.
- Plastics are recycled based on different resin types.

Applications and skills:

- Deduction of the equation for any given combustion reaction.
- Discussion of why the recycling of polymers is an energy intensive process.
- Discussion of the environmental impact of the use of plastics.
- Comparison of the structures of polychlorinated biphenyls (PCBs) and dioxins.
- Discussion of the health concerns of using volatile plasticizers in polymer production.
- Distinguish possible Resin Identification Codes (RICs) of plastics from an IR spectrum.

International-mindedness:

- The international symbol for recycle, reuse and reduce is a Mobius strip designed in the late 1960s. However, global recognition of this symbol ranks well below other symbols. What factors influence the recognition of symbols?
- How can nations address the problem of the plastic gyre in the Pacific Ocean?

Theory of knowledge:

- The products of science and technology can have a negative impact on the environment. Are scientists ethically responsible for the impact of their products?

Utilization:

Syllabus and cross-curricular links:
Topic 9.1—redox reactions
Topic 10.1—organic compounds
Topic 11.3—infrared spectroscopy
Biology option C.3—impact of humans on ecosystems

Aims:

- **Aim 7**: Database of RIC codes and IR spectra can be used.
- **Aim 8**: The development of green chemistry has raised the awareness of the environmental and the ethical implications of using science and technology.

A.7 Environmental impact—plastics	
Guidance: • Dioxins do not decompose in the environment and can be passed on in the food chain. • Consider polychlorinated dibenzodioxins (PCDD) and PCBs as examples of carcinogenic chlorinated dioxins or dioxin-like substances. • Consider phthalate esters as examples of plasticizers. • House fires can release many toxins due to plastics (shower curtains, etc). Low smoke zero halogen cabling is often used in wiring to prevent these hazards. • Resin Identification Codes (RICs) are in the data booklet in section 30. • Structures of various materials molecules are in the data booklet in section 31.	

Additional higher level topics

Essential idea: Superconductivity is zero electrical resistance and expulsion of magnetic fields. X-ray crystallography can be used to analyse structures.

A.8 Superconducting metals and X-ray crystallography

Nature of science:

Importance of theories—superconducting materials, with zero electrical resistance below a certain temperature, provide a good example of theories needing to be modified to fit new data. It is important to understand the basic scientific principles behind modern instruments. (2.2)

Understandings:

- Superconductors are materials that offer no resistance to electric currents below a critical temperature.
- The Meissner effect is the ability of a superconductor to create a mirror image magnetic field of an external field, thus expelling it.
- Resistance in metallic conductors is caused by collisions between electrons and positive ions of the lattice.
- The Bardeen–Cooper–Schrieffer (BCS) theory explains that below the critical temperature electrons in superconductors form Cooper pairs which move freely through the superconductor.
- Type 1 superconductors have sharp transitions to superconductivity whereas Type 2 superconductors have more gradual transitions.
- X-ray diffraction can be used to analyse structures of metallic and ionic compounds.
- Crystal lattices contain simple repeating unit cells.
- Atoms on faces and edges of unit cells are shared.
- The number of nearest neighbours of an atom/ion is its coordination number.

International-mindedness:

- Analytical techniques have applications in forensics, mineral exploration, medicine and elsewhere. How does the unequal access to advanced technology affect world economies?

Theory of knowledge:

- X-ray diffraction has allowed us to probe the world beyond the biological limits of our senses. How reliable is our knowledge of the microscopic world compared to what we know at the macroscopic level?

Utilization:

Syllabus and cross-curricular links:
Topic 2.2—Pauli exclusion principle
Topic 3.2—atomic radius and periodicity
Topic 21.1—X-ray crystallography
Physics topic 4.2—travelling waves

Aims:

- **Aim 7**: Animations and simulations would be very useful to explain superconductivity and X-ray crystallography.

A.8 Superconducting metals and X-ray crystallography	
Applications and skills: • Analysis of resistance versus temperature data for Type 1 and Type 2 superconductors. • Explanation of superconductivity in terms of Cooper pairs moving through a positive ion lattice. • Deduction or construction of unit cell structures from crystal structure information. • Application of the Bragg equation, $n\lambda = 2dsin\theta$, in metallic structures. • Determination of the density of a pure metal from its atomic radii and crystal packing structure. **Guidance:** • Only a simple explanation of BCS theory with Cooper pairs is required. At low temperatures the positive ions in the lattice are distorted slightly by a passing electron. A second electron is attracted to this slight positive deformation and a coupling of these two electrons occurs. • Operating principles of X-ray crystallography are not required. • Only pure metals with simple cubic cells, body centred cubic cells (BCC) and face centred cubic cells (FCC) should be covered. • Perovskite crystalline structures of many superconductors can be analysed by X-ray crystallography but these will not be assessed. • Bragg's equation will only be applied to simple cubic structures.	

Essential idea: Condensation polymers are formed by the loss of small molecules as functional groups from monomers join.

A.9 Condensation polymers

Nature of science:

Speculation—we have had the Stone Age, Iron Age and Bronze Age. Is it possible that today's age is the Age of Polymers, as science continues to manipulate matter for desired purposes? (1.5)

Understandings:

- Condensation polymers require two functional groups on each monomer.
- NH_3, HCl and H_2O are possible products of condensation reactions.
- Kevlar® is a polyamide with a strong and ordered structure. The hydrogen bonds between O and N can be broken with the use of concentrated sulfuric acid.

Applications and skills:

- Distinguishing between addition and condensation polymers.
- Completion and descriptions of equations to show how condensation polymers are formed.
- Deduction of the structures of polyamides and polyesters from their respective monomers.
- Explanation of Kevlar®'s strength and its solubility in concentrated sulfuric acid.

Guidance:

- Consider green chemistry polymers.

International-mindedness:

- Does science, economics or politics play the most essential role in research, such as the development of new polymers?

Utilization:

Syllabus and cross-curricular links:
Topic 10.2—addition and condensation reactions
Topic 20.2—synthesis techniques
Option A.5—polymers

Aims:

- **Aim 6**: Synthesis of nylon could be performed.

Essential idea: Toxicity and carcinogenic properties of heavy metals are the result of their ability to form coordinated compounds, have various oxidation states and act as catalysts in the human body.

A.10 Environmental impact—heavy metals

Nature of science:

Risks and problems—scientific research often proceeds with perceived benefits in mind, but the risks and implications also need to be considered. (4.8)

Understandings:

- Toxic doses of transition metals can disturb the normal oxidation/reduction balance in cells through various mechanisms.
- Some methods of removing heavy metals are precipitation, adsorption, and chelation.
- Polydentate ligands form more stable complexes than similar monodentate ligands due to the chelate effect, which can be explained by considering entropy changes.

Applications and skills:

- Explanation of how chelating substances can be used to remove heavy metals.
- Deduction of the number of coordinate bonds a ligand can form with a central metal ion.
- Calculations involving K_{sp} as an application of removing metals in solution.
- Compare and contrast the Fenton and Haber–Weiss reaction mechanism.

Guidance:

- Ethane-1,2-diamine acts as a bidentate ligand and $EDTA^{4-}$ acts as hexadentate ligand.
- The Haber–Weiss reaction generates free radicals naturally in biological processes. Transition metals can catalyse the reaction with the iron-catalysed (Fenton) reaction being the mechanism for generating reactive hydroxyl radicals.
- K_{sp} values are in the data booklet in section 32.

Theory of knowledge:

- What responsibility do scientists have for the impact of their endeavours on the planet?

Utilization:

Syllabus and cross-curricular links:
Topic 9.1—redox reactions
Topic 13.2—transition metal complexes
Biology option C.3—impact of humans on ecosystems

Aims:

- **Aims 1** and **8**: Investigations of waste water treatment.
- **Aim 6**: Experiments could include investigations of K_{sp}.

Core topics

Essential idea: Metabolic reactions involve a complex interplay between many different components in highly controlled environments.

B.1 Introduction to biochemistry

Nature of science:

Use of data—biochemical systems have a large number of different reactions occurring in the same place at the same time. As technologies have developed, more data has been collected leading to the discovery of patterns of reactions in metabolism. (3.1)

Understandings:

- The diverse functions of biological molecules depend on their structures and shapes.
- Metabolic reactions take place in highly controlled aqueous environments.
- Reactions of breakdown are called catabolism and reactions of synthesis are called anabolism.
- Biopolymers form by condensation reactions and are broken down by hydrolysis reactions.
- Photosynthesis is the synthesis of energy-rich molecules from carbon dioxide and water using light energy.
- Respiration is a complex set of metabolic processes providing energy for cells.

Applications and skills :

- Explanation of the difference between condensation and hydrolysis reactions.
- The use of summary equations of photosynthesis and respiration to explain the potential balancing of oxygen and carbon dioxide in the atmosphere.

Guidance:

- Intermediates of aerobic respiration and photosynthesis are not required.

International-mindedness:

- Metabolic reactions in the human body are dependent on the supply of nutrients through a regular balanced diet. Globally there are significant differences in the availability of nutritious food, which have major and diverse impacts on human health.

Utilization:

- Biochemistry is fundamental to the study of many other subjects, including genetics, immunology, pharmacology, nutrition and agriculture.

Syllabus and cross-curricular links:
Topic 10.2—S_N reactions (condensation and hydrolysis)
Topic 13.2 and Option B.9—metal complexes and light absorption
Option C.8—electronic conjugation and light absorption

Essential idea: Proteins are the most diverse of the biopolymers responsible for metabolism and structural integrity of living organisms.

B.2 Proteins and enzymes

Nature of science:

Collaboration and peer review—several different experiments on several continents led to the conclusion that DNA, and not protein as originally thought, carried the information for inheritance. (4.4)

Understandings:

- Proteins are polymers of 2-amino acids, joined by amide links (also known as peptide bonds).
- Amino acids are amphoteric and can exist as zwitterions, cations and anions.
- Protein structures are diverse and are described at the primary, secondary, tertiary and quaternary levels.
- A protein's three-dimensional shape determines its role in structural components or in metabolic processes.
- Most enzymes are proteins that act as catalysts by binding specifically to a substrate at the active site.
- As enzyme activity depends on the conformation, it is sensitive to changes in temperature and pH and the presence of heavy metal ions.
- Chromatography separation is based on different physical and chemical principles.

Applications and skills:

- Deduction of the structural formulas of reactants and products in condensation reactions of amino acids, and hydrolysis reactions of peptides.
- Explanation of the solubilities and melting points of amino acids in terms of zwitterions.
- Application of the relationships between charge, pH and isoelectric point for amino acids and proteins.

International-mindedness:

- The Universal Protein Resource (UniProt) is a consortium of bioinformatics institutes. Its mission is to act as a resource for the scientific community by providing comprehensive, high-quality and freely accessible data on protein sequence and functional information.

Utilization:

- Many synthetic materials are polyamides. Examples include nylon and Kevlar®.
- Electrophoresis is used in some medical diagnostics to identify patterns of unusual protein content in blood serum or urine.
- The first protein to be sequenced was insulin by Frederick Sanger in 1951, in a process that took over ten years. Today, protein sequencing is a routine and very efficient process, and is a major part of the study known as proteomics.

Syllabus and cross-curricular links:
Topics 8.3 and 18.2—pH and pK_a and pK_b values
Topic 20.3—stereoisomerism
Option A.9—condensation polymers
Option B.9—chromatography
Biology topics 2.4, 2.5 and 8.1—proteins and enzymes

Aims:

- **Aim 6**: Experiments could involve hydrolysis of a protein, separation and identification of amino acid mixtures by paper chromatography, or gel electrophoresis of proteins and DNA.
- **Aim 7**: Data logging experiments involving absorption/concentration studies for protein content using the Biuret reagent.

B.2 Proteins and enzymes	
• Description of the four levels of protein structure, including the origin and types of bonds and interactions involved. • Deduction and interpretation of graphs of enzyme activity involving changes in substrate concentration, pH and temperature. • Explanation of the processes of paper chromatography and gel electrophoresis in amino acid and protein separation and identification. **Guidance:** • The names and structural formulas of the amino acids are given in the data booklet in section 33. • Reference should be made to alpha helix and beta pleated sheet, and to fibrous and globular proteins with examples of each. • In paper chromatography the use of R_f values and locating agents should be covered. • In enzyme kinetics K_m and V_{max} are not required.	• **Aim 7**: Simulations can be used for gel electrophoresis.

Essential idea: Lipids are a broad group of biomolecules that are largely non-polar and therefore insoluble in water.

B.3 Lipids

Nature of science:

Significance of science explanations to the public—long-term studies have led to knowledge of the negative effects of diets high in saturated fat, cholesterol, and *trans*-fat. This has led to new food products. (5.2)

Understandings:

- Fats are more reduced than carbohydrates and so yield more energy when oxidized.
- Triglycerides are produced by condensation of glycerol with three fatty acids and contain ester links. Fatty acids can be saturated, monounsaturated or polyunsaturated.
- Phospholipids are derivatives of triglycerides.
- Hydrolysis of triglycerides and phospholipids can occur using enzymes or in alkaline or acidic conditions.
- Steroids have a characteristic fused ring structure, known as a steroidal backbone.
- Lipids act as structural components of cell membranes, in energy storage, thermal and electrical insulation, as transporters of lipid soluble vitamins and as hormones.

Applications and skills:

- Deduction of the structural formulas of reactants and products in condensation and hydrolysis reactions between glycerol and fatty acids and/or phosphate.
- Prediction of the relative melting points of fats and oils from their structures.
- Comparison of the processes of hydrolytic and oxidative rancidity in fats with respect to the site of reactivity in the molecules and the conditions that favour the reaction.

International-mindedness:

- There are large global and cultural differences in the dietary sources of lipids and methods used to prevent rancidity.

Theory of knowledge:

- Different countries have very different standards towards food labelling. Is access to information a human right? What knowledge should be universally available?
- What are the different responsibilities of government, industry, the medical profession and the individual in making healthy choices about diet? Public bodies can protect the individual but also limit their freedom. How do we know what is best for society and the individual?

Utilization:

- Alkaline hydrolysis of fats is used in the process of soap-making, known as saponification.
- Steroid abuse, especially in sports, and methods for detection.

Syllabus and cross-curricular links:
Topics 10.1 and 10.2—functional groups, hydrogenation of alkenes
Topic 10.2—free radical mechanisms
Topic 20.3—configurational isomerism
Biology topic 2.3—lipids

B.3 Lipids	
• Application of the concept of iodine number to determine the unsaturation of a fat. • Comparison of carbohydrates and lipids as energy storage molecules with respect to their solubility and energy density. • Discussion of the impact of lipids on health, including the roles of dietary high-density lipoprotein (HDL) and low-density lipoprotein (LDL) cholesterol, saturated, unsaturated and *trans*-fat and the use and abuse of steroids. **Guidance:** • The structures of some fatty acids are given in the data booklet in section 34. • Specific named examples of fats and oils do not have to be learned. • The structural differences between *cis*- and *trans*-fats are not required.	**Aims:** • **Aim 6**: Experiments could include the calculation of the iodine number of fats to measure degree of unsaturation, calorimetric experiments on different fats and oils, or the separation of lipids from common food sources using different solvents and a separating funnel.

Essential idea: Carbohydrates are oxygen-rich biomolecules, which play a central role in metabolic reactions of energy transfer.

B.4 Carbohydrates

Nature of science:

Construct models/visualizations—understanding the stereochemistry of carbohydrates is essential to understanding their structural roles in cells. Haworth projections help focus on the nature and position of attached groups by making carbon and hydrogen implicit. (1.10)

Obtaining evidence for scientific theories—consider the structural role of carbohydrates. (1.8)

Understandings:

- Carbohydrates have the general formula $C_x(H_2O)_y$.
- Haworth projections represent the cyclic structures of monosaccharides.
- Monosaccharides contain either an aldehyde group (aldose) or a ketone group (ketose) and several –OH groups.
- Straight chain forms of sugars cyclize in solution to form ring structures containing an ether linkage.
- Glycosidic bonds form between monosaccharides forming disaccharides and polysaccharides.
- Carbohydrates are used as energy sources and energy reserves.

Applications and skills:

- Deduction of the structural formulas of disaccharides and polysaccharides from given monosaccharides.
- Relationship of the properties and functions of monosaccharides and polysaccharides to their chemical structures.

International-mindedness:

- Sugar is a major international commodity and is produced in about 130 different countries. Approximately three-quarters of production comes from sugar cane in tropical and subtropical regions and the remainder comes from sugar beet which is cultivated in temperate climates.
- Diabetes is a chronic disease that occurs when the body cannot effectively regulate blood sugar, due to a failure in the production or functioning of insulin. The World Health Organization projects that deaths from diabetes will double between 2005 and 2030.
- Lactose intolerance is a condition in which the individual is not able to digest lactose, the sugar found in milk and dairy products. It is due to a failure to produce sufficient levels of lactase, the enzyme that hydrolyses lactose into glucose and galactose. Globally lactose intolerance is the norm. It is an example of a Western perspective invading science.

Theory of knowledge:

- The use of aspartame as an artificial sweetener has been controversial for many years as the side effects are not fully investigated. Should scientists be held morally responsible for the adverse consequences of their work?

B.4 Carbohydrates	
Guidance: • The straight chain and α-ring forms of glucose and fructose are given in the data booklet in section 34. • The component monosaccharides of specific disaccharides and the linkage details of polysaccharides are not required. • The distinction between α- and β- forms and the structure of cellulose are not required.	**Utilization:** • Carbohydrates are used in the pharmaceutical industry to bind preparations into tablets. • Ethanol is produced as a biofuel from the fermentation of carbohydrates in crops such as corn or sugar cane. Syllabus and cross-curricular links: Topics 10.1 and 10.2—organic functional groups Topic 20.1—organic reactions Topic 20.3—stereoisomerism Option C.4—biofuels Biology topic 2.3—carbohydrates **Aims:** • **Aim 6**: Experiments could include using Benedict's or Fehling's solution tests to distinguish between reducing sugars and non-reducing sugars or using iodine solution to test for the presence of starch. • **Aim 8**: The production of biofuels from crops raises many questions about related issues such as deforestation, soil erosion and sustainability. The "food vs fuel" debate refers to the controversies arising from developments that divert agricultural crops into biofuel production.

Essential idea: Vitamins are organic micronutrients with diverse functions that must be obtained from the diet.

B.5 Vitamins

Nature of science:

Making observations and evaluating claims—the discovery of vitamins (*vital amines*) is an example of scientists seeking a cause for specific observations. This resulted in the explanation of deficiency diseases (eg scurvy and beriberi). (1.8)

Understandings:

- Vitamins are organic micronutrients which (mostly) cannot be synthesized by the body but must be obtained from suitable food sources.
- The solubility (water or fat) of a vitamin can be predicted from its structure.
- Most vitamins are sensitive to heat.
- Vitamin deficiencies in the diet cause particular diseases and affect millions of people worldwide.

Applications and skills:

- Comparison of the structures of vitamins A, C and D.
- Discussion of the causes and effects of vitamin deficiencies in different countries and suggestion of solutions.

Guidance:

- The structures of vitamins A, C and D are provided in the data booklet section 35.
- Specific food sources of vitamins or names of deficiency diseases do not have to be learned.

International-mindedness:

- The food supplements industry, especially the sale of vitamin pills, has become very lucrative in many countries.
- Vitamin D deficiency is increasing, partly as a result of greater protection of the skin from sunlight.

Theory of knowledge:

- What are the ethical considerations in adding supplements to commonly consumed foods, such as fluoride to water or iodine to salt? Public bodies can protect the individual but also limit their freedom. How do we know what is best for society and the individual?
- Linus Pauling is the only man to win two individual Nobel Prizes. His claim that vitamin C supplements could prevent diseases such as the common cold led to their widespread use. What is the role of authority in communicating scientific knowledge to the public?

Utilization:

Syllabus and cross-curricular links:
Topics 4.1, 4.2 and 4.3—structure and physical properties
Topic 10.1—organic functional groups
Topic 20.3—configurational isomerism
Biology option D.2—human nutrition and health

Aims:

- **Aim 6**: Experiments could include the DCPIP determination of vitamin C levels in foods.

Essential idea: Our increasing knowledge of biochemistry has led to several environmental problems, while also helping to solve others.

B.6 Biochemistry and the environment

Nature of science:

Risk assessment, collaboration, ethical considerations—it is the responsibility of scientists to consider the ways in which products of their research and findings negatively impact the environment, and to find ways to counter this. For example, the use of enzymes in biological detergents and to break up oil spills, and green chemistry in general. (4.8)

Understandings:

- Xenobiotics refer to chemicals that are found in an organism that are not normally present there.
- Biodegradable/compostable plastics can be consumed or broken down by bacteria or other living organisms.
- Host–guest chemistry involves the creation of synthetic host molecules that mimic some of the actions performed by enzymes in cells, by selectively binding to specific guest species, such as toxic materials in the environment.
- Enzymes have been developed to help in the breakdown of oil spills and other industrial wastes.
- Enzymes in biological detergents can improve energy efficiency by enabling effective cleaning at lower temperatures.
- Biomagnification is the increase in concentration of a substance in a food chain.
- Green chemistry, also called sustainable chemistry, is an approach to chemical research and engineering that seeks to minimize the production and release to the environment of hazardous substances.

Applications and skills:

- Discussion of the increasing problem of xenobiotics such as antibiotics in sewage treatment plants.
- Description of the role of starch in biodegradable plastics.

International-mindedness:

- The term green chemistry was first coined in 1991, and acceptance of its philosophy has led to developments in education and legislation in many countries.
- Use of the pesticide DDT is banned in most countries due to its toxic effects and biomagnification. Its use continues, however, in countries where malaria remains a major public health challenge.

Utilization:

Syllabus and cross-curricular links:
Topic 4.4—intermolecular forces
Topic 10.1—natural and synthetic organic compounds
Options A.5 and A.7—environmental impact of plastics
Option D.2—antibiotics

Aims:

- **Aim 6**: Experiments could include the comparison of the breakdown of biodegradable and non-biodegradable plastics in the environment.
- **Aim 6**: Risk assessment, including the risks to the environment, is an essential part of all experimental work.
- **Aim 8**: The development of the science of green chemistry has raised awareness of the environmental and ethical implications of using science and technology.

B.6 Biochemistry and the environment	
• Application of host–guest chemistry to the removal of a specific pollutant in the environment. • Description of an example of biomagnification, including the chemical source of the substance. Examples could include heavy metals or pesticides. • Discussion of the challenges and criteria in assessing the "greenness" of a substance used in biochemical research, including the atom economy. **Guidance:** • Specific names of "green chemicals" such as solvents are not expected. • The emphasis in explanations of host–guest chemistry should be on non-covalent bonding within the supramolecule.	

Additional higher level topics

Essential idea: Analyses of protein activity and concentration are key areas of biochemical research.

B.7 Proteins and enzymes

Nature of science:

Theories can be superseded—"lock and key" hypothesis to "induced fit" model for enzymes. (1.9)

Collaboration and ethical considerations—scientists collaborate to synthesize new enzymes and to control desired reactions (ie waste control). (4.5)

Understandings:

- Inhibitors play an important role in regulating the activities of enzymes.
- Amino acids and proteins can act as buffers in solution.
- Protein assays commonly use UV-vis spectroscopy and a calibration curve based on known standards.

Applications and skills:

- Determination of the maximum rate of reaction ($V_{max)}$ and the value of the Michaelis constant ($K_{m)}$ for an enzyme by graphical means, and explanation of its significance.
- Comparison of competitive and non-competitive inhibition of enzymes with reference to protein structure, the active site and allosteric site.
- Explanation of the concept of product inhibition in metabolic pathways.
- Calculation of the pH of buffer solutions, such as those used in protein analysis and in reactions involving amino acids in solution.
- Determination of the concentration of a protein in solution from a calibration curve using the Beer–Lambert law.

International-mindedness:

- Technologies based on enzyme activity go back to ancient times in many parts of the world. Brewing and cheese-making are often associated with particular place names.

Theory of knowledge:

- The term "lock-and-key" is an effective metaphor but the "induced fit" model is a better model. How are metaphors and models used in the construction of knowledge?

Utilization:

- Enzymes are widely used in industrial and domestic applications. Examples include biological detergents, textiles, foods and beverages, and biodegradable plastics. Advances in protein engineering have led to the synthesis of enzymes that are effective in a wide range of conditions.

Syllabus and cross-curricular links:
Topic 6.1—chemical kinetics
Topics 8.1, 8.3 and 8.4—the pH scale and conjugate acids and bases
Topics 18.2 and 18.3—acid–base calculations and pH curves

B.7 Proteins and enzymes	
Guidance: • The effects of competitive and non-competitive inhibitors on K_m and V_{max} values should be covered. • The Henderson–Hasselbalch equation is given in the data booklet in section 1. • For UV-vis spectroscopy, knowledge of particular reagents and wavelengths is not required.	**Aims:** • **Aim 6**: Experiments could include measuring enzyme activity with changing conditions of temperature, pH and heavy metal ion concentration. • **Aim 7**: Data-logging experiments with temperature or pH probes to investigate enzyme activity under different conditions; or computer modelling of enzyme–substrate interactions. • **Aim 8**: Many enzyme technologies help mitigate damaging environmental effects of chemicals, such as from leather, paper and oil industries.

Essential idea: DNA is the genetic material that expresses itself by controlling the synthesis of proteins by the cell.

B.8 Nucleic acids

Nature of science:

Scientific method—the discovery of the structure of DNA is a good example of different approaches to solving the same problem. Scientists used models and diffraction experiments to develop the structure of DNA. (1.3)

Developments in scientific research follow improvements in apparatus—double helix from X-ray diffraction provides explanation for known functions of DNA. (3.7)

Understandings:

- Nucleotides are the condensation products of a pentose sugar, phosphoric acid and a nitrogenous base—adenine (A), guanine (G), cytosine (C), thymine (T) or uracil (U).
- Polynucleotides form by condensation reactions.
- DNA is a double helix of two polynucleotide strands held together by hydrogen bonds.
- RNA is usually a single polynucleotide chain that contains uracil in place of thymine, and a sugar ribose in place of deoxyribose.
- The sequence of bases in DNA determines the primary structure of proteins synthesized by the cell using a triplet code, known as the genetic code, which is universal.
- Genetically modified organisms have genetic material that has been altered by genetic engineering techniques, involving transferring DNA between species.

Applications and skills:

- Explanation of the stability of DNA in terms of the interactions between its hydrophilic and hydrophobic components.
- Explanation of the origin of the negative charge on DNA and its association with basic proteins (histones) in chromosomes.
- Deduction of the nucleotide sequence in a complementary strand of DNA or a molecule of RNA from a given polynucleotide sequence.

International-mindedness:

- The Human Genome Project was an international research programme whose goal was to complete the mapping and sequencing of all the genes in the human genome.
- The policies on the labelling of genetically modified (GM) foods vary greatly in different countries.
- Most of the genetically modified organisms are protected by international patents. What effect does this have on the global economy and scientific community?

Theory of knowledge:

- DNA stores information but not knowledge.
- What are the differences between information and knowledge?
- The Nobel Prize in Physiology or Medicine 1962 was awarded jointly to Crick, Watson and Wilkins "for their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material". What is the role of collaboration in advancing knowledge?
- The existence of DNA databases opens up questions of individual privacy and the extent to which government has the right of access to personal information. Who has the right to access knowledge of an individual's DNA?

B.8 Nucleic acids	
• Explanation of how the complementary pairing between bases enables DNA to replicate itself exactly. • Discussion of the benefits and concerns of using genetically modified foods. **Guidance:** • Structures of the nitrogenous bases and ribose and deoxyribose sugars are given in the data booklet in section 34. • Knowledge of the different forms of RNA is not required. • Details of the process of DNA replication are not required. • Limit expression of DNA to the concept of a four-unit base code determining a twenty-unit amino acid sequence. Details of transcription and translation are not required.	**Utilization:** • Knowledge of DNA sequencing has transformed several aspects of legal enquiry, including forensics and paternity cases. It is also widely used in studies of ancestry and human migration. • DNA sequencing is an important aspect of the study of biochemical evolution. Syllabus and cross-curricular links: Topic 4.4—hydrogen bonding, intermolecular interactions Topic 8.1—acid–base interactions Biology topics 2.6 and 7.1—DNA and RNA structure **Aims:** • **Aim 5**: The story of the rivalry between the different teams involved in the elucidation of DNA structure in the 1950s is an example of a failure of effective collaboration and communication during scientific activities. • **Aim 6**: Experiments could include DNA extraction from cells and investigation of its physical properties, and model building exercises of DNA structure, including the specific base pairings between a purine and a pyrimidine. • **Aim 7**: Databases exist of genetic sequences from different organisms. • **Aim 8**: Many ethical questions are raised by our knowledge of the human genome, including cloning, genetic engineering, gene therapy, and so on.

Essential idea: Biological pigments include a variety of chemical structures with diverse functions which absorb specific wavelengths of light.

B.9 Biological pigments

Nature of science:

Use of data—quantitative measurements of absorbance are a reliable means of communicating data based on colour, which was previously subjective and difficult to replicate. (3.1)

Understandings:

- Biological pigments are coloured compounds produced by metabolism.
- The colour of pigments is due to highly conjugated systems with delocalized electrons, which have intense absorption bands in the visible region.
- Porphyrin compounds, such as hemoglobin, myoglobin, chlorophyll and many cytochromes are chelates of metals with large nitrogen-containing macrocyclic ligands.
- Hemoglobin and myoglobin contain heme groups with the porphyrin group bound to an iron(II) ion.
- Cytochromes contain heme groups in which the iron ion interconverts between iron(II) and iron(III) during redox reactions.
- Anthocyanins are aromatic, water-soluble pigments widely distributed in plants. Their specific colour depends on metal ions and pH.
- Carotenoids are lipid-soluble pigments, and are involved in harvesting light in photosynthesis. They are susceptible to oxidation, catalysed by light.

Applications and skills:

- Explanation of the sigmoidal shape of hemoglobin's oxygen dissociation curve in terms of the cooperative binding of hemoglobin to oxygen.
- Discussion of the factors that influence oxygen saturation of hemoglobin, including temperature, pH and carbon dioxide.
- Description of the greater affinity of oxygen for foetal hemoglobin.

International-mindedness:

- Artificial colours are commonly added during the commercial preparation and processing of food. The list of approved food colours varies greatly by country, which raises questions for international trade.

Theory of knowledge:

- Experiments show that our appreciation of food is based on an interaction between our senses. How do the different senses interact in giving us empirical knowledge about the world?

Utilization:

- Different tones of skin, eye and hair colour are the result of differences in the concentration of the pigment melanin.
- People whose ancestors have lived at high altitude for many generations have developed hemoglobin with a higher affinity for oxygen.
- The purplish-red colour of meat is largely due to the presence of myoglobin. The change in colour to brown on cooking occurs as the iron ion becomes oxidized to Fe^{3+}.
- Anthocyanins and carotenoids provide visible signals for plants to attract insects and birds for pollination and seed dispersal. They also protect plants from damage caused by UV light.

Syllabus and cross-curricular links:
Topic 8.2—indicators
Topic 13.2—complex ions
Option C.8—electronic conjugation and dye-sensitized solar cells

B.9 Biological pigments	
• Explanation of the action of carbon monoxide as a competitive inhibitor of oxygen binding. • Outline of the factors that affect the stabilities of anthocyanins, carotenoids and chlorophyll in relation to their structures. • Explanation of the ability of anthocyanins to act as indicators based on their sensitivity to pH. • Description of the function of photosynthetic pigments in trapping light energy during photosynthesis. • Investigation of pigments through paper and thin layer chromatography. **Guidance:** • The structures of chlorophyll, heme B and specific examples of anthocyanins and carotenoids are given in the data booklet in section 35; details of other pigment names and structures are not required. • Explanation of cooperative binding in hemoglobin should be limited to conformational changes occurring in one polypeptide when it becomes oxygenated. • Knowledge of specific colour changes with changing conditions is not required.	**Aims:** • **Aim 6**: Experiments could include the extraction and isolation of pigments from plant sources using solvents and separating funnel or the use of anthocyanins as pH indicators. • **Aim 7**: Use of data loggers for collecting absorption data.

Essential idea: Most biochemical processes are stereospecific and involve only molecules with certain configuration of chiral carbon atoms.

B.10 Stereochemistry in biomolecules

Nature of science:

Theories used to explain natural phenomena/evaluate claims—biochemistry involves many chiral molecules with biological activity specific to one enantiomer. Chemical reactions in a chiral environment act as a guiding distinction between living and non-living matter. (2.2)

Understandings:

- With one exception, amino acids are chiral, and only the L-configuration is found in proteins.
- Naturally occurring unsaturated fat is mostly in the *cis* form, but food processing can convert it into the *trans* form.
- D and L stereoisomers of sugars refer to the configuration of the chiral carbon atom furthest from the aldehyde or ketone group, and D forms occur most frequently in nature.
- Ring forms of sugars have isomers, known as α and β, depending on whether the position of the hydroxyl group at carbon 1 (glucose) or carbon 2 (fructose) lies below the plane of the ring (α) or above the plane of the ring (β).
- Vision chemistry involves the light activated interconversion of *cis*- and *trans*-isomers of retinal.

Applications and skills:

- Description of the hydrogenation and partial hydrogenation of unsaturated fats, including the production of *trans*-fats, and a discussion of the advantages and disadvantages of these processes.
- Explanation of the structure and properties of cellulose, and comparison with starch.
- Discussion of the importance of cellulose as a structural material and in the diet.
- Outline of the role of vitamin A in vision, including the roles of opsin, rhodopsin

International-mindedness:

- Different countries have very different standards of food labelling with respect to its chemical content, including the type of fats present.

Utilization:

Syllabus and cross-curricular links:
Topic 10.1—organic functional groups
Topic 20.1—organic reactions
Topic 20.3—stereoisomerism
Option A.4—intermolecular/London forces

Aims:

- **Aim 8**: Ethical questions arise through the use of saturated and *trans*-fats, particularly in the fast-food industry.

B.10 Stereochemistry in biomolecules	
and *cis*- and *trans*-retinal. **Guidance:** • Names of the enzymes involved in the visual cycle are not required. • Relative melting points of saturated and *cis*-/*trans*-unsaturated fats should be covered.	

Core topics

Essential idea: Societies are completely dependent on energy resources. The quantity of energy is conserved in any conversion but the quality is degraded.

C.1 Energy sources

Nature of science:

Use theories to explain natural phenomena—energy changes in the world around us result from potential and kinetic energy changes at the molecular level.

Energy has both quantity and quality. (2.2)

Understandings:

- A useful energy source releases energy at a reasonable rate and produces minimal pollution.
- The quality of energy is degraded as heat is transferred to the surroundings. Energy and materials go from a concentrated into a dispersed form. The quantity of the energy available for doing work decreases.
- Renewable energy sources are naturally replenished. Non-renewable energy sources are finite.
- $\text{Energy density} = \frac{\text{energy released from fuel}}{\text{volume of fuel consumed}}$.
- $\text{Specific energy} = \frac{\text{energy released from fuel}}{\text{mass of fuel consumed}}$.
- $\text{The effeciency of an energy transfer} = \frac{\text{useful output energy}}{\text{total input energy}} \times 100\%$.

Applications and skills:

- Discussion of the use of different sources of renewable and non-renewable energy.
- Determination of the energy density and specific energy of a fuel from the enthalpies of combustion, densities and the molar mass of fuel.
- Discussion of how the choice of fuel is influenced by its energy density or specific energy.

International-mindedness:

- The International Energy Agency is an autonomous organization based in Paris which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond.
- The International Renewable Energy Agency (IRENA), based in Abu Dhabi, UAE, was founded in 2009 to promote increased adoption and sustainable use of renewable energy sources (bioenergy, geothermal energy, hydropower, ocean, solar and wind energy).

Theory of knowledge:

- "I have no doubt that we will be successful in harnessing the sun's energy. If sunbeams were weapons of war we would have had solar energy centuries ago." (Lord George Porter). In what ways might social, political, cultural and religious factors affect the types of research that are financed and undertaken, or rejected?
- There are many ethical issues raised by energy generation and its consequent contributions to pollution and climate change.What is the influence of political pressure on different areas of knowledge?

Utilization:

Syllabus and cross-curricular links:
Topic 5.1—enthalpies of combustion
Topic 10.2—the combustion of hydrocarbons
Environmental systems and societies topics—3.2, 3.3, 3.5 and 3.6
Physics topic 8.1—energy density

C.1 Energy sources	
• Determination of the efficiency of an energy transfer process from appropriate data. • Discussion of the advantages and disadvantages of the different energy sources in C.2 through to C.8.	**Aims:** • **Aim 1**: Discussions of the possible energy sources provide opportunities for scientific study and creativity within a global context. • **Aim 6**: The energy density of different fuels could be investigated experimentally. • **Aim 7**: Databases of energy statistics on a global and national scale can be explored here. • **Aim 8**: Energy production has global economic and environmental dimensions. The choices made in this area have moral and ethical implications.

Essential idea: The energy of fossil fuels originates from solar energy which has been stored by chemical processes over time. These abundant resources are non-renewable but provide large amounts of energy due to the nature of chemical bonds in hydrocarbons.

C.2 Fossil fuels

Nature of science:

Scientific community and collaboration—the use of fossil fuels has had a key role in the development of science and technology. (4.1)

Understandings:

- Fossil fuels were formed by the reduction of biological compounds that contain carbon, hydrogen, nitrogen, sulfur and oxygen.
- Petroleum is a complex mixture of hydrocarbons that can be split into different component parts called fractions by fractional distillation.
- Crude oil needs to be refined before use. The different fractions are separated by a physical process in fractional distillation.
- The tendency of a fuel to auto-ignite, which leads to "knocking" in a car engine, is related to molecular structure and measured by the octane number.
- The performance of hydrocarbons as fuels is improved by the cracking and catalytic reforming reactions.
- Coal gasification and liquefaction are chemical processes that convert coal to gaseous and liquid hydrocarbons.
- A carbon footprint is the total amount of greenhouse gases produced during human activities. It is generally expressed in equivalent tons of carbon dioxide.

Applications and skills:

- Discussion of the effect of chain length and chain branching on the octane number.
- Discussion of the reforming and cracking reactions of hydrocarbons and explanation how these processes improve the octane number.
- Deduction of equations for cracking and reforming reactions, coal gasification and liquefaction.

International-mindedness:

- The choice of fossil fuel used by different countries depends on availability, and economic, societal, environmental and technological factors.
- Different fuel rating systems (RON, MON or PON) are used in different countries.
- Ocean drilling, oil pipelines and oil spills are issues that demand international cooperation and agreement.

Utilization:

Syllabus and cross-curricular links:
Topics 5.1 and 5.3—enthalpy changes of combustion
Topics 10.1 and 20.3—hydrocarbons and isomerism
Topic 10.2 and option C.5—global warming
Option C.8—solar cells
Biology topic 4.3—carbon cycling

Aims:

- **Aim 6**: Possible experiments include fractional distillation and catalytic cracking reactions.
- **Aim 7**: Databases of energy statistics on a global and national scale can be explored here.
- **Aim 7**: Many online calculators are available to calculate carbon footprints.
- **Aim 8**: Consideration of the advantages and disadvantages of fossil fuels illustrates the economic and environmental implications of using science and technology.

C.2 Fossil fuels	
• Discussion of the advantages and disadvantages of the different fossil fuels. • Identification of the various fractions of petroleum, their relative volatility and their uses. • Calculations of the carbon dioxide added to the atmosphere, when different fuels burn and determination of carbon footprints for different activities. **Guidance:** • The cost of production and availability (reserves) of fossil fuels and their impact on the environment should be considered.	

Essential idea: The fusion of hydrogen nuclei in the sun is the source of much of the energy needed for life on Earth. There are many technological challenges in replicating this process on Earth but it would offer a rich source of energy. Fission involves the splitting of a large unstable nucleus into smaller stable nuclei.

C.3 Nuclear fusion and fission

Nature of science:

Assessing the ethics of scientific research—widespread use of nuclear fission for energy production would lead to a reduction in greenhouse gas emissions. Nuclear fission is the process taking place in the atomic bomb and nuclear fusion that in the hydrogen bomb. (4.5)

Understandings:

Nuclear fusion

- Light nuclei can undergo fusion reactions as this increases the binding energy per nucleon.
- Fusion reactions are a promising energy source as the fuel is inexpensive and abundant, and no radioactive waste is produced.
- Absorption spectra are used to analyse the composition of stars.

Nuclear fission

- Heavy nuclei can undergo fission reactions as this increases the binding energy per nucleon.
- ^{235}U undergoes a fission chain reaction:
  $^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow$ X + Y + neutrons.
- The critical mass is the mass of fuel needed for the reaction to be self-sustaining.
- ^{239}Pu, used as a fuel in "breeder reactors", is produced from ^{238}U by neutron capture.
- Radioactive waste may contain isotopes with long and short half-lives.
- Half-life is the time it takes for half the number of atoms to decay.

International-mindedness:

- The use of nuclear energy is monitored internationally by the International Atomic Energy Agency.
- High-energy particle physics research involves international collaboration. There are accelerator facilities at CERN, DESY, SLAC, Fermi lab and Brookhaven. Results are disseminated and shared by scientists in many countries.
- The ITER project is a collaboration between many countries and aims to demonstrate that fusion is an energy source of the future.

Theory of knowledge:

- The use of nuclear energy carries risks as well as benefits. Who should ultimately be responsible for assessing these? How do we know what is best for society and the individual?

Utilization:

Syllabus and cross-curricular links:
Topic 2.1—isotopes
Topic 2.2—the emission spectrum of hydrogen
Physics topic 7.2—nuclear fusion

Aims:

- **Aim 7**: Computer animations and simulations of radioactive decay, and nuclear fusion and fission reactions.
- **Aim 8**: Consideration of the environmental impact of nuclear energy illustrating

C.3 Nuclear fusion and fission	
Applications and skills: *Nuclear fusion* • Construction of nuclear equations for fusion reactions. • Explanation of fusion reactions in terms of binding energy per nucleon. • Explanation of the atomic absorption spectra of hydrogen and helium, including the relationships between the lines and electron transitions. *Nuclear fission* • Deduction of nuclear equations for fission reactions. • Explanation of fission reactions in terms of binding energy per nucleon. • Discussion of the storage and disposal of nuclear waste. • Solution of radioactive decay problems involving integral numbers of half-lives. **Guidance:** • Students are not expected to recall specific fission reactions. • The workings of a nuclear power plant are not required. • Safety and risk issues include: health, problems associated with nuclear waste and core meltdown, and the possibility that nuclear fuels may be used in nuclear weapons. • The equations, $N = N_0 e^{-\lambda t}$ and $t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$ are given in section 1 of the data booklet.	the implications of using science and technology.

Essential idea: Visible light can be absorbed by molecules that have a conjugated structure with an extended system of alternating single and multiple bonds. Solar energy can be converted to chemical energy in photosynthesis.

C.4 Solar energy

Nature of science:

Public understanding—harnessing the sun's energy is a current area of research and challenges still remain. However, consumers and energy companies are being encouraged to make use of solar energy as an alternative energy source. (5.2)

Understandings:

- Light can be absorbed by chlorophyll and other pigments with a conjugated electronic structure.
- Photosynthesis converts light energy into chemical energy:
  $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
- Fermentation of glucose produces ethanol which can be used as a biofuel:
  $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$
- Energy content of vegetable oils is similar to that of diesel fuel but they are not used in internal combustion engines as they are too viscous.
- Transesterification between an ester and an alcohol with a strong acid or base catalyst produces a different ester:

  $RCOOR^1 + R^2OH \rightarrow RCOOR^2 + R^1OH$
- In the transesterification process, involving a reaction with an alcohol in the presence of a strong acid or base, the triglyceride vegetable oils are converted to a mixture mainly comprising of alkyl esters and glycerol, but with some fatty acids.
- Transesterification with ethanol or methanol produces oils with lower viscosity that can be used in diesel engines.

Applications and skills:

- Identification of features of the molecules that allow them to absorb visible light.

Theory of knowledge:

- The claims of "cold fusion" were dismissed as the results are not reproducible. Is it always possible to obtain replicable results in the natural sciences? Are reproducible results possible in other areas of knowledge?

Utilization:

Syllabus and cross-curricular links:
Topic 5.3—bond enthalpies
Topic 20.1—mechanism of nuclear substitution reactions
Biology topic 2.9—photosynthesis

Aims:

- **Aim 2**: The conversion of solar energy is important in a number of different technologies.
- **Aim 6**: Experiments could include those involving photosynthesis, fermentation and transesterification.
- **Aim 8**: Transesterification reactions, with waste cooking oil, could reduce waste and produce excellent biofuels.

C.4 Solar energy	
• Explanation of the reduced viscosity of esters produced with methanol and ethanol. • Evaluation of the advantages and disadvantages of the use of biofuels. • Deduction of equations for transesterification reactions. **Guidance:** • Only a conjugated system with alternating double bonds needs to be covered.	

Essential idea: Gases in the atmosphere that are produced by human activities are changing the climate as they are upsetting the balance between radiation entering and leaving the atmosphere.

C.5 Environmental impact—global warming

Nature of science:

Transdisciplinary—the study of global warming encompasses a broad range of concepts and ideas and is transdisciplinary. (4.1)

Collaboration and significance of science explanations to the public—reports of the Intergovernmental Panel on Climate Change (IPCC). (5.2)

Correlation and cause and understanding of science—CO_2 levels and Earth average temperature show clear correlation but wide variations in the surface temperature of the Earth have occurred frequently in the past. (2.8)

Understandings:

- Greenhouse gases allow the passage of incoming solar short wavelength radiation but absorb the longer wavelength radiation from the Earth. Some of the absorbed radiation is re-radiated back to Earth.
- There is a heterogeneous equilibrium between concentration of atmospheric carbon dioxide and aqueous carbon dioxide in the oceans.
- Greenhouse gases absorb IR radiation as there is a change in dipole moment as the bonds in the molecule stretch and bend.
- Particulates such as smoke and dust cause global dimming as they reflect sunlight, as do clouds.

Applications and skills:

- Explanation of the molecular mechanisms by which greenhouse gases absorb infrared radiation.
- Discussion of the evidence for the relationship between the increased concentration of gases and global warming.
- Discussion of the sources, relative abundance and effects of different greenhouse gases.
- Discussion of the different approaches to the control of carbon dioxide emissions.

International-mindedness:

- This issue involves the international community working together to research and reduce the effects of global warming. Such attempts include the Intergovernmental Panel on Climate Change (IPCC) and the Kyoto Protocol which was extended in Qatar.

Theory of knowledge:

- Some people question the reality of climate change, and question the motives of scientists who have “exaggerated” the problem. How do we assess the evidence collected and the models used to predict the impact of human activities?

Utilization:

Syllabus and cross-curricular links:
Topics 7.1 and 17.1—equilibrium systems
Topic 8.2—acid–base equilibria
Topic 11.3—infrared spectra
Topic 13.2—transition metal complexes
Biology topic 4.4—climate change
Physics topic 8.1—thermal energy transfer

Aims:

- **Aim 6**: The equilibrium between aqueous and gaseous carbon dioxide could be experimentally investigated.

C.5 Environmental impact—global warming	
• Discussion of pH changes in the ocean due to increased concentration of carbon dioxide in the atmosphere. **Guidance:** • Greenhouse gases to be considered are CH_4, H_2O and CO_2.	• **Aim 7**: Computer modelling is a powerful tool by which knowledge can be gained about the greenhouse effect. • **Aim 8**: Discussions of climate change and green chemistry raise awareness of the ethical, economic and environmental implications of using science and technology.

Additional higher level topics

Essential idea: Chemical energy from redox reactions can be used as a portable source of electrical energy.

C.6 Electrochemistry, rechargeable batteries and fuel cells

Nature of science:

Environmental problems—redox reactions can be used as a source of electricity but disposal of batteries has environmental consequences. (4.8)

Understandings:

- An electrochemical cell has internal resistance due to the finite time it takes for ions to diffuse. The maximum current of a cell is limited by its internal resistance.
- The voltage of a battery depends primarily on the nature of the materials used while the total work that can be obtained from it depends on their quantity.
- In a primary cell the electrochemical reaction is not reversible. Rechargeable cells involve redox reactions that can be reversed using electricity.
- A fuel cell can be used to convert chemical energy, contained in a fuel that is consumed, directly to electrical energy.
- Microbial fuel cells (MFCs) are a possible sustainable energy source using different carbohydrates or substrates present in waste waters as the fuel.
- The Nernst equation, $E = E^0 - \left(\frac{RT}{nF}\right) \ln Q$, can be used to calculate the potential of a half-cell in an electrochemical cell, under non-standard conditions.
- The electrodes in a concentration cell are the same but the concentration of the electrolyte solutions at the cathode and anode are different.

Applications and skills:

- Distinction between fuel cells and primary cells.
- Deduction of half equations for the electrode reactions in a fuel cell.

International-mindedness:

- Are battery recycling programmes equivalent in different areas of the globe?

Theory of knowledge:

- Does scientific language and vocabulary have primarily a descriptive or an interpretative function? Are the terms “electric current” and “internal resistance” accurate descriptions of reality or metaphors?

Utilization:

Syllabus and cross-curricular links:
Topic 9.1—redox reactions
Topic 19.1—electrochemical cells
Biology topic 6.5—muscle and nerve cells discussed in biology are concentration cells
Physics topic 5.3—the relationship between electrical power, voltage, resistance and current

Aims:

- **Aim 2**: The conversion of chemical energy to electricity is important in a number of different technologies.
- **Aim 6**: The factors that affect the voltage of a cell and the lead–acid battery could be investigated experimentally.

C.6 Electrochemistry, rechargeable batteries and fuel cells	
• Comparison between fuel cells and rechargeable batteries. • Discussion of the advantages of different types of cells in terms of size, mass and voltage. • Solution of problems using the Nernst equation. • Calculation of the thermodynamic efficiency ($\Delta G/\Delta H$) of a fuel cell. • Explanation of the workings of rechargeable and fuel cells including diagrams and relevant half-equations. **Guidance:** • A battery should be considered as a portable electrochemical source made up of one or more voltaic (galvanic) cells connected in series. • The Nernst equation is given in the data booklet in section 1. • Hydrogen and methanol should be considered as fuels for fuel cells. The operation of the cells under acid and alkaline conditions should be considered. Students should be familiar with proton-exchange membrane (PEM) fuel cells. • The *Geobacter* species of bacteria, for example, can be used in some cells to oxidize the ethanoate ions (CH_3COO^-) under anaerobic conditions. • The lead–acid storage battery, the nickel–cadmium (NiCad) battery and the lithium–ion battery should be considered. • Students should be familiar with the anode and cathode half-equations and uses of the different cells.	• **Aim 8**: Consideration of the advantages and disadvantages of the different energy sources shows the economic and environmental implications of using science and technology. The environmental aspects of fuel cells, especially with regard to methanol, could be discussed. • **Aim 8**: Disposal of primary batteries and the chemicals they use can introduce land and water pollution problems. Appreciation of the environmental impact of cadmium and lead pollution. • **Aim 8**: Bacterial fuel cells use substrates found in waste water as the fuel and so can be used to clean up the environment.

Essential idea: Large quantities of energy can be obtained from small quantities of matter.

C.7 Nuclear fusion and nuclear fission

Nature of science:

Trends and discrepancies—our understanding of nuclear processes came from both theoretical and experimental advances. Intermolecular forces in UF_6 are anomalous and do not follow the normal trends. (3.1)

Understandings:

Nuclear fusion:

- The mass defect (Δm) is the difference between the mass of the nucleus and the sum of the masses of its individual nucleons.
- The nuclear binding energy (ΔE) is the energy required to separate a nucleus into protons and neutrons.

Nuclear fission:

- The energy produced in a fission reaction can be calculated from the mass difference between the products and reactants using the Einstein mass–energy equivalence relationship $E = mc^2$.
- The different isotopes of uranium in uranium hexafluoride can be separated, using diffusion or centrifugation causing fuel enrichment.
- The effusion rate of a gas is inversely proportional to the square root of the molar mass (Graham's Law).
- Radioactive decay is kinetically a first order process with the half-life related to the decay constant by the equation $\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$.
- The dangers of nuclear energy are due to the ionizing nature of the radiation it produces which leads to the production of oxygen free radicals such as superoxide (O_2^-), and hydroxyl ($HO^{\cdot}$). These free radicals can initiate chain reactions that can damage DNA and enzymes in living cells.

International-mindedness:

- There are only a very small number of countries that have developed nuclear weapons and the International Atomic Energy Agency strives to limit the spread of this technology. There are disputes about whether some countries are developing nuclear energy for peaceful or non-peaceful purposes.
- Nuclear incidents have a global effect; the accidents at Three Mile Island and Chernobyl and the problems at Fukushima caused by a tsunami could be discussed to illustrate the potential dangers.

Theory of knowledge:

- "There is no likelihood that humans will ever tap the power of the atom." (Robert Millikan, Nobel Laureate Physics 1923 quoted in 1928). How can the impact of new technologies be predicted? How reliable are these predictions? How important are the opinions of experts in the search for knowledge?
- The release of energy during fission reactions can be used in times of peace to generate energy, but also can lead to destruction in time of war. Should scientists be held morally responsible for the applications of their discoveries? Is there any area of scientific knowledge the pursuit of which is morally unacceptable?

Utilization:

Syllabus and cross-curricular links:
Topics 4.1 and 4.3—structure and bonding
Topic 16.1—first order reactions
Physics topic 7.2—nuclear fusion
Geography—the different polices and attitudes to nuclear energy are discussed in resources sections in the guide

C.7 Nuclear fusion and nuclear fission	
Applications and skills: *Nuclear fusion:* • Calculation of the mass defect and binding energy of a nucleus. • Application of the Einstein mass–energy equivalence relationship, $E = mc^2$, to determine the energy produced in a fusion reaction. *Nuclear fission:* • Application of the Einstein mass–energy equivalence relationship to determine the energy produced in a fission reaction. • Discussion of the different properties of UO_2 and UF_6 in terms of bonding and structure. • Solution of problems involving radioactive half-life. • Explanation of the relationship between Graham's law of effusion and the kinetic theory. • Solution of problems on the relative rate of effusion using Graham's law. **Guidance:** • Students are not expected to recall specific fission reactions. • The workings of a nuclear power plant are not required. • Safety and risk issues include: health, problems associated with nuclear waste, and the possibility that nuclear fuels may be used in nuclear weapons. • Graham's law of effusion is given in the data booklet in section 1. • Decay relationships are given in the data booklet in section 1. • A binding energy curve is given in the data booklet in section 36.	**Aims**: • **Aim 7**: Computer animations and simulations of radioactive decay, and nuclear fusion and fission reactions. • **Aim 8**: Consideration of the advantages and disadvantages of nuclear fusion illustrates the economic and environmental implications of using science and technology. The use of fusion reactions in the hydrogen bomb can also be discussed.

Essential idea: When solar energy is converted to electrical energy the light must be absorbed and charges must be separated. In a photovoltaic cell both of these processes occur in the silicon semiconductor, whereas these processes occur in separate locations in a dye-sensitized solar cell (DSSC).

C.8 Photovoltaic cells and dye-sensitized solar cells (DSSC)

Nature of science:

Transdisciplinary—a dye-sensitized solar cell, whose operation mimics photosynthesis and makes use of TiO_2 nanoparticles, illustrates the transdisciplinary nature of science and the link between chemistry and biology. (4.1)

Funding—the level of funding and the source of the funding is crucial in decisions regarding the type of research to be conducted. The first voltaic cells were produced by NASA for space probes and were only later used on Earth. (4.7)

Understandings:

- Molecules with longer conjugated systems absorb light of longer wavelength.
- The electrical conductivity of a semiconductor increases with an increase in temperature whereas the conductivity of metals decreases.
- The conductivity of silicon can be increased by doping to produce n-type and p-type semiconductors.
- Solar energy can be converted to electricity in a photovoltaic cell.
- DSSCs imitate the way in which plants harness solar energy. Electrons are "injected" from an excited molecule directly into the TiO_2 semiconductor.
- The use of nanoparticles coated with light-absorbing dye increases the effective surface area and allows more light over a wider range of the visible spectrum to be absorbed.

Applications and skills:

- Relation between the degree of conjugation in the molecular structure and the wavelength of the light absorbed.
- Explanation of the operation of the photovoltaic and dye-sensitized solar cell.
- Explanation of how nanoparticles increase the efficiency of DSSCs.
- Discussion of the advantages of the DSSC compared to the silicon-based

International-mindedness:

- The harnessing of solar energy could change the economic fortunes of countries with good supplies of sunlight and unused land.

Theory of knowledge:

- A conjugated system has some similarities with a violin string. How useful is this metaphor? What are the underlying reasons for these similarities? What role do models and metaphors play in the acquisition of knowledge?

Utilization:

Syllabus and cross-curricular links:
Topic 3.2—patterns in ionization energy
Topic 9.1—redox reactions
Biology topic 2.9—photosynthesis

Aims:

- **Aim 6**: Students could build an inexpensive dye-sensitized solar cell and investigate their photovoltaic properties.
- **Aim 7**: The properties of DSSCs can be best investigated using data loggers.

C.8 Photovoltaic cells and dye-sensitized solar cells (DSSC)	
photovoltaic cell. **Guidance:** • The relative conductivity of metals and semiconductors should be related to ionization energies. • Only a simple treatment of the operation of the cells is needed. In p-type semiconductors, electron holes in the crystal are created by introducing a small percentage of a group 3 element. In n-type semiconductors inclusion of a group 5 element provides extra electrons. • In a photovoltaic cell the light is absorbed and the charges separated in the silicon semiconductor. The processes of absorption and charge separation are separated in a dye-sensitized solar cell. • Specific redox and electrode reactions in the newer Grätzel DSSC should be covered. An example is the reduction of I_2/I_3^- ions to I^-.	

Core topics

Essential idea: Medicines and drugs have a variety of different effects on the functioning of the body.

D.1 Pharmaceutical products and drug action

Nature of science:

Risks and benefits—medicines and drugs go through a variety of tests to determine their effectiveness and safety before they are made commercially available. Pharmaceutical products are classified for their use and abuse potential. (4.8)

Understandings:

- In animal studies, the therapeutic index is the lethal dose of a drug for 50% of the population (*LD50*) divided by the minimum effective dose for 50% of the population (*ED50*).
- In humans, the therapeutic index is the toxic dose of a drug for 50% of the population (*TD50*) divided by the minimum effective dose for 50% of the population (*ED50*).
- The therapeutic window is the range of dosages between the minimum amounts of the drug that produce the desired effect and a medically unacceptable adverse effect.
- Dosage, tolerance, addiction and side effects are considerations of drug administration.
- Bioavailability is the fraction of the administered dosage that reaches the target part of the human body.
- The main steps in the development of synthetic drugs include identifying the need and structure, synthesis, yield and extraction.
- Drug–receptor interactions are based on the structure of the drug and the site of activity.

International-mindedness:

- In some countries certain drugs are only available with prescription while in other countries these same drugs are available over the counter.

Theory of knowledge:

- The same drug can be identified by different names. Are names simply labels or do they influence our other ways of knowing?
- Drugs trials use double blind tests. When is it ethically acceptable to deceive people?
- All drugs carry risks as well as benefits. Who should ultimately be responsible for assessing these? Public bodies can protect the individual but also limit their freedom. How do we know what is best for society and the individual?

Aims:

- **Aim 9**: There have been advances in the development of pharmaceuticals, but there are many limitations to their impact and reach.
- **Aim 10**: The development of new medicines is often done in collaboration with biologists and physicists.

D.1 Pharmaceutical products and drug action	
Applications and skills: • Discussion of experimental foundations for therapeutic index and therapeutic window through both animal and human studies. • Discussion of drug administration methods. • Comparison of how functional groups, polarity and medicinal administration can affect bioavailability. **Guidance:** • For ethical and economic reasons, animal and human tests of drugs (for LD_{50}/ED_{50} and TD_{50}/ED_{50} respectively) should be kept to a minimum.	

Essential idea: Natural products with useful medicinal properties can be chemically altered to produce more potent or safer medicines.

D.2 Aspirin and penicillin

Nature of science:

Serendipity and scientific discovery—the discovery of penicillin by Sir Alexander Fleming. (1.4)

Making observations and replication of data—many drugs need to be isolated, identified and modified from natural sources. For example, salicylic acid from bark of willow tree for relief of pain and fever. (1.8)

Understandings:

Aspirin:

- Mild analgesics function by intercepting the pain stimulus at the source, often by interfering with the production of substances that cause pain, swelling or fever.
- Aspirin is prepared from salicylic acid.
- Aspirin can be used as an anticoagulant, in prevention of the recurrence of heart attacks and strokes and as a prophylactic.

Penicillin:

- Penicillins are antibiotics produced by fungi.
- A beta-lactam ring is a part of the core structure of penicillins.
- Some antibiotics work by preventing cross-linking of the bacterial cell walls.
- Modifying the side-chain results in penicillins that are more resistant to the penicillinase enzyme.

International-mindedness:

- Aspirin is used in many different ways across the globe.
- The first antibacterial changed the way that disease was treated across the globe.

Theory of knowledge:

- Different painkillers act in different ways. How do we perceive pain, and how are our perceptions influenced by the other ways of knowing?
- “Chance favours only the prepared mind.” (Louis Pasteur). Fleming’s discovery of penicillin is often described as serendipitous but the significance of his observations would have been missed by non-experts. What influence does an open-minded attitude have on our perceptions?

Utilization:

Syllabus and cross-curricular links:
Topic 1.3—yield of reaction
Topic 10.2—functional groups
Biology topic 6.3—defence against infectious disease

D.2 Aspirin and penicillin	
Applications and skills: *Aspirin* • Description of the use of salicylic acid and its derivatives as mild analgesics. • Explanation of the synthesis of aspirin from salicylic acid, including yield, purity by recrystallization and characterization using IR and melting point. • Discussion of the synergistic effects of aspirin with alcohol. • Discussion of how the aspirin can be chemically modified into a salt to increase its aqueous solubility and how this facilitates its bioavailability. *Penicillin* • Discussion of the effects of chemically modifying the side-chain of penicillins. • Discussion of the importance of patient compliance and the effects of the over-prescription of penicillin. • Explanation of the importance of the beta-lactam ring on the action of penicillin. **Guidance:** • Students should be aware of the ability of acidic (carboxylic) and basic (amino) groups to form ionic salts, for example soluble aspirin. • Structures of aspirin and penicillin are available in the data booklet in section 37.	**Aims:** • **Aim 6**: Experiments could include the synthesis of aspirin. • **Aim 8**: Discuss the use/overuse of antibiotics for animals.

Essential idea: Potent medical drugs prepared by chemical modification of natural products can be addictive and become substances of abuse.

D.3 Opiates

Nature of science:

Data and its subsequent relationships—opium and its many derivatives have been used as a painkiller in a variety of forms for thousands of years. One of these derivatives is diamorphine. (3.1)

Understandings:

- The ability of a drug to cross the blood–brain barrier depends on its chemical structure and solubility in water and lipids.
- Opiates are natural narcotic analgesics that are derived from the opium poppy.
- Morphine and codeine are used as strong analgesics. Strong analgesics work by temporarily bonding to receptor sites in the brain, preventing the transmission of pain impulses without depressing the central nervous system.
- Medical use and addictive properties of opiate compounds are related to the presence of opioid receptors in the brain.

Applications and skills:

- Explanation of the synthesis of codeine and diamorphine from morphine.
- Description and explanation of the use of strong analgesics.
- Comparison of the structures of morphine, codeine and diamorphine (heroin).
- Discussion of the advantages and disadvantages of using morphine and its derivatives as strong analgesics.
- Discussion of side effects and addiction to opiate compounds.
- Explanation of the increased potency of diamorphine compared to morphine based on their chemical structure and solubility.

Guidance:

- Structures of morphine, codeine and diamorphine can be found in the data booklet in section 37.

International-mindedness:

- Many illegal drugs are cultivated or produced in a small number of countries and then sold and distributed globally. Cultural and economic viewpoints differ on the production and sale of opiates around the world.

Theory of knowledge:

- Cultures often clash over different perspectives and ideas. Is there any knowledge which is independent of culture?

Utilization:

Syllabus and cross-curricular links:
Topic 10.2—functional groups

Aims:

- **Aim 7**: Use computer animations for the investigation of 3-D visualizations of drugs and receptor sites.

Essential idea: Excess stomach acid is a common problem that can be alleviated by compounds that increase the stomach pH by neutralizing or reducing its secretion.

D.4 pH regulation of the stomach

Nature of science:

Collecting data through sampling and trialling—one of the symptoms of dyspepsia is the overproduction of stomach acid. Medical treatment of this condition often includes the prescription of antacids to instantly neutralize the acid, or H_2-receptor antagonists or proton pump inhibitors which prevent the production of stomach acid. (2.8)

Understandings:

- Non-specific reactions, such as the use of antacids, are those that work to reduce the excess stomach acid.
- Active metabolites are the active forms of a drug after it has been processed by the body.

Applications and skills:

- Explanation of how excess acidity in the stomach can be reduced by the use of different bases.
- Construction and balancing of equations for neutralization reactions and the stoichiometric application of these equations.
- Solving buffer problems using the Henderson–Hasselbalch equation.
- Explanation of how compounds such as ranitidine (Zantac) can be used to inhibit stomach acid production.
- Explanation of how compounds like omeprazole (Prilosec) and esomeprazole (Nexium) can be used to suppress acid secretion in the stomach.

Guidance:

- Antacid compounds should include calcium hydroxide, magnesium hydroxide, aluminium hydroxide, sodium carbonate and sodium bicarbonate.
- Structures for ranitidine and esomeprazole can be found in the data booklet in section 37.

International-mindedness:

- Different cultures (ie diet, lifestyle, etc) and genetics can affect the need for pH regulation of the stomach.

Theory of knowledge:

- Sometimes we utilize different approaches to solve the same problem. How do we decide between competing evidence and approaches?

Utilization:

Syllabus and cross-curricular links:
Topic 1.3—calculations involving solutions
Topics 8.2 and 8.4—neutralization
Topic 10.2—functional groups
Topic 20.3—enantiomers
Option B.7—amino acid buffers
Biology option D.1—digestion

Aims:

- **Aim 6**: Experiments could include titrations to test the effectiveness of various antacids.

Essential idea: Antiviral medications have recently been developed for some viral infections while others are still being researched.

D.5 Antiviral medications

Nature of science:

Scientific collaboration—recent research in the scientific community has improved our understanding of how viruses invade our systems. (4.1)

Understandings:

- Viruses lack a cell structure and so are more difficult to target with drugs than bacteria.
- Antiviral drugs may work by altering the cell's genetic material so that the virus cannot use it to multiply. Alternatively, they may prevent the viruses from multiplying by blocking enzyme activity within the host cell.

Applications and skills:

- Explanation of the different ways in which antiviral medications work.
- Description of how viruses differ from bacteria.
- Explanation of how oseltamivir (Tamiflu) and zanamivir (Relenza) work as a preventative agent against flu viruses.
- Comparison of the structures of oseltamivir and zanamivir.
- Discussion of the difficulties associated with solving the AIDS problem.

Guidance:

- Structures for oseltamivir and zanamivir can be found in the data booklet in section 37.

International-mindedness:

- How has the AIDS epidemic changed since its discovery in the early 1980s? What is needed to stop the spread of the disease? What is the global impact of this disease?

Utilization:

Syllabus and cross-curricular links:
Options B.2 and B.7—proteins and enzymes
Biology topic 11.1—vaccination

Aims:

- **Aim 8**: The control and treatment of HIV is exacerbated by the high price of anti-retroviral agents and sociocultural issues.

Essential idea: The synthesis, isolation, and administration of medications can have an effect on the environment.

D.6 Environmental impact of some medications

Nature of science:

Ethical implications and risks and problems—the scientific community must consider both the side effects of medications on the patient and the side effects of the development, production and use of medications on the environment (ie disposal of nuclear waste, solvents and antibiotic waste). (4.8)

Understandings:

- High-level waste (HLW) is waste that gives off large amounts of ionizing radiation for a long time.
- Low-level waste (LLW) is waste that gives off small amounts of ionizing radiation for a short time.
- Antibiotic resistance occurs when micro-organisms become resistant to antibacterials.

Applications and skills:

- Describe the environmental impact of medical nuclear waste disposal.
- Discussion of environmental issues related to left-over solvents.
- Explanation of the dangers of antibiotic waste, from improper drug disposal and animal waste, and the development of antibiotic resistance.
- Discussion of the basics of green chemistry (sustainable chemistry) processes.
- Explanation of how green chemistry was used to develop the precursor for Tamiflu (oseltamivir).

Guidance:

- The structure of oseltamivir is provided in the data booklet in section 37.

International-mindedness:

- Consider how pharmaceutical companies determine how to spend research funds to develop new medications.
- Do pharmaceutical companies have a responsibility to do research on rare diseases that will not provide them with significant financial profit?
- Production of a drug typically involves a number of different organic reactions. What are the ethics governing the design (synthesis) of drugs? Do standards and practices vary by country and region?

Theory of knowledge:

- How do we balance ethical concerns that appear to be at odds with each other when trying to formulate a solution to the problem?

Aims:

- **Aim 8**: How do we safely dispose of medicinal nuclear waste?
- **Aim 8**: The Pacific yew tree which is the source of the chemotherapy drug Taxol is facing extinction.
- **Aim 8**: Solvent disposal is a growing environmental problem.

Additional higher level topics

Essential idea: Chiral auxiliaries allow the production of individual enantiomers of chiral molecules.

D.7 Taxol—a chiral auxiliary case study

Nature of science:

Advances in technology—many of these natural substances can now be produced in laboratories in high enough quantities to satisfy the demand. (3.7)

Risks and problems—the demand for certain drugs has exceeded the supply of natural substances needed to synthesize these drugs. (4.8)

Understandings:

- Taxol is a drug that is commonly used to treat several different forms of cancer.
- Taxol naturally occurs in yew trees but is now commonly synthetically produced.
- A chiral auxiliary is an optically active substance that is temporarily incorporated into an organic synthesis so that it can be carried out asymmetrically with the selective formation of a single enantiomer.

Applications and skills:

- Explanation of how taxol (paclitaxel) is obtained and used as a chemotherapeutic agent.
- Description of the use of chiral auxiliaries to form the desired enantiomer.
- Explanation of the use of a polarimeter to identify enantiomers.

Guidance:

- The structure of taxol is provided in the data booklet in section 37.

International-mindedness:

- There is an unequal availability and distribution of certain drugs and medicines around the globe.

Utilization:

Syllabus and cross-curricular links:
Topic 20.2—synthetic routes
Topic 20.3—stereoisomerism

Aims:

- **Aim 8**: Consider the ethical implications of using synthetic drugs instead of natural sources.

Essential idea: Nuclear radiation, whilst dangerous owing to its ability to damage cells and cause mutations, can also be used to both diagnose and cure diseases.

D.8 Nuclear medicine

Nature of science:

Risks and benefits—it is important to try and balance the risk of exposure to radiation with the benefit of the technique being considered. (4.8)

Understandings:

- Alpha, beta, gamma, proton, neutron and positron emissions are all used for medical treatment.
- Magnetic resonance imaging (MRI) is an application of NMR technology.
- Radiotherapy can be internal and/or external.
- Targeted Alpha Therapy (TAT) and Boron Neutron Capture Therapy (BNCT) are two methods which are used in cancer treatment.

Applications and skills:

- Discussion of common side effects from radiotherapy.
- Explanation of why technetium-99m is the most common radioisotope used in nuclear medicine based on its half-life, emission type and chemistry.
- Explanation of why lutetium-177 and yttrium-90 are common isotopes used for radiotherapy based on the type of radiation emitted.
- Balancing nuclear equations involving alpha and beta particles.
- Calculation of the percentage and amount of radioactive material decayed and remaining after a certain period of time using the nuclear half-life equation.
- Explanation of TAT and how it might be used to treat diseases that have spread throughout the body.

Guidance:

- Common side effects discussed should include hair loss, nausea, fatigue and sterility. Discussion should include the damage to DNA and growing or regenerating tissue.
- Isotopes used in nuclear medicine including; Tc-99m, Lu-177, Y-90, I-131 and Pb-212.

International-mindedness:

- The use of nuclear technology in medical treatments is not consistent across the globe. Culture, cost, availability and beliefs are some factors that can influence its use.

Theory of knowledge:

- There is often no reference to the term “nuclear” in MRI. Are names simply labels or do they influence our other ways of knowing? How does public perception influence scientific progress and implementation?

Utilization:

Syllabus and cross-curricular links:
Topics 11.3 and 21.1—NMR
Options C.3 and C.7—nuclear reactions and half-life
Physics option C.4—medical imaging.

Essential idea: A variety of analytical techniques is used for detection, identification, isolation and analysis of medicines and drugs.

D.9 Drug detection and analysis

Nature of science:

Advances in instrumentation—advances in technology (IR, MS and NMR) have assisted in drug detection, isolation and purification. (3.7)

Understandings:

- Organic structures can be analysed and identified through the use of infrared spectroscopy, mass spectroscopy and proton NMR.
- The presence of alcohol in a sample of breath can be detected through the use of either a redox reaction or a fuel cell type of breathalyser.

Applications and skills:

- Interpretation of a variety of analytical spectra to determine an organic structure including infrared spectroscopy, mass spectroscopy and proton NMR.
- Description of the process of extraction and purification of an organic product. Consider the use of fractional distillation, Raoult's law, the properties on which extractions are based and explaining the relationship between organic structure and solubility.
- Description of the process of steroid detection in sport utilizing chromatography and mass spectroscopy.
- Explanation of how alcohol can be detected with the use of a breathalyser.

Guidance:

- Students should be able to identify common organic functional groups in a given compound by recognition of common drug structures and from IR (section 26 of the data booklet), ^{1}H NMR (section 27 of the data booklet) and mass spectral fragment (section 28 of the data booklet) data.
- A common steroid structure is provided in section 34 in the data booklet.

International-mindedness:

- The misuse of drugs in sport is an international problem.

Theory of knowledge:

- Developments in technology have increased the chances of people being caught using illegal substances. How do changes in technology influence our ethical choices?

Utilization:

Syllabus and cross-curricular links:
Topic 10.2—functional groups

Aims:

- **Aim 4**: A variety of spectroscopy techniques can be used to identify newly developed molecules.
- **Aim 7**: Computer databases with spectroscopy data could be used to confirm the identity of newly synthesized molecules.
- **Aim 8**: Developments in technology have increased the chances of people being caught using illegal substances. How do changes in technology influence our ethical choices?