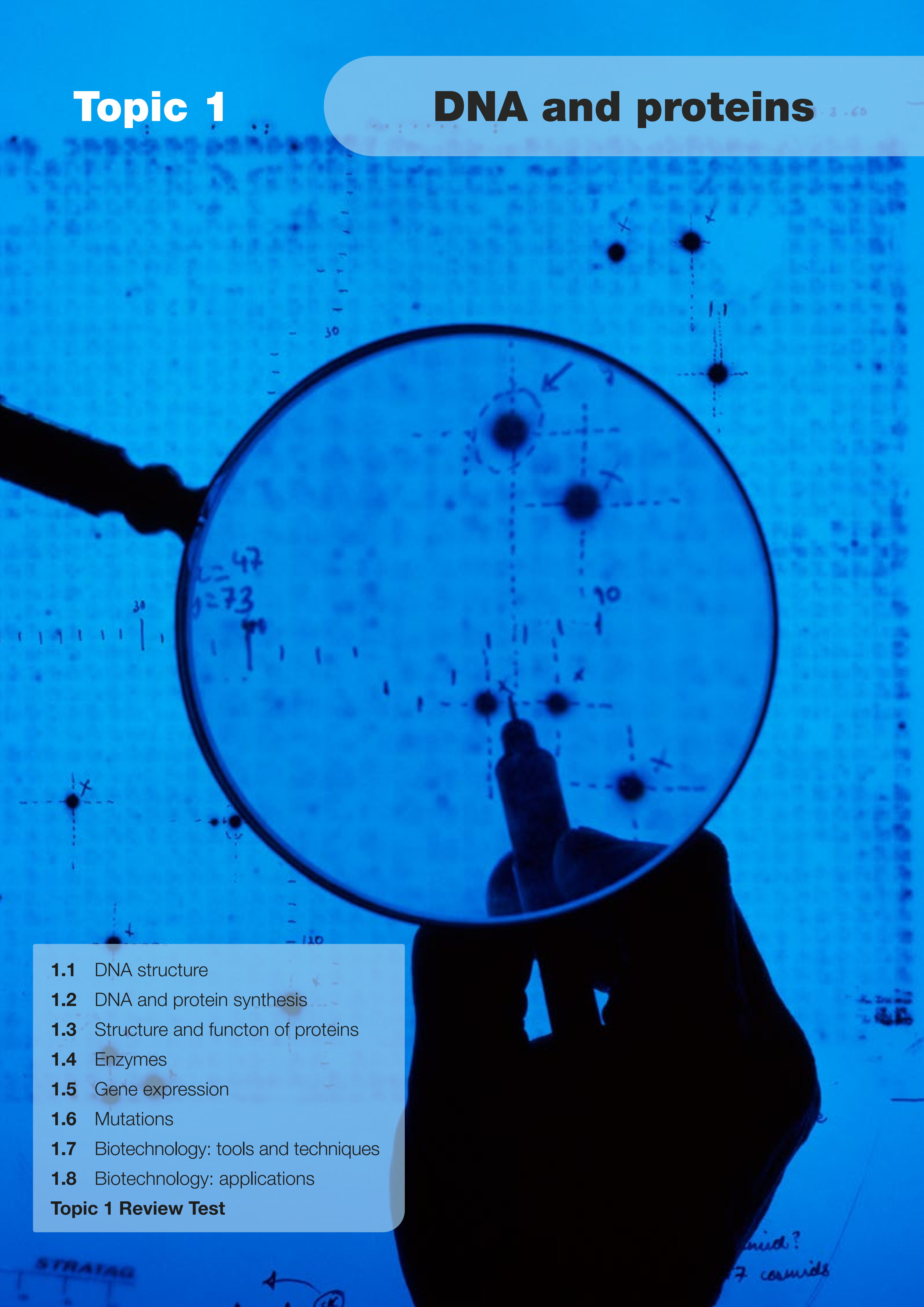


Topic 1 DNA and proteins

1.1 DNA structure

1.2 DNA and protein synthesis

1.3 Structure and functon of proteins

1.4 Enzymes

1.5 Gene expression

1.6 Mutations

1.7 Biotechnology: tools and techniques

1.8 Biotechnology: applications

Topic 1 Review Test

Chapter 1.1 DNA structure

Science Understanding

DNA stores and transmits genetic information; it functions in the same way in all living things.

DNA is a helical double-stranded molecule.

In eukaryotes, DNA is bound to proteins (histones) in linear chromosomes, which are found in the nucleus.

DNA is unbound and circular in the cytosol of prokaryotes and in the mitochondria and chloroplasts of eukaryotes.

- Compare chromosomes in prokaryotes and eukaryotes.

Replication of DNA allows for genetic information to be inherited.

Base-pairing rules and method of DNA replication are universal.

- Describe the structural properties of the DNA molecule, including:
  - nucleotide composition and pairing
  - the weak bonds between strands of DNA that allow for replication.
- Explain the importance of complementary base pairing (A–T and C–G).
- Recognise that DNA strands are directional and are read 5' to 3'
- Describe and represent the process of semi-conservative replication of DNA.

DNA

Large molecules that are found in living organisms are called macromolecules. They usually consist of smaller units that are joined together.

Deoxyribonucleic acid (**DNA**) is a macromolecule found in all living cells, and is the chemical that controls virtually everything that happens in cells. It is the most fundamental chemical of life, believed to have been formed some 3 billion years ago when the first forms of life arose.

DNA was first isolated in 1869 by a Swiss chemist, *Friedrich Miescher,* who discovered it was acidic and contained the element phosphorous. It was found mainly in the **nucleus** of cells and was thus named a nucleic acid. It was in the 1940s that the structure of DNA began to be discovered. The two scientists credited with the work were a young American scientist, *James Watson* and a British scientist, *Francis Crick*. Refer to the '*Science as a Human Endeavour*' Activity at the end of this chapter for more details on the discovery of DNA structure, as a double-stranded molecule. *Figure 111* shows a section of a DNA molecule and the highly recognisable DNA **double helix** structure.

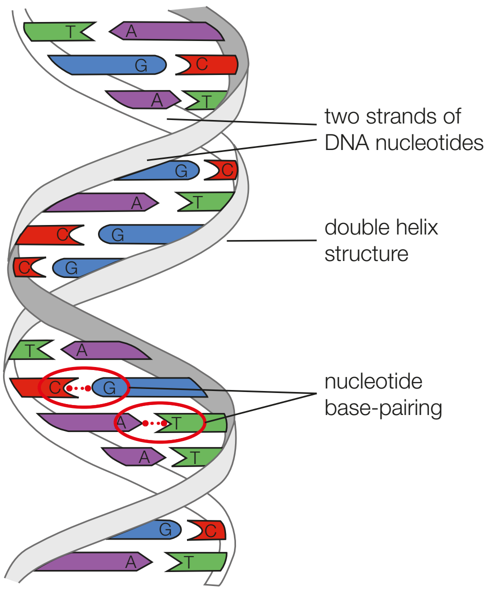


Figure 111 A section of a double stranded DNA molecule

Chromosomes and DNA

DNA in cells is found in structures called **chromosomes.** These are often referred to as the structural unit of information in cells. DNA stores and transmits **genetic information**, managing the requirements and activities of the cell. DNA is **universal** and functions the same way in all living things. This means that DNA from one species can be inserted into the genome of another species and the message can still be transmitted (these concepts will be explored further in this Topic).

Two different types of cells have evolved over time: **prokaryotic cells** and **eukaryotic cells.** Prokaryotic cells are thought to have existed first, they are relatively unspecialised and do not contain membrane-bound organelles. The cells of all bacteria are prokaryotic.

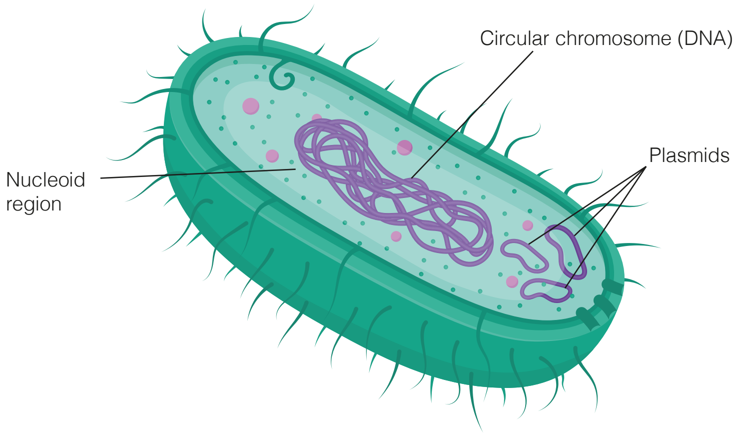


Figure 112 The circular chromosome and separate plasmids of a prokaryotic cell

As can be seen in *Figure 112*, the DNA is located in the liquid part of the cytoplasm (or cytosol). The location of DNA in the cytosol is called the **nucleoid region.** The **DNA is circular**, consisting of **one chromosome** and is double-stranded. This region also contains another nucleic acid called RNA (ribonucleic acid) and proteins which are another type of macromolecule. Also found in many types of prokaryotic cells are **plasmids** which are small amounts of **circular**, double-stranded DNA that are **separate** from the cell's chromosomal DNA.

The cells that make up large, complex, multicellular organisms are termed eukaryotic cells. The cells of all animals, plants and fungi are eukaryotic cells. These cells are highly organised and more specialised than prokaryotic cells. They contain smaller internal structures, called membrane-bound organelles, that have specific functions in the cells. Examples of these organelles include the nucleus, mitochondria, chloroplasts, Golgi bodies and endoplasmic reticulum.

Most of the DNA in a eukaryotic cell is found in the **nucleus** of that cell. Human somatic (body) cells consist of **46 chromosomes**, which are organised into 23 pairs. There are 22 pairs of autosomal (non-sex) chromosomes and one pair of sex chromosomes (either XX for female or XY for male). A set of human chromosomes is known as a **karyotype** (see *Figure 113*).

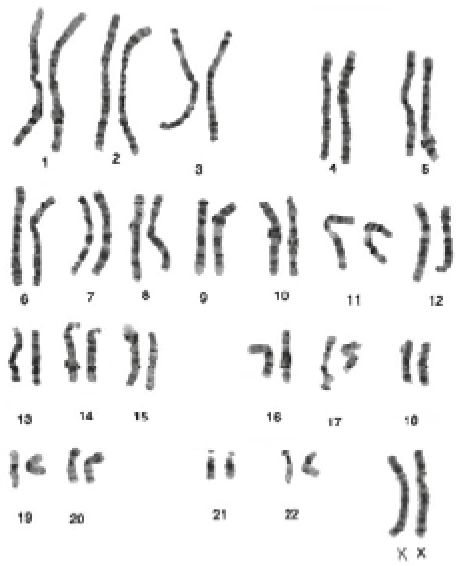


Figure 113 A human karyotype of a female

The chromosomes are arranged into **condensed linear** strands consisting of a double stranded **DNA molecule** and **histone proteins** (see *Figure 114*). The ends of chromosomes have short lengths of DNA called telomeres. These protect the tips of chromosomes from breakdown and stop chromosomes from binding to one another. Chromosomes are **only visible** under a light microscope **during cell division** when the DNA is tightly coiled around histone proteins (condensed). The **decondensed** form of chromosomes is called **chromatin** (see *Figure 114*). Chromatin is present in the nucleus of cells throughout the cell cycle (excluding cell division). It is important that the **genetic code is accessible** during the growth and development of a cell so that DNA synthesis, protein synthesis and RNA synthesis can occur. If the DNA molecule is condensed, the genetic code is very hard to access, and these processes are unlikely to occur. Conversely, it is important for the chromatin to condense into chromosomes prior to cell division to **protect the genetic code** and ensure identical copies are transferred to both daughter cells. Each human somatic (body) cell contains about 2 to 3 metres of DNA when completely decondensed to linear form. If chromatin was present during cell division, it is likely that the decondensed DNA would get tangled and result in DNA breakages.

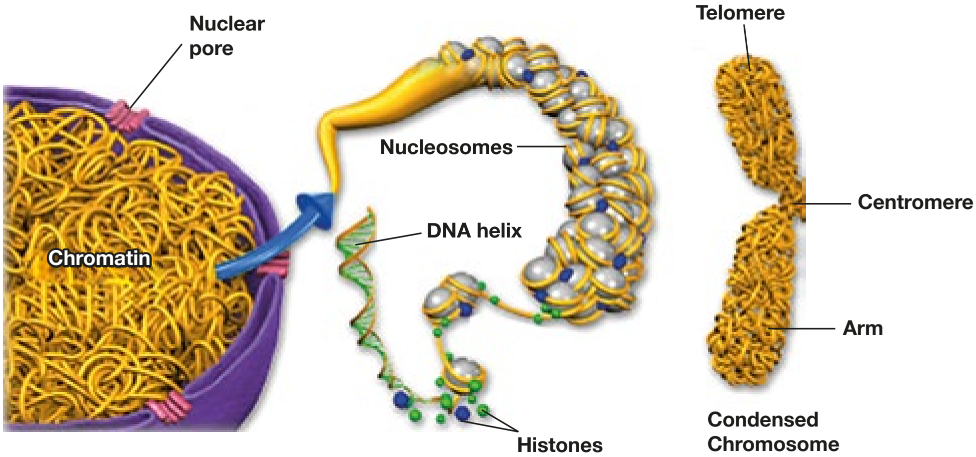


Figure 114 The structural difference between chromatin and chromosomes

Two types of eukaryotic membrane-bound organelles also contain DNA, **mitochondria (mtDNA) and chloroplasts (cpDNA).** mtDNA and cpDNA are both double stranded, circular and not bound to histone proteins (similar to prokaryotic cells). There are theories for the existence of DNA in these organelles, including the fact that mitochondria and chloroplasts were once ‘free-living’ unicellular organisms that were capable of their own independent existence. *The table below provides a comparison of DNA molecules in prokaryotic cells, mitochondria, chloroplasts and eukaryotic cells:*

	Prokaryotic DNA	Mitochondria & chloroplasts DNA	Eukaryotic DNA
Number of DNA strands	Two	Two	Two
Number of chromosomes	One	One	Two or more in pairs (generally)
Shape of chromosome(s)	Circular	Circular	Linear
Location in cell	Nucleoid region	Mitochondrial matrix, stroma	Nucleus

DNA structure

It has been stated that DNA stores and transmits genetic information. For this to be possible, the molecule must be capable of enormous variation to be able to code for the endless variety that is seen across life on the planet. The structure of DNA enables it to perform two vital functions necessary for life:

1. Make identical copies of itself so that genetic information can pass from cell to cell and can be inherited or passed on to the next generation.
2. Provide a code that can be used by cells to manufacture protein molecules.

DNA is a large macromolecule made up of repeating units called **DNA nucleotides** (see *Figure 115*). Nucleotides are complex molecules made up of three smaller molecules that are linked together by covalent bonds:

- a pentose (or 5-carbon) sugar called **deoxyribose**
- a **phosphate** group, and
- one of four **organic bases:** adenine (A), cytosine (C), thymine (T) and guanine (G).

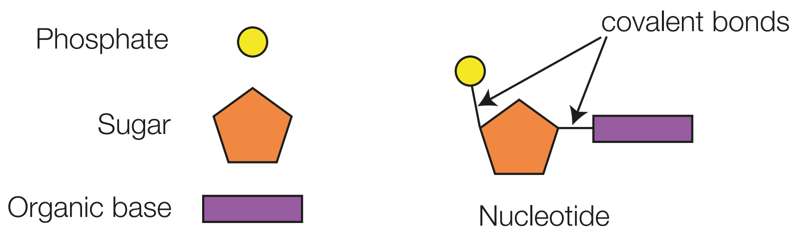


Figure 115 The components of a nucleotide

The phosphate of one nucleotide is attached to the sugar of the next nucleotide, this results in a backbone of alternating phosphates and sugars from which the bases project. This structure of the phosphate-sugar backbone results in one end of the DNA strand ending in a phosphate, and the other ending in a sugar. This gives the DNA strand **directionality**. The end of the DNA strand with the phosphate (PO_4^{3-}) sticking out is called the **5' end** (pronounced 5 prime) and is the **beginning** of the DNA strand. At the opposite end of the chain, a sugar molecule is exposed with a hydroxyl group (OH) sticking out. This is called the **3' end** (pronounced 3 prime) of the DNA strand (see *Figure 116*). The sequence of DNA is therefore written in the 5' to 3' direction. Additionally, the phosphate group is **negatively charged**, giving the DNA molecule an overall negative charge. This charge can be used to help separate DNA molecules and will be re-visited in Chapter 1.7.

Each base forms **weak hydrogen bonds** with its complementary base located at the same position on the other strand (see *Figure 116*). Weak hydrogen bonds between complementary base pairs in DNA are an advantage to cells because they are easy to break and re-form. This is important in **DNA replication** which involves breaking apart the DNA double helix to expose its organic bases for base pairing. The base pairing rules are:

Adenine only bonds to Thymine with two hydrogen bonds forming (A=T).

Guanine only bonds to Cytosine with three hydrogen bonds forming (C≡G).

Evidence for complementary bonding is supported by DNA analysis which reveals that each species has identical amounts of adenine and thymine and also identical amounts of guanine and cytosine. For example, if there is 20% thymine in a DNA molecule there will also be 20% adenine and therefore 30% guanine and 30% cytosine.

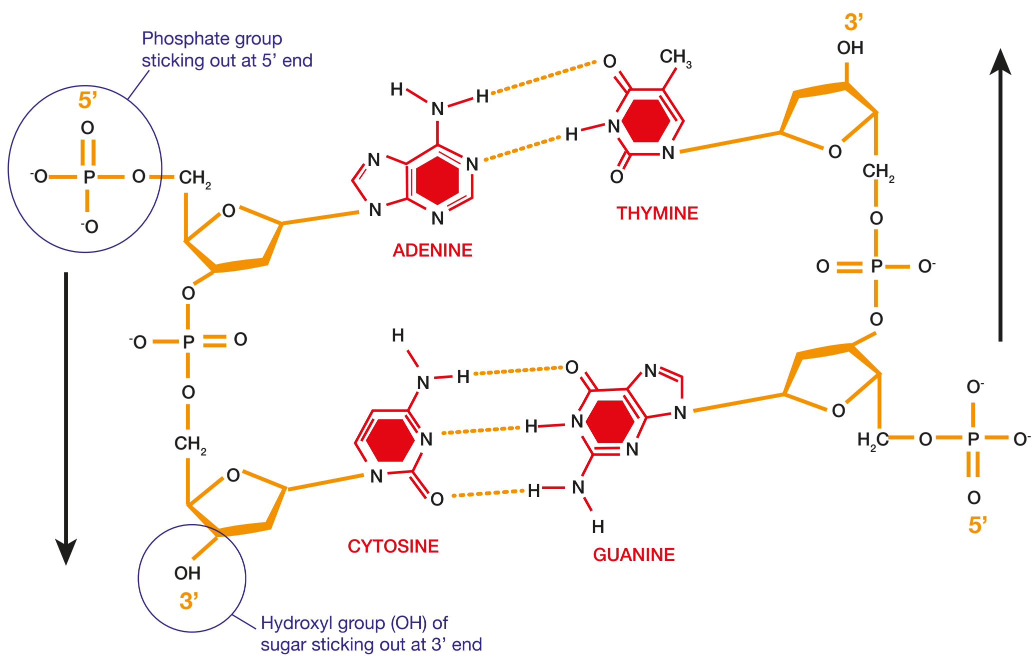


Figure 116 A small section of DNA illustrating the number of hydrogen bonds that form between complementary DNA bases

When DNA is assembled, it consists of **two complementary strands** linked by the complementary base pairs. As the two strands are complementary, they are **read in opposite directions**. With reference to *Figure 117*, the DNA strand on the left is read from top to bottom in the 5' to 3' direction; however, the DNA strand on the right is read from bottom to top in the 5' to 3' direction. It is important to note that both strands are read in the 5' (yellow phosphate) to 3' (orange sugar) direction.

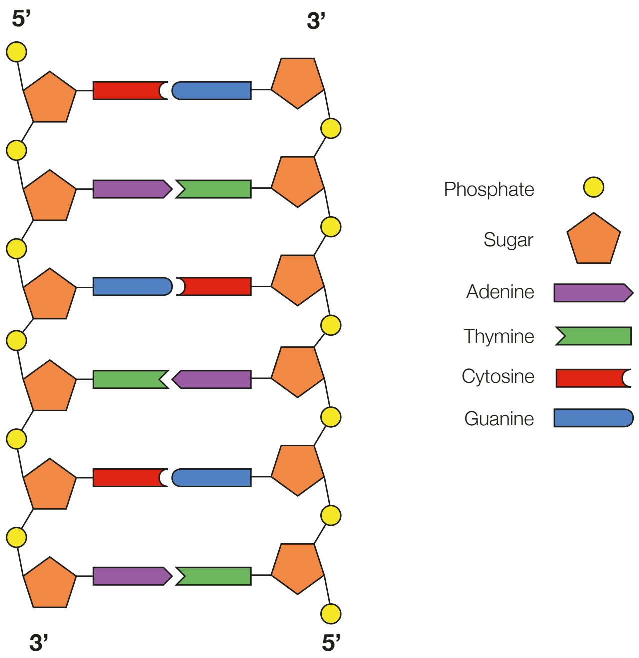


Figure 117 A section of unwound DNA illustrating the two DNA strands running in opposite directions

A chromosome is made up of many functional units of information called **genes**. Each gene is a unique sequence of bases on one strand of DNA (the coding strand). The sequence of bases in genes varies from one DNA molecule to another and it is this variation in the base code that enables DNA to be such a versatile and diverse molecule.

Different species have different characteristics and therefore different numbers of genes and chromosomes. For example, simple bacterial cells require hundreds of genes because they require hundreds of proteins to function. Different species on Earth differ in:

- the number of chromosomes found in cells (and therefore, number of genes)
- the base sequences of genes found in their DNA
- the length of the DNA molecules and hence the number of bases.

The table below illustrates the chromosome number of a few common organisms:

Organism	Number of chromosomes per cell
Human	46
Bacterium	1
Rock Dove	80
Pea	14
Simple alga	16

Helpful online resources

Cognito: GCSE Biology - What is DNA? (Structure and Function of DNA)
<https://www.youtube.com/watch?v=T6_wKPAbf2k>

TED-Ed: The twisting tale of DNA - Judith Hauck
<https://www.youtube.com/watch?v=0_b80fHmuWw>

Stated Clearly: What is a Chromosome?
<https://www.youtube.com/watch?v=IePMXxQ-KWY>

DNA replication

In an earlier section of this chapter, it was noted that one of the vital functions of DNA is the ability to make copies of itself so that genetic information can be inherited by daughter cells and descendants. The process that enables this to occur is called **DNA replication** and occurs in both prokaryotic and eukaryotic cells. DNA replication is the mechanism for copying (or doubling) DNA. It takes place in the **nucleoid region** of prokaryotic cells and the **nucleus** of eukaryotic cells. DNA replication is said to be **semi-conservative** because each double-strand of DNA consists of one old strand (retained or conserved from the original parent DNA molecule) and one newly synthesised strand. As the two DNA strands of the parent DNA molecule are complementary, the DNA nucleotides are **added in opposite directions**. DNA nucleotides are **added in the 5' to 3' direction** by DNA polymerase to the exposed bases of the existing 'old' strands. The product is **two identical** double-stranded DNA molecules that contain the same genetic information as the original DNA molecule (see *Figures 118 and 119*). Refer to the following table for a summary of the steps involved in DNA replication:

Summary of DNA replication	
1.	The enzyme **helicase** breaks the hydrogen bonds between the complementary bases joining the two strands, unwinding, and exposing their bases (see *Figure 119*).
2.	Each strand serves as a template for making a new complementary strand.
3.	Enzymes, called **DNA polymerase**, add free DNA nucleotides to the exposed corresponding bases on the separate strands, according to complementary base pairing rule: A binds with T and C binds with G (see *Figure 119*).
4.	The new DNA is **synthesised in the 5' to 3' direction**; therefore, DNA polymerases add DNA nucleotides to the 3' end of the DNA strands (see *Figures 118* and 119).
5.	Each new double-stranded DNA molecule rewinds into a double helix and are joined at the centromere (see *Figure 1110*).

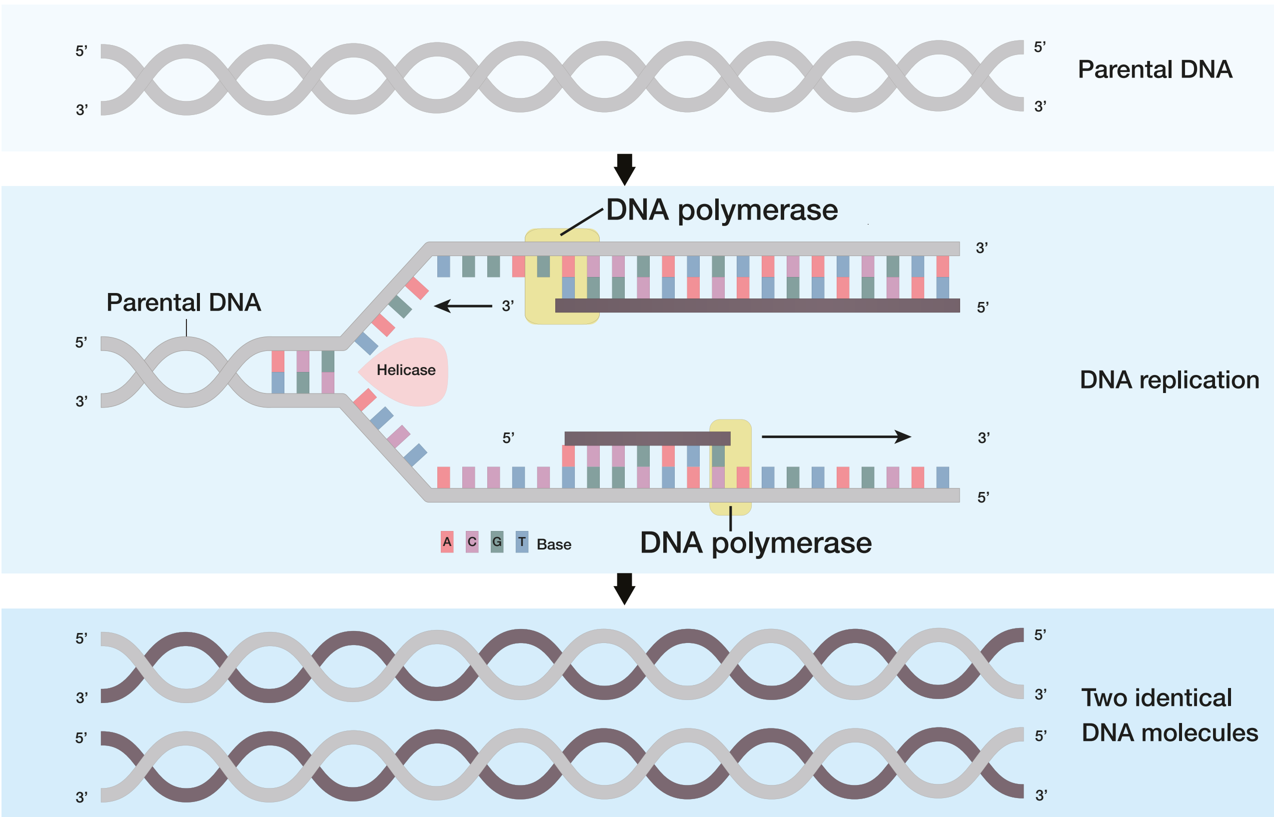


Figure 118 The production of two identical DNA molecules through semi-conservative DNA replication

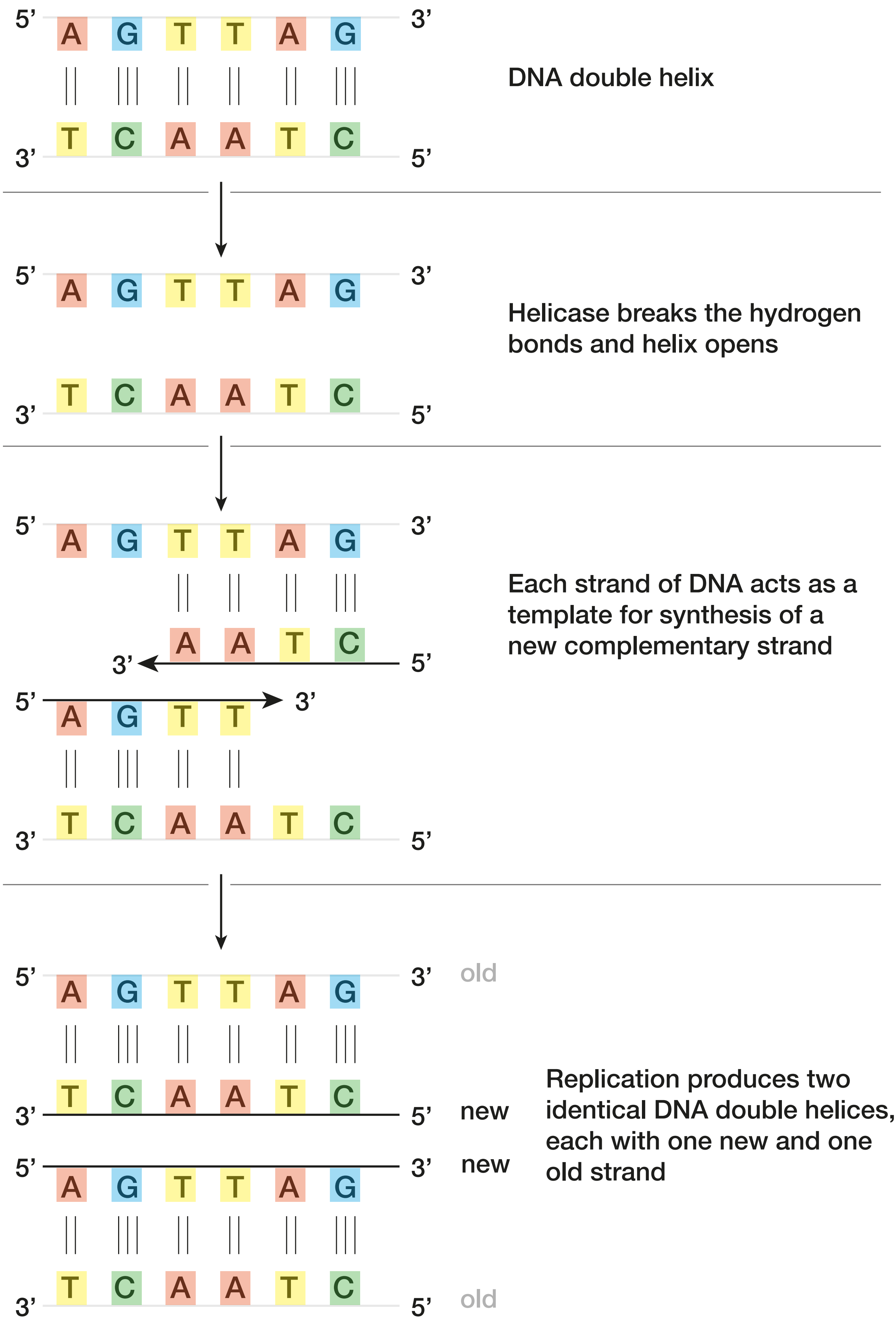


Figure 119 A summary of the DNA replication process

Following DNA replication, the DNA is doubled and all chromosomes in the cell consist of **two identical sister chromatids** (see *Figure 1110*). DNA can therefore be seen in three forms:

- decondensed chromatin
- as a condensed chromosome
- after DNA replication as a chromosome consisting of two identical sister chromatids

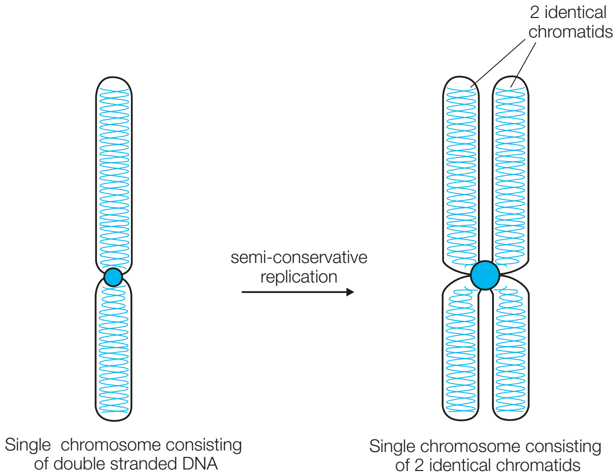


Figure 1110 The process of DNA replication at the chromosome level

The number of times DNA replication can occur is limited. This is because every time DNA in chromosomes is replicated, the **telomeres** at the ends of the chromosome shorten. After a certain number of DNA replications, the telomeres are too short for further replication to occur.

Each strand of a DNA molecule has the information necessary to construct the other strand. DNA replication occurs **prior to cell division** in both prokaryotic cells (binary fission) and eukaryotic cells (mitotic division) so that each daughter cell produced contains **identical DNA to the parent cell.**

As seen in *Figure 1111*, the amount of DNA in the original cell **doubles during replication,** although the number of chromosomes remains the same, before the chromosomes separate during cell division. The result is that each new cell formed has the same number of chromosomes and the same amount of DNA as in the original cell.

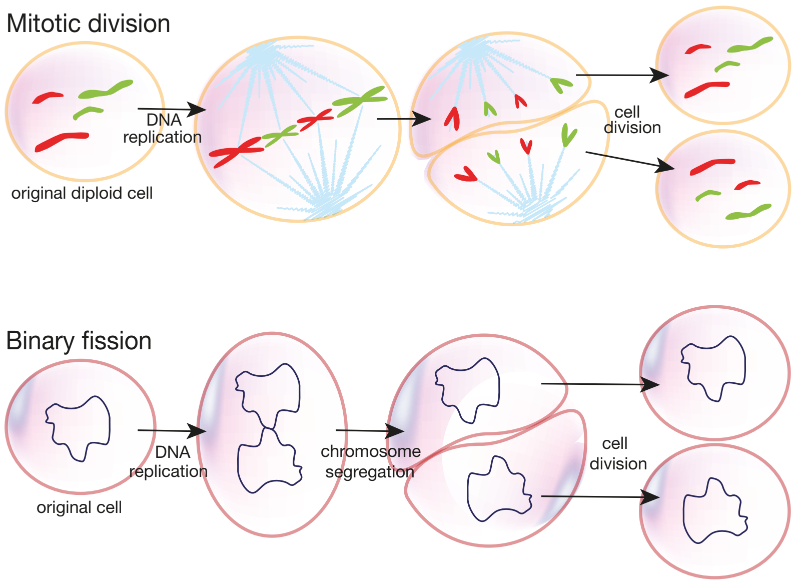


Figure 1111 DNA replication ensures that the amount of DNA doubles prior to cell division

Helpful online resources

Fuse School - Global Education: DNA Replication | Genetics | Biology | FuseSchool

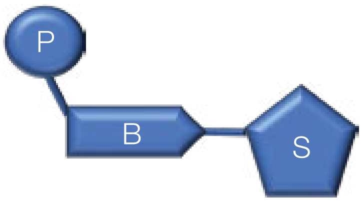
<https://www.youtube.com/watch?v=lSvF5-rBRGQ>

1.1 Review questions

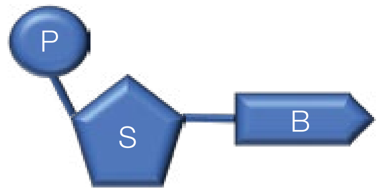
Multiple choice questions

1. Which one of the following drawings represents the correct orientation of molecules in a nucleotide?

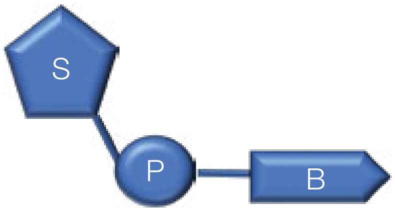
J.



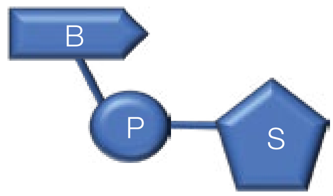
K.



L.

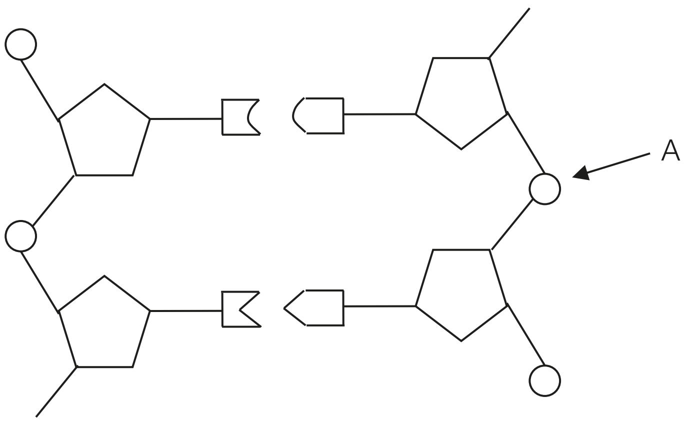


M.



- ◯ J
- ◯ K
- ◯ L
- ◯ M

2. Refer to the diagram below of a molecule of DNA to answer the question that follows.



DNA molecule DNA molecule

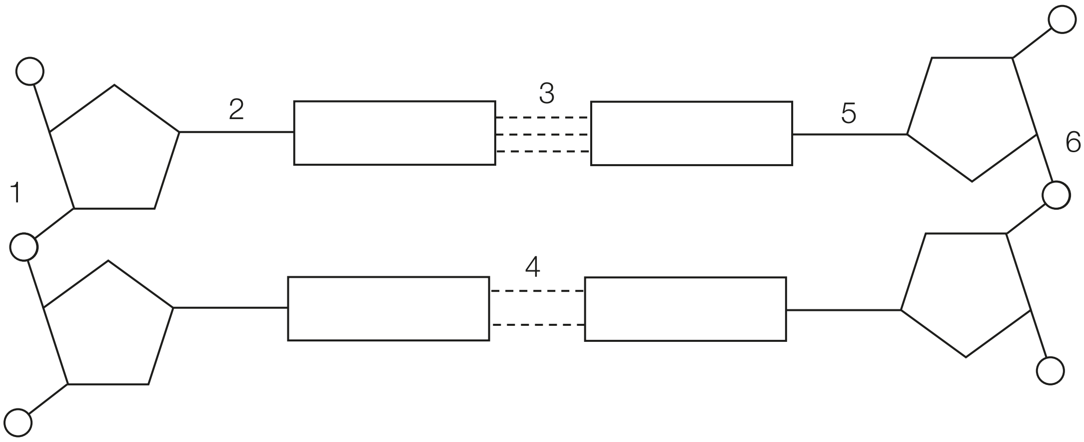
What does component A represent?

- ◯ J Phosphate
- ◯ K Deoxyribose sugar
- ◯ L Nitrogen base
- ◯ M Ribose sugar

3. Replication of DNA….

- ◯ J is necessary for the process of transcription.
- ◯ K occurs prior to protein synthesis.
- ◯ L occurs prior to mitosis.
- ◯ M does not occur in binary fission.

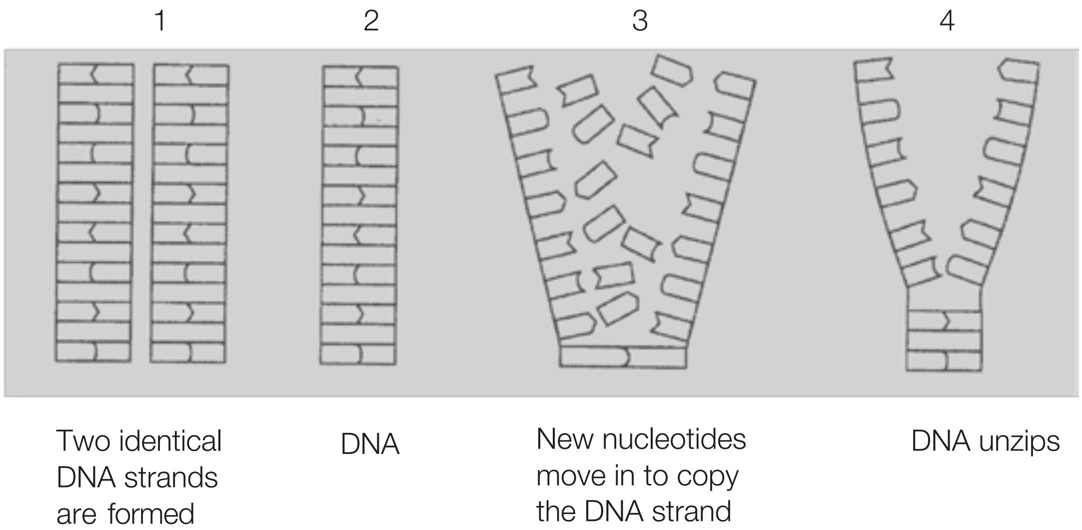
4. *Refer to the diagram below of part of a DNA molecule to answer the question that follows. The numbers refer to the bonds in the DNA molecule.*



During the process of semi-conservative replication which bonds are broken?

- ◯ J 2 and 5
- ◯ K 1, 2, 3, 4, 5 and 6
- ◯ L 2, 3, 4 and 5
- ◯ M 3 and 4

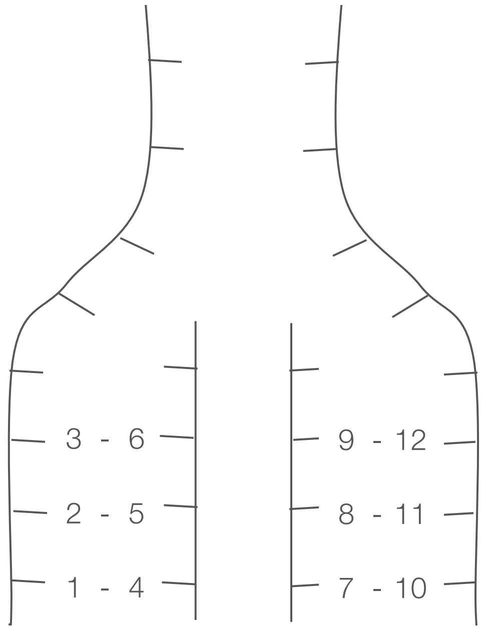
5. *Refer to the diagram below showing the steps in the semi-conservative process of DNA replication to answer the question that follows.*



The correct order of the steps in DNA replication is:

◯	J	4	3	2	1
◯	K	4	3	1	2
◯	L	2	4	3	1
◯	M	2	3	4	1

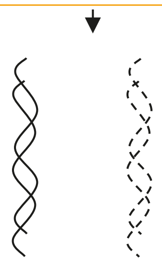
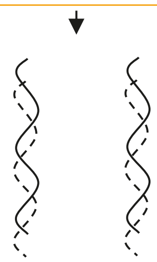
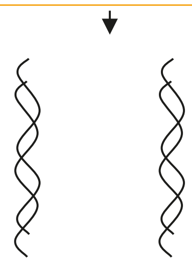
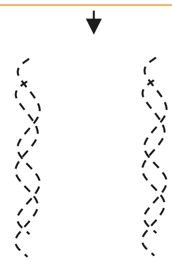
6. *Refer to the diagram below representing DNA replication to answer the question that follows.*



If bases 1, 2 and 3 respectively represent Adenine, Guanine and Thymine which other 2 bases would also represent thymine?

- ◯ J 8 and 11
- ◯ K 9 and 10
- ◯ L 7 and 12
- ◯ M 10 and 12

7. Refer to the diagrams below to answer the question that follows:

Four theoretical models of DNA replication			
1	2	3	4
			
One round of DNA replication (newly synthesized DNA is shown as dotted lines)			
			

Which number represents the model of DNA replication that occurs in human cells?

- ◯ J 1
- ◯ K 2
- ◯ L 3
- ◯ M 4

8. Which of the following statements is correct with regards to the bonds in a DNA molecule?
- ◯ J The bonds between the bases in a DNA molecule are strong covalent bonds.
- ◯ K Adenine and thymine bases form two strong covalent bonds.
- ◯ L The bonds between the bases in a DNA molecule cannot be broken.
- ◯ M Cytosine and guanine bases form three hydrogen bonds.

9. During DNA replication, DNA polymerase adds DNA nucleotides:
- ◯ J in the 3' to 5' direction for both exposed strands.
- ◯ K in the 3' to 5' direction for one exposed strand and 5' to 3' direction for the other exposed strand.
- ◯ L in the 5' to 3' direction for both exposed strands.
- ◯ M in the 5' to 5' direction for both exposed strands.

10. Identify the true statement comparing prokaryotic and eukaryotic chromosomes.
- ◯ J Prokaryotic chromosomes are circular and consist of a DNA molecule bound to histone proteins.
- ◯ K Eukaryotic chromosomes are linear and consist of a DNA molecule bound to histone proteins.
- ◯ L Mitochondria and chloroplasts of eukaryotes contain chromosomes that consist of a DNA molecule bound to histone proteins.
- ◯ M Mitochondria and chloroplasts of eukaryotes contain a pair of circular chromosomes.

Free response questions

1. State the differences between linear and circular chromosomes, giving examples of the types of species in which each might be found.

2. Describe why chromosomes are not visible in cells that are not dividing.

3. Name the four possible complementary base pairings that can be found in a DNA molecule.

4. *Refer to the diagram below of one strand of a DNA molecule to answer the questions that follow:*

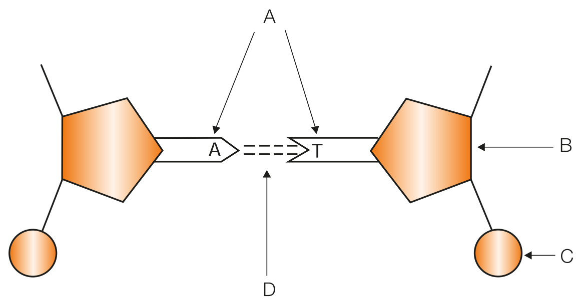
— Sugar — Phosphate — Sugar — Phosphate — Sugar — Phosphate — Sugar — Phosphate –

Base Base Base Base

a) Circle one nucleotide.

b) State the number of nucleotides shown in this diagram. ____________________

5. Refer to the figure below to identify structures A, B, C and D.



6. Explain why DNA replication is called 'semi-conservative'.

7. It is stated that DNA is the molecule that stores and transmits genetic information.

    a) State how DNA stores information.

    b) State how DNA transmits information from parent cells to daughter cells.

8. Name two organelles, other than the nucleus, in which DNA might be found in a eukaryotic cell. Suggest one possible reason for the presence of this DNA.

9. Discuss the differences between a chromosome and a sister chromatid.

10. Explain the significance of different species having different numbers and types of chromosomes.

11. Discuss the likely reasons that chromosomes are often referred to as 'structural units of information in organisms'.

12. A section of DNA molecule is analysed and it is found that 30% of its bases are guanine. Using your understanding of complementary base pairing, predict the percentage of bases that would be thymine.

13. The following sequence of bases was found in a segment of DNA.

    Write the sequence of bases that would be found in the complementary strand including 5' and 3' labelling.

    5' ...A A G G C T T G C... 3'

14. Watson and Crick, who were credited with discovering the structure of DNA, stated:

    "It has not escaped our notice that the specific base pairing we have postulated, immediately suggests a possible copying mechanism for genetic material."

    a) Using your knowledge of DNA structure provide reasons to justify this statement.

    b) Explain why DNA replication is essential for the production of new cells.

Science as a Human Endeavour 1.1 - A model for the structure of DNA

The work of *James Watson* and *Francis Crick* in determining the structure of DNA did not involve their original research but used the findings of other scientists. It started in 1869, when *Friedrich Miescher* from Switzerland identified a compound inside cell nuclei that was unknown until that time.

Phoebus Levene, from Russia, not only identified components of nucleotides but also suggested in 1919 that nucleic acids were polymers and that their monomers were nucleotides.

Oswald Avery was born in Canada but moved to the US when he was 10 years old. He demonstrated in 1944 that DNA carried genetic information.

Erwin Chargaff from Austria (emigrated to the United States in 1935), worked on the concept that the organic base adenine always seems to be present in the same amount as thymine and that the same applies to cytosine and guanine. In a discussion with Watson and Crick in 1952, this led to the idea of complementary base pairs.

Around this time, *Linus Pauling* suggested a helix shape for some proteins, using a relatively new technique at the time, called X-ray crystallography.

Rosalind Franklin, from the UK, used the same technique and found that DNA must also have a helical shape. From her X-ray patterns, she calculated the basic dimensions of the DNA molecule. Apparently, *Maurice Wilkins* (UK) showed Franklin's findings to Watson and Crick without her knowledge or permission.

Using all this information, Watson and Crick's first realisation, using cardboard cut-outs, was that the organic bases which are found between the sugar-phosphate backbones are paired only A-T and C-G. Then, using pieces of metal, they were able to build a model of DNA and found, among other things, that the sugar-phosphate backbones would have to run in opposite directions to satisfy known facts on bond angles and the way to account for the base-pairing.

The practical approach of Watson and Crick, building a model and checking it against known information, changing it and checking again, helped them make rapid progress in the discovery of the structure of DNA. One of the actual models they made is now on display in the National Science Museum in London.

Watson, Crick, and Wilkins received the Nobel Prize for their work on DNA in 1962. Since *Rosalind Franklin* had died in 1958, she could not be nominated for her vital contribution to this breakthrough in science. Wilkins was able to share the prize because of his working relationship with *Rosalind Franklin.*

Please refer to the online resource below to help answer question 2.

1. Discuss how developing the model for the structure of DNA relied on evidence across different disciplines of science.

Our understanding of the genetic code has continued to increase, especially since the completion of the Human Genome Project, which mapped every base of all 46 chromosomes.

Scientists now want to build the entire genome to increase our understanding of the human genome even further.

2. Discuss one positive and one negative impact that could possibly arise from building the human genome.

Helpful online resources

Columbia University Irving Medical Center: Building a human genome from scratch
<https://www.youtube.com/watch?v=Y0Ani2aw6cM>