BIOCHEMISTRY

B.1 INTRODUCTION TO BIOCHEMISTRY

You should know:
✓ the functions of biological molecules depend on their structures and shapes;
✓ metabolism is the sum of chemical reactions that take place within a living organism;
✓ catabolic reactions, such as cellular respiration and digestion, produce energy by breaking down large organic molecules into smaller units;
✓ anabolic reactions, such as photosynthesis and tissue growth, require energy to synthesize larger molecules from smaller units;
✓ biopolymers are typically produced by condensation reactions and broken down by hydrolysis reactions.

You should be able to:
✓ explain the difference between condensation and hydrolysis reactions;
✓ define oxidation and reduction in terms of the gain or loss of oxygen and hydrogen atoms;
✓ identify whether a given biochemical reaction is a catabolic or anabolic process;
✓ use the summary equations of photosynthesis and respiration to explain oxygen and carbon dioxide exchange with the atmosphere;
✓ state the names and outline the composition of common biopolymers.

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✓ state the names and outline the composition of common biopolymers.

Common biopolymers and their structural units are discussed in topics B.2 [proteins and amino acids], B.3 [fats, fatty acids and glycerol], B.4 [poly- and monosaccharides] and B.8 [nucleic acids, nucleotides and nitrogenous bases].

Metabolic processes are essential for life. Catabolic reactions provide energy for living organisms by hydrolysing large molecules of nutrients (proteins, fats and carbohydrates) into smaller units (amino acids, fatty acids, glycerol and monosaccharides) and then oxidizing these units into carbon dioxide and water. This energy is used by the organism for performing physical activity, maintaining constant body temperature and carrying out anabolic reactions, which are opposite to catabolism and typically involve condensation and reduction.

Example B.1.1.
Aerobic respiration of sucrose ($M_r = 342.34$) is a complex catabolic process that can be summarized as follows:

**Step 1:** $C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$

- **sucrose**
- **glucose**
- **fructose**

**Step 2:** $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

- **a** State, with a reason, the reaction type for each step.
- **b** Suggest whether energy is released or consumed at each step.
- **c** Calculate the mass, in grams, of water produced by aerobic respiration of 10.0 g of sucrose.

Solution

- **a** The first step is a hydrolysis reaction, as a larger molecule reacts with water to produce two smaller molecules. The second step is an oxidation reaction, as the organic molecule gains oxygen atoms.
- **b** Both steps are catabolic processes, so they are likely to release energy.
- **c** Water is consumed in Step 1 and released in Step 2. To simplify the calculations, it is convenient to combine both steps into a single equation:

$$C_{12}H_{22}O_{11} + 12O_2 \rightarrow 12CO_2 + 11H_2O$$

Now we can see that one mole of sucrose produces 11 moles of water. Therefore:

$$n(C_{12}H_{22}O_{11}) = 10.0 \text{ g} / 342.34 \text{ g mol}^{-1} = 0.0292 \text{ mol}$$

$$n(H_2O) = 11 \times 0.0292 \text{ mol} = 0.321 \text{ mol}$$

$$m(H_2O) = 0.321 \text{ mol} \times 18.02 \text{ g mol}^{-1} = 5.78 \text{ g}$$

The summary equation of photosynthesis is the reverse of Step 2 from example B.1.1. Together with respiration, photosynthesis is a part of the carbon cycle that maintains a balance of carbon dioxide and oxygen in the atmosphere.

**Sample Student Answer**

Describe what is meant by a condensation reaction. This answer could have achieved 1/2 marks:

A condensation reaction is a redox reaction that builds a polymer from monomers.

Water is formed as a by-product.

**Practice problems for Topic B.1**

**Problem 1**
The peptidase enzyme in the digestive system hydrolysates peptide bonds. Identify the type of metabolic process that occurs when a peptide undergoes hydrolysis.

**Problem 2**
Depending on the substrate, the standard enthalpy changes for both hydrolysis and condensation reactions can be either positive or negative. However, nearly all hydrolysis reactions in living organisms release energy while nearly all condensation reactions in living organisms consume energy. Suggest a possible reason for this fact, with a reference to Le Châtelier’s principle.
B.2 PROTEINS AND ENZYMES

You should know:

 ✓ amino acids are amphoteric species that can exist as cations, zwitterions and anions;
 ✓ proteins and peptides are polymers of 2-amino acids, in which the units are joined by amide links (–C(O)–NH–), also known as peptide bonds;
 ✓ protein structures can be described at primary to quaternary levels, and the shapes of proteins relate to their roles;
 ✓ enzymes are biological catalysts, usually protein-based, that provide an active site for binding to a specific substrate;
 ✓ enzymes lose their shape and thus activity outside the optimum ranges of pH and temperature, or in the presence of heavy metal ions.

You should be able to:

 ✓ explain the solubilities and melting points of amino acids in terms of zwitterions;
 ✓ deduce equations and structural formulas for condensation and hydrolysis reactions involving amino acids and peptides;
 ✓ apply the relationships between charge, pH and isoelectric point to explain the properties of amino acids and proteins;
 ✓ explain how amino acids and proteins can be separated and identified by paper chromatography and gel electrophoresis;
 ✓ describe the four levels of protein structure, including the types of bonds and interactions at each level;
 ✓ deduce and interpret plots of enzyme activity against substrate concentration, pH and temperature.

Amino acids

Amino acids are polyfunctional compounds that contain a basic amino group (–NH2) and an acidic carboxyl group (–COOH) in the same molecule. In the solid state and in neutral aqueous solutions, amino acids exist as zwitterions:

\[
\text{H}_2\text{N}–\text{CH}–\text{COOH} \quad \rightarrow \quad \text{H}_2\text{N}–\text{CH}–\text{COO}^– \quad \text{cation (pH < pI)}
\]

\[
\text{R}
\]

\[
\text{H}_2\text{N}–\text{CH}–\text{COO}^– \quad \rightarrow \quad \text{H}_2\text{N}–\text{CH}–\text{COO}^+ \quad \text{zwitterion (pH = pI)}
\]

\[
\text{R}
\]

\[
\text{H}_2\text{N}–\text{CH}–\text{COO}^+ \quad \rightarrow \quad \text{R}^+ \quad \text{anion (pH > pI)}
\]

The pH at which nearly all amino acid species exist as zwitterions is known as the isoelectric point (pI). The pI value depends on the side chain (R) so is specific for each amino acid.

Example B.2.1.

The molecular formulas and isoelectric points of 2-amino acids are given in section 33 of the data booklet.

a) Draw the structural formulas of organic species that are present in aqueous solutions of alanine at pH 4.5 and 7.5.

b) Explain, with a reference to the bonding, why alanine is readily soluble in water and has a high melting point.

Solution

a) The pI of alanine is 6.0 (section 33 of the data booklet). At pH 4.5 this amino acid will exist as a mixture of cationic and zwitterionic species, while at pH 7.5 it will form zwitterionic and anionic species:

\[
\text{H}_2\text{N}–\text{CH}–\text{COOH} \quad \rightarrow \quad \text{H}_2\text{N}–\text{CH}–\text{COO}^– \quad \text{cation (pH < pI)}
\]

\[
\text{R}
\]

\[
\text{H}_2\text{N}–\text{CH}–\text{COO}^– \quad \rightarrow \quad \text{H}_2\text{N}–\text{CH}–\text{COO}^+ \quad \text{zwitterion (pH = pI)}
\]

\[
\text{R}
\]

\[
\text{H}_2\text{N}–\text{CH}–\text{COO}^+ \quad \rightarrow \quad \text{R}^+ \quad \text{anion (pH > pI)}
\]

b) Alanine has two polar groups, amino and carboxyl, which can form hydrogen bonds with water. In the solid state, the zwitterions of alanine form ionic and hydrogen bonds with one another. The non-polar side chain of alanine is small, so it does not affect the overall polar nature of this compound.

A mixture of amino acids can be separated by paper chromatography. A spot of the sample to be analysed is placed on a piece of paper (stationary phase) and eluted with a solvent (mobile phase). Because of the differences in solubility and affinity for the stationary phase, amino acids travel along the paper at different speeds and separate into individual colourless spots, which can be developed by staining the paper with ninhydrin. Each amino acid has a unique retention factor (Rf), the ratio of the distances travelled by the amino acid (Rf) and the solvent front (f). The composition of the mixture can be deduced by comparing the Rf value of each spot with known Rf values for amino acids under the same conditions.

Example B.2.2.

A mixture of amino acids was analysed by paper chromatography. After development with ninhydrin, three spots were detected at distances of 3.3, 6.1 and 7.0 cm from the start line, while the solvent front was at 10.3 cm from the start line.

a) Using the table on the right, identify two amino acids in the original mixture.

b) Suggest two possible changes in the experimental conditions that could enable determination of the number of amino acids in the mixture.

Solution

a) The spot at 6.1 cm is produced by cysteine (Rf ≈ 0.64, section 33 of the data booklet). The spot at 3.3 cm (Rf ≈ 0.32) cannot be identified, as it might be produced by alanine, aspartic acid, or a mixture of both.

b) To determine whether the spot at 3.3 cm contains one or two amino acids, we can repeat the experiment using different solvent pH and temperature. If any of these changes produce a chromatogram with four spots, the mixture contains four amino acids. Otherwise, it is likely to contain only three.

Gel electrophoresis is another technique used for the analysis of amino acids. A mixture of amino acids is placed in the centre of a gel saturated with a buffer solution (topic B.7) of a certain pH. When a potential difference is applied, the amino acids move at different rates towards one or the other electrode or remain stationary depending on their charges and sizes.

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Note that zwitterions exist in solutions at any pH, but their proportion will be the highest at pH << pI and become very low at pH >> pI.
The three-dimensional shapes of proteins determine their roles in living organisms. Fibrous proteins have structural, supportive and protective functions, while globular proteins act as biological catalysts (enzymes), messengers (hormones) and carriers of biologically important molecules and ions.

### Enzymes
Most enzymes are protein-based molecules that provide an active site for binding to a specific substrate. The activity of an enzyme depends on the shape of its active site, which in turn is affected by the overall native structure of the enzyme. Maximum enzyme activity is achieved within narrow ranges of pH and temperature. Outside these ranges or in the presence of heavy metal ions the enzyme becomes denatured – it changes shape and loses its activity.

#### Example B.2.4.

Enzyme activity depends on many factors. Explain how pH change causes the loss of activity of an enzyme.

**Solution**
When the pH changes, some amino, carbonyl and other ionizable groups in the side chains of amino acid units lose or gain protons. This alters ionic and hydrogen bonds between different parts of the enzyme and distorts its native structure. The distortion affects the conformation and charge of the active site, which no longer fits the substrate, so no reaction takes place.

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### Table B.2.1. The four levels of protein structure

<table>
<thead>
<tr>
<th>Structure</th>
<th>Description</th>
<th>Bonding types</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary</td>
<td>sequence of amino acid units</td>
<td>covalent bonds (peptide linkages)</td>
<td>Ala–Glu–Arg–Ser–…</td>
</tr>
<tr>
<td>secondary</td>
<td>regular folding pattern of the polypeptide backbone</td>
<td>hydrogen bonds between peptide linkages</td>
<td>α-helix (coil) and β-sheet (twisted ribbon)</td>
</tr>
<tr>
<td>tertiary</td>
<td>overall three-dimensional shape of the polypeptide chain</td>
<td>van der Waals (interactions, ionic, hydrogen and disulfide bonds) between side chains of amino acids</td>
<td>globular (insulin and hemoglobin) and fibrous (keratin and collagen) proteins</td>
</tr>
<tr>
<td>quaternary</td>
<td>three-dimensional arrangement of several polypeptide chains and non-protein units</td>
<td>van der Waals (interactions, ionic, hydrogen and sometimes covalent bonds)</td>
<td>insulin (two polypeptide chains), hemoglobin (four polypeptide chains with one non-protein unit each)</td>
</tr>
</tbody>
</table>

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### Assessment tip

An enzyme is a biological catalytic polypeptide, usually a globular protein-based molecule.

A substrate is a molecule or ion that is changed by an enzyme.

The active site is the part of an enzyme that binds to the substrate by non-covalent interactions.

Native structure is the three-dimensional (tertiary and quaternary) structure of a functional (active) protein.

Denaturation is the loss of the native structure and activity of a protein.

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### Peptides and Proteins

- Peptides are polycondensation polymers of 2-amino acids containing up to 50 structural units.
- Proteins contain over 50 amino acid units and can spontaneously adopt specific three-dimensional shapes.

Proteins
Amino acids undergo condensation reactions (topic B.1), producing peptides and proteins. The side chains of amino acids in such reactions usually remain unchanged.

In turn, peptides and proteins can be hydrolysed to amino acids in the presence of enzymes or hot concentrated hydrochloric acid.

Proteins are polycondensation polymers containing 50 or more 2-amino acid units. In contrast to peptides that typically have no permanent three-dimensional shape, proteins can have up to four structural levels of increasing complexity (table B.2.1).
You should know:

- Amino acids are usually identified by their common names. Discuss the advantages and disadvantages of this approach.
- Fatty acids are long-chain carboxylic acids containing more than three carbon atoms.
- Triglycerides (oils and fats) are esters of glycerol with fatty acids.

You should be able to:

- State the types of interaction responsible for holding the protein in this arrangement.
- Compare carbohydrates and lipids as energy storage molecules with respect to their solubility and energy density.
- Deduce the structural formulas of reactants and products in condensation and hydrolysis reactions involving glycerol, fatty acids, triglycerides and phospholipids.
- Identify the functional groups responsible for these interactions.
- Predict the relative melting points of fats and oils from their structures.
- Compare the processes of hydrolytic and oxidative rancidity in fats and oils.
- Apply the iodine number to determine the unsaturation of a lipid.
- Discuss the physiological effects of saturated, unsaturated and trans-fats, HDL and LDL cholesterol, and the use and abuse of steroids.

**Problem 1**

The structures of amino acids are given in section 33 of the data booklet.

- a) State the IUPAC names for glycine and leucine.
- b) Suggest, with a reason, the best method for separating a mixture of these two amino acids.
- c) Deduce the number of different dipeptides that can be made from glycine and leucine.
- d) Draw the structural formula of one dipeptide from part c.
- e) Amino acids are usually identified by their common names. Discuss the advantages and disadvantages of this approach.

**Problem 2**

The fibrous protein keratin has a secondary structure with a helical arrangement. The structures of amino acids are given in section 33 of the data booklet.

- a) State the type of interaction responsible for holding the protein in this arrangement.
- b) Identify the functional groups responsible for these interactions.

**Problem 3**

Bioplastics are broken down by enzyme-catalysed reactions. Sketch a graph illustrating how the rate of this reaction varies with pH.

Lipids are a diverse group of biomolecules with large hydrocarbon backbones and very few polar functional groups. Unlike carbohydrates (topic B.4), lipids are predominantly non-polar and thus insoluble in water, as they cannot form enough hydrogen bonds with the solvent. Lipids have a low ratio of oxygen to carbon atoms, so they are less oxidized than carbohydrates and thus store more energy per unit mass than other dietary compounds.

Common lipids are fatty acids, triglycerides (fats and oils, found in living organisms), phospholipids and steroids. Saturated fatty acids contain no C=C bonds, monounsaturated acids contain one C=C bond, and polyunsaturated acids contain two or more C=C bonds. Two polyunsaturated fatty acids, linoleic and linolenic (see section 34 of the data booklet), are essential fatty acids, as they cannot be synthesized in the human body and must be obtained from food.

**Fatty acids**

Unsaturated fatty acids have lower melting and boiling points than their saturated analogues. The C=C fragments in naturally occurring molecules usually have cis-configuration, so they form kinks in the hydrocarbon chains. These kinks prevent the chains from packing closely and thus weaken the intermolecular London (dispersion) forces. The melting and boiling points of fatty acids increase with chain length, as the strength of London (dispersion) forces increases with the number of electrons.

**Triglycerides**

Steroids have a characteristic fused ring structure (the steroidal backbone) and act as hormones.

**Biochemistry**

**B.3 LIPIDS**

**Assessment tip**

Lipids are not biopolymers. In biopolymers the structural units are linked by covalent bonds. In contrast, the molecules of lipids are held together by weak London (dispersion) forces and other van der Waals interactions (topic 4.4).

**Fatty acids**

- Saturated fatty acids contain no C=C bonds. The correct statement is “saturated fatty acids contain no double carbon–carbon bonds”. The same is true for triglycerides.
The number of C=C bonds in a lipid (its degree of unsaturation) can be determined from its reaction with iodine. Unsaturated fatty acids can be saturated by hydrogenation in the presence of a nickel catalyst, at high temperature and pressure:

\[
\text{CH}_2\text{CH}(_2\text{CH}(_2\text{CH}(_2\text{CH}(_2\text{OH} + 3\text{H}_2 \xrightarrow{\text{Ni}} \text{CH}_2\text{CH}(_2\text{CH}(_2\text{COOH}
\]

linolenic acid

\[
\text{steearic acid}
\]

Triglycerides and phospholipids

Triglycerides are triesters of fatty acids and glycerol. They are produced by condensation reactions, for example:

\[
\begin{align*}
\text{H}_2\text{C} & \quad \text{O} & \quad \text{H} & \quad \text{H} & \quad \text{C}_17\text{H}_{35} \quad \text{H} \\
\text{O} & \quad \text{H} & \quad \text{H} & \quad \text{O} & \quad \text{H} & \quad \text{C}_17\text{H}_{35} \\
\text{H}_2\text{C} & \quad \text{O} & \quad \text{H} & \quad \text{H} & \quad \text{C}_17\text{H}_{35} \\
\text{ester fragment}
\end{align*}
\]

Phospholipids are similar to triglycerides but one fatty acid is replaced with phosphoric acid. Hydrolysis reactions of triglycerides and phospholipids are catalysed by enzymes, strong acids or strong bases.

Melting points of triglycerides and phospholipids, like those of fatty acids, decrease as the number of C=C bonds they contain increases. Liquid triglycerides (oils) contain a larger proportion of unsaturated fatty acid residues than solid triglycerides (fats). Oils can be converted to fats by catalytic hydrogenation. Incomplete hydrogenation may produce trans-isomers of the unsaturated fatty acid residues. Like saturated fatty acids, these increase the risk of heart disease by lowering the ratio of HDL to LDL cholesterol (see below) in the blood, thus contributing to the formation of atherosclerotic plaque. Unsaturated fatty acids and their derivatives have the opposite effect and are beneficial for health.

Dietary fats and oils can develop unpleasant odours and flavours due to rancidity (table B.3.1). Hydrolytic rancidity (also known as microbial rancidity when caused by bacteria) affects all triglycerides, while oxidative rancidity affects polyunsaturated compounds, such as vegetable and fish oils.

<table>
<thead>
<tr>
<th>Rancidity type</th>
<th>Group affected</th>
<th>Products</th>
<th>Conditions</th>
<th>Prevention</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrolytic</td>
<td>ester linkages</td>
<td>fatty acids, glycerol, mono- and diglycerides</td>
<td>moisture, acids, heat, bacterial enzymes</td>
<td>freezing or refrigeration, sterilization</td>
</tr>
<tr>
<td>oxidative</td>
<td>double carbon-carbon bonds</td>
<td>volatile aldehydes and ketones</td>
<td>exposure to air and sunlight</td>
<td>addition of antioxidants, protective atmosphere, antioxidants</td>
</tr>
</tbody>
</table>

Steroids and cholesterol

Most steroids act as chemical messengers (hormones) that regulate metabolism, immune responses and reproductive functions. Anabolic steroids stimulate the growth of muscle tissue and have many medical uses, but are also abused in sports as performance-enhancing drugs.

All steroids in the human body are synthesized from cholesterol, shown in section 34 of the data booklet, which is also an important component of cell membranes.

Example B.3.1

Cholesterol is synthesized in the liver and has various biological functions.

a) Suggest, with a reason, whether cholesterol is soluble in water or not.

b) Describe how cholesterol is transported around the body.

Solution

a) The cholesterol molecule has a large hydrocarbon backbone and only one hydroxyl group. Its overall polarity is low, so it is insoluble in water.

b) Cholesterol is transported from the liver to body tissues by the blood in the form of complexes with low-density lipoproteins (LDL). High-density lipoproteins (HDL) form more stable complexes with cholesterol and transport it back to the liver, where it is metabolized.

Suggested answers

This answer could have achieved 4/5 marks:

a) Stearic acid, as it is saturated and so molecules can pack closer together, giving stronger London dispersion forces between molecules.

b) 10.0 g of sunflower oil reacts completely with 123 cm$^3$ of 0.500 mol dm$^{-3}$ iodine solution. Calculate the iodine number of sunflower oil to the nearest whole number.

This answer could have achieved 3/5 marks:

a) Explain why one of these fatty acids has the highest boiling point.

b) 10.0 g of sunflower oil reacts completely with 123 cm$^3$ of 0.500 mol dm$^{-3}$ iodine solution. Calculate the iodine number of sunflower oil to the nearest whole number.

This answer could have achieved 2/5 marks:

a) Iodine number is the mass of molecular iodine that reacts with 100 g of the lipid.

Steroids have a characteristic arrangement of four fused rings, known as the steroidal backbone (figure B.3.1).

HDL cholesterol (HDL-C) and LDL cholesterol (LDL-C) are sometimes called “good cholesterol” and “bad cholesterol”, respectively. You should never use such colloquial names in examinations, as they will not be accepted.

Table B.3.1. Types of rancidity

A The last step is correct, so the third mark is awarded with “error carried forward”; the correct answer is 136 (whole number without units)

A Correct; the question requires an explanation, so the nature of intermolecular forces must be stated for the second mark

A Correct amount of iodine

A Correct amount of iodine

A Atomic mass of iodine (126.9) is used instead of its molecular mass (253.8)

A The last step is correct, so the third mark is awarded with “error carried forward”; the correct answer is 136 (whole number without units)

A Table B.3.1. Types of rancidity

A Correct; the question requires an explanation, so the nature of intermolecular forces must be stated for the second mark

A Correct amount of iodine

A Correct amount of iodine

A Atomic mass of iodine (126.9) is used instead of its molecular mass (253.8)
You should know:
✓ Carbohydrates have the general formula C\(_n\)(H\(_{2n}\)O\(_{x}\)), and function as energy sources and reserves;
✓ Monosaccharides contain several –OH groups and a carbonyl group;
✓ Straight-chain and cyclic forms of monosaccharides interconvert in solutions;
✓ Monosaccharides join together via glycosidic bonds to form di- and polysaccharides.

You should be able to:
✓ Deduce Haworth projections of cyclic monosaccharides;
✓ Deduce the structural formulas of di- and polysaccharides from given monosaccharides;
✓ Discuss the properties and functions of monosaccharides and polysaccharides in relation to their chemical structure.

Carbohydrates ("hydrates of carbon") are oxygen-rich biomolecules with multiple hydroxyl groups and the general formula C\(_n\)(H\(_{2n}\)O\(_{x}\)). Broader terms saccharides and sugars include other structurally similar compounds. Monosaccharides have a single carbon chain with a carbonyl group either at the end of the chain (aldoses) or at the second carbon atom (ketoses). For example, glucose is an aldose while fructose is a ketose (see section 34 of the data booklet).

Most monosaccharides can exist in straight-chain and cyclic forms that interconvert rapidly in solution, where the carbonyl and one of the hydroxyl groups join in a hemiacetal group, –O–CH(OH)\(_2\). The –OH part of the hemiacetal group can be trans or cis to the –CH\(_2\)OH group, producing α- and β-isomers, respectively (see topic B.10).

Monosaccharides participate in condensation reactions to give di- and polysaccharides, in which the structural units are joined by glycosidic links.

\[
\text{Example B.4.1.}
\]
Sucrose is a disaccharide formed from α-glucose and β-fructose. Deduce the structural formula of sucrose and identify the glycosidic link in its molecule.

**Solution**

Carbohydrates are more oxidized than fats (topic B.3) and thus store less energy per unit mass. However, they have many hydroxyl and other polar functional groups that can participate in a wide range of reactions. Hydroxyl groups can form hydrogen bonds with water, so all mono- and disaccharides are readily soluble in water and can be quickly delivered to cells by the blood. Therefore, glucose is used as a source of energy in many biological processes. Polysaccharides, such as glycogen and starch (topics B.6 and B.10), are less water-soluble, so they are used for storing energy and hydrolysed into glucose when needed.
B.5 VITAMINS

You should know:

✓ vitamins are organic micronutrients that must be obtained from food;
✓ most vitamins are sensitive to heat, light and atmospheric oxygen;
✓ vitamin deficiencies cause particular diseases that affect many people worldwide.

You should be able to:

✓ compare the structures of vitamins A, C and D;
✓ predict the solubility of a vitamin in water and fats from its structure;
✓ discuss the causes and effects of vitamin deficiencies and suggest preventive measures.

Vitamins are small organic molecules with diverse functions (Table B.5.1). With the exception of vitamin D, they cannot be synthesized by the body and must be obtained from food. Vitamin deficiencies affect health and can be fatal, even if all other nutrients (proteins, fats, carbohydrates, minerals, and water) are present in the diet.

Vitamins A and D have large hydrocarbon backbones, so they are predominantly non-polar and thus insoluble in water. In the human body, both vitamins accumulate in fatty tissues, where their molecules are retained by London (dispersion) forces. In contrast, vitamin C (ascorbic acid) has many polar groups that can form hydrogen bonds with water. As a result, vitamin C is soluble in water but insoluble in fats, so it cannot be stored in the body for long and requires regular uptake.

Example B.5.1.

Vitamin A is an essential micronutrient.

a) Suggest why a low-fat diet can result in a deficiency of this vitamin even if it is consumed in sufficient quantities.

b) State three methods of preventing vitamin deficiencies.

Solution

a) Vitamin A is insoluble in water but soluble in fats, so its absorption from the gastrointestinal tract requires the presence of fats and lipoproteins (see topic B.3).

b) The use of vitamin supplements (pills), fortification (addition of vitamins to milk and other dietary products) and changes in diet (selection of foods rich in certain vitamins). Another method is the use of food made from genetically modified organisms (topic B.8) with increased vitamin content.

Many vitamins, especially ascorbic acid, are sensitive to heat, light and atmospheric oxygen, so fried or overcooked food loses most of its vitamin content. The decomposition of vitamins is catalysed by metal ions, which are always present in canned food. To reduce loss of vitamins, food must be cooked quickly, stored in airtight glass or plastic packaging, protected from light and refrigerated or frozen.

Vitamin deficiencies cause particular diseases

<table>
<thead>
<tr>
<th>Vitamin</th>
<th>Solubility</th>
<th>Biological role</th>
<th>Deficiency disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>fats</td>
<td>vision, immune system, tissue growth and development</td>
<td>night blindness</td>
</tr>
<tr>
<td>C</td>
<td>water</td>
<td>collagen synthesis, tissue repair, energy transfer, immune and nervous systems</td>
<td>scurvy</td>
</tr>
<tr>
<td>D</td>
<td>fats</td>
<td>calcium absorption, bone and muscle development, immune system</td>
<td>rickets</td>
</tr>
</tbody>
</table>

* Structures of these vitamins are given in section 35 of the data booklet.

When the question does not specify the solvent, you should discuss the vitamin solubility in both water and fats. The phrase “at the molecular level” means that you must state the nature and polarity of the vitamin molecule and the type of interactions (London forces or hydrogen bonding) between the vitamin and solvent.
Many, such as DDT, dioxins and polychlorinated biphenyls (PCBs), are very resistant to biodegradation and accumulate in plant cells or animal fatty tissues, eventually reaching dangerous concentrations. These concentrations increase exponentially along food chains, which is known as biomagnification. As a result, top predators are particularly affected by xenobiotics. Another class of xenobiotics, antibacterial drugs, do not accumulate in living organisms but cause antibiotic resistance in bacteria.

Certain heavy metals, such as arsenic and mercury, can also undergo biomagnification, especially in aqueous ecosystems. Therefore, these metals must be removed from industrial waste water by various techniques, including precipitation, chelation (topic A.10) and host–guest chemistry.

Practice problems for Topic B.5

Problem 1

a) State one structural and one physical characteristic of vitamins A and D that make them more similar to each other than they are to vitamin C.

b) Deduce which of the three vitamins (A, C or D) is more soluble in water.

Example B.6.1.

Heavy metals are a serious environmental concern.

a) Explain how host–guest chemistry can be used to selectively remove mercury(II) ions from an aqueous solution.

b) State two similarities and one difference between host–guest chemistry and the action of enzymes.

Solution

a) The “host” material must have pores or channels of a size and shape that closely match the size and shape of Hg\(^{2+}\)(aq) ions. These “guest” ions will enter the pores and be held tightly by multiple non-covalent interactions with the host. Larger ions will not fit into the pores while smaller ions will be held loosely and return to the solution.

b) Similarity 1: active sites in enzymes and pores in host materials both have specific sizes and shapes, so they selectively bind to specific targets (substrates or guests, respectively).

Similarity 2: in both cases, the species are held together by non-covalent interactions (such as van der Waals forces, ionic and hydrogen bonds). Differences: enzymes select substrates not only by their size and shape but also by their chemical nature (identity and orientation of functional groups), while hosts select guests by size and shape only.

Plastics constitute a large proportion of landfill waste. Polyethylene and other hydrocarbon-based plastics are non-biodegradable, so they remain in soil or seawater for hundreds of years. Birds and marine animals often die because they swallow pieces of plastic or get entangled in plastic debris. Biodegradable plastics contain carbohydrates (options B.4 and B.10) that can be broken down by bacteria.
Example B.6.2.

Explain how the inclusion of starch in hydrocarbon-based plastics makes them biodegradable.

Solution

Starch-based plastics are hydrophilic due to the presence of hydroxyl groups in carbohydrate units. Bacterial enzymes hydrolyse glycosidic bonds in starch and produce glucose, which is then catabolized by the bacteria. In addition, starch fragments prevent hydrocarbon chains from packing closely and thus weaken the London dispersion forces between these chains. This makes the plastic more permeable to oxygen and water and thus more accessible to microorganisms that decompose it.

Green chemistry

Green chemistry is an approach to chemical research and engineering that seeks to minimize the production and release to the environment of hazardous substances. Common practices of green chemistry include atom economy (topic A.5) and the use of aqueous or solvent-free reactions, renewable starting materials, mild reaction conditions, energy-saving techniques and efficient catalysts, and utilization of by-products.

Non-hazardous substances, such as biodegradable plastics, are often marketed as “green” but still require toxic chemicals or large amounts of energy for their production. In addition, the use of plant oils and starch in industry takes up agricultural land, affects biodiversity and increases the cost of food. Therefore, the “greenness” of a product must be assessed using all direct and indirect environmental implications of its entire life cycle.

SAMPLE STUDENT ANSWER

Glucose is the basic building block of starch that can be used to make bioplastics. Outline two advantages and two disadvantages of biodegradable plastics.

This answer could have achieved 2/4 marks:

Two advantages:

1. The plastic will be quickly digested by bacteria and free up landfills.
2. The plastic will be recycled by returning to the environment for use by organisms.

Two disadvantages:

1. Lots of starch needed, for which lots of crop has to be grown.
2. Uses land to grow the crop.

Rates of enzyme reactions

The composition and action of enzymes are discussed in topic B.2. The rates of enzymatic reactions are quantitatively described by the Michaelis–Menten equation,

\[ v = \frac{V_{\text{max}} [S]}{K_m + [S]} \]

where \( v \) and \( V_{\text{max}} \) are the actual and maximum reaction rates, respectively, [S] is the substrate concentration and \( K_m \) is the Michaelis constant, which is equal to [S] at \( v = \frac{1}{2} V_{\text{max}} \).

You should know:

✓ inhibitors regulate the activity of enzymes;
✓ amino acids and proteins can act as acid–base buffers;
✓ the concentration of a protein can be determined by UV-vis spectroscopy.

You should be able to:

✓ determine \( K_m \) and \( V_{\text{max}} \) from a plot and explain the importance of these values;
✓ compare competitive and non-competitive inhibition of enzymes;
✓ calculate the pH of buffer solutions involving amino acids;
✓ determine the concentration of a protein using the Beer–Lambert law.

Example B.7.1.

The graph in figure B.7.1 shows a Michaelis–Menten plot for an enzymatic reaction.

[Graph showing Michaelis–Menten plot]

Problems for Topic B.6

Problem 1

Biodegradable boxes made from polylactic acid, PLA, disintegrate when exposed to water.

State the formula of the product formed when water reacts with PLA.

Problem 2

Suggest how lead ions could be removed from an individual suffering from lead poisoning.
Inhibitors regulate metabolic processes by decreasing the activity of enzymes. A competitive inhibitor binds to the active site, making the enzyme temporarily unavailable for the substrate. A non-competitive inhibitor binds to an allosteric site (away from the active site), altering the shape of the whole enzyme molecule and distorting the active site so enzyme–substrate binding is less effective. The type of inhibition can be determined from the effects of the inhibitor concentration on $V_{\text{max}}$ and $K_m$ (table B.7.1).

### Table B.7.1. Competitive and non-competitive inhibition of enzymes

<table>
<thead>
<tr>
<th>Inhibitor</th>
<th>Structure and shape</th>
<th>Binding site</th>
<th>$V_{\text{max}}$</th>
<th>$K_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>competitive</td>
<td>similar to substrate</td>
<td>active</td>
<td>no change</td>
<td>increases</td>
</tr>
<tr>
<td>non-competitive</td>
<td>dissimilar to substrate</td>
<td>allosteric</td>
<td>decreases</td>
<td>no change</td>
</tr>
</tbody>
</table>

### Example B.7.2.

On the graph from the previous example, sketch and label two curves to show the effect of adding a competitive and a non-competitive inhibitor to the enzyme.

**Solution**

![Graph showing effect of inhibitors](image)

### Amino acid buffers

Amino acids and proteins can act as acid–base buffers (topic 18.3). An amino acid buffer consists of a zwitterion and either the cation or the anion of the same amino acid (table B.7.2).

<table>
<thead>
<tr>
<th>Solution pH</th>
<th>Conjugate acid</th>
<th>Conjugate base</th>
<th>Reaction with a strong acid</th>
<th>Reaction with a strong base</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH &lt; pK (acidic)</td>
<td>cation</td>
<td>zwitterion</td>
<td>cation + $\text{H}^+$ → cation</td>
<td>cation + $\text{OH}^-$ → cation + $\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>pH &gt; pK (alkaline)</td>
<td>zwitterion</td>
<td>anion</td>
<td>anion + $\text{H}^+$ → zwitterion</td>
<td>anion + $\text{H}_2\text{O}$</td>
</tr>
</tbody>
</table>

**Table B.7.2. Amino acid buffers**

The pH of a buffer solution can be calculated using the Henderson–Hasselbalch equation:

$$\text{pH} = \text{pK}_a + \log \frac{[\text{conjugate base}]}{[\text{conjugate acid}]}$$

### Example B.7.3.

A buffer solution contains 0.200 mol dm$^{-3}$ of the cation and 0.500 mol dm$^{-3}$ of the zwitterion of glycine. Calculate the pH of this solution if the pK$^+$ of glycine is 2.34.

**Solution**

The cation in this solution is the conjugate acid, as it contains one more proton than the zwitterion. Therefore:

$$\text{pH} = 2.34 + \log \frac{0.500}{0.200} = 2.74$$

**Assessment tip**

The product of an enzymatic reaction can itself act as a competitive or non-competitive inhibitor, providing negative feedback to metabolic processes. Inhibition by the product is a biochemical equivalent of Le Châtelier’s principle (topic 7.1): excess product slows the forward reaction until the product concentration returns to its normal physiological level.

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UV-vis spectroscopy

Proteins absorb UV light because of electron conjugation (topic B.9) in the aromatic rings of phenylalanine, tyrosine and tryptophan residues. The absorbance \( A \) of a protein is proportional to its concentration \( c \) in the solution and the cuvette length \( l \) (the Beer–Lambert law):

\[
A = \varepsilon cl
\]

The constant \( \varepsilon \) depends on the solvent and the temperature of the solution. In a typical experiment, the unknown protein concentration is determined from a calibration curve.

**Example B.7.4.**

UV-vis spectroscopy is commonly used for protein assay. The absorbances of a series of standard protein solutions are given below.

<table>
<thead>
<tr>
<th>Concentration ( c ) / mol dm(^{-3} )</th>
<th>Absorbance ( A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.047</td>
</tr>
<tr>
<td>1.10</td>
<td>0.259</td>
</tr>
<tr>
<td>2.00</td>
<td>0.470</td>
</tr>
<tr>
<td>2.90</td>
<td>0.682</td>
</tr>
<tr>
<td>3.80</td>
<td>0.893</td>
</tr>
</tbody>
</table>

a) Using graph paper, construct the calibration curve.

b) Determine the extinction coefficient \( \varepsilon \), in mol\(^{-1}\) dm\(^2\), if the cuvette used in all experiments has a length of 1.00 cm. Refer to section 1 of the data booklet.

c) Determine the concentration of a protein solution with an absorbance of 0.540 measured under the same experimental conditions.

**Solution**

- a) Using graph paper, construct the calibration curve.
- b) The Beer–Lambert law: \( A = \varepsilon cl \), so \( \varepsilon = \frac{A}{cl} \). Since the concentration is given in mol dm\(^{-3}\), we need to convert the cuvette length to dm: 1.00 cm = 0.100 dm. The calibration curve is linear, and all points are on the line, so we can use any pair of \( A \) and \( c \) values from the table, for example:

\[
\varepsilon = \frac{0.470}{0.100 \text{ dm} \times 2.00 \times 10^{-5} \text{ mol dm}^{-3}} = 2.35 \times 10^6 \text{ mol}^{-1} \text{ dm}^2
\]

- c) We can find the unknown concentration from the calibration curve, or calculate it using the Beer–Lambert law:

\[
c = \frac{A}{\varepsilon l} = \frac{0.540}{2.35 \times 10^6 \text{ mol}^{-1} \text{ dm}^{-3} \times 0.100 \text{ dm}} = 2.3 \times 10^{-3} \text{ mol dm}^{-3}
\]

- This is a very common error: \( K_a \) is not \( \frac{1}{2}V_{\max} \), it is the \( [S] \) value at \( v = \frac{1}{2}V_{\max} \), so \( K_a = 0.67 \text{ mmol dm}^{-3} \)
- The first sentence is correct, so one mark is scored
- The substrate can still bind to the distorted active site (although less efficiently), so the reaction continues at a reduced rate; \( V_{\max} \) decreases but does not fall to zero

**Practice problems for Topic B.7**

**Problem 1**

Para-aminobenzoic acid (PABA) plays an important role in the growth of bacteria and fungi. The rate of an enzyme-catalysed reaction between PABA and glucose depends on the PABA concentration as shown below.

<table>
<thead>
<tr>
<th>substrate concentration / 10(^{-3}) mol dm(^{-3} )</th>
<th>reaction rate / arbitrary scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.67</td>
<td>0.067</td>
</tr>
<tr>
<td>1.5</td>
<td>0.259</td>
</tr>
<tr>
<td>2.0</td>
<td>0.470</td>
</tr>
<tr>
<td>4.0</td>
<td>0.682</td>
</tr>
<tr>
<td>6.0</td>
<td>0.786</td>
</tr>
<tr>
<td>8.0</td>
<td>0.878</td>
</tr>
<tr>
<td>10.0</td>
<td>0.893</td>
</tr>
</tbody>
</table>

a) Determine the Michaelis constant \( K_m \) from the graph.

b) Non-competitive inhibitor binds to allosteric site and changes active site’s shape. Substrate cannot bind to changed active site, so reaction stops.

c) Sketch a curve on the graph in part [a] showing the effect of sulfanilamide on the reaction rate.

**Problem 2**

An aqueous buffer solution contains 0.250 mol dm\(^{-3}\) of the zwitterion and 0.100 mol dm\(^{-3}\) of the anionic form of phenylalanine.

- a) Calculate the pH of this buffer solution if the \( pK_a \) for phenylalanine is 9.13.
- b) Explain how the concentration of phenylalanine in solution can be determined by UV-vis spectroscopy.
Genetically modified organisms (GMOs) have artificially altered genetic material. Common genetic modifications include transferring useful material to wild species. Many issues, including the use of GMOs raises concerns about their safety and ethics. When the strands are separated, two identical copies of the original DNA can be produced by adding the sequence of complementary nucleotides to each strand.

Example B.8.1

A fragment of a DNA strand has the nucleotide sequence –ATTGCCTAC–.

a) Deduce the nucleotide sequence in the complementary strand of this DNA.

b) The DNA strand from part (a) was used as a template for creating an RNA molecule. State two differences between this RNA and the first DNA strand (–ATTGCCTAC–).

Solution

a) To construct a complementary DNA strand, we need to replace each adenine residue with thymine, thymine with adenine, guanine with cytosine and cytosine with guanine: –TAACCGATG–.

b) The RNA will be complementary to the second strand. Therefore, it will have the same nucleotide sequence as the first strand except that all thymine residues will be replaced with uracil: –AUUGCUAG–.

Negatively charged phosphoanhydride groups repel one another and form multiple hydrogen bonds with surrounding water molecules. In addition, phosphoanhydride groups can form ionic bonds with basic chromosomal proteins, histones, which are positively charged at physiological pH. The hydrogen and ionic bonds further stabilize the double-helical shape of DNA and protect the strands from damage.

The sequence of nucleotides in DNA is used by the cell as a program for synthesizing specific proteins. Three consecutive bases (tripllets) encode one amino acid. The genetic information from a DNA strand is first copied (transcribed) into a complementary RNA molecule before the RNA is decoded (translated) into the amino acid sequence of a protein.

GMOs

Genetically modified organisms (GMOs) have artificially altered genetic material. Common genetic modifications include transferring useful DNA fragments between species or deleting parts of existing DNA. The most common GMOs, transgenic plants, are resistant to pests, viruses and harsh weather, have higher crop yields or increased nutritional value.

Alongside their advantages, the use of GMOs raises many issues, including the unknown long-term effects of GM foods on health and the possibility of transferring altered genetic material to wild species.
B.9 BIOLOGICAL PIGMENTS (AHL)

You should know:

- biological pigments are coloured compounds produced by living organisms;
- pigments absorb visible light due to extensive electron conjugation;
- heme is a chelate complex of iron with a large macrocyclic ligand (porphyrin);
- hemoglobin, myoglobin and cytochrome are heme-containing proteins;
- chlorophyll is similar to heme but contains magnesium instead of iron;
- carotenoids are non-aromatic lipid-soluble pigments involved in photosynthesis;
- anthocyanins are aromatic water-soluble pigments occurring in plants.

You should be able to:

- explain the sigmoidal shape of the oxygen saturation curve of hemoglobin in terms of cooperative binding;
- discuss the factors that affect oxygen saturation of hemoglobin;
- describe the higher affinity of oxygen for fetal hemoglobin over adult hemoglobin;
- explain the action of carbon monoxide on hemoglobin in terms of competitive inhibition;
- describe the function of pigments in photosynthesis;
- explain the ability of anthocyanins to act as acid-base indicators.

The sequence of nitrogenous bases in DNA determines hereditary characteristics. Calculate the mole percentages of cytosine, guanine and thymine in a double-helical DNA structure if it contains 17% adenine by mole.

**Sample Student Answer**

Each adenine in DNA pairs with a thymine, so mole percentage of adenine is the same as thymine (17%).

Together adenine and thymine make up $17 + 17 = 34$ mole % of DNA.

Cytosine and guanine make up the rest: $100 - 34 = 66$ mole %.

Each cytosine pairs up with a guanine, so their percentages are the same: $66 / 2 = 33$% each.

You should know:

- other bases
- percentage of only one nitrogenous base in the DNA to calculate the mole percentages of the three other bases

**Practice problems for Topic B.8**

**Problem 1**

DNA is a biological macromolecule.

**Problem 2**

Hereditary information is stored in DNA and transferred by RNA.

**Example B.9.1.**

Hemoglobin is a metalloprotein that carries oxygen from lungs to tissues.

- At low $p(O_2)$, hemoglobin is deoxygenated and its affinity for oxygen is low, so the curve rises slowly. When an $O_2$ molecule binds to iron(II) in any hemoglobin subunit, the conformation of that subunit changes. This affects the conformations of all other subunits and their binding sites, increasing their affinities for oxygen so that the saturation curve rises steeply at medium $p(O_2)$. At high $p(O_2)$, the hemoglobin is nearly saturated, so the curve flattens out again.

- The oxygen saturation of hemoglobin decreases when temperature increases or pH decreases due to unfavourable changes in the conformation of binding sites. It also decreases in the presence of carbon dioxide and organic phosphates, which act as non-competitive inhibitors (topic B.7).

- Fetal hemoglobin has a different amino acid sequence and is less sensitive to inhibitors than adult hemoglobin. Therefore, it can work at low $p(O_2)$ and receive oxygen from partly deoxygenated blood.

Carbon monoxide (CO) is highly toxic because it is a competitive inhibitor of oxygen binding in hemoglobin. It replaces one oxygen molecule in hemoglobin by binding to the iron(II) ion and prevents the release of other oxygen molecules to tissues, causing hypoxia.

Chlorophyll is similar to heme but contains a magnesium ion instead of iron(II) ion. Together with carotenoids (long-chain polyunsaturated hydrocarbons), chlorophyll initiates the process of photosynthesis (topic B.1 and table B.9.1). Almost all plant pigments are sensitive to photo-oxidation.

**Assessment tip**

In answers, it is essential to state that electron conjugation in coloured pigments is extensive or involves many electrons/atoms/bonds. Similarly, it is important to state that pigments absorb visible light (not just "light") and transmit/ have the complementary colour (which is opposite the absorbed colour in the colour wheel).

Sample
Table B.9.1. Plant pigments

<table>
<thead>
<tr>
<th>Pigment</th>
<th>Metal ion</th>
<th>Colour</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>chlorophyll</td>
<td>Mg^{2+}</td>
<td>green</td>
<td>absorbs light energy in photosynthesizing cells</td>
</tr>
<tr>
<td>carotenoids</td>
<td>none</td>
<td>orange</td>
<td>extend the absorption spectrum of chlorophyll</td>
</tr>
<tr>
<td>anthocyanins</td>
<td>none</td>
<td>various</td>
<td>natural antioxidants, UV-protectors and colourants in plants</td>
</tr>
</tbody>
</table>

Carotenoids have no polar groups in their molecules (section 35 of the data booklet) and thus are insoluble in water but soluble in lipids. In contrast, anthocyanins are soluble in water because they have many polar groups that can form hydrogen bonds with the solvent.

In aqueous solutions, anthocyanins act as weak acids and/or bases that gain protons at low pH and lose protons at high pH. These processes affect the extent of electron conjugation in anthocyanins and thus change the wavelength of light they absorb. Therefore, anthocyanins (for example, from red cabbage juice) can be used as acid–base indicators.

Problem 1
A hemoglobin–oxygen saturation curve does not follow the same model as enzyme–substrate reactions (see figure B.9.1).

a) Explain the shape of the curve from 0 to X kPa.
b) Sketch a curve on the axes in figure B.9.1 to show the effect of decreasing pH on the oxygen saturation of hemoglobin.
c) Explain why carbon monoxide is toxic to humans.

d) Deduce the colour of a quinoidal base that strongly absorbs visible light in the range 600–640 nm (see section 3 of the data booklet).

Problem 2
Anthocyanins are pigments that give colour to many flowers and fruits. The general structures of two forms of anthocyanins, quinoidal base and flavylium cation, are given in section 35 of the data booklet.

a) State, with a reason, which of the two forms will exist in an aqueous solution at low pH.
b) Explain, with a reference to specific functional groups, why anthocyanins are soluble in water.
c) Outline why quinoidal base and flavylium cation absorb light of different wavelengths.
d) Deduce the colour of a quinoidal base that strongly absorbs visible light in the range 600–640 nm (see section 3 of the data booklet).

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Vision chemistry involves the light-activated interconversion of cis- and trans-isomers of retinal, a form of vitamin A (topic B.5). In photoreceptor cells, retinal forms a complex with the protein opsin, producing a light-sensitive pigment, rhodopsin. Opsin extends the system of electron conjugation in retinal and allows it to absorb photons across the whole spectrum of visible light.

**SAMPLE STUDENT ANSWER**

*Assessment tip*  
No mark, as the absorption of a photon is not mentioned, and the name of the complex (rhodopsin) is erroneously used instead of the protein name (opsin).

▲ Correct point: the words “an electrical signal” instead of “a nerve impulse” would also be acceptable.

▼ Naturally” is not accepted, as this conversion requires enzymes.

▲ Example of a correct answer.

**Problem 1**
Serine is a chiral amino acid.

a) Draw both enantiomers of serine.

b) State the enantiomeric form of serine found in proteins.

**Problem 2**
The structures of biologically important carbohydrates are given in section 34 of the data booklet.

a) Draw the Haworth structures of α-deoxyribose and β-fructose.

b) Identify, by marking with asterisk (*) symbols, all chiral carbon atoms in the structures from part (a).

**Problem 3**
Retinal reacts with opsin to produce rhodopsin. Refer to section 35 of the data booklet for one structure of retinal.

a) Identify the structural feature that enables rhodopsin to absorb visible light.

b) Outline the change that occurs in the retinal residue during the absorption of visible light.

c) Rhodopsin is commonly called “visual purple” while pure retinal is a bright-yellow solid. Suggest why the colours of these two biological pigments are different.