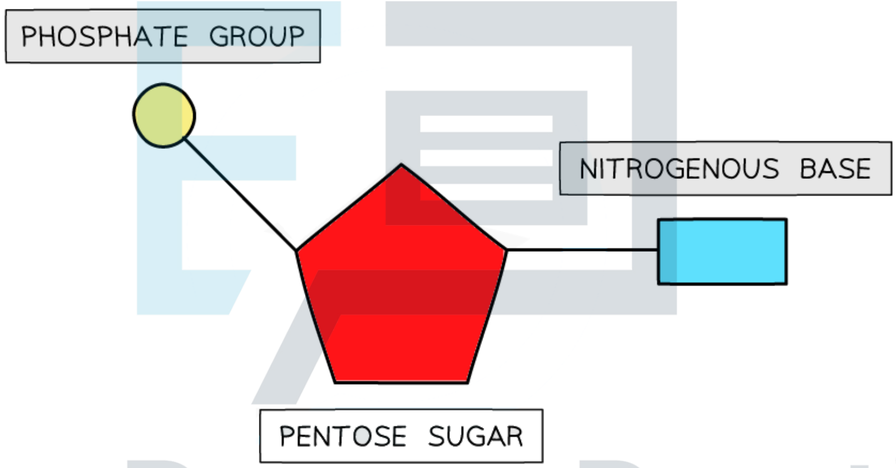
2.5 Nucleic Acids: Structure & DNA Replication

IB Biology - Revision Notes

2.5.1 DNA & RNA Structure

Nucleic Acids: Structure

- The nucleic acids DNA and RNA are polymers of nucleotides
- Both DNA and RNA are **polymers** that are made up of **many repeating units** called **nucleotides**
- Each nucleotide is formed from:
  - A **pentose sugar** (a sugar with 5 carbon atoms)
  - A nitrogen-containing **organic base** (with either 1 or 2 rings of atoms)
  - A **phosphate group** (this is acidic and negatively charged)
- The base and phosphate group are both **covalently bonded** to the sugar



The basic structure of a nucleotide

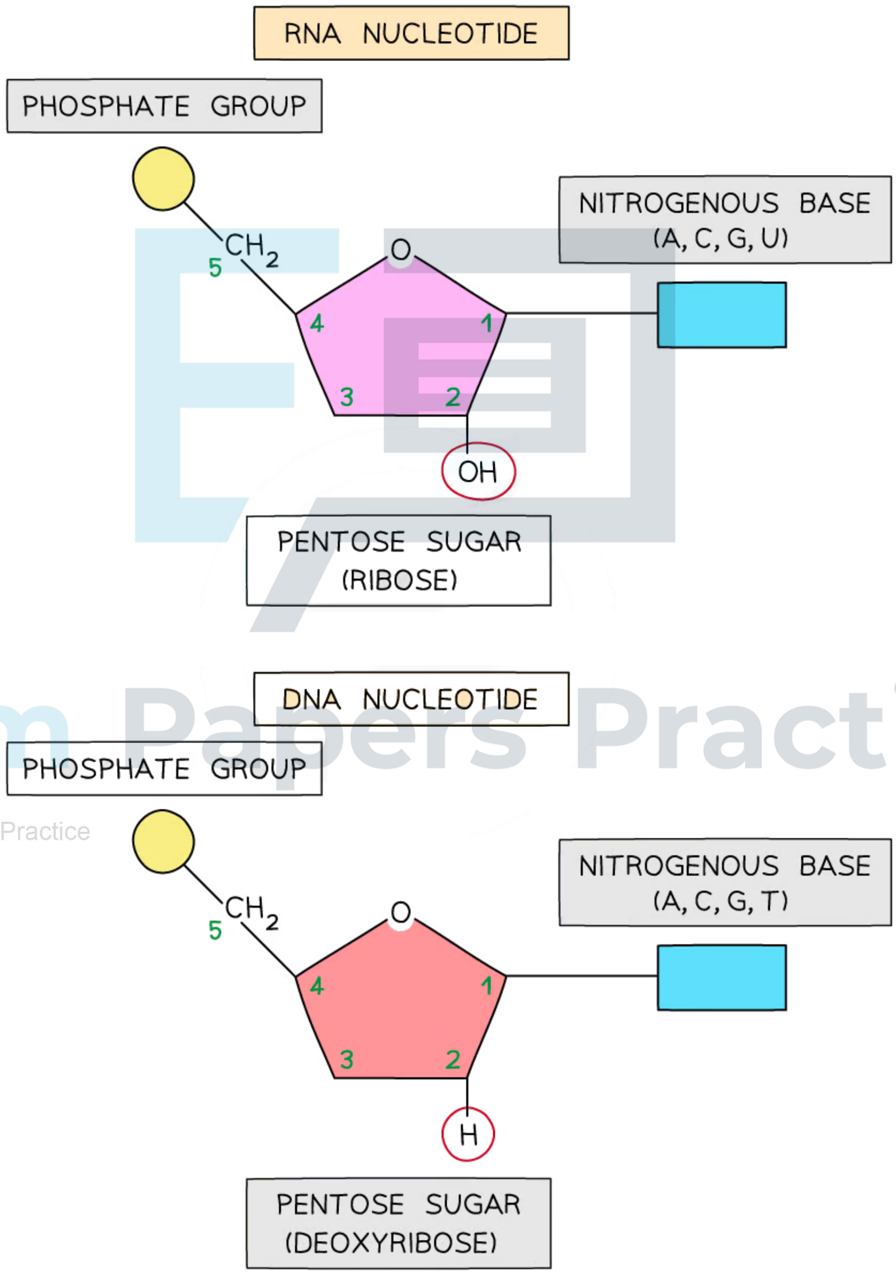
- Nucleotides join together in chains to form DNA or RNA strands
- The **phosphate group of one nucleotide** forms a covalent bond to the **pentose sugar of the next one**
  - This carries on to form a **large polymer**
- This forms a '**sugar-phosphate backbone**' with a base linked to each sugar
- The polymer of nucleotides is known as a **strand**
- DNA is double-stranded, RNA is usually single-stranded
- There are just **4 separate bases** that can be joined in **any combination/sequence**
  - Because the **sugar and phosphate are the same** in every nucleotide
- This sequence is the basis of the genetic code as a **store of genetic information**

Exam Tip

A common error is to describe DNA or RNA as polymers of bases; more correctly, they are **polymers of nucleotides**

DNA & RNA: Comparison

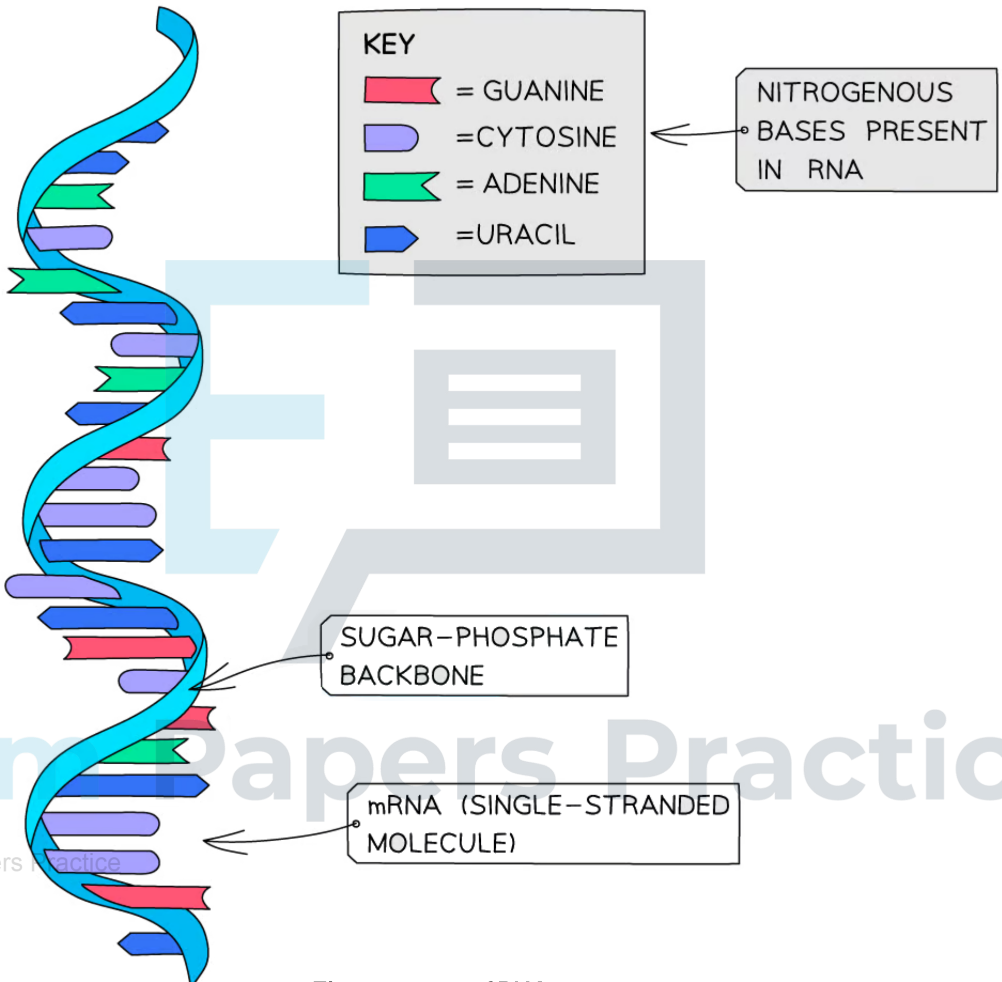
- **Like DNA**, the nucleic acid RNA (ribonucleic acid) is a **polynucleotide** – it is made up of **many nucleotides** linked together in a chain
- **Like DNA**, RNA nucleotides contain the nitrogenous bases adenine (A), guanine (G) and cytosine (C)
- **Unlike DNA**, RNA nucleotides **never contain** the nitrogenous base **thymine** (T) – in place of this they contain the nitrogenous base **uracil** (U)
- **Unlike DNA**, RNA nucleotides contain the pentose sugar **ribose** (instead of deoxyribose)



An RNA nucleotide compared with a DNA nucleotide

- **Unlike DNA**, RNA molecules are only made up of **one polynucleotide strand** (they are **single-stranded**)

- **Unlike DNA,** RNA polynucleotide chains are relatively **short compared to DNA**
- **Like DNA,** the **sugar-phosphate bonds** (between different nucleotides in the same strand) are strong **covalent bonds**
- **Like DNA,** the nitrogenous bases **stick out sideways** from the sugar-phosphate backbone



The structure of RNA

Nucleotide Structure Summary Table

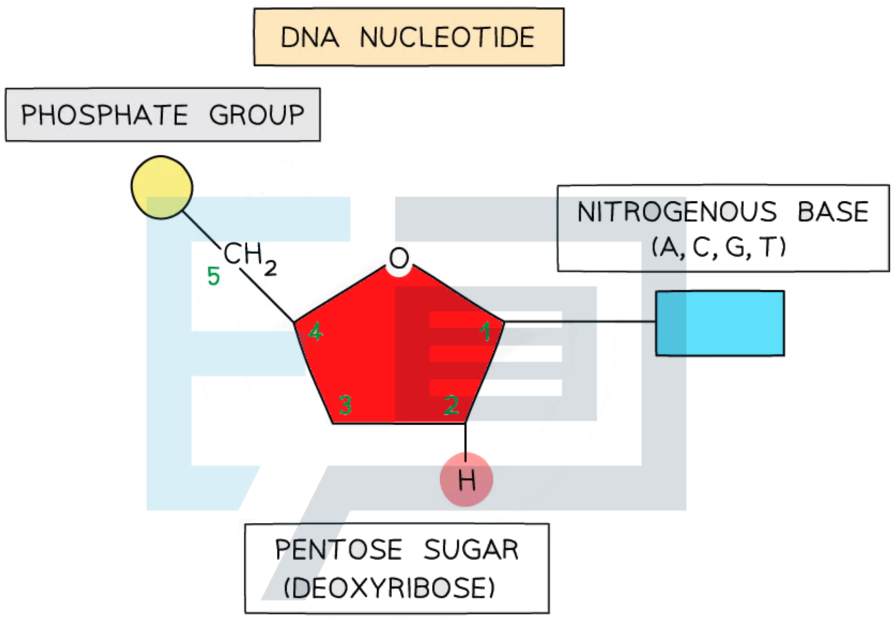
Properties	DNA	RNA
Pentose sugar	Deoxyribose	Ribose
Bases	Adenine (A) **Thymine (T)** Cytosine (C) Guanine (G)	Adenine (A) **Uracil (U)** Cytosine (C) Guanine (G)
Number of strands	Double–stranded (double helix)	single–stranded

Exam Tip

You need to know the difference between DNA and RNA molecules (base composition, number of strands, pentose sugar present).

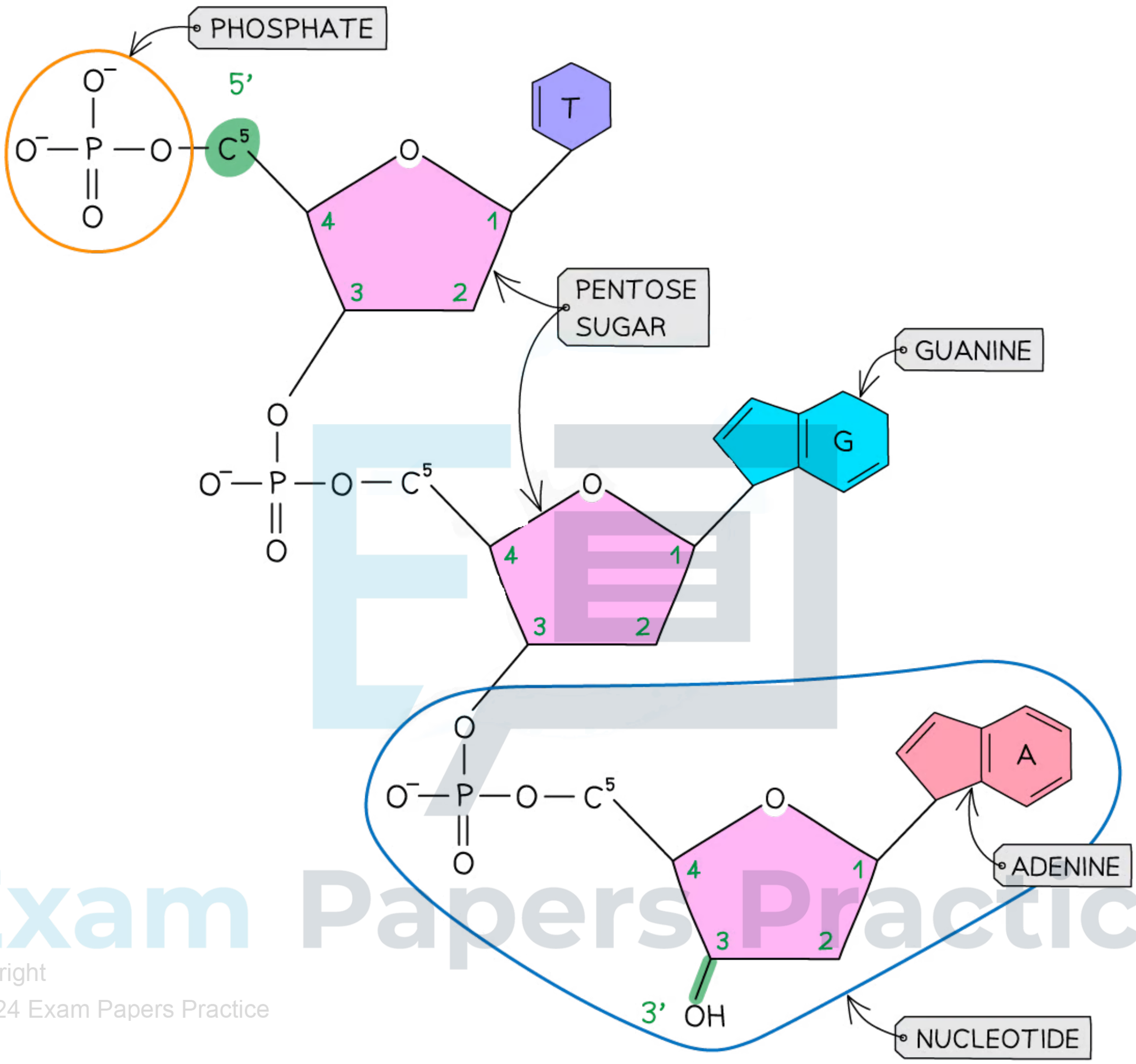
Double Helix Structure

- DNA is a double helix made of two antiparallel strands of nucleotides linked by hydrogen bonding between complementary base pairs
- The nucleic acid DNA is a **polynucleotide** – it is made up of **many nucleotides** bonded together in a **long chain**



A DNA nucleotide

- DNA molecules are made up of **two polynucleotide strands** lying side by side, running in opposite directions – the strands are said to be **antiparallel**
- Each DNA polynucleotide strand is made up of **alternating deoxyribose sugars and phosphate groups bonded together** to form the **sugar-phosphate backbone**
- Each DNA polynucleotide strand is said to have a **3' end and a 5' end** (these numbers relate to which carbon atom on the pentose sugar could be bonded with another nucleotide)
- Because the strands run in opposite directions (they are **antiparallel**), one is known as the **5' to 3' strand** and the other is known as the **3' to 5' strand**
- The nitrogenous bases of each nucleotide project out from the backbone **towards the interior** of the double-stranded DNA molecule

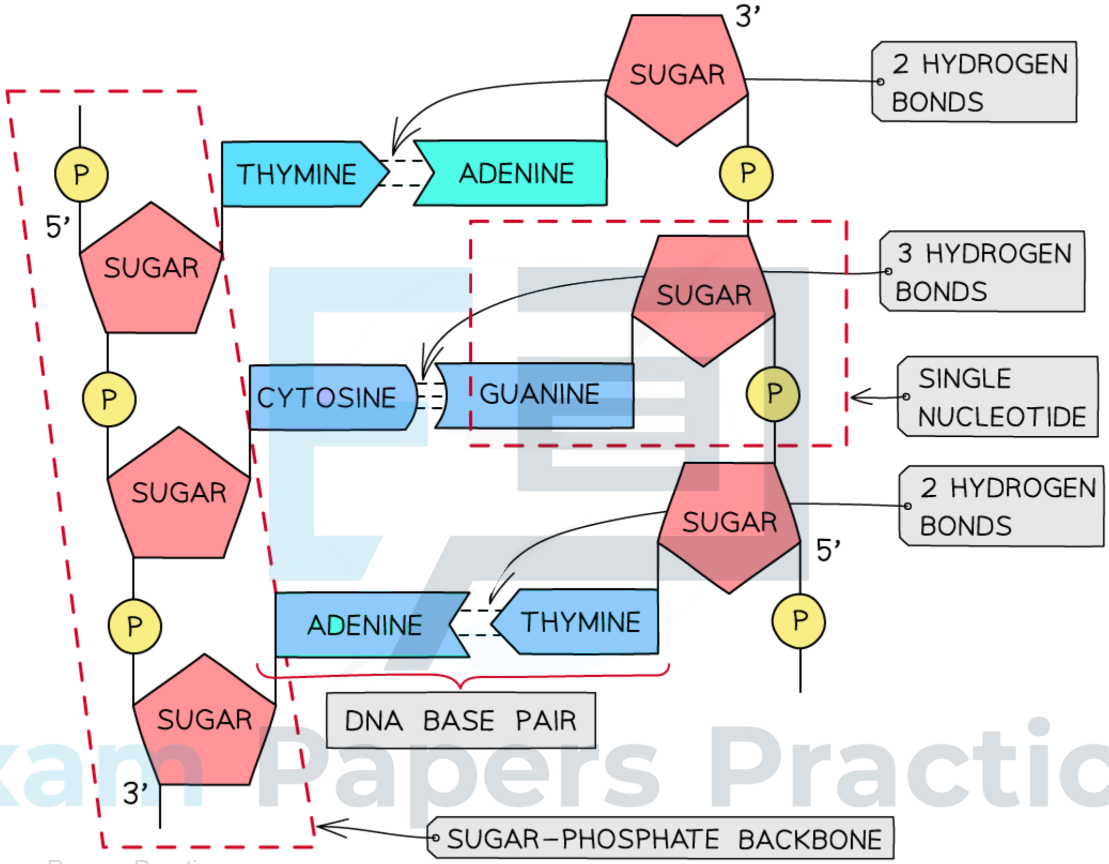


A single DNA polynucleotide strand showing 3 nucleotides in a sequence

Hydrogen bonding

- The two antiparallel DNA polynucleotide strands that make up the DNA molecule are **held together by hydrogen bonds** between the nitrogenous bases
- These hydrogen bonds always occur between the **same pairs of bases**:
  - The purine **adenine** (A) always pairs with the pyrimidine **thymine** (T) – two hydrogen bonds are formed between these bases

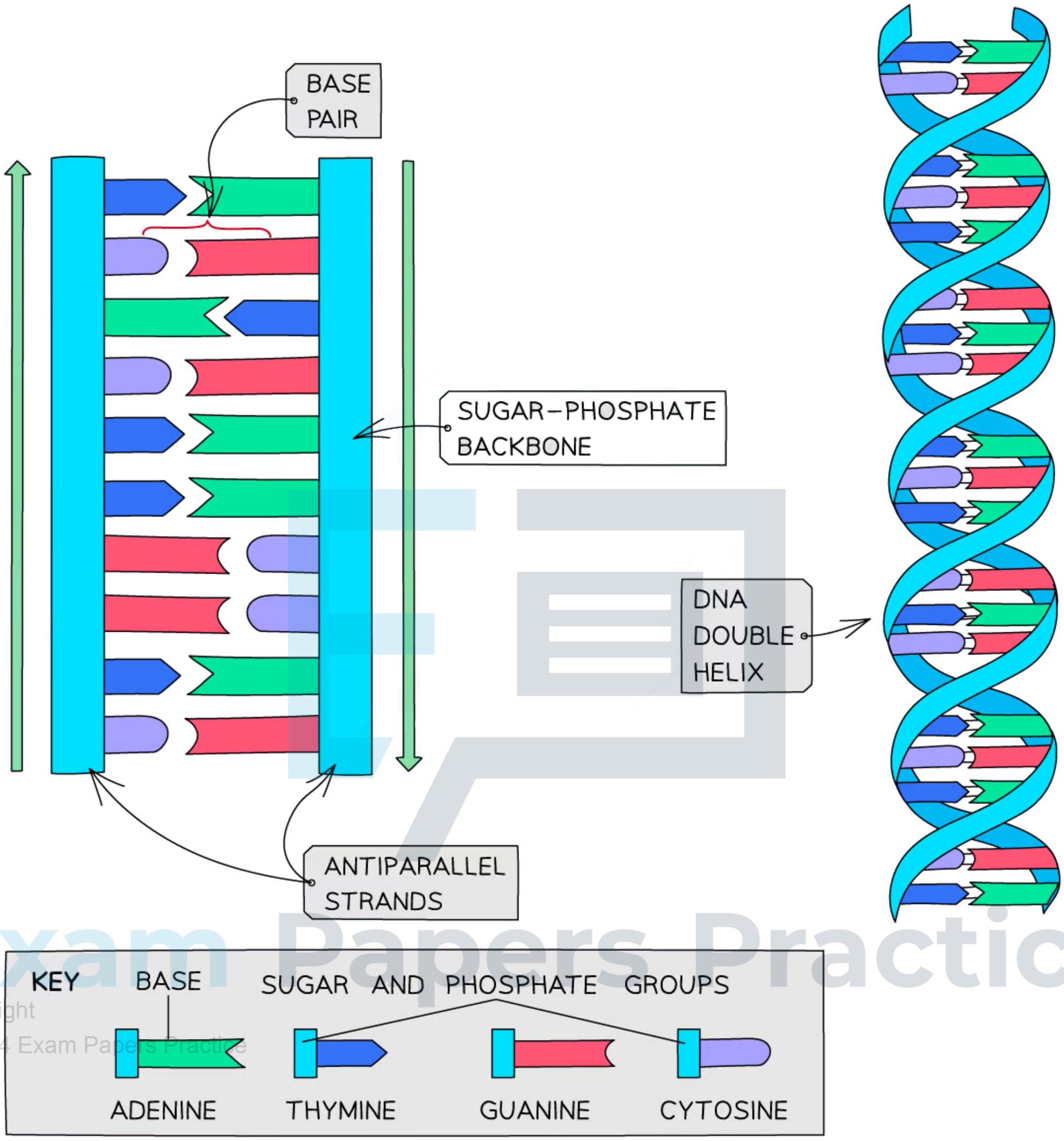
- The purine **guanine** (G) always pairs with the pyrimidine **cytosine** (C) – three hydrogen bonds are formed between these bases
- This is known as **complementary base pairing**
- These pairs are known as **DNA base pairs**



A section of DNA – two antiparallel DNA polynucleotide strands held together by hydrogen bonds

Double helix

- DNA is not two-dimensional as shown in the diagram above
- DNA is described as a **double helix**
- This refers to the **three-dimensional shape** that DNA molecules form



DNA molecules form a three-dimensional structure known as a DNA double helix

Exam Tip

Make sure you can name the different components of a DNA molecule (sugar-phosphate backbone, nucleotide, complementary base pairs, hydrogen bonds) and make sure you are able to locate these on a diagramRemember that covalent bonds join the nucleotides in the sugar-phosphate backbone, and hydrogen bonds join the bases of the two complementary strands togetherRemember that the bases are complementary, so the number of A = T and C = G. You could be asked to determine how many bases are present in a DNA molecule if given the number of just one of the bases.

Crick & Watson

- Francis Crick and James Watson were two Cambridge scientists who worked together to establish the **double helix** structure of DNA in 1953
- They used data from **their previous experiments** on the composition of DNA
- Published findings from **other research labs** played a role in developing their model
  - Rosalind Franklin, Edwin Chargaff and Linus Pauling, all of whom were leading research efforts in **other universities**, contributed important data to Crick & Watson's discovery
  - This suggests that there was a close-knit collaboration, but in fact, there was **a lot of competition between the groups** to make the breakthrough discovery

- Physical **model-making** played a large role in their success
- **Early versions of the model were rejected** for various reasons
  - It was **not compact enough**
  - It would have been too **unstable** (DNA is a highly stable molecule)
  - It did not allow **equivalent amounts** of A and T, and C and G bases to be present (Chargaff's findings)
  - It fitted together much better once the **second strand was flipped** to become antiparallel

- Their final model was constructed carefully with **clamps**, **metal rods** for bonds and with the **correct bond angles**
- Their model was **the basis of a lot of genetic research** globally in the years that followed
  - Notably, Crick and Watson's model sparked work to prove **the way in which DNA replicates** in cells

NOS: Using models as a representation of the real world; Crick and Watson used model making to discover the structure of DNA

- Models in science are built **to represent concepts** and ideas in a way that can be pictured by our brains
- Models can be **accepted or rejected** based on experimental data generated by further research
- Crick and Watson **built physical, scale** models of DNA to explain biological observations
  - Using **simple laboratory equipment** (clamps, stands, metal rods etc)
  - They **adapted their models** by making them more realistic eg. by building in the correct bond angles within molecules

- They built successive models, using **trial-and-error** to arrive at the finalised model
- Their **first model of DNA was rejected**, based on the findings of Rosalind Franklin
  - Crick and Watson **received the Nobel prize** for their work
  - Franklin died aged 37 so never received the recognition she deserved for **her significant role** in defining DNA structure

- Today, **sophisticated computer modelling** is performed, that

  - **Takes the place of physical model-making** and provides further explanation of the functions of various biomolecules
  - **Shortens the 'trial-and-error' cycles** of model-making as experienced by Crick and Watson

Exam Tip

Crick and Watsons' model has been universally accepted because all further research findings have supported their model.

2.5.2 DNA Replication

DNA Replication

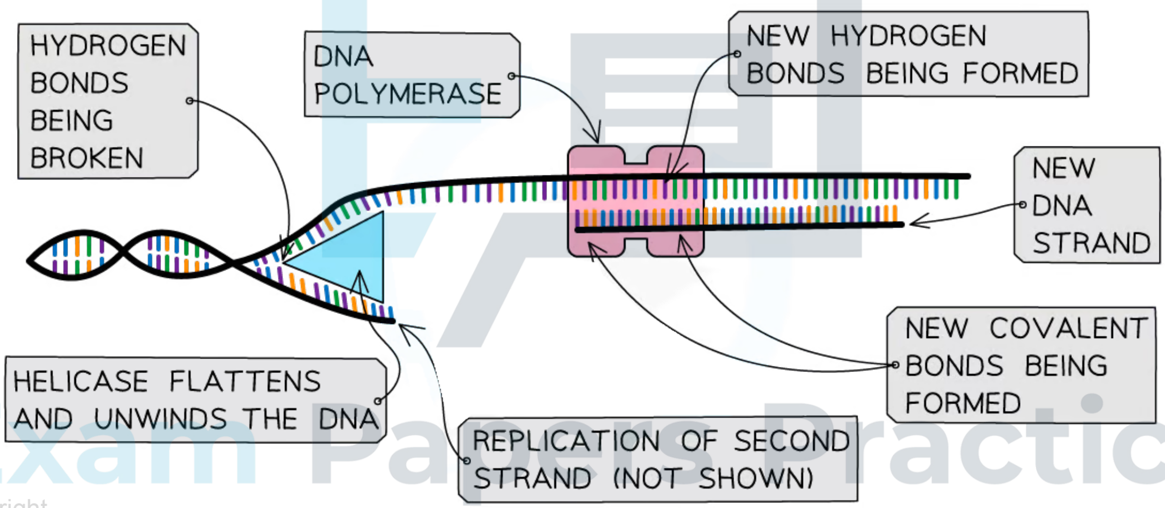
- The replication of DNA is semi-conservative and depends on complementary base pairing
- Semi-conservative means that **one strand of the 'parent' DNA is kept** in the 'daughter' molecule
- This is called the **template strand**
- The other half is determined by the code on the template strand and is built up from **free nucleotides** in the nuclear space around the chromosomes
- This takes place in the **nucleus**
- Nucleotides are added **one by one** to the new strand according to the rules of **complementary base-pairing**
  - If an **adenine** is the next exposed base on the original strand, a **thymine** nucleotide is added and *vice versa*
  - If a **cytosine** is the next exposed base on the original strand, a **guanine** nucleotide is added and *vice versa*
- **Hydrogen bonds** can only form between the template strand and the new strand if the **correct bases** are paired up
- Therefore, the new DNA molecule has **kept half** of the parent DNA and then used this to create a new, daughter strand

Exam Tip

Make sure you don't confuse 'parent cell' with 'parent organism'. A **parent cell** is any cell in the body that divides into two cells and the terminology is used to refer to the **'original' cell** that the DNA came from before it was split and replicated semi-conservatively.

Enzymes Involved in Replication

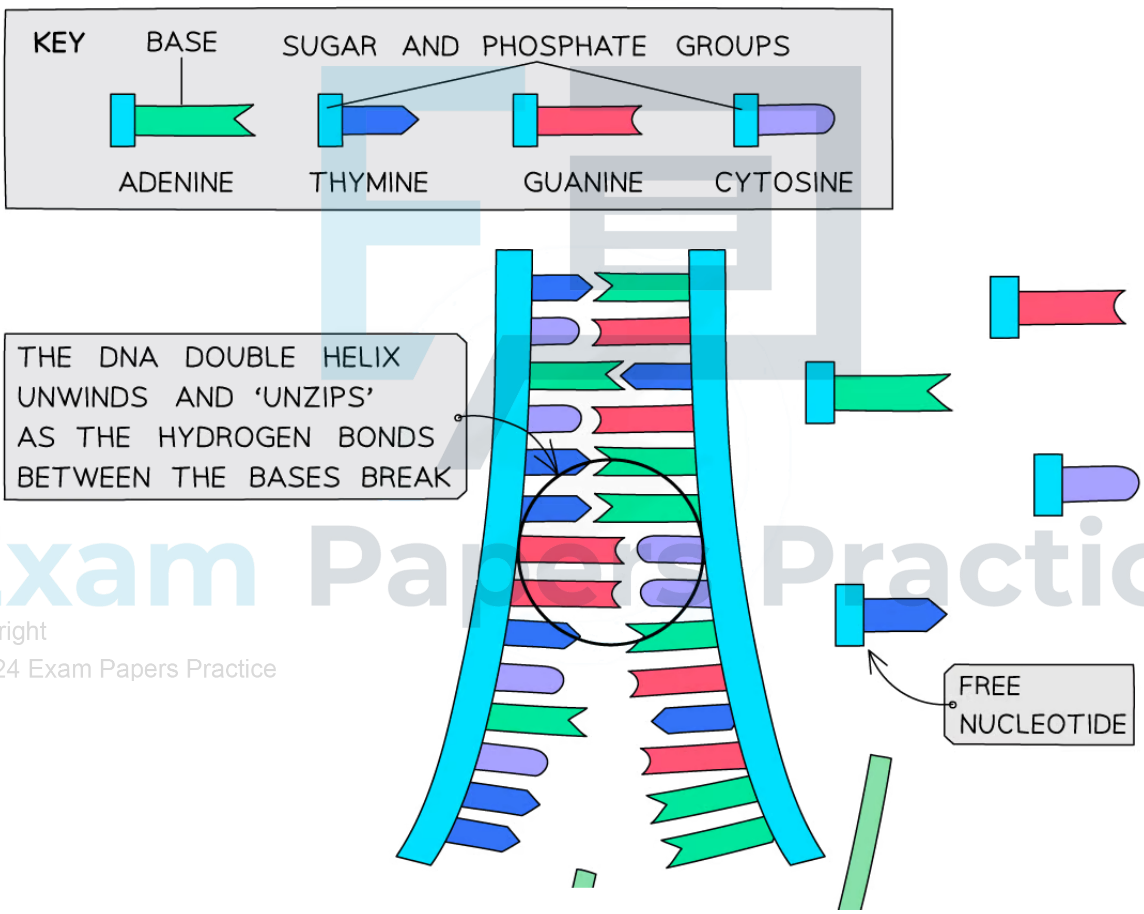
- Helicase unwinds the double helix and separates the two strands by breaking hydrogen bonds
- DNA replication occurs in preparation for **mitosis,** when DNA must be **doubled** before the parent cell can divide to produce two genetically identical daughter cells
- The enzyme **helicase** first **unwinds the DNA**, by flattening out its helical structure
  - Analogy - think about **untwisting a rope ladder**
- **Helicase** then causes the **hydrogen bonds to break** between pairs of bases, exposing bases on either strand
  - Analogy - **unzipping a zipper**
- Each of these single polynucleotide DNA strands acts as a **template** for the formation of a **new strand** made from free nucleotides that are attracted to the exposed DNA bases by **base pairing**

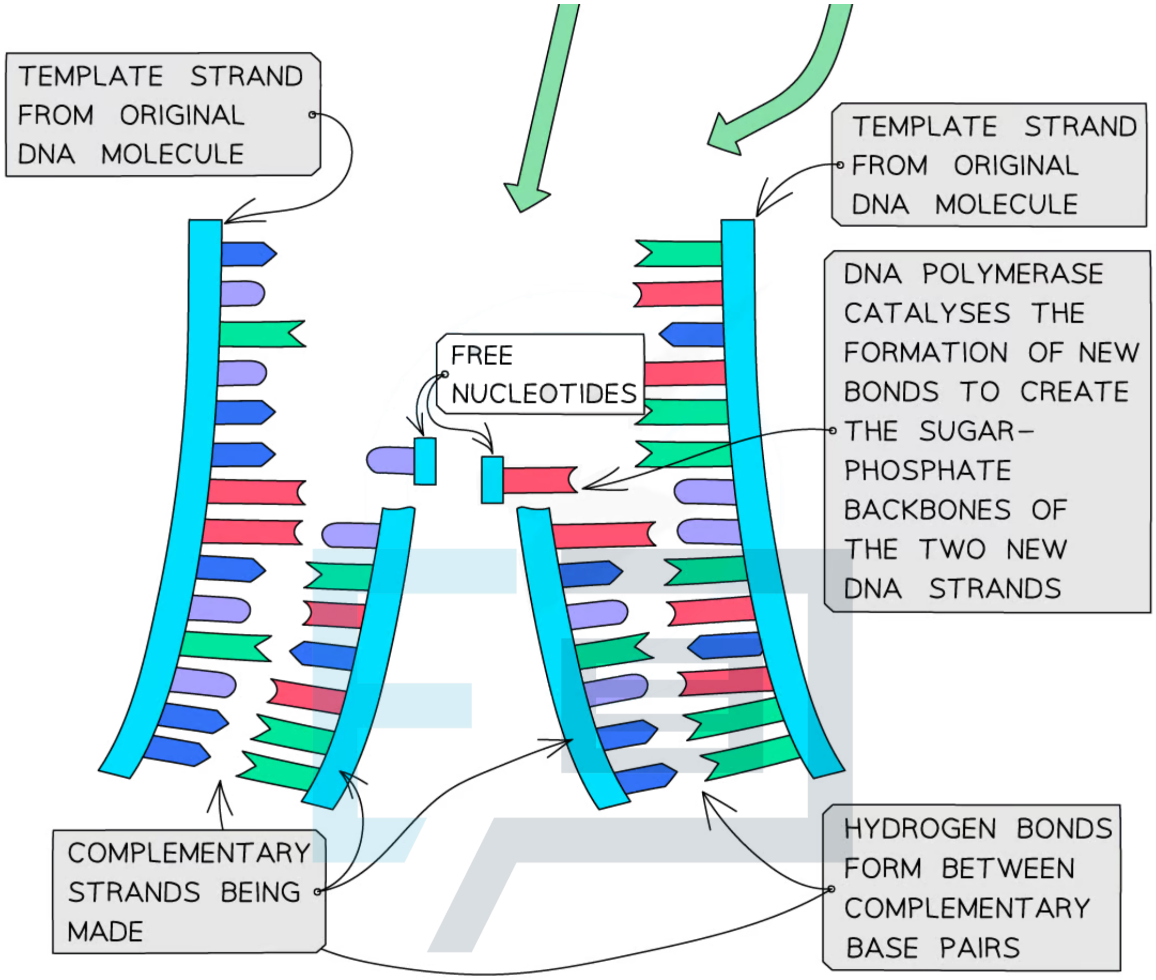


Helicase and DNA polymerase work together to replicate each strand of DNA

- DNA polymerase links nucleotides together to form a new strand, using the pre-existing strand as a template
- Following the action of helicase, the template strand is exposed and new nucleotides are **joined together by DNA polymerase,** which catalyses **condensation reactions,** to form a new strand
- The original strand and the new strand **join together through hydrogen bonding** between base pairs to form the new DNA molecule
- This method of replicating DNA is known as **semi-conservative replication** because **half of the original** DNA molecule is kept (**conserved**) in each of the two new DNA molecules
- The enzyme **DNA polymerase synthesises new DNA strands** from the two template strands

- It does this by **catalysing condensation reactions** between the **deoxyribose sugar and phosphate groups** of adjacent nucleotides within the new strands, creating the **sugar-phosphate backbone** of the new DNA strands
- DNA polymerase always works **in the same direction** along a strand of DNA, the 5' to 3' direction
- Adding the **5' terminal** of the new nucleotide to the **3' terminal** of the strand being built
- **Hydrogen bonds** then form between the **complementary base pairs** of the template and new DNA strands
- The **copying accuracy** of DNA polymerase is **very high**
  - Very few copying errors are made in DNA replication

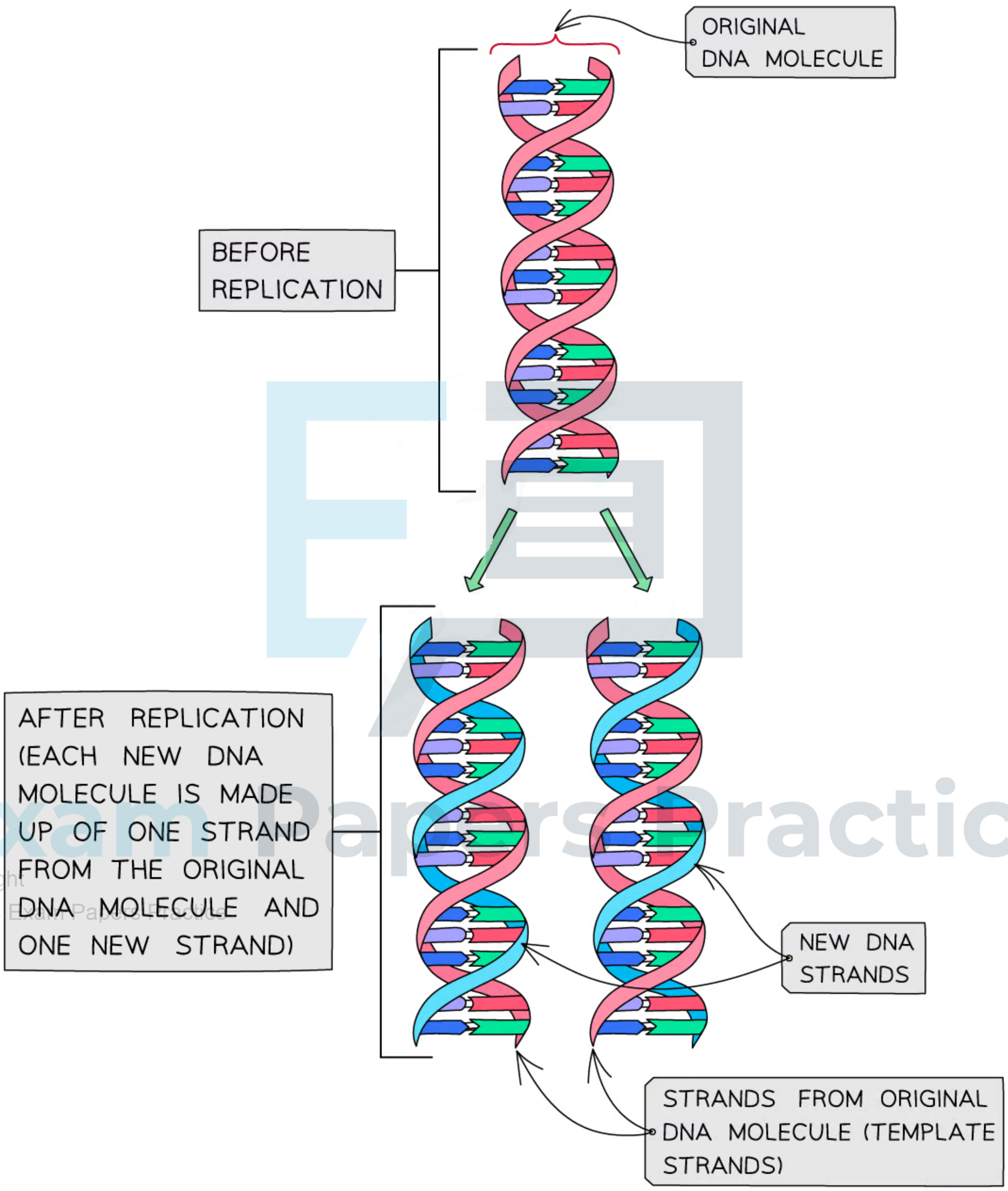




The combined actions of helicase and DNA polymerase create new complementary DNA strands

Semi-Conservation Replication

- DNA polymerase links nucleotides together to form a new strand, using the pre-existing strand as a template
- **Before** a (parent) cell **divides**, it needs to **copy the DNA** contained within it
  - This is so that the two new (daughter) cells produced will both receive the **full copies of the parental DNA**
- The DNA is copied via a process known as **semi-conservative replication** (half the DNA is kept)
  - The process is called so because **in each new DNA molecule** produced, one of the polynucleotide DNA strands (**half** of the new DNA molecule) is **from the original DNA molecule** being copied
  - The other polynucleotide DNA strand (the other half of the new DNA molecule) has to be **newly created** by the cell



Semi-conservative replication of DNA

The importance of keeping one original DNA strand

- It **ensures** there is **genetic continuity** between generations of cells
  - In other words, it ensures that the new cells produced during cell division **inherit all their genes** from their parent cells
- This is important because cells in our body are **replaced regularly** and therefore we need the new cells to be able to do the same role as the old ones
  - Replication of DNA and cell division also occurs during **growth**

Crick and Watson proposed semi-conservative replication

- As part of their discovery of the double-helix structure of DNA, Crick and Watson **made a hypothesis about how DNA copies** during cell growth
- They proposed a **semi-conservative** model, but had **not provided the evidence**
- This was provided by two later scientists, **Meselson** and **Stahl**, in another award-winning piece of research
- Analysis of Meselson and Stahl's results **gave the necessary support for Crick & Watsons' hypothesis** of semi-conservative replication of DNA

2.5.3 Skills: DNA Replication

Meselson & Stahl's Experiments

Analysis of Meselson and Stahl's results to obtain support for the theory of semi-conservative replication of DNA

- Crick and Watson, as they defined the shape of DNA, suggested a **credible explanation** of how the DNA molecule replicates itself
  - This was the theory of **semi-conservative replication**
- Like any scientific theory, this explanation **required evidence** to back up the claims
- Five years after their discovery, two other scientists, **Matthew Meselson** and **Franklin Stahl**, provided data to prove Crick and Watsons' theory

Meselson and Stahls' Experiment

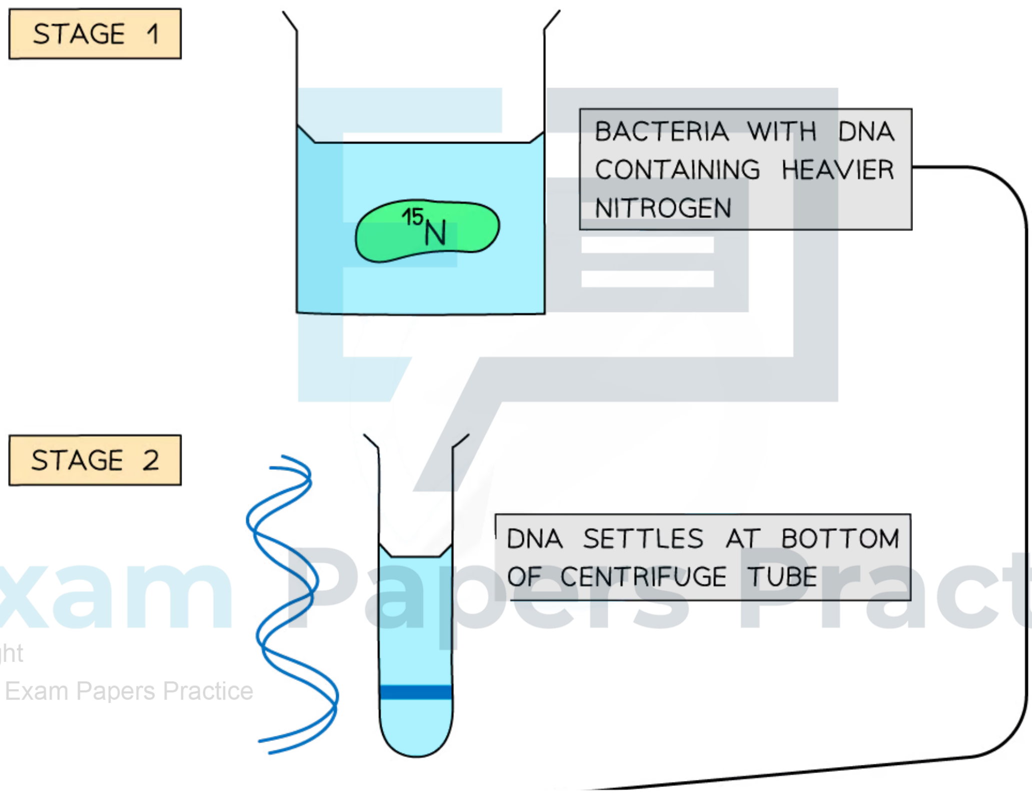
- Bacteria were grown in a broth containing the **heavy (^{15}N) nitrogen isotope**
  - DNA contains nitrogen in its bases
  - As the bacteria replicated, they used nitrogen from the broth to make **new DNA nucleotides**
  - After some time, the culture of bacteria had DNA containing **only heavy (^{15}N) nitrogen**
- A sample of **DNA** from the ^{15}N culture of bacteria was extracted and **spun in a centrifuge**
  - This showed that the DNA containing the heavy nitrogen settled near the bottom of the centrifuge tube
- The bacteria containing only ^{15}N DNA were then taken out of the ^{15}N broth and added to a broth containing **only the lighter ^{14}N nitrogen**. The bacteria were left for enough time for **one round of DNA replication** to occur before their DNA was extracted and **spun in a centrifuge**
  - If **conservative DNA replication** had occurred, the original template DNA molecules would only contain the heavier nitrogen and would settle at the bottom of the tube, whilst the new DNA molecules would only contain the lighter nitrogen and would settle at the top of the tube
  - If **semi-conservative replication** had occurred, **all** the DNA molecules would now contain **both** the **heavy ^{15}N** and **light ^{14}N** nitrogen and would therefore settle in the **middle of the tube** (one strand of each DNA molecule would be from the original DNA containing the heavier nitrogen and the other (new) strand would be made using only the lighter nitrogen)
- Meselson and Stahl confirmed that the bacterial DNA had undergone **semi-conservative replication**.
  - The DNA from this second round of centrifugation settled in the middle of the tube, showing that each DNA molecule contained a **mixture** of the **heavier and lighter nitrogen isotopes**

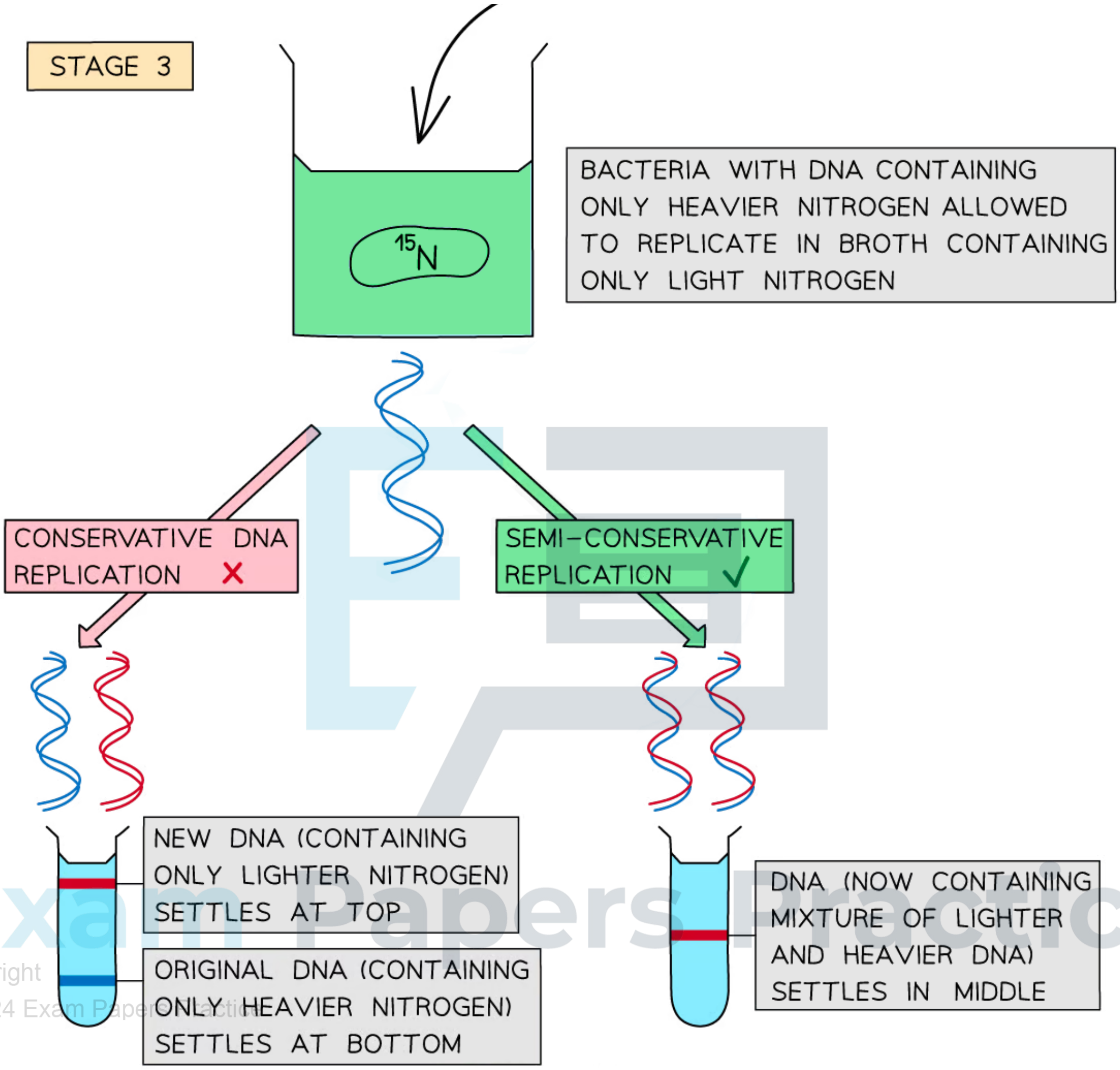
- If more rounds of replication were allowed to take place, the **ratio of ^{15}N:^{14}N** would go from 1:1 after the first round of replication, to 3:1 after the second and 7:1 after the third

- This experiment **proved Crick and Watsons' theory correct**

NOS: Obtaining evidence for scientific theories; Meselson and Stahl obtained evidence for the semi-conservative replication of DNA

- Meselson and Stahl's experiment is a great example of how scientists can obtain evidence to back up a theory about a biological process





Meselson and Stahls' experiment provided unequivocal proof that DNA replicates via semi-conservative DNA replication