1.5.1 DNA and RNA

Recap

We learnt about enzymes and their function within the body, and how many factors alter the rate of enzyme controlled reactions. You now understand the effects of concentration on competitive and non-competitive inhibition, and how the induced fit model is an improvement of the lock and key model.

Key Aims

1. *Structure and Function of DNA and RNA*
2. *Structure and Function of Ribosomes*
3. *Structure of Nucleotides and Nitrogenous Bases*

AQA Specification

Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are important information-carrying molecules. In all living cells, DNA holds genetic information and RNA transfers genetic information from DNA to the ribosomes.

Function of DNA and RNA

DNA and RNA are both types of **nucleic acids**:

- **DNA is responsible for storing genetic information**. DNA is the key store of genetic information, which means all the instructions necessary for an organism to grow and to carry out necessary functions day to day.

- **RNA is responsible for passing genetic information from DNA to ribosomes**. RNA is structurally similar to DNA. The main function of RNA is to transfer genetic information to **ribosomes**, which is done by messenger RNA (**mRNA**).

Structure and Function of Ribosomes

- **Ribosomes "read" information carried by mRNA to make proteins**. These proteins are then used to carry out a variety of cellular functions to drive the growth and function of an organism. Ribosomes are a type of organelle.

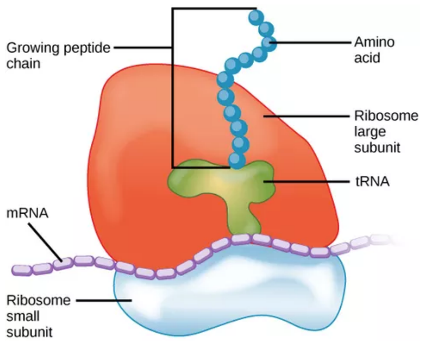

Fig 1. Protein Synthesis: Translation. Diagram showing the involvement of a ribosome molecule in protein synthesis. Ribosomes "reads"/"translate" the mRNA amino acid codes to create a growing polypeptide chain.

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Ribosomes are formed from RNA and proteins.

- **Ribosomes are made up of ribosomal RNA.** In addition to messenger RNA, there are almost 30 other types of RNA. Ribosomes are one example of the other types of RNA. They are made up of ribosomal RNA (**rRNA**).

- **Ribosomes are also made up of proteins**. These proteins help ribosomes carry out their job of making new proteins.

Structure of Nucleotides

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Both DNA and RNA are polymers of nucleotides. Each nucleotide is formed from a pentose, a nitrogen-containing organic base and a phosphate group.

- **DNA and RNA are polymers made up of nucleotides**. DNA and RNA contain many monomers called nucleotides, which make up the overall polymer. This is why we classify DNA and RNA as **nucleic acids** - because they are made up of nucleotides.

- **Every nucleotide is made up of 3 components**.
  - A pentose sugar
  - A nitrogen containing organic base
  - A phosphate group.

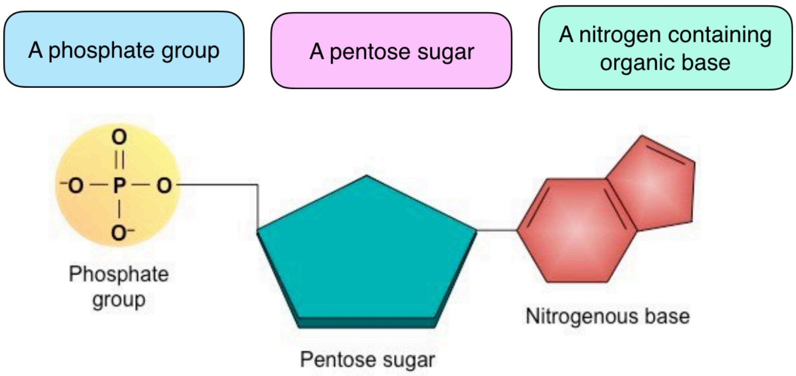

Fig 2. Components of Nucleotides. There are five different bases (A, C, G, T, U)

Nitrogenous Bases

- **Nitrogenous bases are organic, nitrogen containing chemical groups**. There are two major classes of nitrogenous bases:

  - **Purines** - include adenine (**A**) and guanine (**G**)

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The components of a DNA nucleotide are deoxyribose, a phosphate group and one of the organic bases adenine, cytosine, guanine or thymine. The components of an RNA nucleotide are ribose, a phosphate group and one of the organic bases adenine, cytosine, guanine or uracil.

- **Pyrimidines** - include thymine (**T**), cytosine (**C**) and uracil (**U**)

It is important to understand the differences between DNA and RNA nucleotides. Carefully analyse both the table and diagrams.

Key differences:
1) RNA has a ribose sugar instead of a deoxyribose.
2) RNA has the base uracil instead of thymine.

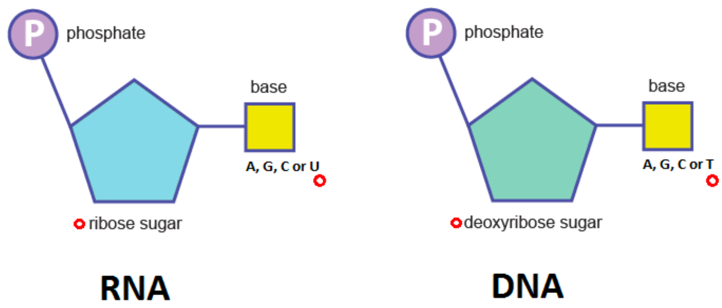

Fig 3. Structure of DNA and RNA Nucleotides.

	DNA	RNA
Sugar	Deoxyribose sugar	Ribose sugar
Nitrogen Bases	A, T, C, G	A, C, G, U

Table 1. Differences Between DNA and RNA.

Study Mind Tip

Make sure that you remember DNA has thymine, while RNA has uracil. This is a very common mistake many students make, and one that you should absolutely avoid.

Remember back to when we first learnt about polymers in 1.1.

Polynucleotide Structure

- **Nucleotides are bonded to each other through condensation reactions**. Multiple nucleotides bonded together form polynucleotides. Water is released as a by-product.

- **Phosphodiester bonds form between nucleotides**. A phosphodiester bond forms between the phosphate group of one nucleotide and the

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A condensation reaction between two nucleotides forms a phosphodiester bond.

pentose sugar of a second nucleotide. **Phosphodiester bonds** are **covalent** bonds.

- **Phosphodiester bonds create a chain of nucleotides called a polynucleotide chain**. These polynucleotide chains also have a **sugar-phosphate backbone** because of the pentose sugars and the phosphate groups which make up the majority of a nucleotide's structure.

- **Phosphodiester bonds can be broken through hydrolysis reactions**. Just like the polymers we studied in 1.1.

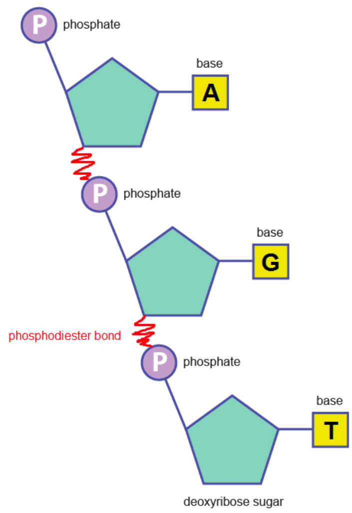

Fig 4. Phosphodiester Bonds. Phosphodiester bonds (in red) form between the pentose sugar of one nucleotide and the phosphate of another nucleotide.

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A DNA molecule is a double helix with two polynucleotide chains held together by hydrogen bonds between specific complementary base pairs.

Structure of DNA

- **DNA is made up of two complementary polynucleotide chains**. The chains run alongside each other and are **antiparallel**.

- **Hydrogen bonds hold the polynucleotide chains together**. The hydrogen bonds form between **complementary base pairs** on two nucleotides.

    - **Adenine** forms a complementary base pair with **thymine** through hydrogen bonding.

- **Guanine** forms a complementary base pair with **cytosine** through hydrogen bonding.

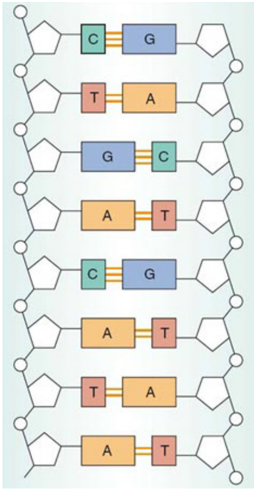

Fig 5. Hydrogen Bonding. A bonds with T, G bonds with C.

- **There are no other base pairing combinations in DNA**. The above rules are the only pairings that exist. Exceptions to this rule are mutations, which are abnormal and can have serious consequences for an organism.

- **A DNA double helix is formed**. The two antiparallel polynucleotide chains twist to form a helical shape called the "DNA double helix".

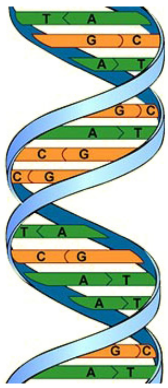

Fig 6. DNA Double Helix.

Structure of RNA

Knowledge Recall

1. What 3 components make up a nucleotide?
2. Is thymine a purine or pyrimidines?
3. What nitrogen bases are in RNA?
4. What nitrogen bases are in DNA?

Knowledge Recall

1. What does a phosphodiester bond form between?
2. What are the complementary base pairing in DNA?
3. What kind of bond forms between DNA nitrogen bases?
4. What is the name of the sugar component of an RNA nucleotide?

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An RNA molecule is a relatively short polynucleotide chain.

- Like DNA, RNA is also made up of a **polynucleotide chain**.

- RNA only has one polynucleotide chain and is single stranded molecule. Whereas DNA is a double stranded molecule.

Components of RNA

- RNA is made up of RNA specific nucleotides.
- RNA has a **ribose sugar** instead of deoxyribose.
- RNA has **uracil** as a nitrogenous base instead of thymine.

Bonding and Structure of RNA

- Like DNA, RNA nucleotides form a single polynucleotide chain held together by phosphodiester bonds.
- The RNA polynucleotide chain also twists and forms a single stranded **helix**.
- RNA is much shorter than DNA.

DNA stores all genetic information in an organism. This genetic information can be replicated and passed down to offspring through reproduction. The AQA specification requires you to know a little about the history of DNA structure, so br.iefly learn the diagram below (dates and names are not essential).

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Students should be able to appreciate that the relative simplicity of DNA led many scientists to doubt that it carried the genetic code.

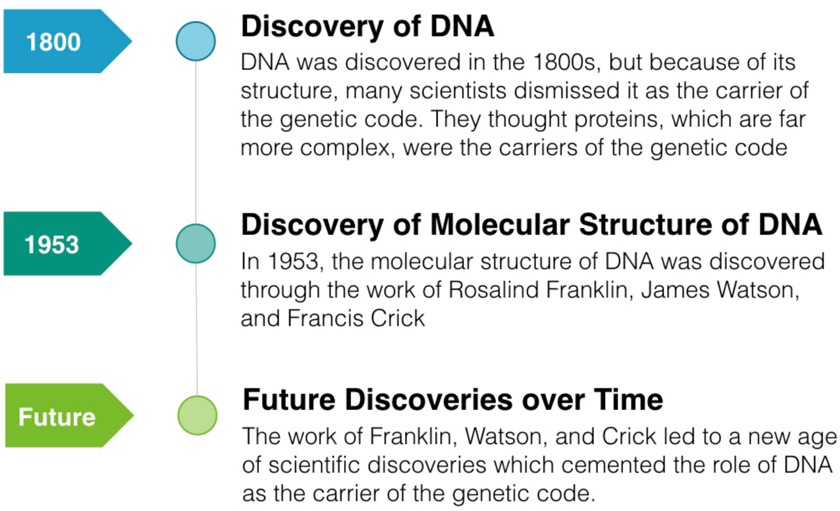

Fig 6. Timeline of DNA Research.

1.5.2 DNA Replication

AQA Specification

The semi-conservative replication of DNA ensures genetic continuity between generation of cells.

Why Does DNA Replicate?

Cell division occurs continuously. Most organisms produce new cells every day through a process called cell division.

DNA replication occurs before the cell divides. DNA replicates itself before cells divide so that each daughter cells has a copy of the DNA after division.

DNA replication mean that parents can pass their DNA to their offspring. This passing of DNA and the genetic information stored in DNA is known as "Genetic Continuity". The replication of DNA is crucial to ensuring genetic continuity both during cell division and between parents and offspring during reproduction.

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The process of semi-conservative replication of DNA in terms of:

1. *Unwinding of the double helix.*
2. *Breakage of hydrogen bonds between complementary bases in the polynucleotide strands.*
3. *The role of DNA helicase in unwinding DNA and breaking its hydrogen bonds.*
4. *Attraction of new DNA nucleotides to exposed bases on template strands and base pairing.*
5. *The role of DNA polymerase in the condensation reaction that joins adjacent nucleotides.*

The Process of DNA Replication

1) Double Helix Unwinding

- **The first step of DNA replication is unwinding of the DNA double helix**. Because DNA is a base-paired double helix, it replicates itself by unwinding and using each of its strands as a template to form a new strand.

- **Hydrogen bonds are broken during unwinding**. There is breakage of hydrogen bonds between complementary base pairs on the two polynucleotide chains.

- **An enzyme called DNA helicase is involved**. DNA helicase unwinds the DNA by breaking the hydrogen bonds between complementary base pairs on the two strands of DNA.

- **It is important to understand that the entire DNA does not unwind simultaneously**. DNA replication occurs along an entire molecule of DNA and the unwinding happens in one region of the molecule at a time. This is done to ensure stability of the molecule.

Knowledge Recall

1. Name a cellular process that DNA replication occurs before?
2. What is step one of DNA replication?
3. During DNA unwinding what bonds are broken?
4. Name the enzyme that breaks these bonds?

- **The unwound region of the DNA is called a "replication fork".**

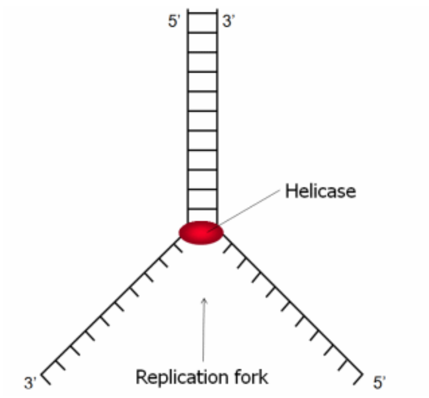

Fig 1. Replication Fork. DNA helicase unwinds the DNA double helix to form free single strands of DNA. This unwound region of the DNA molecule is referred to as the replication fork.

2) Semi-Conservative Replication

- **DNA replication is semiconservative**. The original strands of DNA act as a template for the synthesis of new strands of DNA. So each new DNA molecule is made up of one **parent strand** (see next point) from the original DNA molecule, and one new, daughter strand.

- **The unwound strands of DNA are referred to as the parental strands**. Free floating nucleotides in the nucleus are attracted to these parental strands of DNA.

Study Mind **Tip**

The AQA specification doesn't mention DNA ligase, and many textbooks will tell you that DNA polymerase both teases and catalyses condensation. Technically speaking, DNA ligase catalyses condensation. We recommend reading mark schemes when doing past papers to see how marks are given.

3) DNA Polymerase (Condensation Reactions)

- **Condensation reactions occur to complete DNA replication**. The newly attracted nucleotides are only hydrogen bonded with the parental strand. To create a new strand of DNA, condensation reactions between these nucleotides need to occur in order to synthesise the daughter polynucleotide chain in order to complete DNA replication.

- **DNA polymerase is the key enzyme.** These condensation reactions are catalysed by the enzyme **DNA polymerase**, which reads the nucleotides and enables them to join. DNA ligase is responsible for the actual condensation reaction.

Mechanism of DNA Polymerase

DNA Has Two Ends

- **A single strand of DNA has two different ends**. Due to the orientation of the deoxyribose sugar, there are two ends:
    - The starting point of a single DNA strand is known as the **5′ (five prime) end**.
    - The end point of a single DNA strand is known as the **3′ (three prime) end**.
- **In a DNA double helix, the two strands are antiparallel.** One strands goes from 5′ to 3′, and the opposite strand goes from 3′ to 5′.

Knowledge Recall

1. *What is step two of DNA replication?*
2. *What does semi-conservative replication mean?*
3. *What is step three of DNA replication?*
4. *What enzyme catalyses this step?*

DNA Polymerase Reads From 3' to 5'

- **DNA polymerase catalyses addition of free nucleotides**. DNA polymerase "reads" the parental strand, and catalyses the addition of the free-floating nucleotides.
- **DNA polymerase starts at the 3′ end**. During replication, the active site of DNA polymerase is only able to bind to the 3′ end of a newly forming strand of DNA. Therefore, daughter strands of DNA are in the 5′ to 3′ direction, and the parental template strand is read by DNA polymerase in a 3′ to 5′ direction.

Knowledge Recall

1. *What is the name given to the starting point of a single DNA strand?*
2. *In what direction does the enzyme DNA polymerase read the DNA nucleotide sequence?*
3. *DNA polymerase catalyses the addition of non-free nucleotides, true or false?*
4. *What role does DNA ligase play in DNA replication?*

DNA Polymerase Reads and DNA Ligase Catalyses

- **DNA polymerase reads the nucleotide sequence**. When DNA polymerase binds to the parental DNA it reads the nucleotide sequence and recruits complementary nucleotides to form a hydrogen bond with the parental nucleotide. In doing so, DNA polymerase carries out a "proofreading" activity. It makes sure that only complementary nucleotides are pairing in order to prevent mutations from happening.
- **DNA ligase catalyses condensation reactions**. As the DNA polymerase recruits new nucleotides, DNA ligase catalyses condensation reactions between the new nucleotides to create a polynucleotide chain.

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Students should be able to evaluate the work of scientists in validating the Watson-Crick model of DNA replication.

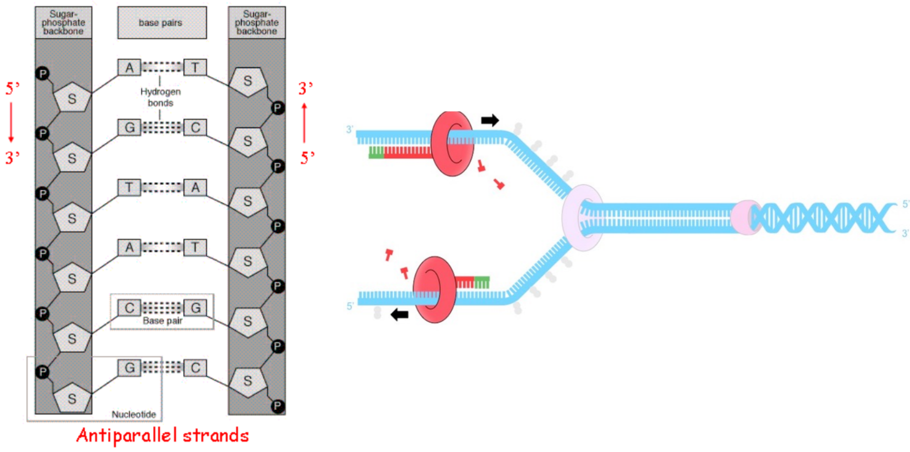

Fig 2. 5′ and 3′ ends of DNA and antiparallel structure of DNA.

Meselson and Stahl's Experiment

A few years after the discovery of the structure of DNA (by Watson-Crick), Meselson and Stahl carried out an experiment which demonstrated that DNA replication is a **semiconservative process**.

Their experiment is outlined below:

1. **A group of bacteria were cultured in light nitrogen**. They grew bacterial cells in a solution containing a **light** nitrogen isotope called **^{14}N**. The bacteria were grown in this environment for many generations. As the bacteria grew, their DNA rapidly incorporated the N14 into its structure.

2. **Another group of bacteria were cultured in heavy nitrogen**. A second group of bacterial cells were grown in a solution containing a **heavy** nitrogen isotope called **^{15}N**. As the bacteria grew, their DNA molecules incorporated N15.

3. **Light and heavy nitrogen bacteria DNA settles at different levels**. Samples of DNA from each group were isolated and spun down together in a centrifuge. The DNA from bacteria in heavy nitrogen settled lower in the tube than the DNA from bacteria in light nitrogen because it was heavier.

Knowledge Recall

1. What are the names of the scientists who carried out an experiment which demonstrated that DNA replication is semi-conservative?
2. What is the light nitrogen isotope used in the experiment called?
3. What is the heavy nitrogen isotope used in the experiment called?

Study Mind Tip

If you are finding Meselson-Stahl experiment difficult to grasp, then focus first on Step 1-6. Just understand that the DNA from a mixed sample of heavy and light nitrogen had an intermediate, middle band, telling us that there is one heavy and one light strand in the dNA double helix. If you can understand Step 7, then great. It is also useful to draw out a diagram of heavy and light strands as shown on the right of Figure 3.

4. **Heavy nitrogen bacteria were added to the light culture**. Next, the bacteria grown in heavy nitrogen were transferred to a solution containing light nitrogen and allowed to carry out one round of DNA replication.

5. **DNA settled at a mid point**. DNA was then removed from these bacteria and spun down in a centrifuge. They found that the new DNA from the bacteria settled in the centrifuge tube at a mid-point in between the heavy and light points.

6. **DNA replication is therefore semi-conservative**. This showed that the new DNA from this group of bacteria had both light and heavy nitrogen, which meant that DNA replication is a semiconservative process.

7. **Further tests were done**. As time passed, the concentration of heavy bacteria in the mixture fell (because we only added a little bit initially), so DNA double strains were produced with 2 light strands. Therefore the high, light band re-appeared, as shown in Figure 3.

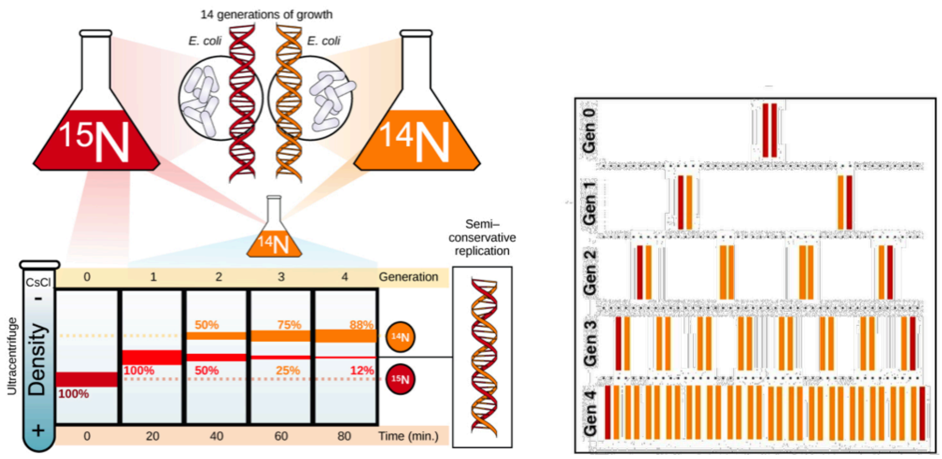

Fig 3. Meselson and Stahl's Experiment. Generation 0 included just the heavy N-15. Generation 1 included an equal mix of heavy and light. As the heavy nitrogen bacteria were used up, the proportion of light nitrogen bacteria increased from Generation 2 to 4.