A1.2 Nucleic acids

Unity and diversity—Molecules

Standard level and higher level: 3 hours

Additional higher level: 2 hours

Guiding questions

• How does the structure of nucleic acids allow hereditary information to be stored?

• How does the structure of DNA facilitate accurate replication?

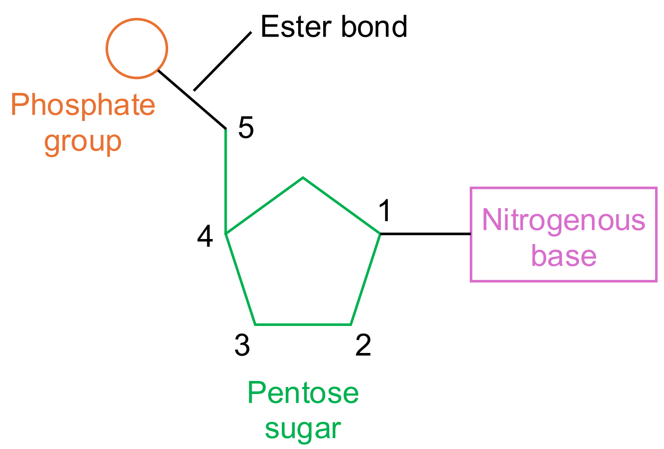
SL and HL

A1.2.1—DNA as the genetic material of all living organisms
Some viruses use RNA as their genetic material but viruses are not considered to be living.

- **Deoxyribonucleic acid (DNA)** is the molecule that stores the genetic material of all living organisms
- Viruses use DNA or **ribonucleic acid (RNA)** as their genetic material but are not considered living because they do not carry out all the functions of life

A1.2.2—Components of a nucleotide
In diagrams of nucleotides use circles, pentagons and rectangles to represent relative positions of phosphates, pentose sugars and bases.

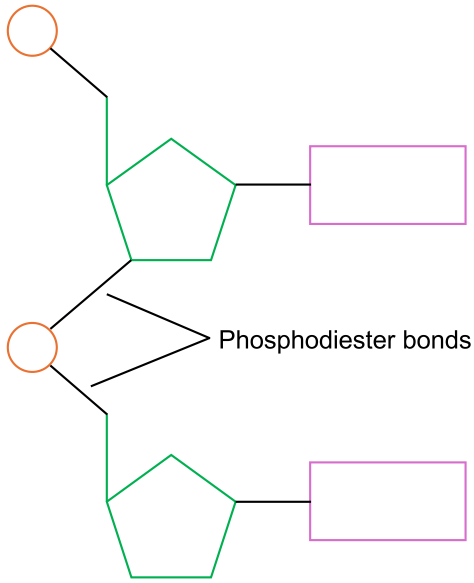
- A **nucleotide** is a molecule consisting of 3 chemical groups:
  - **Pentose (5-carbon) sugar**: connected to the nitrogenous base at the 1’ carbon and to the phosphate group at the 5’ carbon within the same nucleotide
    - The pentose sugar can be either **deoxyribose** (in DNA) or **ribose** (in RNA)
  - **Phosphate group (PO_4^{-3})**: connected to the 5’ carbon of one pentose sugar via an **ester bond**
    - This group gives DNA its acidity and negative charge
  - **Nitrogenous base**: connected to the pentose sugar at the 1’ carbon
    - Nitrogenous bases are composed of one or two carbon rings that contain nitrogen



A1.2.3—Sugar–phosphate bonding and the sugar–phosphate "backbone" of DNA and RNA

Sugar–phosphate bonding makes a continuous chain of covalently bonded atoms in each strand of DNA or RNA nucleotides, which forms a strong "backbone" in the molecule.

- Nucleotides can connect to other nucleotides via **condensation** reactions in which the hydroxyl group of the 3' carbon in a pentose sugar bonds with the phosphate group of another nucleotide, forming an **ester bond** (a type of covalent bond)
  - This results in a **phosphodiester bond**, which links 1 phosphate group to 2 different pentose sugars (each via 1 ester bond, hence **di**ester)
- A **polynucleotide** is formed when many nucleotides are covalently linked via phosphodiester bonds
  - Since only the nitrogenous bases change within a polynucleotide, the continuous chain of alternating sugar and phosphate groups, linked by phosphodiester bonds, is considered the "backbone"
- DNA is composed of **two** polynucleotide chains (**strands**) linked by hydrogen bonding at their nitrogenous bases
- RNA is composed of **one** polynucleotide chain



A1.2.4—Bases in each nucleic acid that form the basis of a code

Students should know the names of the nitrogenous bases.

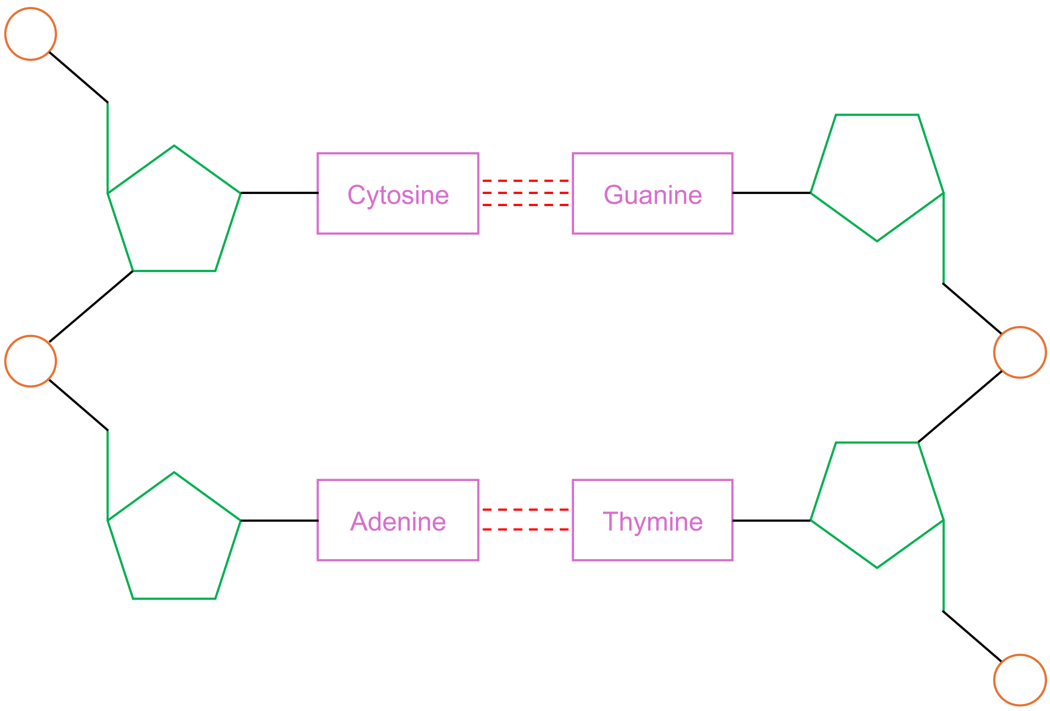
- There are 5 nitrogenous bases that give nucleotides their identities:
  - **Adenine (A)** – hydrogen bonds with T and U only
  - **Guanine (G)** – hydrogen bonds with C only
  - **Cytosine (C)** – hydrogen bonds with G only
  - **Thymine (T)** – hydrogen bonds with A only (only found in DNA)
  - **Uracil (U)** – only found in RNA
- The sequence of nucleotides (i.e. the code) within a DNA or RNA molecule stores information about the proteins and RNA molecules that govern cellular functions

A1.2.5—RNA as a polymer formed by condensation of nucleotide monomers
Students should be able to draw and recognize diagrams of the structure of single nucleotides and RNA polymers.

- **RNA** is a polymer formed by condensation of ribose nucleotides with many functions:
  - **Messenger RNA (mRNA)**: transcribes DNA and acts as a template during protein synthesis
  - **Transfer RNA (tRNA)**: transfers amino acids to a growing polypeptide chain during protein synthesis
  - **Ribosomal RNA (rRNA)**: catalyzes protein synthesis

A1.2.6—DNA as a double helix made of two antiparallel strands of nucleotides with two strands linked by hydrogen bonding between complementary base pairs
In diagrams of DNA structure, students should draw the two strands antiparallel, but are not required to draw the helical shape. Students should show adenine (A) paired with thymine (T), and guanine (G) paired with cytosine (C). Students are not required to memorize the relative lengths of the purine and pyrimidine bases, or the numbers of hydrogen bonds.

- DNA has a double helix structure
  - The sugar-phosphate backbone lies outside the helix and the nitrogenous bases are stacked inside it
  - The helix's two strands run in opposite directions (**antiparallel** to each other)
    - The 5′ carbon end of one strand (i.e. the phosphate group) will face the 3′ carbon end (i.e. the pentose sugar) of its matching strand



A1.2.7—Differences between DNA and RNA

Include the number of strands present, the types of nitrogenous bases and the type of pentose sugar. Students should be able to sketch the difference between ribose and deoxyribose. Students should be familiar with examples of nucleic acids.

DNA	RNA
Double stranded	Single stranded
Deoxyribose sugar	Ribose sugar
Uses thymine but not uracil	Uses uracil but not thymine
Double helix	Variable shape depending on type of RNA
Fixed function (storage of genetic information)	Variable functions
Stable	Less stable
Use adenine, guanine, and cytosine	
Sugar-phosphate backbone	

A1.2.8—Role of complementary base pairing in allowing genetic information to be replicated and expressed

Students should understand that complementarity is based on hydrogen bonding.

- **Complementary base pairing** is the specific pairing of nitrogenous bases with each other through hydrogen bonding
  - This is important because it creates structural stability and integrity that allows genetic information to be stored, replicated, and transcribed in an accurate manner
- Cytosine and Guanine pair together because they both only form 3 hydrogen bonds
- Adenine and Thymine pair together because they both only form 2 hydrogen bonds

A1.2.9—Diversity of possible DNA base sequences and the limitless capacity of DNA for storing information

Explain that diversity by any length of DNA molecule and any base sequence is possible. Emphasize the enormous capacity of DNA for storing data with great economy.

- Genetic information in DNA is stored in the sequence of nitrogenous bases
- Every sequence of 3 consecutive DNA nucleotides is a **codon**, corresponding to a specific amino acid
  - The amino acids are used to build proteins, which control life functions
- For a DNA or RNA strand with ***n*** bases, there are $\mathbf{4^n}$ possible different sequences
  - This makes the capacity of DNA for storing information virtually limitless, which explains the great biodiversity on Earth

A1.2.10—Conservation of the genetic code across all life forms as evidence of universal common ancestry
Students are not required to memorize any specific examples.

- The genetic code (instructions stored in nitrogenous bases for protein synthesis) is universal because all organisms use the 5 nitrogenous bases
- The conservation of the genetic code across all life forms is evidence of universal common ancestry
  - This is because if different organisms originated independently, it is more likely that they would evolve different genetic codes (but this is not the case)

Additional higher level

A1.2.11—Directionality of RNA and DNA
Include 5' to 3' linkages in the sugar–phosphate backbone and their significance for replication, transcription and translation.

- Each DNA strand has a 5' and 3' end; the 3' end is aligned with the 5' end of the other strand (antiparallel)
- The directionality of DNA and RNA is crucial for DNA replication, transcription, and translation
  - **DNA replication**: enzymes synthesize DNA nucleotides in a **5' to 3' direction** relative to the **new strand** and a **3' to 5' direction** relative to the **template** strand
  - **Transcription**: enzymes synthesize RNA nucleotides in a **5' to 3' direction** relative to the **mRNA strand** and a **3' to 5' direction** relative to the **template** (**antisense**) strand
  - **Translation**: ribosomes bind to the **5' end** of mRNA to begin protein synthesis

A1.2.12—Purine-to-pyrimidine bonding as a component of DNA helix stability
Adenine–thymine (A–T) and cytosine–guanine (C–G) pairs have equal length, so the DNA helix has the same three-dimensional structure, regardless of the base sequence.

- **Purines** are nitrogenous bases with 2 carbon–nitrogen rings, like A and G
- **Pyrimidines** are nitrogenous bases with 1 carbon–nitrogen ring, like C, T, and U
- Purines form hydrogen bonds with pyrimidines (vice versa), which stabilizes DNA by ensuring equidistance of the two DNA strands at every point along the molecule
  - Even though cytosine and guanine form 3 hydrogen bonds and adenine with thymine only form 2 hydrogen bonds, all pairs have equal length

A1.2.13—Structure of a nucleosome

Limit to a DNA molecule wrapped around a core of eight histone proteins held together by an additional histone protein attached to linker DNA.
Application of skills: Students are required to use molecular visualization software to study the association between the proteins and DNA within a nucleosome.

- The length of 1 DNA molecule is ~ 2 meters, so it needs to be condensed to fit into a cell
- **Nucleosomes** are most basic structural unit of DNA packing in eukaryotes, consisting of:
  - **Histone octamer (nucleosome core)**: an 8-protein complex composed of 4 pairs of histones (H2A, H2B, H3, H4)
    - Each histone is rich in positively charged amino acids (lysine and arginine) in order to associate strongly with the negatively charged DNA
  - **H1 linker histone**: binds to the DNA as it enters and exists the octamer core to control coiling
  - **Linker DNA**: a section of the DNA strand that connects two nucleosomes together
  - **Core DNA**: ~147 nucleotides in length of DNA wrapping around the nucleosome core
- Nucleosomes play an essential role in gene expression by packing DNA into 30nm fibers

A1.2.15—Chargaff's data on the relative amounts of pyrimidine and purine bases across diverse life forms

NOS: Students should understand how the "problem of induction" is addressed by the "certainty of falsification". In this case, Chargaff's data falsified the tetranucleotide hypothesis that there was a repeating sequence of the four bases in DNA.

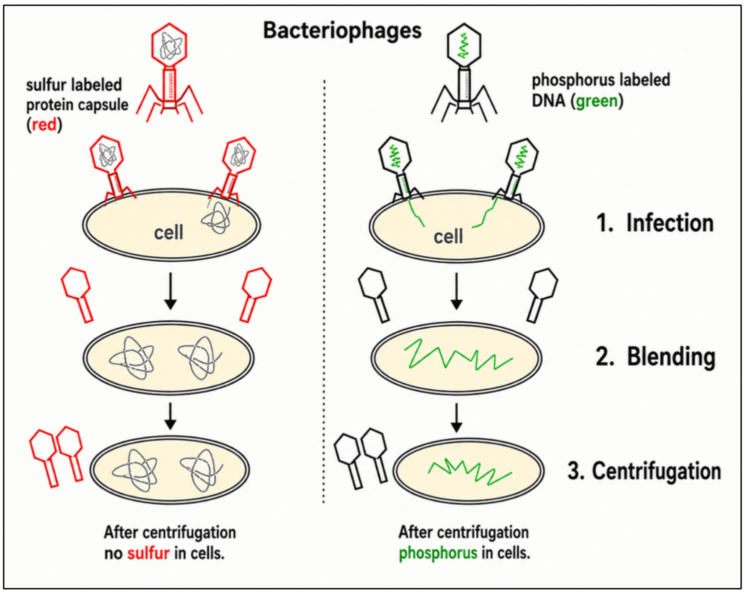
- The **tetranucleotide hypothesis** posits that DNA contains a repeating sequence of the 4 bases
  - This implies that all 4 nitrogenous bases are in equal amounts (A = T = C = G)
- A criticism of the tetranucleotide hypothesis is that the repetitive DNA sequence could **not** explain the diversity of life
- Chargaff conducted experiments to measure the relative amounts of pyrimidine and purine bases in different organisms
  - He observed that A = T, C = G, but A ≠ C
- Chargaff's data thus falsified the tetranucleotide hypothesis by contradicting its predictions, which serves as an example of how the problem of induction in science is addressed by the certainty of falsification
  - The problem of induction is that repeated observations cannot prove a hypothesis, but an observation that contradicts the hypothesis is enough to falsify it

NOS: Students should appreciate that technological developments can open up new possibilities for experiments. When radioisotopes were made available to scientists as research tools, the Hershey–Chase experiment became possible.

- **Radioisotopes** are **isotopes** (versions) of chemical elements that are **radioactive** (unstable and decay with time)
  - They emit radiation when they decay to more stable forms, which can be detected by scientists and then used in experiments for visualization
- Technological developments, like the use of radioisotopes, open up new possibilities for experiments

A1.2.14—Evidence from the Hershey–Chase experiment for DNA as the genetic material
Students should understand how the results of the experiment support the conclusion that DNA is the genetic material.

- The goal of the **Hershey–Chase experiment** was to determine whether the genetic material of living organisms is nucleic acids or proteins
- **Method**
  - A **bacteriophage** (a virus that infects bacteria) was grown in 2 different cultures:
    - A culture containing **radioisotopes** of **sulfur (S^{35})**: the sulfur would be incorporated in the protein outer coat of the virus but not in the DNA
    - A culture containing radioisotopes of **phosphorus (P^{32})**: the phosphorus would be incorporated in the viral DNA but not in its outer coat
  - The bacteriophage was allowed to infect *Escherichia coli*
  - After infection, the virus was detached from the bacteria using a blender & a centrifuge was used to separate the infected bacteria from the viral coats (by weight)
- **Results**
  - *E. coli* infected with S^{35} bacteriophages showed no radioactivity in the pellet
    - Since **s**ulfur is only found in proteins, & viral outer coatings do not enter bacterial cells, radioactivity was only detected in the **s**upernatant
  - *E. coli* infected with P^{32} bacteriophages showed radioactivity in the supernatant
    - Since **p**hosphorus is only found in DNA, which enters the bacteria, radioactivity was only detected in the **p**ellet
- This experiment provided strong evidence that DNA is the genetic material, but further research was done by scientists to confirm this



Linking questions

• What makes RNA more likely to have been the first genetic material, rather than DNA?

• How can polymerization result in emergent properties?

References

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