Cell Biology: Introductory Biological Concepts

AI-Generated Study Guide

(Based on lectures delivered by Dr. Ty C.M. Hoffman)

I. Core Concepts of Life

A. Defining Life: The Six Characteristics of Organisms

Organisms, or living things, are distinguished from non-living and dead things by possessing all six of the following characteristics. While some non-living things may exhibit one or two of these, only living things display all of them:

1. **Response to Environment:** Organisms react to stimuli and changes in their surroundings. This can be as simple as a bacterium dying due to a toxic substance or as complex as an animal seeking shelter.
2. **Reproduction:** Organisms produce offspring, either sexually or asexually, ensuring the continuation of their species.
- **Growth and Development:Growth:** An irreversible increase in size. For unicellular organisms, this involves the cell becoming enlarged before division. For multicellular organisms, it involves an increase in cell number and size.
- **Development:** Changes in an individual organism over its lifetime, often involving differentiation of cells and tissues from a single starting cell (like a zygote).
1. **Energy Processing (Metabolism):** Organisms acquire and transform energy to power their life processes. Life, biologically speaking, is defined by metabolism – the sum of all chemical reactions occurring within an organism. Cells act as "test tubes" where these reactions happen, isolated by a membrane.
2. **Regulation (Homeostasis):** Organisms maintain a relatively constant internal environment despite external fluctuations. This involves controlling thousands of chemical reactions through turning processes on and off.
- **Variables and Set Points:** Homeostasis involves maintaining biological variables (e.g., temperature) around an ideal "set point."
- **Error:** The difference between the set point and the actual value.
- **Feedback Mechanisms:Negative Feedback:** The primary mechanism for homeostasis. It *reduces* the error, bringing the variable back towards the set point. Most biological feedback is negative feedback.

- **Positive Feedback:** *Amplifies* the error, moving the variable further from the set point. It is temporary and rare in biological systems (e.g., childbirth).

1. **Evolutionary Adaptation:** Populations of organisms change over generations to become better suited (more "fit") to their environment. This occurs primarily through **natural selection**, where individuals with advantageous traits are more likely to survive and reproduce, passing on those beneficial genes.

B. The Three Categories of "Things" in the Universe

1. **Living Things (Organisms):** Possess all six characteristics of life and are made of at least one cell.
2. **Non-Living Things:** Have never been alive (e.g., a rock).
3. **Dead Things:** Were once alive but no longer possess the characteristics of life.

C. The Cellular Basis of Life

- **Minimum Requirement:** The bare minimum structural requirement for being an organism is having at least one cell.
- **Viruses:** Are biotic entities (related to life) but are *not* organisms because they are not cellular and cannot perform life processes independently. They are merely a few molecules that only exert their effects by altering host organisms.

II. Levels of Biological Organization (Hierarchy)

Biology studies life at various nested levels, from the smallest to the largest:

1. **Atoms:** The basic units of matter; the smallest level considered relevant to biology.
2. **Molecules:** Atoms bonded together (e.g., water, oxygen).
3. **Organelles:** "Little organs" within a cell, composed of molecules, performing specific functions (e.g., ribosomes, mitochondria, nucleus).
4. **Cells:** The fundamental unit of life; the smallest level at which an organism can exist. Unicellular organisms consist of a single cell, which also represents the organism level.
5. **Tissues:** Groups of similar cells working together to perform a specific function (e.g., muscle tissue, nervous tissue, epithelial tissue, connective tissue in vertebrates).
6. **Organs:** Structures composed of multiple types of tissues working together for a specialized function (e.g., liver, heart, leaf).
7. **Organ Systems:** Groups of organs that cooperate to perform major functions in a multicellular organism (e.g., digestive system, circulatory system).
8. **Organism:** An individual living being. For multicellular organisms, this is a distinct level from the cell.
9. **Population:** A group of individuals of the same species living in a specific area.
10. **Community:** All the different populations (different species) living and interacting in a particular area.

11. **Ecosystem:** A community of living organisms (biotic factors) interacting with their non-living physical environment (abiotic factors), such as water, rocks, and air.
- **Energy Flow:** Energy enters an ecosystem (e.g., as sunlight), is transformed and transferred, and eventually leaves as heat (flow-through).
- **Material Cycling:** Matter/materials are largely recycled within an ecosystem.

1. **Biosphere:** The sum of all ecosystems on Earth; the global ecological system integrating all living beings and their relationships, including their interaction with the elements of the lithosphere, hydrosphere, and atmosphere. It is a hollow sphere of certain thickness where life exists.

III. Form Follows Function

- In biology, there is a tight relationship between the structure (form) of a biological feature and its role (function).
- Organisms are not "designed" but rather undergo continuous refinement through evolutionary adaptation (natural selection).
- Evolution starts with existing structures and gradually modifies them, leading to efficient but not necessarily "perfect" solutions.
- **Example:** Pneumatized (air-filled) bones in birds provide strength with minimal weight, allowing for flight. A hollow tube design is stronger per unit of material than a solid rod of the same material.

IV. Cell Types: Prokaryotic vs. Eukaryotic

There are two fundamental categories of cells:

1. **Prokaryotic Cells:**
- **"Before Kernel":** Lack a true, membrane-bounded nucleus.
- **No Membrane-Bounded Organelles:** Do not have other internal compartments enclosed by membranes.
- **Single Compartment:** The entire internal space is the cytoplasm.
- **Size:** Generally much smaller than eukaryotic cells (approximately 1/10th the size in each dimension, meaning 1/1000th the volume).
- **Examples:** Bacteria and Archaea (members of the domains Bacteria and Archaea).

1. **Eukaryotic Cells:**
- **"True Kernel":** Possess a true, membrane-bounded nucleus (enclosed by a nuclear envelope).
- **Membrane-Bounded Organelles:** Contain other internal compartments enclosed by membranes (e.g., mitochondria, chloroplasts, endoplasmic reticulum).
- **Compartmentalization:** The presence of these organelles allows for specialized functions to occur in different "test tubes" within the cell.

- **Cytoplasm vs. Nucleoplasm:** In eukaryotic cells, cytoplasm refers to the material inside the cell but *outside* the nucleus and other membrane-bounded organelles. Nucleoplasm is the material inside the nucleus.
- **Size:** Generally much larger than prokaryotic cells.
- **Examples:** All organisms in the domain Eukarya (protists, fungi, plants, animals).

V. Genetic Information and Macromolecules

A. DNA and its Role

- **DNA (Deoxyribonucleic Acid):** The most famous molecule in biology; vital for life.
- **Self-Duplication:** DNA has the special ability to make exact copies of itself, which is crucial for cell division (each new cell needs a full set of DNA).
- **Genetic Makeup:** DNA contains "codes" called genes.
- **Indirect Trait Determination:** DNA *indirectly* determines an organism's traits:

1. DNA codes for how to make RNA molecules.
2. RNA molecules carry the code and instruct the cell on how to build **proteins**.
3. **Proteins** are the macromolecules that directly give an organism its traits (e.g., structure, function, appearance).

B. Macromolecules: The Building Blocks of Life

All organisms are made of four categories of large, carbon-containing molecules (macromolecules). Three of these are **polymers** (large molecules built from repeating smaller units called **monomers**).

- **Nucleic Acids:Monomer:** Nucleotides (e.g., A, T, C, G in DNA).
- **Polymer:** Polynucleotides.
- **Examples:** DNA and RNA. Informational molecules.
- **Proteins:Monomer:** Amino acids.
- **Polymer:** Polypeptides (due to peptide bonds between amino acids).
- **Function:** Directly determine traits; highly diverse in function (structural, enzymatic, transport, etc.).
- **Polysaccharides:Monomer:** Monosaccharides (simple sugars like glucose).
- **Polymer:** Large carbohydrates.
- **Examples:** Starch (energy storage in plants), Glycogen (energy storage in animals).
- **Lipids:Not Polymers:** Do not typically form long chains of repeating monomers.
- **Examples:** Fats, oils, phospholipids (component of cell membranes).
- **Function:** Energy storage, structural components (membranes), signaling molecules.

VI. Cell Theory

- A major tenet of biology states that **cells come only from pre-existing cells**.
- This means new cells are formed by the division (splitting or fusion followed by splitting) of existing cells.
- This principle has held true for billions of years since the original successful cells arose, which were the ancestors of all life.

VII. Taxonomy and Phylogeny

A. Taxonomy: Classification of Organisms

- **Hierarchy:** Organisms are classified into nested groups (taxa) based on similarities and shared ancestry.
- **Levels (from broadest to most specific):Domains:** The largest and most inclusive groups, encompassing all life. There are three domains.
- **Kingdom**
- **Phylum**
- **Class**
- **Order**
- **Family**
- **Genus**
- **Species**

B. The Three Domains of Life

All organisms belong to one of three domains:

1. **Bacteria:** All members are prokaryotic (lack a nucleus and membrane-bounded organelles).
2. **Archaea:** All members are prokaryotic, chemically distinct from Bacteria despite similar appearance under a microscope.
3. **Eukarya:** All members are eukaryotic (possess a true nucleus and membrane-bounded organelles). This domain includes protists, fungi, plants, and animals (including humans).

C. Phylogeny: Evolutionary Relationships

- **Phylogenetic Tree:** A diagram that illustrates the evolutionary history and relationships among groups of organisms.
- **Common Ancestry:** Branches on the tree represent lineages splitting from common ancestors, indicating closer relationships among groups that branched more recently.

VIII. The Scientific Process

Science is a way of understanding the natural world based on evidence, differing fundamentally from faith (belief without or despite evidence).

1. **Observation:** Noticing phenomena or patterns in the natural world.
2. **Question:** Forming an inquiry based on an observation.
3. **Hypothesis:** A testable **explanation** for an observation. It is a declarative statement, often implying a cause ("because").
4. **Prediction:** A statement of what **will** happen if the hypothesis is true. It logically follows from the hypothesis and is often in an "if...then..." format.
5. **Experimentation:** A formal test designed to determine whether a prediction comes true.

- **Refutation:** If the prediction *does not* come true, the hypothesis is refuted (shown to be incorrect, at least in part).
- **Support (Not Proof):** If the prediction *does* come true, the hypothesis is supported or bolstered; it *could* be correct, but it is not definitively proven true. Scientific hypotheses are repeatedly tested, and those that consistently withstand refutation gain status as "facts" (e.g., gravity, evolution), though they are still subject to further testing and refinement.

Quiz: Introduction to Biology

Instructions: Answer each question in 2-3 sentences.

1. Distinguish between a "non-living thing" and a "dead thing" in biological terms. Provide an example for each.
2. Why is a virus not considered an organism, even though it interacts with living systems? What is the fundamental requirement for something to be an organism?
3. Explain the concept of "metabolism" and its significance in defining life.
4. Describe the difference between "growth" and "development" in multicellular organisms.
5. What is the primary role of "negative feedback" in biological systems? How does it differ from "positive feedback"?
6. List the four major categories of macromolecules found in all organisms. Which three of these are polymers?
7. Explain the relationship between DNA, RNA, and proteins in determining an organism's traits.
8. Briefly define the terms "population," "community," and "ecosystem" in the context of biological organization.
9. What is the main difference between a prokaryotic cell and a eukaryotic cell, based on their internal structure?
10. Differentiate between a "hypothesis" and a "prediction" within the scientific method.

Quiz Answer Key

1. A "non-living thing" has never been alive, such as a rock. A "dead thing" was once alive but no longer exhibits the characteristics of life, like a fallen leaf or a deceased animal. The key distinction is whether it ever possessed life.
2. A virus is not an organism because it is not cellular; it lacks the fundamental cell structure required for life. The bare minimum requirement for being an organism is having at least one cell, which viruses do not possess.
3. Metabolism is defined as the sum of all chemical reactions occurring within an individual organism. It is considered the biological definition of life, as these constant chemical processes, isolated within cells, are what enable an organism to function and survive.
4. Growth in multicellular organisms refers to an increase in size, primarily by adding more cells. Development, on the other hand, describes the changes in form and function that take place throughout an individual's lifetime, such as the differentiation of cells from a zygote into various tissues and organs.
5. Negative feedback is the primary homeostatic mechanism, working to reduce any error and bring a variable closer to its set point. Positive feedback, in contrast, amplifies an error, moving a variable further from its set point, and is typically temporary and non-homeostatic.
6. The four major categories of macromolecules are nucleic acids, proteins, polysaccharides, and lipids. Nucleic acids, proteins, and polysaccharides are all polymers, built from repeating monomer units.
7. DNA contains genes that code for RNA molecules. These RNA molecules then use that code to direct the synthesis of proteins. It is the specific proteins produced that directly determine an organism's observable traits and functions.
8. A population is a group of individuals of the same species living in a specific area. A community consists of all the different populations (different species) interacting in the same area. An ecosystem expands on this by including the community of living things plus all the non-living physical components of the environment.
9. The main difference is the presence of a true, membrane-bounded nucleus and other membrane-bounded organelles in eukaryotic cells. Prokaryotic cells lack these internal membrane-bound compartments and are essentially a single compartment (cytoplasm).
10. A hypothesis is a proposed explanation for an observation, stated as a declarative sentence ("because"). A prediction is a logical consequence of the hypothesis, describing what *will* happen if the hypothesis is true, often using "if...then..." phrasing.

Essay Format Questions (No Answers Provided)

1. Discuss the interconnectedness of the six major characteristics of living things. Choose at least three characteristics and explain how they rely on or influence one another to maintain life in an organism.

2. Trace the flow of energy and the cycling of materials within a typical ecosystem. Explain how these two processes differ fundamentally and provide specific examples of transformations and transfers involved.
3. Compare and contrast prokaryotic and eukaryotic cells, focusing on their structural differences and how these differences relate to their cellular functions and overall complexity.
4. Explain the concept of biological hierarchy by selecting and describing at least five levels of organization, starting from a molecular level and progressing to an ecological level. Provide an example of how a disruption at a lower level might impact a higher level.
5. Describe the core steps of the scientific method. Using a novel example (not the flashlight), illustrate how a scientific hypothesis is formulated, tested, and potentially supported or refuted through experimentation.

Glossary of Key Terms

- **Adaptation:** In biology, refers to a trait or characteristic that increases an individual's fitness (suitability) to its environment.
- **Amino Acid:** The monomer unit that links together to form proteins (polypeptides).
- **Archaea:** One of the three domains of life; consists of prokaryotic organisms chemically distinct from bacteria.
- **Atom:** The smallest unit of an element that retains the chemical properties of that element; the fundamental building block of matter.
- **Bacteria:** One of the three domains of life; consists of prokaryotic organisms.
- **Biosphere:** The entire portion of Earth inhabited by life; the sum of all ecosystems.
- **Cell:** The fundamental unit of life; the smallest structural and functional unit of an organism, typically microscopic and consisting of cytoplasm and a nucleus enclosed in a membrane.
- **Cell Theory:** The scientific theory stating that all living things are composed of cells, and all cells come from pre-existing cells.
- **Community:** All the populations of different species living and interacting in a particular area.
- **Dead Thing:** An entity that was once alive but no longer exhibits the characteristics of life.
- **Development:** The process of change and differentiation that occurs during the lifetime of an individual organism, from its origin to maturity.
- **DNA (Deoxyribonucleic Acid):** A nucleic acid macromolecule that carries the genetic instructions used in the growth, development, functioning, and reproduction of all known living organisms.
- **Domain:** The highest (most inclusive) taxonomic rank of organisms, above kingdom. There are three domains: Bacteria, Archaea, and Eukarya.
- **Ecosystem:** All the living organisms (biotic community) in an area interacting with their non-living physical environment (abiotic factors).

- **Energy Processing:** The characteristic of life involving the acquisition, transformation, and utilization of energy (metabolism).
- **Eukarya:** One of the three domains of life; includes all eukaryotic organisms (those with cells containing a true nucleus and membrane-bound organelles).
- **Eukaryotic Cell:** A type of cell that has a membrane-bounded nucleus and other membrane-bounded organelles.
- **Evolution:** Change in the heritable characteristics of biological populations over successive generations.
- **Evolutionary Adaptation:** The process by which populations of organisms become better suited to their environment over generations due to evolution.
- **Experimentation:** A scientific procedure undertaken to make a discovery, test a hypothesis, or demonstrate a known fact.
- **Feedback Mechanism:** A process in which the output of a system (or a product of a process) affects the input or activity of the system, either to increase (positive feedback) or decrease (negative feedback) the output.
- **Fitness:** In biology, refers to how well an organism is suited to its environment, often measured by its reproductive success.
- **Form Follows Function:** A principle in biology stating that the structure (form) of a biological feature is closely related to its purpose or role (function).
- **Genes:** Segments of DNA that contain instructions for making RNA and, indirectly, proteins, thus influencing traits.
- **Growth:** An irreversible increase in size of an organism.
- **Hierarchy of Biological Organization:** The structural levels of biological complexity, from atoms to the biosphere, with each level building upon the one below it.
- **Homeostasis:** The maintenance of a relatively constant internal environment by a living organism.
- **Hypothesis:** A testable explanation for an observation, proposed as a declarative statement.
- **Lipid:** A diverse group of macromolecules (not typically polymers) including fats, oils, and steroids, characterized by their insolubility in water; vital for energy storage and cell membranes.
- **Macromolecule:** A very large molecule commonly created by the polymerization of smaller subunits; includes proteins, nucleic acids, polysaccharides, and lipids.
- **Metabolism:** The sum of all chemical reactions that occur within a living organism, essential for maintaining life.
- **Molecule:** Two or more atoms held together by chemical bonds.
- **Monomer:** A small molecule that can be bonded to other identical or similar monomers to form a polymer.
- **Natural Selection:** A mechanism of evolution where individuals with traits better suited to their environment are more likely to survive and reproduce, passing on those beneficial traits.
- **Negative Feedback:** A type of regulatory mechanism that reduces the output of a system or process, thereby stabilizing it and maintaining homeostasis.

- **Nervous Tissue:** One of the four basic types of animal tissue; specialized for communication by transmitting electrical impulses.
- **Non-Living Thing:** An entity that has never been alive.
- **Nucleic Acid:** A macromolecule (polymer of nucleotides) that carries genetic information; examples include DNA and RNA.
- **Nucleoplasm:** The protoplasm (material) contained within the nucleus of a eukaryotic cell.
- **Nucleotide:** The monomer unit of nucleic acids (DNA and RNA), consisting of a sugar, a phosphate group, and a nitrogenous base.
- **Nucleus (Cellular):** In eukaryotic cells, a membrane-bounded organelle that contains the cell's genetic material (DNA) organized into chromosomes.
- **Observation:** The action or process of observing something carefully or in order to gain information.
- **Organ:** A collection of different tissues that work together to perform a specific function (e.g., heart, liver, leaf).
- **Organelle:** A specialized subunit within a cell that has a specific function (e.g., mitochondria, ribosomes, nucleus).
- **Organism:** An individual living thing capable of growth, reproduction, and response to stimuli.
- **Organ System:** A group of organs that work together to perform one or more functions (e.g., digestive system, circulatory system).
- **Phylogenetic Tree:** A diagram that shows the evolutionary relationships among various biological species or other entities, based upon similarities and differences in their physical or genetic characteristics.
- **Phylogeny:** The evolutionary history of a species or group of related species.
- **Plasma Membrane (Cell Membrane):** The biological membrane that separates the interior of all cells from the outside environment.
- **Polymer:** A large molecule (macromolecule) composed of many repeated smaller units (monomers) linked together.
- **Polysaccharide:** A large carbohydrate macromolecule (polymer of monosaccharides), such as starch or glycogen.
- **Population:** A group of individuals of the same species living in the same area at the same time.
- **Positive Feedback:** A type of regulatory mechanism that amplifies the output of a system or process, moving it further from a set point; typically temporary and non-homeostatic.
- **Prediction:** A statement of what is expected to happen under specific conditions if a hypothesis is true.
- **Prokaryotic Cell:** A type of cell that lacks a true, membrane-bounded nucleus and other membrane-bounded organelles.
- **Protein:** A complex macromolecule (polymer of amino acids) essential to all living organisms, performing a vast array of functions from structural support to enzymatic activity.

- **Regulation:** The characteristic of life involving processes that control an organism's internal environment and metabolism (homeostasis).
- **Reproduction:** The biological process by which new individual organisms (offspring) are produced from their parents.
- **Response to Environment:** The characteristic of life involving an organism's ability to react to stimuli from its surroundings.
- **RNA (Ribonucleic Acid):** A nucleic acid macromolecule involved in various biological roles in coding, decoding, regulation, and expression of genes.
- **Scientific Method:** A systematic approach to research, typically involving observation, hypothesis formulation, prediction, experimentation, and analysis.
- **Set Point:** The ideal or desired value for a particular biological variable that is maintained through homeostasis.
- **Tissue:** A group of similar cells and their extracellular matrix from the same origin that together carry out a specific function.
- **Unicellular Organism:** An organism that consists of a single cell.
- **Virus:** A non-cellular infectious agent that can only replicate inside the living cells of organisms.