Nucleic Acid DNA and RNA

Nucleic Acids and Their Components

DNA and RNA are the two types of nucleic acids essential for genetic information storage and transfer. DNA serves as the genetic material in most organisms, while RNA functions mainly as a messenger and in some viruses as genetic material.

Structure of Polynucleotide Chain

Polynucleotides are polymers of nucleotides, each consisting of a nitrogenous base, a pentose sugar (deoxyribose in DNA and ribose in RNA), and a phosphate group. Nitrogenous bases are classified as purines (adenine and guanine) and pyrimidines (cytosine, thymine in DNA, and uracil in RNA). Nucleotides link via 3' to 5' phosphodiester bonds forming polynucleotide chains.

DNA Structure and Packaging

DNA is a double helix composed of two antiparallel polynucleotide strands with complementary base pairing (A-T and C-G) held by hydrogen bonds. Chargaff's rule states that the amount of adenine equals thymine and guanine equals cytosine. DNA is packaged in cells as chromatin, with nucleosomes formed by DNA wrapped around histone octamers, further coiling into chromosomes.

Genetic Material and Key Experiments

Experiments by Griffith, Avery, MacLeod, McCarty, and Hershey-Chase established DNA as the genetic material. Griffith's experiment demonstrated transformation in bacteria, while Avery and colleagues identified DNA as the transforming substance. Hershey and Chase confirmed DNA's role using bacteriophages labeled with radioactive isotopes.

RNA and Central Dogma

RNA is typically single-stranded and includes mRNA, tRNA, and rRNA, each playing roles in protein synthesis. The central dogma of molecular biology describes the flow of genetic information from DNA to RNA to protein, with reverse transcription occurring in some viruses.

DNA Replication

DNA replication is semi-conservative, producing two DNA molecules each with one original and one new strand. It involves unwinding by helicase, synthesis of RNA primers by primase, elongation by DNA polymerase in the 5' to 3' direction, and joining of Okazaki fragments on the lagging strand by DNA ligase. Proofreading ensures replication fidelity.

Transcription

Transcription is the synthesis of RNA from a DNA template strand in the 5' to 3' direction by RNA polymerase. It involves initiation at the promoter, elongation of the RNA chain, and termination at specific sequences. In eukaryotes, primary transcripts undergo capping, splicing to remove introns, and polyadenylation to form mature mRNA.

Solved Examples

Example 1

Calculate the number of nucleosomes in the nucleus of diploid eukaryotic cells with 2.2×10^6 base pairs.

Solution:

One nucleosome contains 200 base pairs.

Number of nucleosomes = Total base pairs / Base pairs per nucleosome = $2.2 \times 10^6 / 200 = 1.1 \times 10^4$ nucleosomes.

Therefore, there are 11,000 nucleosomes in the nucleus.

Practice Set

- **Level 1:** What are the three components of a nucleotide?
- **Level 2:** Explain Chargaff's rule and its significance in DNA structure.
- **Level 3:** Describe the role of histone proteins in DNA packaging in eukaryotic cells.

Answer Key

- **Level 1:** A nucleotide consists of a nitrogenous base, a pentose sugar, and a phosphate group.
- **Level 2:** Chargaff's rule states that in DNA, the amount of adenine equals thymine and guanine equals cytosine. This base pairing is crucial for the double helix structure and complementary strand formation.

- **Level 3:** Histone proteins, rich in basic amino acids, form octamers around which DNA wraps to form nucleosomes, aiding in compacting DNA into chromatin and regulating gene expression.

Genetic Material and Replication

Identification of Genetic Material

Experiments by Griffith demonstrated bacterial transformation, suggesting a 'transforming principle'. Avery, MacLeod, and McCarty identified DNA as this principle. Hershey and Chase confirmed DNA as genetic material using radioactive labeling of bacteriophage DNA and proteins.

Properties of Genetic Material

Genetic material must replicate accurately, be chemically stable, allow mutations for evolution, store genetic information, and express Mendelian traits. DNA is more stable than RNA, making it a better genetic material for long-term storage.

DNA Replication Mechanism

DNA replication is semi-conservative, with each parental strand serving as a template. Replication begins at origins, forming replication forks. DNA polymerase synthesizes new strands in the 5' to 3' direction, with continuous synthesis on the leading strand and discontinuous synthesis on the lagging strand via Okazaki fragments joined by DNA ligase.

Experimental Proof of Semi-Conservative Replication

Meselson and Stahl used isotopes of nitrogen to label DNA and demonstrated that after replication, DNA molecules contain one old and one new strand, confirming the semi-conservative model.

Solved Examples

Example 1

Explain the significance of Meselson and Stahl's experiment in understanding DNA replication.

Solution:

They cultured bacteria in heavy nitrogen (^{15}N) and then transferred them to light nitrogen (^{14}N). After replication, DNA showed intermediate density, indicating each DNA molecule had one old and one new strand, proving semi-conservative replication.

Practice Set

- **Level 1:** What is meant by semi-conservative replication?
- **Level 2:** Describe the role of DNA polymerase in replication.
- **Level 3:** Outline the steps of Meselson and Stahl's experiment.

Answer Key

- **Level 1:** Semi-conservative replication means each new DNA molecule contains one original and one newly synthesized strand.
- **Level 2:** DNA polymerase adds nucleotides to the growing DNA strand in the 5' to 3' direction and proofreads to correct errors.
- **Level 3:** Bacteria grown in heavy nitrogen, transferred to light nitrogen, DNA extracted after replication, centrifuged to separate DNA by density, showing hybrid DNA indicating semi-conservative replication.

Transcription and Translation

Transcription Process

Transcription is the synthesis of RNA from a DNA template. RNA polymerase binds to the promoter, unwinds DNA, and synthesizes RNA in the 5' to 3' direction using the 3' to 5' DNA strand as a template. In eukaryotes, primary transcripts undergo capping, splicing to remove introns, and polyadenylation to form mature mRNA.

Types of RNA

mRNA carries the genetic code from DNA to ribosomes. tRNA brings amino acids to ribosomes and has an anticodon complementary to mRNA codons. rRNA forms the core of ribosome structure and catalyzes protein synthesis.

Translation Process

Translation occurs in ribosomes and involves charging tRNA with amino acids, initiation at the start codon, elongation by peptide bond formation, and termination at stop codons. Polyribosomes allow simultaneous translation of a single mRNA.

Solved Examples

Example 1

Describe the role of tRNA in protein synthesis.

Solution:

tRNA acts as an adaptor molecule that carries specific amino acids to the ribosome. Its anticodon pairs with the complementary codon on mRNA, ensuring the correct amino acid is added to the growing polypeptide chain.

Practice Set

- **Level 1:** What is the direction of RNA synthesis during transcription?
- **Level 2:** Explain the significance of the anticodon in tRNA.
- **Level 3:** Outline the four steps of translation.

Answer Key

- **Level 1:** RNA is synthesized in the 5' to 3' direction.
- **Level 2:** The anticodon of tRNA pairs with the mRNA codon, ensuring the correct amino acid is incorporated during protein synthesis.
- **Level 3:** Charging of tRNA, initiation, elongation, and termination.

Genetic Code and Regulation

Genetic Code

The genetic code consists of triplet codons in mRNA, each coding for one amino acid. It is universal, non-overlapping, and degenerate, with start (AUG) and stop codons (UAA, UAG, UGA) signaling initiation and termination of translation.

Gene Expression Regulation

Gene expression is regulated at transcriptional, processing, and translational levels to conserve energy and respond to environmental changes. Housekeeping genes are constitutively expressed.

Operon Concept and Lac Operon

An operon is a cluster of genes under a single promoter controlling a metabolic pathway. The lac operon in E. coli regulates lactose metabolism via a repressor protein that binds the operator to block transcription in the absence of lactose. Lactose acts as an inducer by binding the repressor, allowing gene expression.

Human Genome Project and Rice Genome Project

The Human Genome Project mapped all human genes, revealing about 25,000 genes and extensive repetitive DNA. The Rice Genome Project aims to sequence rice DNA to improve crop production.

DNA Fingerprinting

DNA fingerprinting analyzes variable number tandem repeats (VNTRs) unique to individuals. The process involves DNA isolation, PCR amplification, restriction digestion, gel electrophoresis, blotting, hybridization with labeled probes, and autoradiography to produce a DNA profile used in forensics and genetic studies.

Solved Examples

Example 1

When does the lac operon get switched off?

Solution:

The lac operon is switched off when the repressor protein binds to the operator gene, blocking RNA polymerase and preventing transcription. This occurs in the absence of lactose (inducer).

Practice Set

- **Level 1:** What is a codon?
- **Level 2:** Describe the role of the repressor in the lac operon.
- **Level 3:** Explain the steps involved in DNA fingerprinting.

Answer Key

- **Level 1:** A codon is a sequence of three nucleotides in mRNA that codes for an amino acid.
- **Level 2:** The repressor binds to the operator to block transcription of lac operon genes when lactose is absent.
- **Level 3:** DNA isolation, PCR amplification, restriction digestion, gel electrophoresis, blotting, hybridization with labeled probes, and autoradiography.

Quick Reference Table

Common Mistakes and Misconceptions

Glossary