H2

CORE IDEA 2: GENETICS AND INHERITANCE
TOPIC 2.1: STRUCTURE & FUNCTION OF NUCLEIC ACIDS

Learning Outcomes:

(a) Describe the structure and roles of DNA and RNA (tRNA, rRNA and mRNA) (knowledge of mitochondrial DNA is not required).

Use the knowledge gained in this section in new situations or to solve related problems.

References:
Reece, J. B., et al. (2011). Campbell Biology (9th Ed) Chapter 16 The Molecular Basis of Inheritance, p351 – 365

Note: These textbooks and references are available in our library. You may wish to borrow them to supplement your reading when necessary.

A Bridge to O Level Biology
(6093 syllabus and 5078 syllabus)

You should have learnt to:

(a) outline the relationship between DNA, genes and chromosomes

(b) state the structure of DNA in terms of the bases, sugar and phosphate groups found in each of their nucleotides

(c) state the rule of complementary base pairing

(d) state that DNA is used to carry the genetic code, which is used to synthesise specific polypeptides (details of transcription and translation are not required)

(e) state that each gene is a sequence of nucleotides, as part of a DNA molecule

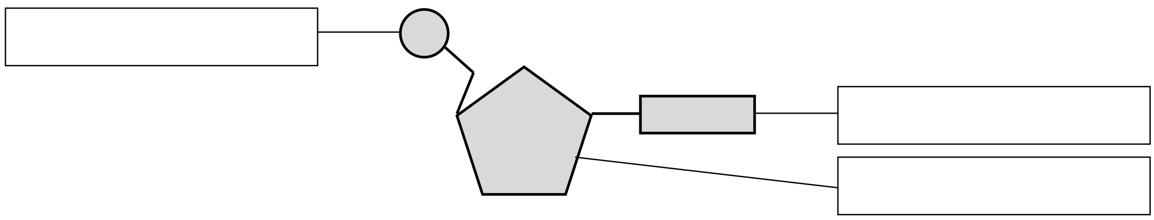
1 INTRODUCTION

Genetic information is stored in an organism's DNA; expression of genes results in the synthesis of functional products, such as rRNA, tRNA and proteins. These products play a role in intra- and extra-cellular biochemical pathways and influence the physiological processes in organisms.

Genomes contain heritable information necessary for continuity of life at all levels: cell, organism and system. This information is stored and passed on to subsequent generations via DNA. Reproduction can occur at the cellular or organismal level; each progeny needs to receive heritable genetic information from its parent(s).

Check Your Prior Knowledge

Fill in the blanks in the diagram below.



2 BASIC STRUCTURE OF NUCLEIC ACIDS

- There are two types of nucleic acids found in living cells:
  (i) deoxyribonucleic acid (DNA)
  (ii) ribonucleic acid (RNA)

- Both DNA and RNA exist as polynucleotide chains, made up of many nucleotides (monomer) joined together via condensation reactions.

2.1 STRUCTURE OF A NUCLEOTIDE

- A nucleotide is made up of three components bonded together via condensation reactions:

  (i) a pentose sugar
  (ii) a nitrogenous base
  (iii) one or more phosphate groups attached at the carbon 5 of the pentose sugar

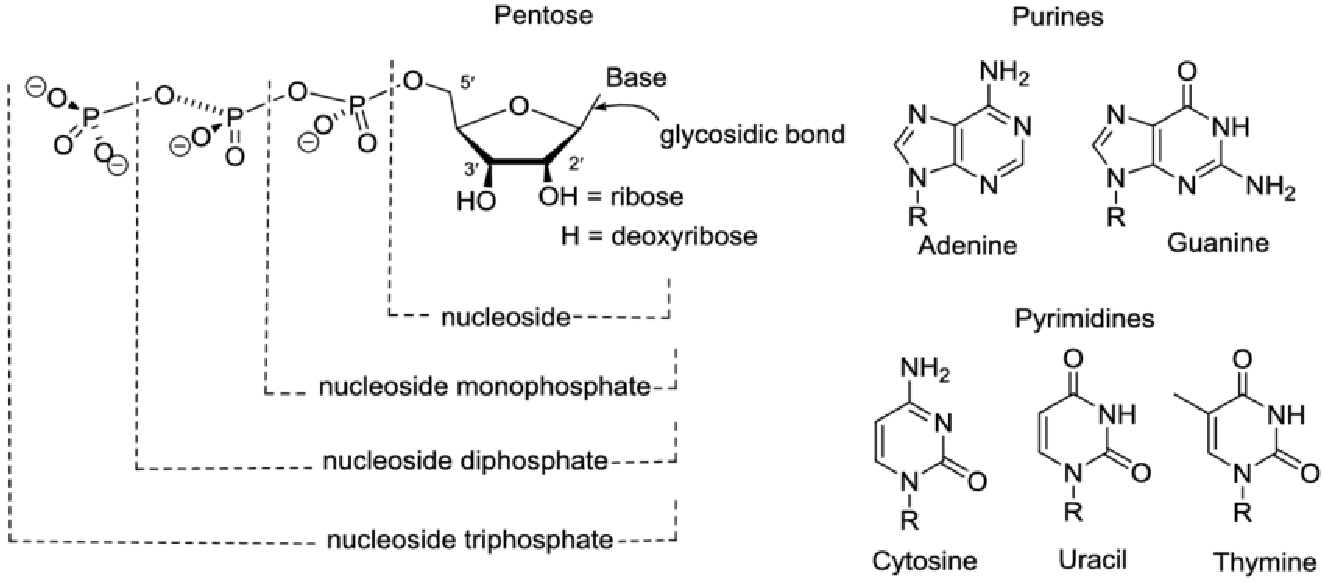


Fig. 2.1.1: Structure of a nucleotide

Pentose Sugar

- A pentose sugar is a monosaccharide with five carbon atoms.

- The pentose sugar in **DNA** is known as **<u>deoxyribose</u>**, and the pentose sugar in **RNA** is known as **<u>ribose</u>**.

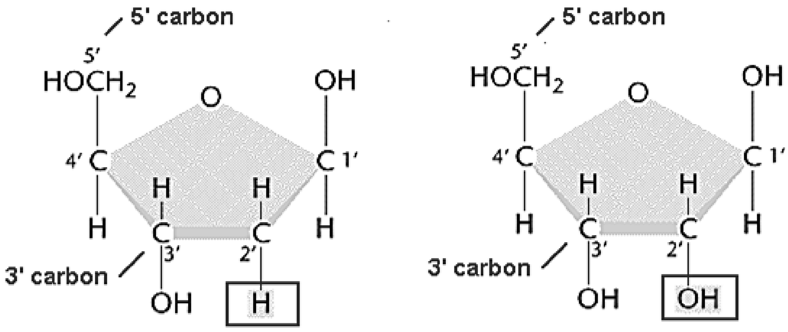


Fig. 2.1.2: Deoxyribose (left) and ribose (right)

Check Your Understanding
How does the structure of deoxyribose differ from ribose sugar?

Nitrogenous base

- Nitrogenous bases are cyclic organic compounds containing the atoms C, H, O, N.

- There are <u>two types of nitrogenous bases</u>: purines and pyrimidines.
  - **Purines** are larger, with a **six-membered ring** fused to a **five-membered ring**.
  - **Pyrimidines** only have a **six-membered ring**.

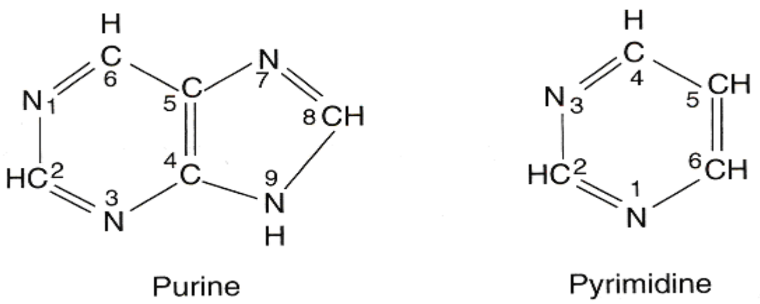
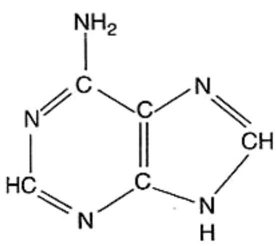


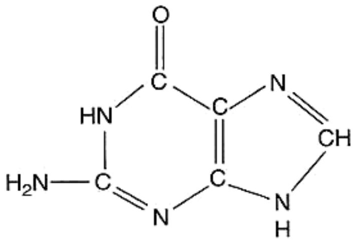
Fig. 2.1.3: Basic structure of purines and pyrimidines

CHECKPOINT 1

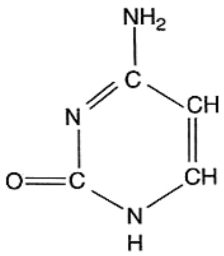
The figure below shows the various nitrogenous bases that make up different nucleotides in nucleic acids. Categorise the bases as **purines** or **pyrimidines**.



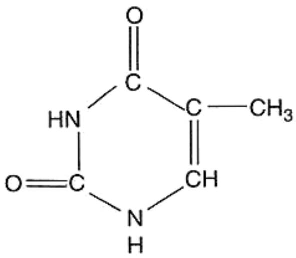
Adenine



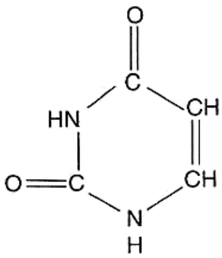
Guanine



Cytosine



Thymine



Uracil

Phosphate groups (originally phosphoric acid H_3PO_4)

- The phosphate group(s) is / are attached to the 5' carbon atom of the pentose sugar. This gives nucleic acids its acidic character.

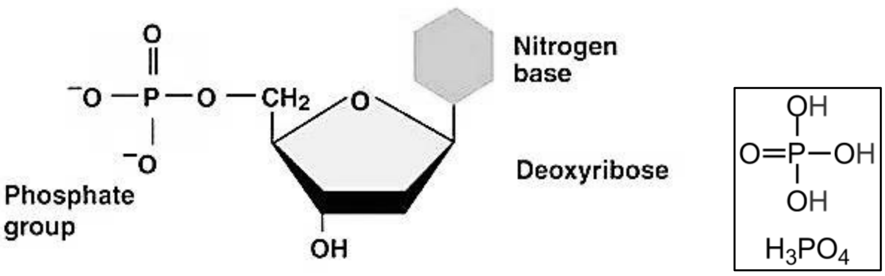


Fig. 2.1.4: Structure of a deoxyribonucleotide (left) and phosphoric acid (right)

2.2 STRUCTURE OF A POLYNUCLEOTIDE

- A polynucleotide chain is made up of multiple nucleotides joined together via the formation of **phosphodiester bond**s, hence resulting in a sugar-phosphate backbone in the polynucleotide.
  - Phosphodiester bonds are formed via a **condensation reaction** between the **phosphate group** on the **carbon 5** (5' phosphate) of one nucleotide and the **hydroxyl group** on the **carbon 3** (3' hydroxyl group) of an adjacent nucleotide.

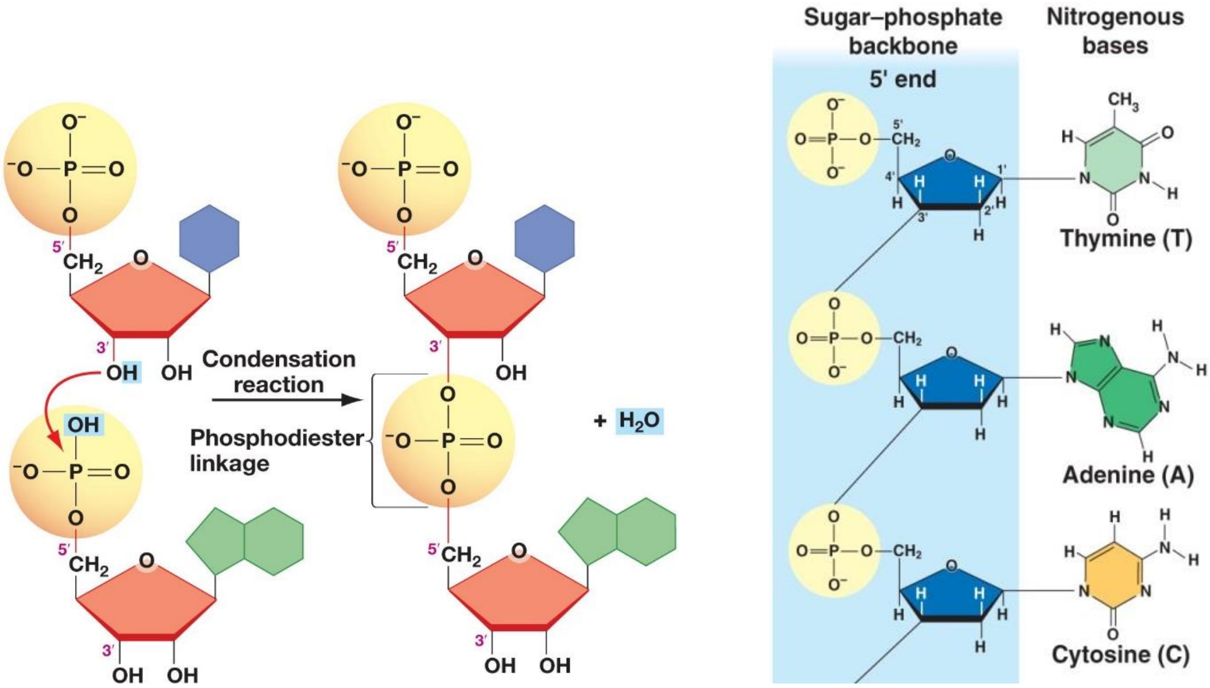


Fig. 2.2.1: Formation of phosphodiester bond (left) to form a polynucleotide (right)

- Polynucleotide chains exhibit polarity, with a **5' end** and **3' end**.
  - The 5' end of a polynucleotide ends with a phosphate group attached to carbon 5 of the sugar (pentose) of the nucleotide.
  - The 3' end of a polynucleotide ends with the hydroxyl group on carbon 3 of the sugar (pentose) of the nucleotide.

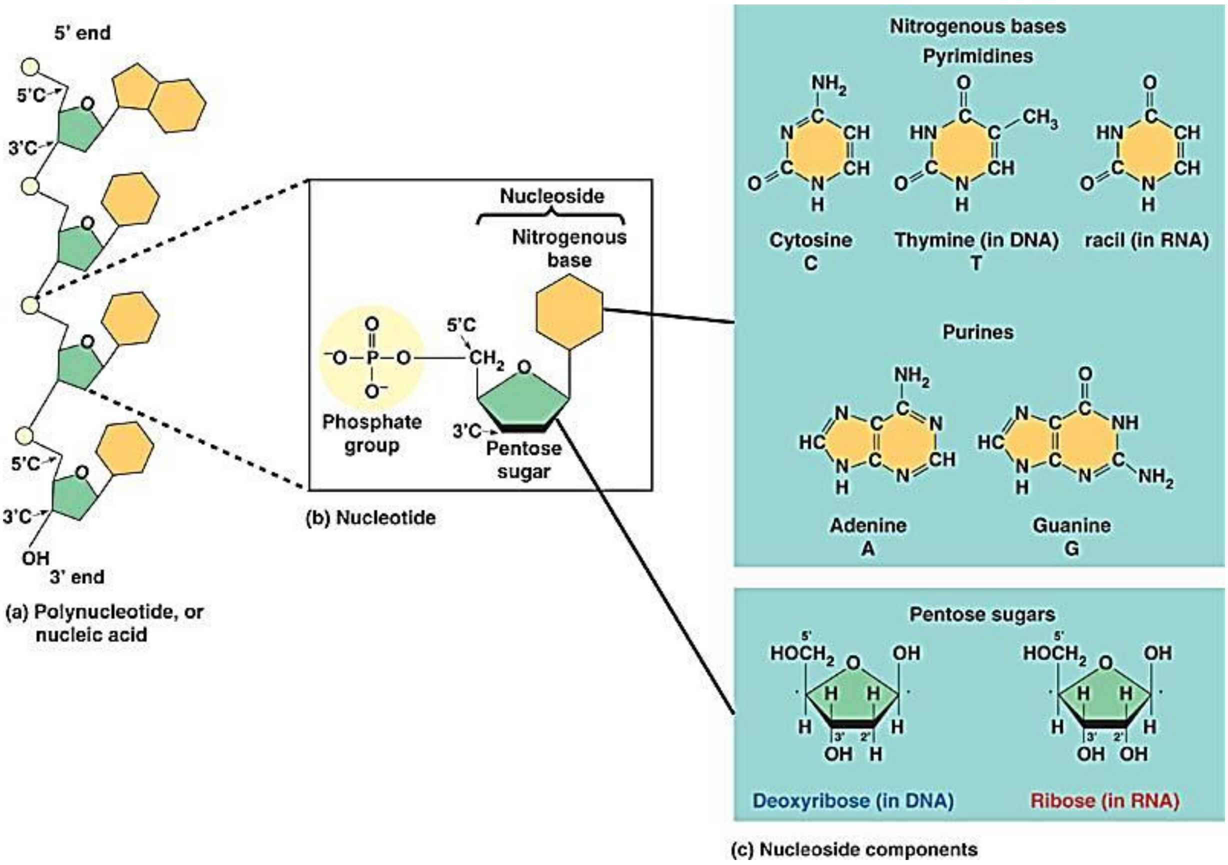


Fig. 2.2.2: Structure of a polynucleotide

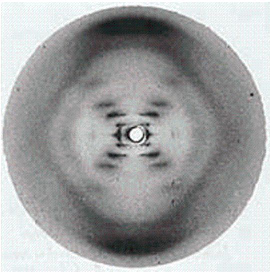
<u>PRACTICES OF SCIENCE</u>

(POS 1.1 and 1.3, pg. 4 syllabus)

DNA was first identified in the late 1860s by Swiss chemist Friedrich Miescher.

Then, in the decades following Miescher's discovery, other scientists – notably, Phoebus Levene and Erwin Chargaff – carried out a series of research efforts that revealed additional details about the DNA molecule, including its primary chemical components and the ways in which they joined with one another.

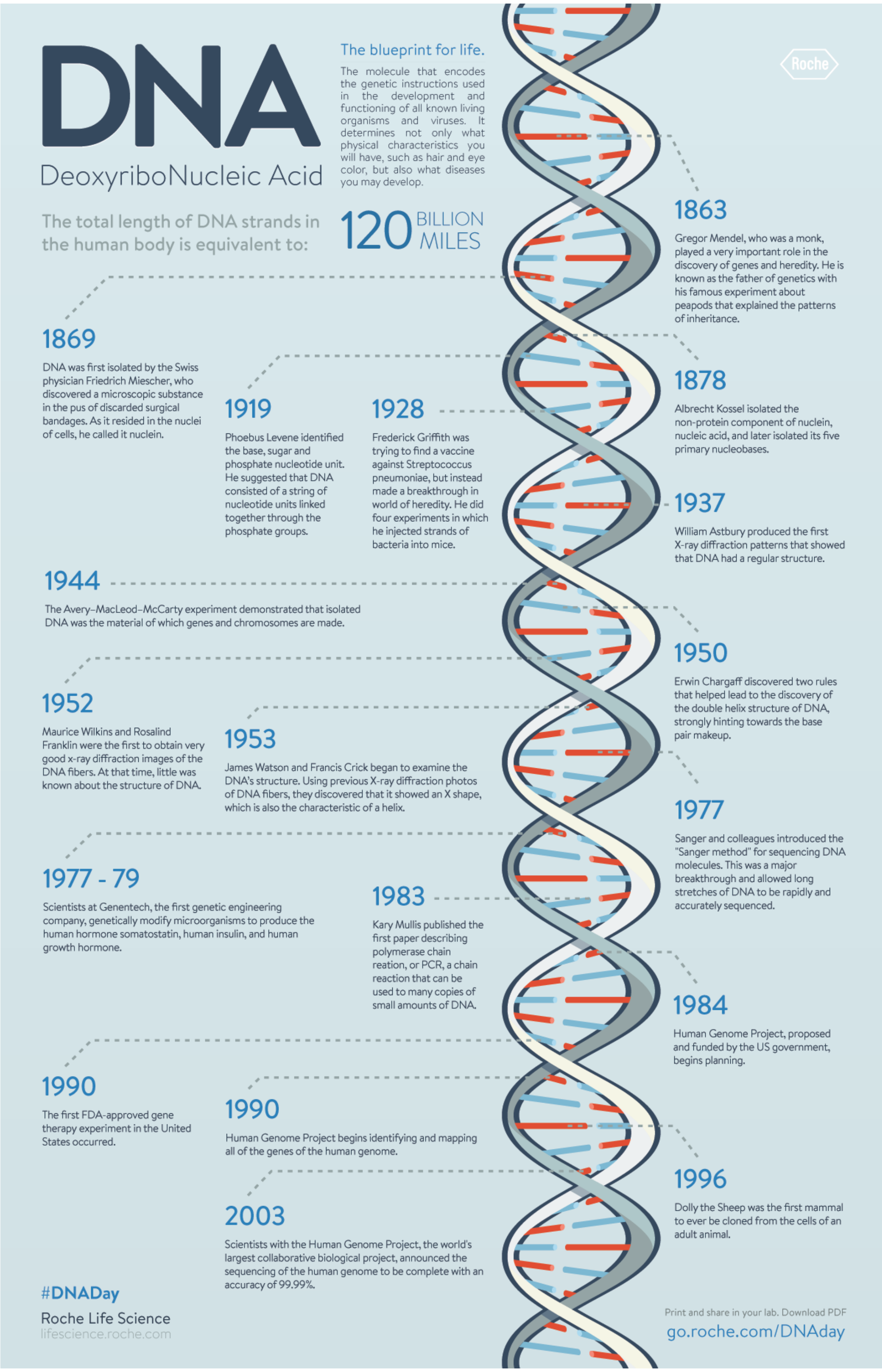
X-ray diffraction studies by Rosalind Franklin (refer to figure below (left)) proved to be one critical piece of information for the discovery of the double helix by **James D. Watson** and **Francis Crick** (refer to figure below (right)) in **1953**. Together with Maurice H. F. Wilkins, Watson and Crick were jointly awarded the **Nobel Prize in Physiology or Medicine in 1962**. They were the first scientists to formulate an accurate description of this molecule's complex, double-helical structure.



PRACTICES OF SCIENCE

(POS 1.1 and 1.3, pg. 4 syllabus)

Apart from the scientists mentioned, many other scientists were involved in the discovery of DNA and its applications. The figure below shows some key milestones in the discovery of DNA.



3 DEOXYRIBONUCLEIC ACID (DNA)

Learning Outcome 2(a) modified:
Describe the **structure** of **DNA**.

3.1 STRUCTURE OF A DNA MOLECULE

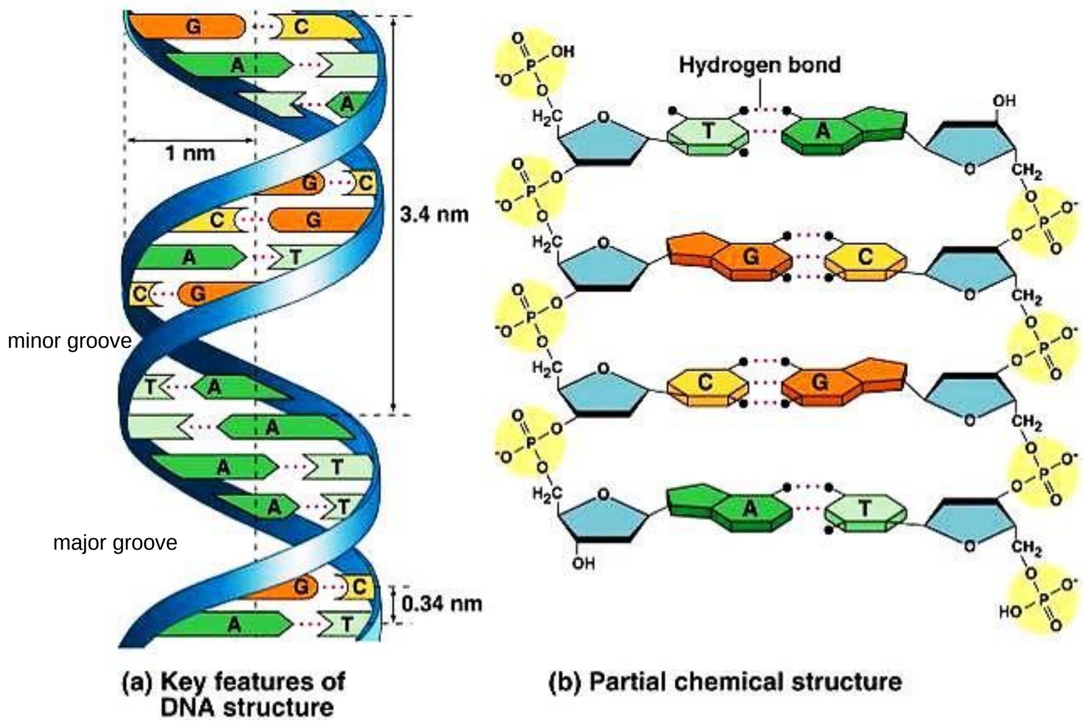


Fig. 3.1.1: Structure of a DNA molecule

The DNA molecule:

(i) consists of **two polynucleotide chains** twisted around each other to form a **double helix**;

(ii) has **sugar-phosphate backbone**s arranged in an **antiparallel** fashion with one strand running in the **5' → 3'** direction and the other strand in the **3' → 5'** direction. The sugar-phosphate backbones of both strands lie on the outside of the DNA molecule with the nitrogenous bases occupying the centre;

(iii) consists of **10 base pairs per complete turn**, with each turn separated by a distance of **3.4 nm** i.e. each base pair being 0.34 nm apart;

(iv) has a constant **diameter of 2 nm** with bases stacked on top of one another in a regular fashion;

(v) is stabilised by **hydrogen bonds** between **nitrogenous bases** of opposite strands between complementary purine and pyrimidine bases (refer to Section 2.1.1);

(vi) is stabilised by **hydrophobic interactions** between the **stacked bases**;

(vii) is **negatively charged** due to the presence of **phosphate groups**;

(viii) consists of **major grooves** and **minor grooves**. The major groove occurs where the sugar-phosphate backbones are far apart, the minor groove occurs where they are close together.

3.1.1 Chargaff's Rule

- Chargaff analysed the ratio of purines to pyrimidines for a variety of organisms and discovered that the concentration of purines always equal that of pyrimidines:

$$[A] + [G] = [T] + [C]$$
$$[A] = [T] \text{ and } [G] = [C]$$

- This indicates that bases display specific base pairing properties, known as **complementary base pairing**:
  - **Adenine** (A) pairs with **Thymine** (T), forming **2 H bonds**.
  - **Cytosine** (C) pairs with **Guanine** (G), forming **3 H bonds**.

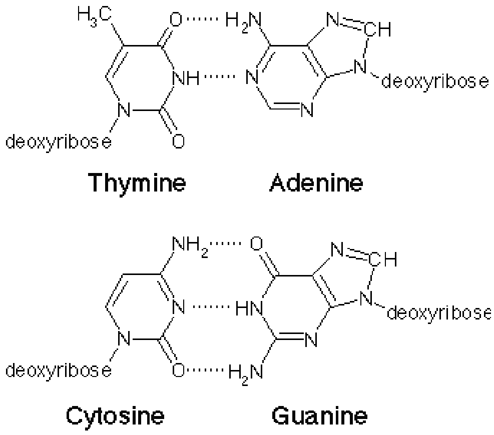


Fig. 3.1.1.1: Complementary base pairing

Organism	Base Composition (mole percent) A	T	G	C
Escherichia coli (K12)	26.0	23.9	24.9	25.2
Mycobacterium tuberculosis	15.1	14.6	34.9	35.4
Yeast	31.3	32.9	18.7	17.1
Herring	27.8	27.5	22.2	22.6
Rat	28.6	28.4	21.4	21.5
Human	30.9	29.4	19.9	19.8

Fig. 3.1.1.2: Composition of DNA in different organisms

Complementary base paring is important in:

(i) DNA replication
Daughter DNA strands are synthesized using complementary base-pairing rules with the parent template, allowing for accurate **replication of DNA** via **semi-conservative replication**.

(ii) DNA repair
It allows for **repair** in the event of DNA mutations. The mutated nucleotide can be replaced using the complementary DNA strand as a template for reference.

(iii) Stability of DNA molecule
In addition to hydrophobic interactions between the stacked bases, hydrogen bonds between complementary bases help to stabilise the DNA double helix.

Pairing of a purine with a pyrimidine also results in a uniform diameter of 2 nm throughout the DNA molecule.

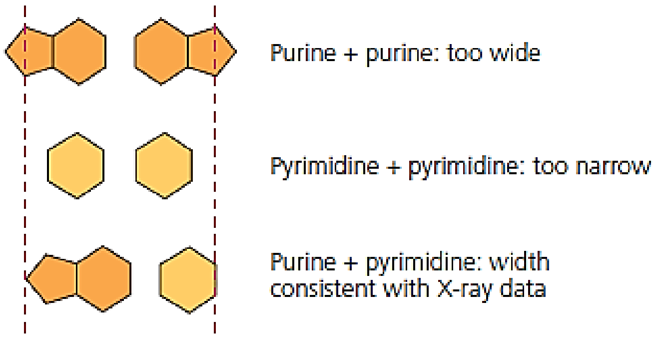
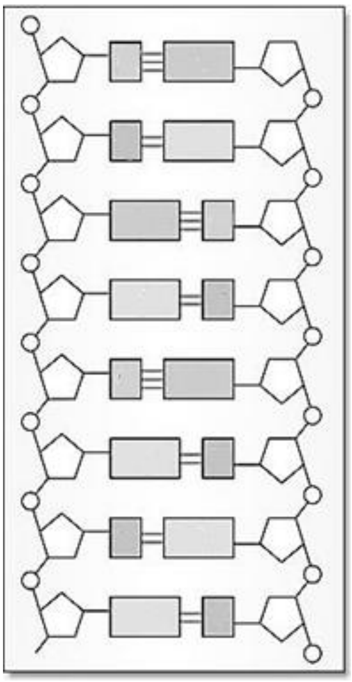


Fig. 3.1.1.3: Diameter between different base pairings

CHECKPOINT 2



(a) Identify the nitrogenous bases.

(b) Calculate the number of hydrogen bonds holding the DNA molecule together as shown in the diagram. Show your working clearly.

(c) The melting point of this DNA molecule is 70ºC. Predict the melting point in terms of higher / lower than 70ºC in a DNA molecule of the same length with a

(i) higher concentration of A / T pairs.

(ii) higher concentration of C / G pairs.

3.2 ROLE OF DNA

Learning Outcome 2(a) modified:

Describe the **role** of **DNA**.

- In each organism, DNA performs the following functions:

(i) Genotypic function of replication

− Genetic material is stored in the form of DNA, which is **inherited** and needs to be accurately transmitted from parent to offspring in every generation. This hereditary information is encoded in a gene, a sequence of nucleotides that code for a functional protein or RNA product.

(ii) Phenotypic function of gene expression

− Genes are **transcribed** to form messenger RNA (mRNA), which are then **translated** to form proteins. Many essential products of gene expression are enzymes involved in biochemical pathways, which control physiological functions.

4 RIBONUCLEIC ACID (RNA)

Learning Outcome 2(a) modified:

Describe the **structure** and **roles** of **RNA** **(tRNA, rRNA and mRNA)**.

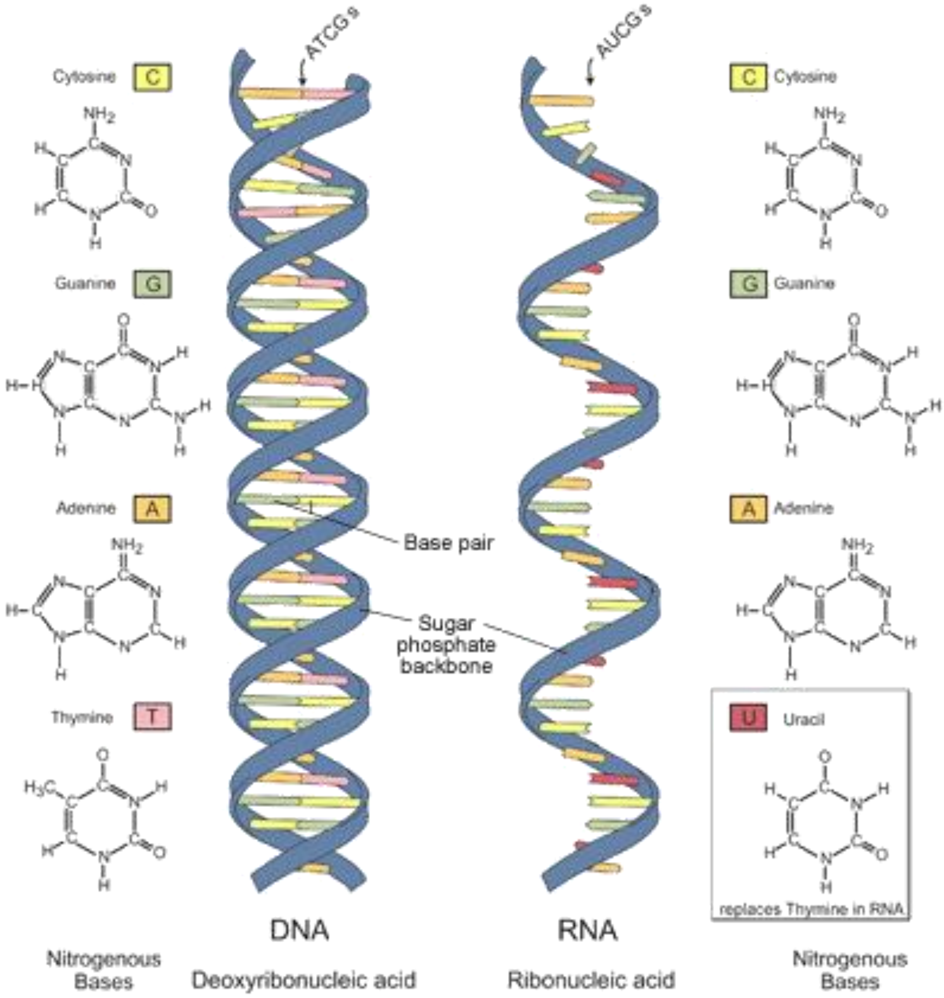


Fig. 4.1: Comparison between DNA and RNA

- In eukaryotes, RNA is usually **single stranded**. RNA exists as polynucleotide chains, made up of many **ribonucleotides** joined together by **phosphodiester bonds**.

- In ribonucleotides, the pentose sugar is a ribose and the nitrogenous bases are adenine, guanine, cytosine and uracil instead of thymine.

4.1 MESSENGER RNA (mRNA)

<u>Structure</u>

- mRNA is a **single-stranded RNA** formed from a DNA template during transcription.

<u>Role</u>

- The base sequence of mRNA is **complementary to the sequence of the DNA template** that it was transcribed from.
- Carries the **genetic code** for a specific polypeptide.
- Upon leaving the nucleus through the nuclear pore, ribosomal subunits bind to mRNA for translation into polypeptide

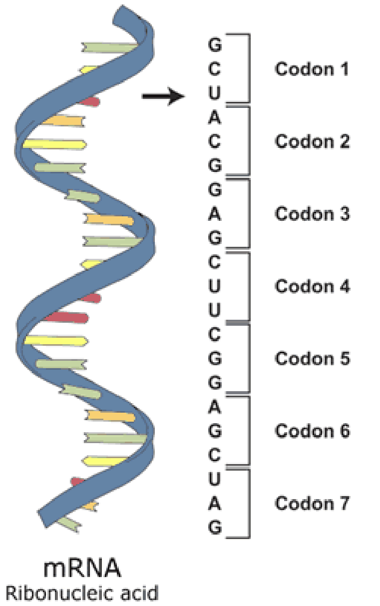


Fig. 4.1.1: Structure of mRNA

4.2 TRANSFER RNA (tRNA)

<u>Structure</u>

- tRNA is a **single-stranded RNA** folded into a **clover-leaf shape**, held by **intramolecular hydrogen bonds** between complementary bases pair at certain regions.
- It consists of **amino acid attachment arm**, **anticodon arm**, and two other loops (refer to table below).

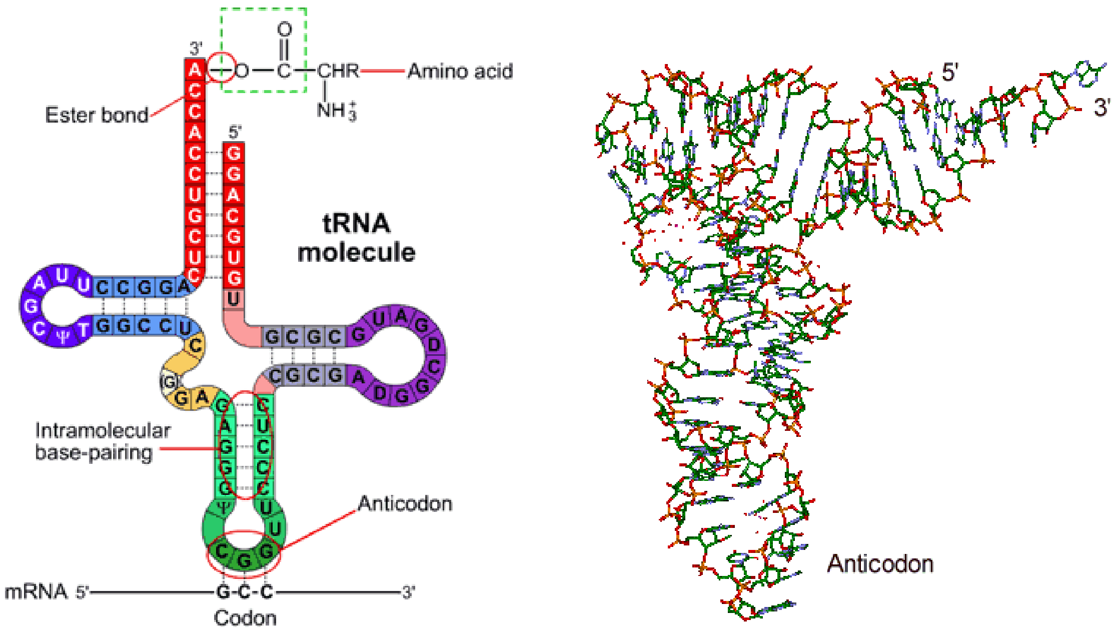


Fig. 4.2.1: Structure of a tRNA molecule

<u>Role</u>

- It functions to **carry a specific amino acid** to the ribosome for translation.

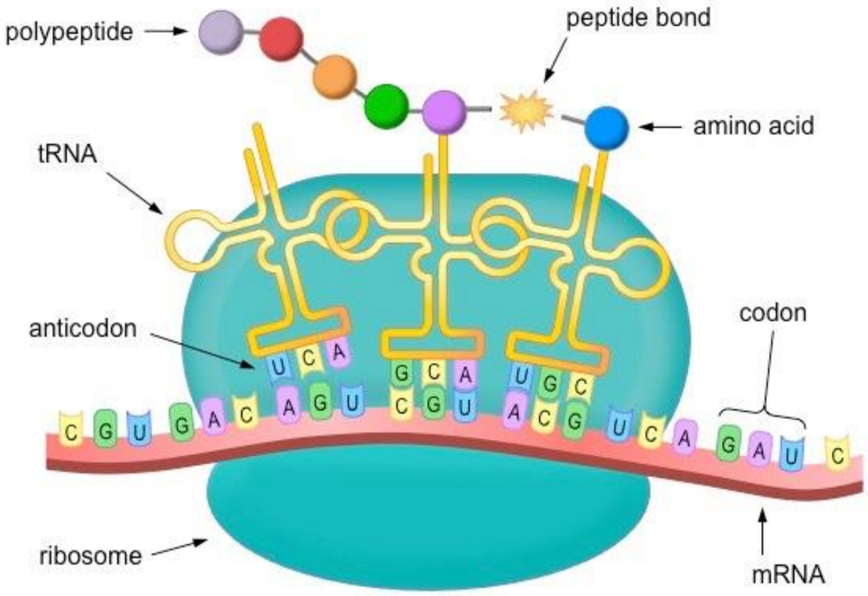


Fig. 4.2.2: Translation of mRNA

Structure	Function
Amino Acid Attachment Arm • 5' end has a guanine base (G) • 3' end has base sequence CCA (also called CCA stem)	**Site for binding of an amino acid** specific to the tRNA molecule by an ester bond
Anticodon Arm • Specific triplet base	This sequence is **complementary to the codon** found on mRNA. The anticodon determines the specific amino acid that is attached to the tRNA.
Clover-leaf Shape	**3D configuration** of the molecule, allowing for specific complementary binding with the ribosome and aminoacyl-tRNA synthetase

4.3 RIBOSOMAL RNA (rRNA)

<u>Structure</u>

- rRNA is a **single-stranded RNA** that folds onto itself into loops and bulges to create complex 3D structures. This structure is **stabilised by hydrogen bonds** between complementary bases and **hydrophobic interactions between the stacked bases**.

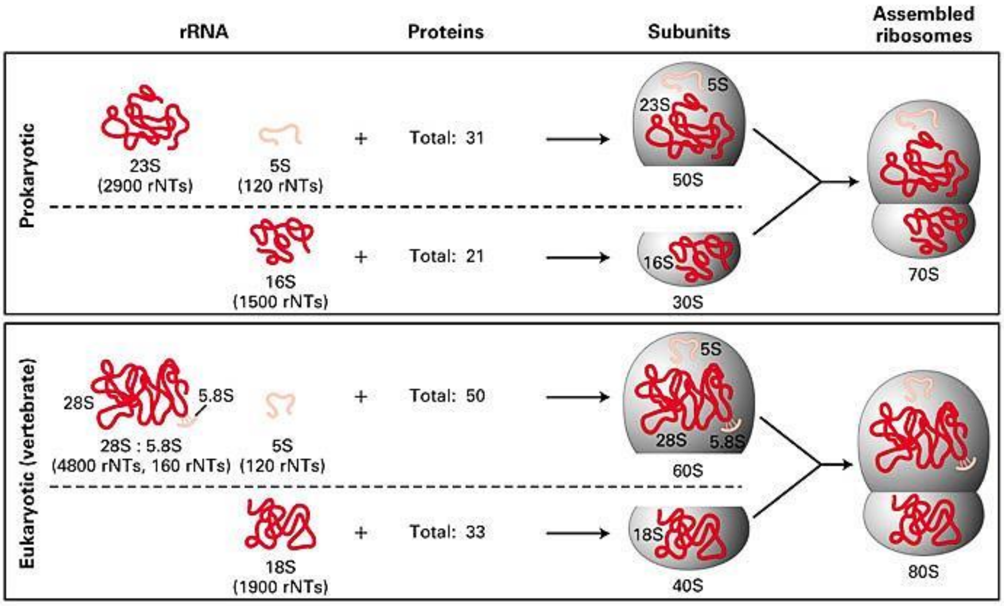


Fig. 4.3.1: Ribosomes made up of rRNA and ribosomal proteins

<u>Role</u>

- rRNA plays an important function in translation of mRNA to synthesise proteins:
  - It **associates with ribosomal proteins** to form ribosomal subunits. A large and small subunit associate to form the functional ribosome.
  - rRNA in the small subunit **binds to initiation tRNA** via complementary base pairing.
  - rRNA in the large subunit **interacts with initiation tRNA at P site** to complete Translation Initiation Complex (TIC).
  - It **binds to 5' UTR of mRNA** to search for the start codon (AUG) during translation initiation.
  - It **acts as peptidyl transferase** to catalyse peptide bond formation between amino acids.

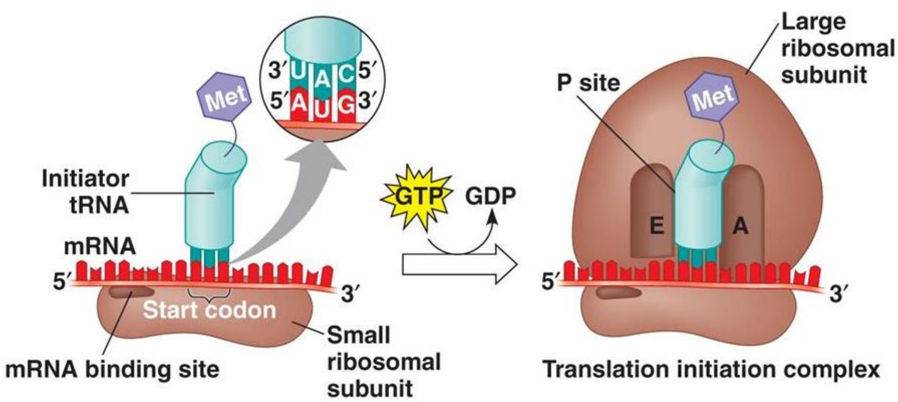


Fig. 4.3.2: Translation initiation

CHECKPOINT 3

Fill in the table below to compare between DNA and RNA.

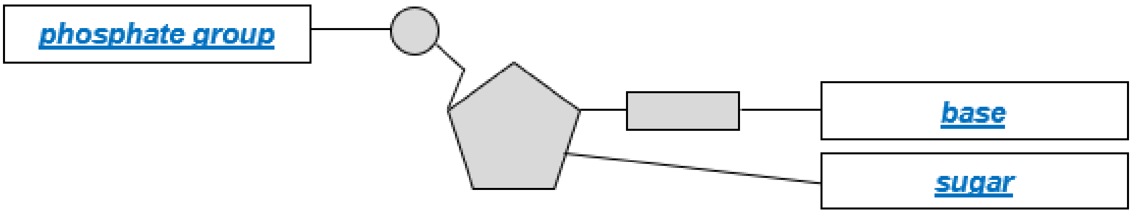
Feature	DNA	RNA
Monomer		
Pentose		
Bases Present		
No. of Strands		
Shape		
Function		
No. of Types		
Polymer		
Bonds		
Synthesis & Breakdown		

Answers

Page 2

Check Your Prior Knowledge

Fill in the blanks in the diagram below.



Page 3

Check Your Understanding

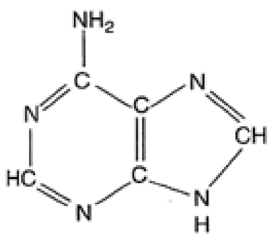
How does the structure of deoxyribose differ from ribose sugar?

C2 of deoxyribose has <u>an</u> hydrogen atom while ribose has a hydroxyl group attached

Page 4

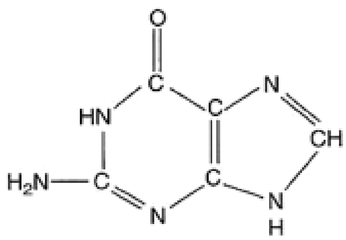
<u>CHECKPOINT 1</u>

The figure below shows the various nitrogenous bases that make up different nucleotides in nucleic acids. Categorise the bases as **purines** or **pyrimidines**.



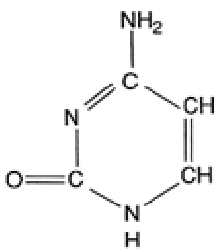
Adenine

purine



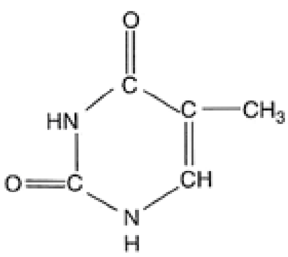
Guanine

purine



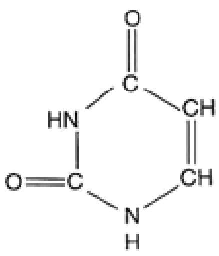
Cytosine

pyrimidine



Thymine

pyrimidine

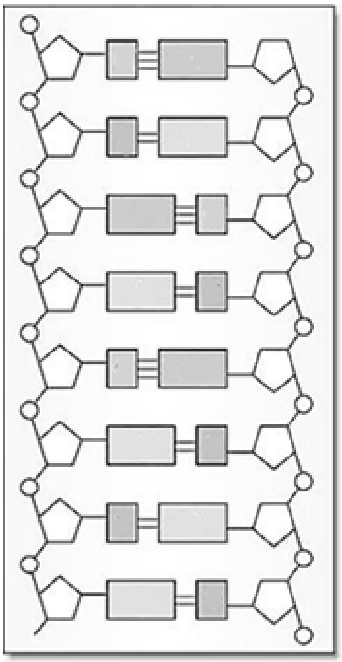


Uracil

pyrimidine

Page 10

CHECKPOINT 2



(a) Identify the nitrogenous bases.

(b) Calculate the number of hydrogen bonds holding the DNA molecule together as shown in the diagram. Show your working clearly.

No. of A-T pairs = 5 ***No. of C-G pairs = 3***
Total no. of H-bonds = (5*2) + (3*3) = 19

(c) The melting point of this DNA molecule is 70ºC. Predict the melting point in terms of higher / lower than 70ºC in a DNA molecule of the same length with a

(i) higher concentration of A / T pairs.

Melting point is ***lower***

(ii) higher concentration of C / G pairs.

Melting point is ***higher***

Page 15

CHECKPOINT 3

Fill in the table below to compare between DNA and RNA.

Feature	DNA	RNA
Monomer	*deoxyribonucleotides*	*ribonucleotides*
Pentose	*deoxyribose*	*ribose*
Bases Present	*adenine, cytosine, guanine, thymine*	*adenine, cytosine, guanine, uracil*
No. of Strands	*double stranded*	*single stranded*
Shape	*double helix*	*different shapes e.g. linear mRNA, clover-leaf shaped tRNA*
Function	*carries heritable genetic information that controls DNA replication and protein synthesis*	*involved in protein synthesis*
No. of Types	*only 1*	*multiple types e.g. mRNA, tRNA, rRNA*
Polymer	*both are polynucleotides*	
Bonds	*both have monomers are held by phosphodiester bonds formed between 5' phosphate and 3' hydroxyl group of adjacent nucleotides*	
Synthesis & Breakdown	*both are formed via condensation reactions of monomers where water will be produced, and broken down via hydrolysis where water is required*	