Chapter 2: Biological molecules

General learning outcomes:

- **Describe** how large biological molecules are made from smaller molecules
- **Describe** the structure and function of carbohydrates, lipids and proteins

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- The study of biological molecules forms an important branch of biology known as **molecular biology**
  - Molecular biology is closely linked with **biochemistry**, which looks at the chemical reactions of biological molecules
  - The sum total of all the biochemical reactions in the body is known as **metabolism**
  - The structure of molecules are closely related to their functions

The building blocks of life

- 4 most common elements in living organisms are, in order of abundance, hydrogen, carbon, oxygen and nitrogen
  - They account for more than 99% of the atoms found in all living things
  - Carbon atoms can join together to form long chains or ring structures
    - Can be thought of as the basic skeletons of *organic molecules* to which groups of other atoms are attached
      - *Organic molecules* <u>always</u> contain carbon and hydrogen
- *See Figure 2.2 page 29

Monomers, polymers and macromolecules

- **Macromolecule** means giant molecule
  - 3 types of macromolecules in living organisms: polysaccharides, proteins (polypeptides) and nucleic acids (polynucleotides)
    - 'poly' means many; the above molecules are **polymers**, meaning that they are made of many repeating subunits that are similar or identical to each other
      - The subunits are referred to as **monomers**
        - They're joined together like beads on a string
      - Making polymers is relatively simple because the same reaction is repeated many times
      - Natural examples of polymers are cellulose and rubber
      - Industrially produced polymers include: polyester, polythene, PVC and nylon
        - These are all made up of carbon-based monomers and contain thousands of carbon atoms joined end to end

Carbohydrates

- All carbohydrates contain the elements carbon, hydrogen and oxygen.
- 'hydrate' refers to water
  - Hydrogen and oxygen atoms are present in the ratio of 2:1 in carbohydrates, as they are in water
- The **general formula** for a carbohydrate: $C_x(H_2O)_y$.
- Three main groups of carbohydrates: monosaccharides, disaccharides and polysaccharides
  - 'saccharide" refers to a sugar or sweet substance

Monosaccharides

- Monosaccharides are **sugars**
  - Sugars dissolve easily in water to form sweet-tasting solutions
  - General formula: $(CH_2O)_n$

- Consist of a **single** sugar molecule; 'mono' means one
  - Main types of monosaccharides classified according to the number of carbon atoms in each molecule:
    - **Trioses** (3C)
    - **Pentoses** (5C)
      - Common examples: ribose and deoxyribose
    - **Hexoses** (6C)
      - Common examples: glucose, fructose and galactose
  - Names of all sugars end with **-ose**
- Molecular and structural formula
  - Formula (aka **molecular formula**) for a hexose: $C_6H_{12}O_6$
  - **Structural formula** shows the arrangements of the atoms in a molecule
  - *See Figure 2.3 page 30

Question: The formula for a hexose is $C_6H_{12}O_6$, or $(CH_2O)_6$. What would be the formula of:

a. a triose?
b. a pentose?

- Ring structures
  - Pentoses and hexoses have long enough chains of carbon atoms that they can close up on themselves and form more stable ring structures
  - Figure 2.4 page 30
    - Two forms of the same chemical are known as **isomers**
- Roles of monosaccharides in living organisms
  - 2 Major functions:
    - Commonly used as a source of energy in respiration due to the larger number of carbon-hydrogen bonds
      - C-H bonds are broken to release energy which is transferred to help make ATP (adenosine triphosphate) from ADP (adenosine diphosphate) and phosphate
      - Most important in energy metabolism is <u>glucose</u>
    - Important as building blocks for larger molecules
      - Example: glucose is used to make the polysaccharides starch, glycogen and cellulose
      - Example: ribose (5C) is one of the molecules used to make RNA (ribonucleic acid) and ATP
      - Example: Deoxyribose (5C) is one of the molecules used to make DNA

Disaccharides

- Disaccharides are sugars
- Three most common disaccharides
  - Maltose (glucose + glucose)
  - Sucrose (glucose + fructose)
    - Transport sugar in plants and commonly bought in stores
  - Lactose (glucose + galactose)
    - Sugar found in milk and important in young mammals diets
- Formed when two monosaccharides are joined together
  - process name is **condensation**
  - *See Figure 2.5
    - For each condensation reaction, two hydroxyl (-OH) groups line up alongside each other

        - One combines with a hydrogen atom from the other to form a water molecule
        - An oxygen 'bridge' forms between the two molecules, holding them together and forming a disaccharide
            - 'di' means two
            - The 'bridge' is called a **glycosidic bond**
    - since monosaccharides have many -OH groups, there are a large number of possible disaccharides
    - the shape of the enzyme controlling the reaction determines which -OH groups come alongside each other
        - Few of the possible disaccharides are common in nature
- The reverse of condensation is the *addition* of water, which is known as **hydrolysis**
    - Occurs during the digestion of disaccharides and polysaccharides when they are broken down to monosaccharides

Testing for the presence of sugars

- Reducing sugars include all monosaccharides (glucose) and some disaccharides (maltose)
    - Named because they can carry out the chemical reaction, **reduction**
        - In the process, reducing sugars are **oxidized**
    - Benedict's test using Benedict's reagent
        - Benedict's reagent is copper (II) sulfate in an alkaline solution (blue color)
        - Reducing sugars reduce soluble blue copper sulfate, containing copper (II) ions, to insoluble brick-red copper oxide (seen as a precipitate), containing copper (I).
        - reducing sugar + Cu^{2+} (blue) → oxidised sugar + Cu^{+} (red-brown)
    - Procedure
        - Add Benedict's reagent to the solution you are testing and heat in a water bath
        - If reducing sugars are present, solution color will change from green to yellow to orange to red-brown
            - color intensity is related to concentration of the reducing sugar
            - You can estimate the concentration by using color standards
- Non-reducing sugars - sucrose
    - Non-reducing sugars give a negative (blue) result for the Benedict's test
    - Non-reducing sugars test
        - Disaccharides are broken down by hydrolysis into two monosaccharides by heating the sugar solution with Hydrochloric acid (HCl)
            - The monosaccharides will be reducing sugars
        - Neutralize the solution by adding sodium hydroxide (NaOH)
        - Add Benedict's reagent and heat in a water bath
            - If the solution goes red but it didn't in the first part of the test, there is a non-reducing sugar present
            - If there is **still** no color change, no sugar of any kind is present

Questions

A. Why do you need to use **excess** Benedict's reagent if you want to get an idea of the concentration of a sugar solution?
B. Outline how you could use the Benedict's test to estimate the concentration of a solution of a reducing sugar.

Polysaccharides

- Polysaccharides are polymers whose subunits (monomers) are monosaccharides
  - Bonded together by glycosidic bonds due to condensation reactions
  - May be several thousand monosaccharides long
  - Most important polysaccharides: starch, glycogen, and cellulose
    - all are polymers of glucose
  - Polysaccharides are **not** sugars
- Glucose
  - is the main source of energy for cells
  - Too much glucose in cells would affect the osmotic properties of the cell
  - is very reactive and can interfere with normal cell chemistry
  - Glucose is converted to a polysaccharide (glycogen) by condensation reactions for storage
    - it’s convenient, inert (unreactive), and insoluble
    - Storage polysaccharide in plants - starch, humans - glycogen
- Starch
  - is a mixture of **amylose** and **amylopectin**
    - Amylose is made by condensations between α-glucose molecules
    - Creates a long, unbranching chain of several thousand 1,4 linked glucose molecules
      - ‘1,4 linked’ means they are linked between carbon atoms **1** and **4** of successive glucose units
      - Chains are curved and coil into helical structures making it more compact
    - Amylopectin is also made of many 1,4 linked α-glucose molecules
      - chains are shorter than in amylose and branch to the sides
        - branches are formed by 1,6 linkages
  - Commonly found in chloroplasts and storage organs (potato tubers and seeds of cereals and legumes)
  - Never found in animal cells
- Glycogen
  - made of chains of 1,4 linked α-glucose with 1,6 linkages forming branches
  - tend to be more branched than amylopectin molecules
  - molecules clump together to form granules
    - visible in liver cells and muscle cells where they form an energy reserve

Question:

List **five** ways in which the molecular structures of glycogen and amylopectin are similar

- Cellulose
  - Most abundant organic molecule on the planet
  - located in plant cell walls for structural support
  - breaks down very slowly in nature
  - is a polymer of β-glucose, not α-glucose
  - To form a glycosidic bond with carbon atom 4, -OH group is **below** the ring, one glucose molecule must be upside down (rotated 180^{o}) relative to the other
    - Creates a strong molecule because the hydrogen atoms of -OH groups are weakly attracted to oxygen atoms in the same cellulose molecule (the oxygen of the glucose ring) and also to oxygen atoms of -OH groups in neighboring molecules
      - These are **hydrogen bonds** and they are weak
      - Form because of the large number of -OH groups
        - collectively provide significant strength

- Between 60-70 cellulose molecules become tightly cross-linked to form bundles called **microfibrils**
  - held together in bundles called **fibers** by hydrogen bonding
- Cell walls have several layers of fibers running in different directions to increase strength
- makes up 20-40% of the average cell wall
- Cellulose fibers have high tensile strength, almost equal to that of steel
  - allows cells to withstand large pressures as a result of osmosis
  - Cells would burst without the wall in dilute solution
  - Pressures provide support for the plant and are responsible for cell expansion during growth
  - arrangement of fibers determine shape of the cell as it grows
  - cellulose fibers are freely permeable
    - allow water and solutes to reach or leave the cell surface membrane

Question:

Make a table to show **three** ways in which the molecular structures of amylose and cellulose differ.

Dipoles and hydrogen bonds

- **Covalent bonds** are when atoms in molecules are held together and a pair of electrons are shared with each other
  - Example: water - two hydrogen atoms each share a pair of electrons with an oxygen atom
    - in water, electrons are not shared absolutely equally
      - the oxygen atom gets slightly more than the hydrogen atoms and therefore has a small negative charge, written as δ- (delta minus)
      - The hydrogen atoms get slightly less than their fair share and therefore have a small positive charge, written δ+ (delta plus)
      - This unequal distribution of charge is called a **dipole**
      - the negatively charged oxygen of one molecule is attracted to a positively charged hydrogen of another
        - this attraction is called a **hydrogen bond**
          - weaker than a covalent bond, but still has a very significant effect
- Dipoles occur in many different molecules, particularly wherever there is an -OH. -CO, or -NH group
  - Hydrogen bonds can form **between** these groups because the negatively charged part of one group is attracted to the positively charged part of another
    - these bonds are important in the structure and properties of carbohydrates and proteins
- Molecules that have groups with dipoles, such as sugars, are said to be **polar**
  - attracted to water molecules, because water molecules also have dipoles
  - such molecules are said to be **hydrophilic** (water loving) and tend to be soluble in water
- Molecules that do not have dipoles are said to be **non-polar**
  - they are not attracted to water and are **hydrophobic** (water hating)
- Polar and nonpolar molecules play an important role in the formation of cell membranes

Lipids

- are all organic molecules which are insoluble in water
- fats are solid at room temp; oils are liquid at room temp
  - chemically, they are very similar
- true lipids are esters formed by fatty acids combining with an alcohol

Fatty acids

- are a series of acids, some of which are found in fats (lipids)
- contain an acidic group -COOH aka a carboxyl group
- larger molecules have long hydrocarbon tails attached to the acid 'head' of the molecule
  - hydrocarbon tail consists of a chain of carbon atoms combined with hydrogen
  - often 15-17 carbon atoms long
- tails of some fatty acids have double bonds between neighboring carbon atoms
  - -C=C-
  - described as **unsaturated**
    - molecule doesn't contain the maximum amount of hydrogen possible
    - form **unsaturated lipids**
  - double bonds make fatty acids and lipids melt more easily
    - most oils are unsaturated
  - more than one double bond is described as **polyunsaturated**
  - one double bond is **monounsaturated**
- animal lipids are often **saturated** (no double bonds)
  - occur as fats
- plant lipids are often unsaturated
  - occur as oils (olive oil and sunflower oil)

Alcohols and esters

- alcohols are a series of organic molecules which contain a hydroxyl group, -OH, attached to a carbon atom
- glycerol is an alcohol with 3 hydroxyl groups
- acid + alcohol → **ester**
  - chemical link between acid and alcohol when the chemicals react is known as an **ester bond** or an ester linkage
  - -COOH group on the acid reacts with the -OH group on the alcohol forming the ester bond, -COO-
    - condensation reaction (water is formed as a product)
    - can be reverted back into an acid and alcohol via hydrolysis (adding water)

Triglycerides

- most common lipid is **triglycerides**
  - fats and oils
- glyceride is an ester formed by a fatty acid combining with the alcohol glycerol
  - glycerol has 3 hydroxyl (-OH) groups
    - undergo condensation reactions with a fatty acid
  - when a triglyceride is made, the final molecule contains 3 fatty acids tails and 3 ester bonds ('tri' means 3)
    - tails can vary in length depending on the fatty acids used
- insoluble in water
- soluble in certain organic solvents
  - chloroform and ethanol
  - because of the non-polar nature of the hydrocarbon tails
    - no uneven distribution of electrical charge
- don't mix with water; hydrophobic (water hating)

Roles of triglycerides

- excellent **energy reserves**
  - rich in carbon-hydrogen bonds (more so than carbohydrates)

- Fat storage in humans is below the dermis of the skin and around the kidneys
  - acts as an **insulator** against loss of heat
  - blubber (found in sea mammals) is a lipid with similar functions as well as providing buoyancy
- **metabolic source of water**
  - when oxidized in respiration, triglycerides are converted to carbon dioxide and water
    - water may be of importance in very dry habitats
      - example: desert kangaroo rat only survives on metabolic water from its fat intake

Phospholipids

- one end of the molecule is soluble in water
  - one of the 3 fatty acids is replaced by a phosphate group which is polar
    - can dissolve in water
    - phosphate group is **hydrophilic** (water loving)
      - makes the head of the phospholipid molecule hydrophilic
      - remaining fatty acid tails are still hydrophobic
- the above allows molecules to form a membrane around a cell
  - hydrophilic heads lie in the watery solution on the outside of the membrane
  - hydrophobic tails form a layer that is impermeable to hydrophilic substances

Testing for the presence of lipids

- lipids are not soluble in water, but soluble in ethanol
  - can be determined with the **emulsion test** for lipids
    - Procedure
      - substance thought to contain lipids is shaken vigorously with ethanol
        - allows lipids to dissolve in the ethanol
      - ethanol is then poured into a tube containing water
        - if lipid is present, a cloudy white suspension is formed
- if no lipid is present, ethanol mixes with water
  - light can pass through the mixture; looks completely transparent
- if lipid is dissolved in ethanol, it cannot remain dissolved when mixed with water
  - lipid molecules form tiny droplets throughout the liquid
    - this is called an **emulsion**
    - droplets reflect and scatter light; liquid looks white and cloudy

Proteins

- More than 50% of the dry mass of most cells is protein
- Important functions:
    - all enzymes are proteins
    - essential components of cell membranes - functions include receptor proteins and signalling proteins
    - some hormones are proteins; ex: insulin and glucagon
    - oxygen-carrying pigments hemoglobin and myoglobin are proteins
    - antibodies, which attack and destroy invading microorganisms, are proteins
    - collagen, another protein, adds strength to many animal tissues, such as bone and the walls of arteries
    - hair, nails and the surface layers of skin contain the protein keratin
    - actin and myosin are the proteins responsible for muscle contraction
    - proteins may be storage products; ex: casein in milk and ovalbumin in egg white
- are made from **amino acids** (monomers that make up proteins)

Amino Acids

- all have a central carbon atom which is bonded to an **amine** group, $-NH_2$, and a **carboxylic acid** group, -COOH
    - third component always bonded to the carbon atom is a hydrogen atom
- Amino acids differ from one another because of the fourth group of atoms bonded to the central carbon atom
    - this is called the **R group**
- 20 different amino acids
    - all have different R groups

Peptide Bond

- One amino acid will lose a hydroxyl (-OH) group from its carboxylic acid (-COOH) group
- The other amino acid will lose a hydrogen atom from its amine ($-NH_2$) group
    - carbon from the first amino acid bonds with the nitrogen from the second amino acid
        - this is called a **peptide bond**
        - formed by a condensation reaction (loss of water)
        - new molecule is called a **dipeptide** (2 amino acids bonded together)
        - many more amino acids can be added to the chain by condensation reactions
            - this would create a **polypeptide** (many amino acids linked together)
                - polypeptides are examples of a polymer and a macromolecule
                    - can be broken down into amino acids by breaking the peptide bonds
                        - hydrolysis reaction (adding water)
                        - happens naturally in the stomach and small intestine during digestion
- complete **protein** molecules may contain 1 polypeptide chain, or it may have 2 or more chains which interact with each other

Primary Structure

- is the particular amino acids contained in the chain in the sequence that they are joined
    - there are an enormous number of different **possible** primary structures
    - if even one amino acid is changed in the sequence of a thousand, that can completely alter the properties of the polypeptide or protein

Secondary Structure

- polypeptide chains, or part of them, often coil into a corkscrew shape called an **α-helix**
    - this is the **secondary structure**
        - due to hydrogen bonding between the oxygen of the -CO- group of one amino acid and the hydrogen of the -NH- group of the amino acid 4 places ahead of it
        - each amino acid has an -NH- and -CO- group which is involved in hydrogen bonding in the α-helix
            - holds the structure firmly in place
            - hydrogen bonding is a result of the polar characteristics of the -CO- and -NH- groups
            - sometimes hydrogen bonding results in looser, straighter shapes than the α-helix, which is called a **β-pleated sheet**
            - hydrogen bonds, while strong enough to hold both shapes of the α-helix and β-pleated sheet, are easily broken by high temperatures and pH changes
- some proteins/parts of proteins show no regular arrangement at all
    - depends on which R groups are present and what attractions occur between amino acids in the chain

- In diagrams of protein structure:
    - α-helices can be represented as coils or cylinders
    - β-sheets are represented as arrows
    - random coils as ribbons