Chapter 1

Introduction: Themes in the Study of Life

Lecture Outline

Overview: Inquiring About the World of Life

- Organisms are adapted to the environments they live in.
- These adaptations are the result of **evolution**, the fundamental organizing principle of biology.
- Posing questions about the living world and seeking science-based answers are the central activities of **biology**, the scientific study of life.
- Biologists ask a wide variety of ambitious questions.
    - They may ask how a single cell becomes a tree or a dog, how the human mind works, or how the living things in a forest interact.
- Biologists can help answer questions that affect our lives in practical ways.
- Research breakthroughs in genetics and cell biology are transforming medicine and agriculture.
    - Molecular biology is providing new tools for anthropology and criminal science.
    - Neuroscience and evolutionary biology are reshaping psychology and sociology.
    - New models in ecology are helping society evaluate environmental issues, such as the causes and biological consequences of global warming.
- What is life?
    - The phenomenon of life defies a simple, one-sentence definition.

Concept 1.1 Themes help connect the concepts of biology.

- Seven unifying themes will help you organize and make sense of biological information.

Theme 1: Evolution is the core theme of biology, the one idea that makes sense of everything we know about living organisms.

- Life has been evolving on Earth for billions of years, resulting in a vast diversity of past and present organisms.
- At the same time, living things share certain features.
- The scientific explanation for this unity and diversity is evolution: the idea that the organisms living on Earth today are the modified descendants of common ancestors.

- In other words, scientists can explain traits shared by two organisms with the idea that they have descended from a common ancestor, and scientists can account for differences with the idea that heritable changes have occurred along the way.

Theme 2: New properties emerge at each level in the biological hierarchy.

- Each level of biological organization has emergent properties.
- Biological organization is based on a hierarchy of structural levels, each building on the levels below.
    - At the lowest level are atoms that are ordered into complex biological molecules.
    - Biological molecules are organized into structures called organelles, the components of cells.
    - Cells are the fundamental unit of structure and function of living things.
- Some organisms consist of a single cell; others are multicellular aggregates of specialized cells.
- Whether multicellular or unicellular, all organisms must accomplish the same functions: uptake and processing of nutrients, excretion of wastes, response to environmental stimuli, and reproduction.
- Multicellular organisms exhibit three major structural levels above the cell: Similar cells are grouped into tissues, several tissues coordinate to form organs, and several organs form an organ system.
- For example, to coordinate locomotory movements, sensory information travels from sense organs to the brain, where nervous tissues composed of billions of interconnected neurons—supported by connective tissue—coordinate signals that travel via other neurons to the individual muscle cells.
    - Organisms make up populations, localized groups of organisms belonging to the same species.
    - Populations of several species in the same area combine to form a biological community.
    - Populations interact with their physical environment to form an ecosystem.
    - The biosphere consists of all the environments on Earth that are inhabited by life.
- As we move from the molecular level to the biosphere, novel **emergent properties** arise at each level that are not present at the preceding level.
    - Emergent properties are created by new arrangements and interactions of parts as complexity increases.
        - For example, photosynthesis can take place only when molecules are arranged in a specific way in an intact chloroplast.
        - The cycling of chemical elements at the ecosystem level depends on a network of diverse organisms interacting with each other and with the soil, water, and air.
- Reductionism—the reduction of complex systems to simpler components that are more manageable to study—is a powerful strategy in biology.

- Biologists must balance the reductionist strategy with the larger-scale, holistic objective of understanding the emergent properties of life—how all the parts of biological systems are functionally integrated.

- Biologists are beginning to complement reductionism with new strategies for studying whole systems.
  - The ultimate goal of **systems biology** is to model the dynamic behavior of whole biological systems.
  - Successful models allow biologists to predict how a change in one or more variables will affect other components as well as the whole system.
- Scientists investigating ecosystems pioneered the systems approach in the 1960s with elaborate models diagramming the interactions of species and nonliving components in ecosystems such as salt marshes.
  - Such models are useful for predicting the responses of systems to changing variables.
- Systems biology is now becoming increasingly important in cellular and molecular biology.

Theme 3: Organisms interact with their environments, exchanging matter and energy.

- Each organism interacts with its environment, which includes other organisms as well as nonliving factors.
  - Both organism and environment are affected by the interactions between them.
- The operation of any ecosystem involves two major processes: the cycling of nutrients and the one-way flow of energy from sunlight to producers to consumers.
  - In most ecosystems, producers are plants and other photosynthetic organisms that convert light energy to chemical energy.
  - Consumers are organisms that feed on producers and other consumers.
- All the activities of life require organisms to perform work, and work requires a source of energy.
  - The exchange of energy between an organism and its environment often involves the transformation of energy from one form to another.
  - In all energy transformations, some energy is lost to the surroundings as heat.
  - In contrast to chemical nutrients, which recycle within an ecosystem, energy flows through an ecosystem, usually entering as light and exiting as heat.

Theme 4: Structure and function are correlated at all levels of biological organization.

- Form fits function; how a device works is correlated with its structure.
  - Applied to biology, this theme is a guide to the anatomy of life at all its structural levels.
  - For example, the thin, flat shape of a leaf maximizes the amount of sunlight that can be captured by its chloroplasts.

Theme 5: Cells are an organism's basic units of structure and function.

- The cell is the lowest level of structure that is capable of performing all the activities of life.
- All the activities of organisms are based on cell activities.
    - For example, the ability of cells to form new cells is the basis of all reproduction and the basis of growth and repair in multicellular organisms.
- Understanding how cells work is a major research focus of modern biology.
- All cells share certain characteristics.
    - Every cell is enclosed by a membrane that regulates the passage of materials between the cell and its surroundings.
    - Every cell uses DNA as its genetic information.
- There are two basic types of cells: prokaryotic cells and eukaryotic cells.
    - The cells of the two groups of microorganisms called bacteria and archaea are prokaryotic.
    - All other forms of life have more complex eukaryotic cells.
- A **eukaryotic cell** is subdivided by internal membranes into various membrane-enclosed organelles.
    - In most eukaryotic cells, the largest organelle is the nucleus, which contains the cell's DNA as chromosomes.
    - The other organelles are located in the cytoplasm, the entire region between the nucleus and the outer membrane of the cell.
- **Prokaryotic cells** are much simpler and smaller than eukaryotic cells.
    - In a prokaryotic cell, DNA is not separated from the cytoplasm in a nucleus.
    - There are no membrane-enclosed organelles in the cytoplasm.
- Whether an organism has prokaryotic or eukaryotic cells, its structure and function depend on its cells.

Theme 6: The continuity of life is based on heritable information in the form of DNA.

- At some point, all cells contain deoxyribonucleic acid, or DNA, the heritable material that directs the cell's activities.
- DNA is the substance of **genes**, the units of inheritance that transmit information from parents to offspring.
- DNA in human cells is organized into chromosomes.
    - Each chromosome has one very long DNA molecule, with hundreds or thousands of genes arranged along its length.
    - The DNA of chromosomes replicates as a cell prepares to divide.
    - Each of the two cellular offspring inherits a complete set of genes.
- Each of us began life as a single cell stocked with DNA inherited from our parents.
    - Replication of that DNA with each round of cell division transmitted copies of those genes to our trillions of cells.

- In each cell, the genes along the length of DNA molecules encode the information for building the cell's other molecules. DNA thus directs the development and maintenance of the entire organism.
- Each DNA molecule is made up of two long chains arranged in a double helix.
    - Each link of a chain is one of four nucleotides, which encode the cell's information in chemical letters.
- The sequence of nucleotides along a gene may code for a specific protein with a unique shape and function.
    - Almost all cellular activities involve the action of one or more proteins.
    - Human proteins include muscle cell contraction proteins and defensive proteins called antibodies.
    - All cells also contain enzymes, crucial proteins that catalyze (speed up) specific chemical reactions.
    - DNA provides the heritable blueprints, but proteins are the tools that actually build and maintain the cell.
- DNA controls protein production indirectly, using a related kind of molecule called RNA as an intermediary.
    - The sequence of nucleotides along a gene is transcribed into RNA, which is then translated into a specific protein with a unique shape and function.
- In the translation process, all forms of life employ essentially the same genetic code.
    - A particular sequence of nucleotides says the same thing to one organism as it says to another.
- Recently, scientists have discovered whole new classes of RNA that are not translated into protein.
    - Some RNA molecules regulate the functioning of protein-coding genes.
- The library of genetic instructions that an organism inherits is called its **genome**.
    - The chromosomes of each human cell contain about 3 billion nucleotides, including genes coding for about 75,000 kinds of proteins, each with a specific function.
- The entire sequence of nucleotides in the human genome is now known.
    - Scientists have also learned the genome sequences of many other organisms, including bacteria, archaea, fungi, plants, and animals.
    - The sequencing of the human genome is a major scientific and technological achievement.
    - The challenge now is to learn how the activities of the proteins encoded by DNA are coordinated in cells and organisms.
- Systems biology is now becoming increasingly important in cellular and molecular biology, driven in part by the deluge of data from the sequencing of genomes and the growing catalog of known protein functions.
    - A large research team has published a network of protein interactions within a cell of a fruit fly, derived from a database of thousands of known proteins and their interactions with other proteins.

- To undertake a systems strategy, scientists must inventory as many parts of the system as possible, such as all the known genes and proteins in a cell (an application of reductionism).
    - Next, scientists investigate how each part behaves in relation to others in the working system—such as all the protein-protein interactions in the fruit fly cell example.
    - Finally, with the help of computers and specialized software, researchers pool all the data into a system network.
- Three key research developments have led to the increased importance of systems biology.
    1. **High-throughput technology.** Systems biology depends on methods that can analyze biological materials very quickly and produce enormous amounts of data. An example is the automatic DNA-sequencing machines used by the Human Genome Project.
    2. **Bioinformatics.** The huge databases from high-throughput methods require the use of computational tools to store, organize, and analyze the huge volume of data.
    3. **Interdisciplinary research teams.** Systems biology teams may include engineers, medical scientists, physicists, chemists, mathematicians, and computer scientists as well as biologists.

Theme 7: Feedback mechanisms regulate biological systems.

- Chemical processes within cells are accelerated, or catalyzed, by specialized protein molecules called enzymes.
- Each type of enzyme catalyzes a specific chemical reaction.
    - In many cases, reactions are linked into chemical pathways, with each step having its own enzyme.
- How does a cell coordinate its various chemical pathways?
    - Many biological processes are self-regulating: The output or product of a process regulates that same process.
- In **negative feedback**, the accumulation of an end product of a process slows down that process.
- Though less common, some biological processes are regulated by **positive feedback**, in which an end product speeds up its own production.
- Feedback is common to life at all levels, from the molecular level to the biosphere.
- Regulation via feedback is an example of the integration that makes living systems much more than the sum of their parts.

Concept 1.2 The Core Theme: Evolution accounts for the unity and diversity of life.

- Evolutionary biologist Theodosius Dobzhansky said, "Nothing in biology makes sense except in the light of evolution."

Living things show both diversity and unity.

- Life is enormously diverse.
    - Biologists have identified and named about 1.8 million species.

- These species include 5,200 known species of prokaryotes, 100,000 fungi, 290,000 plants, 52,000 vertebrates, and 1,000,000 insects.

- Thousands of newly identified species are added each year.
  - Estimates of the total species count range from 10 million to more than 400 million.
- In the face of this complexity, humans are inclined to categorize diverse items into a smaller number of groups.
  - Taxonomy is the branch of biology that names and classifies species into a hierarchical order.
- Until about 20 years ago, biologists divided the diversity of life into five kingdoms: plants, animals, fungi, single-celled eukaryotic organisms, and prokaryotes.
- New research methods, including comparisons of DNA among organisms, have led to a reassessment of the number and boundaries of the kingdoms.
  - Various classification schemes have proposed anywhere from six kingdoms to dozens of kingdoms.
- This debate has brought about the recognition that there are three even higher levels of classification: the domains Bacteria, Archaea, and Eukarya.
- The first two domains, **domain Bacteria** and **domain Archaea**, consist of prokaryotes.
  - Most prokaryotes are single-celled and microscopic.
- All the eukaryotes are now grouped into various kingdoms of the **domain Eukarya**.
  - The recent taxonomic trend has been to split the single-celled eukaryotes and their close relatives into several kingdoms.
- Domain Eukarya also includes the three kingdoms of multicellular eukaryotes, Plantae, Fungi, and Animalia, distinguished partly by their modes of nutrition.
  - Most plants produce their own sugars and food by photosynthesis.
  - Most fungi are decomposers that absorb nutrients by breaking down dead organisms and organic wastes.
  - Animals obtain food by ingesting other organisms.
- Underlying the diversity of life is a striking unity, especially at the molecular and cellular levels of organization.
  - The universal genetic language of DNA unites prokaryotes and eukaryotes.
  - Among the eukaryotes, unity is evident in many details of cell structure.
- How do scientists account for life's dual nature of unity and diversity?
  - The process of evolution explains both the similarities and differences among living things.
- The history of life is the saga of a changing Earth, billions of years old, inhabited by a evolving cast of living forms.
- Charles Darwin brought evolution into focus in 1859 when he presented two main points in one of the most important and influential books ever written, *On the Origin of Species by Means of Natural Selection.*

- Darwin's first point was that contemporary species arose from a succession of ancestors through "descent with modification."
    - This term captured the duality of life's unity and diversity: unity in the kinship among species that descended from common ancestors and diversity in the modifications that evolved as species branched from their common ancestors.
- Darwin's second point was his mechanism for descent with modification: natural selection.
- Darwin started with observations from nature.
    - Individuals in a population of any species vary in many heritable traits.
    - A population can potentially produce far more offspring than the environment can support; therefore, competition is inevitable.
    - Species generally are suited to their environments.
- Darwin made inferences from these observations to arrive at his theory of evolution.
    - Individuals with inherited traits that are best suited to the local environment will produce more healthy, fertile offspring than less fit individuals.
    - Over many generations, heritable traits that enhance survival and reproductive success will tend to increase in frequency among a population's individuals.
    - Evolution occurs as the unequal reproductive successes of individuals adapt the population to its environment.
- Darwin called this mechanism of evolutionary adaptation "natural selection" because the natural environment "selects" for the propagation of certain traits.
- Natural selection, by its cumulative effects over vast spans of time, can produce new species from ancestral species.
    - For example, a population fragmented into several isolated populations in different environments may gradually diversify into many species as each population adapts over many generations to different environmental problems.
- Fourteen species of finches found on the Galápagos Islands diversified after an ancestral finch species reached the archipelago from the South American mainland.
    - Each species adapted to exploit different food sources on different islands.
- Biologists' diagrams of evolutionary relationships generally take a treelike form.
- Just as individuals have a family tree, each species is one twig of a branching tree of life.
    - Similar species like the Galápagos finches share a relatively recent common ancestor.
    - Finches share a more distant ancestor with all other birds.
    - The common ancestor of all vertebrates is even more ancient.
    - If life is traced back far enough, all living things have a common ancestor.
- All of life is connected through its long evolutionary history.

Concept 1.3 Scientists use two main forms of inquiry in their study of nature.

- The word *science* is derived from a Latin verb meaning "to know."

- At the heart of science is **inquiry**, asking questions about nature and focusing on specific questions that can be answered.
- Biologists use two main types of scientific inquiry: discovery science and hypothesis-based science.
    - Discovery science is mostly about *describing* nature.
    - Hypothesis-based science is mostly about *explaining* nature.
    - Most scientific inquiry combines the two approaches.
- **Discovery science**, sometimes called descriptive science, describes natural structures and processes as accurately as possible through careful observation and analysis of data.
    - Discovery science built our understanding of cell structure and is expanding our databases of genomes of diverse species.
    - Observation is the use of the senses to gather information, directly or indirectly, with the help of tools such as microscopes that extend our senses.
- Recorded observations are called **data,** which can be qualitative or quantitative.
    - Quantitative data are numerical measurements.
    - Qualitative data may be in the form of recorded descriptions.
    - For example, Jane Goodall has spent decades recording qualitative data in the form of her observations of chimpanzee behavior during field research in Gambia. She has also collected volumes of quantitative data.
- Discovery science can lead to important conclusions based on **inductive reasoning**.
    - Through induction, scientists derive generalizations based on a large number of specific observations.
- In science, inquiry frequently involves proposing and testing hypotheses.
    - In science, a **hypothesis** is a tentative answer to a well-framed question.
    - A hypothesis is usually an educated guess based on experience and data available from discovery science.
    - A scientific hypothesis leads to predictions that can be tested by recording additional observations or by performing experiments.
- A type of logic called deduction is built into hypothesis-based science.
    - In **deductive reasoning**, logic flows from the general to the specific.
    - From general premises, scientists extrapolate to a specific result that should be expected if the premises are true.
- In hypothesis-based science, deduction usually takes the form of predictions about what scientists should expect if a particular hypothesis is correct.
    - Scientists test the hypothesis by performing the experiment to see whether or not the results are as predicted.
    - Deductive logic takes the form *"If . . . , then . . . ."*
- Scientific hypotheses must be *testable.*
    - There must be some way to check the validity of the idea.

- Scientific hypotheses must be *falsifiable*.
    - There must be some observation or experiment that could reveal if a hypothesis is actually *not* true.
- The ideal in hypothesis-based science is to frame two or more alternative hypotheses and design experiments to falsify them.
- No amount of experimental testing can *prove* a hypothesis.
    - A hypothesis gains support by surviving various tests that could falsify it; testing falsifies alternative hypotheses.

We can explore the scientific method.

- There is an idealized process of inquiry called the *scientific method*.
    - Very few scientific inquiries adhere rigidly to the sequence of steps prescribed by the textbook scientific method.
    - Discovery science has contributed a great deal to our understanding of nature without most of the steps of the so-called scientific method.
- We will consider a case study of scientific research that begins with a set of observations and generalizations from discovery science.
- Many poisonous animals have warning coloration that signals danger to potential predators.
    - Imposter species mimic poisonous species, although they are harmless.
    - What is the function of such mimicry? What advantage does it give the mimic?
- In 1862, Henry Bates proposed that mimics benefit when predators mistake them for harmful species.
    - This deception may lower the mimic's risk of predation.
- In 2001, David and Karin Pfennig of the University of North Carolina, together with undergraduate William Harcombe, designed a set of field experiments to test Bates's mimicry hypothesis.
- In North and South Carolina, a poisonous snake called the eastern coral snake has warning red, yellow, and black coloration.
    - Predators avoid these snakes.
    - It is unlikely that predators learn to avoid coral snakes because a strike is usually lethal.
    - Natural selection may have favored an instinctive recognition and avoidance of the warning coloration of the coral snake.
- The nonpoisonous scarlet king snake mimics the ringed coloration of the coral snake.
- Both king snakes and coral snake live in North and South Carolina, but the king snake's range also extends into areas that have no coral snakes.
- The geographic distribution of these two species allowed the Pfennigs and Harcombe to test a key prediction of the mimicry hypothesis.
    - Mimicry should protect the king snake from predators, but *only* in regions where coral snakes live.

- Predators in areas with no coral snakes should attack king snakes more frequently than predators in areas where coral snakes are present.

- To test the mimicry hypothesis, Harcombe made hundreds of artificial snakes.
  - The *experimental group* had the red, black, and yellow ring pattern of king snakes.
  - The *control group* had plain brown coloring.
- Equal numbers of both types of snakes were placed at field sites, including areas that have no coral snakes.
- After four weeks, the scientists retrieved the fake snakes and counted bite or claw marks made by foxes, coyotes, raccoons, and black bears.
- The data fit the predictions of the mimicry hypothesis: The ringed snakes were attacked by predators less frequently than the brown snakes *only* in the geographic range of the coral snakes.
- The snake mimicry experiment provides an example of how scientists design experiments to test the effect of one variable by canceling out the effects of unwanted variables.
  - The design is called a **controlled experiment**.
  - An experimental group (artificial king snakes) is compared with a control group (artificial brown snakes).
  - The experimental and control groups differ only in the one factor the experiment is designed to test—the effect of the snake's coloration on the behavior of predators.
  - The artificial brown snakes allowed the scientists to rule out such variables as predator density and temperature as possible determinants of the number of predator attacks.
- A common misconception is that the term *controlled experiment* means that scientists control the experimental environment to keep everything constant except the one variable being tested.
  - Researchers usually "control" unwanted variables, not by eliminating them, but by canceling their effects using control groups.

Let's look at the nature of science.

- The kinds of questions that scientists can address are limited by science's requirements that hypotheses are testable and falsifiable and that observations and experimental results are repeatable.
- Naturalism also sets limits on science.
  - Science seeks natural causes for natural phenomena.
  - Science cannot support or falsify supernatural explanations, which are outside the bounds of science.
- The everyday use of the term *theory* implies an untested speculation; *theory* has a very different meaning in science.
- A scientific **theory** is much broader in scope than a hypothesis.
  - This is a hypothesis: "Mimicking poisonous snakes is an adaptation that protects nonpoisonous snakes from predators."
  - This is a theory: "Evolutionary adaptations evolve by natural selection."
- A theory is general enough to generate many new, specific hypotheses that can be tested.

- Compared to any one hypothesis, a theory is generally supported by a much more massive body of evidence.
- The theories that become widely adopted in science (such as the theory of adaptation by natural selection) explain many observations and are supported by a great deal of evidence.
- In spite of the body of evidence supporting a widely accepted theory, scientists may have to modify or reject theories when new evidence is found.
    - As an example, the five-kingdom theory of biological diversity was called into question as new molecular methods made it possible to test some of the hypotheses about the relationships among living organisms.
- Scientists may construct **models** in the form of diagrams, graphs, computer programs, or mathematical equations.
    - Models may range from lifelike representations to symbolic schematics.
    - The test of a model's success is how well it fits the available data, how comfortably it accommodates new observations, how accurately it predicts the outcomes of new experiments or observations, and how effectively it communicates.
- Science is an intensely social activity.
    - Most scientists work in teams, which often include graduate and undergraduate students.
- Both cooperation and competition characterize scientific culture.
    - Scientists attempt to confirm each other's observations and may repeat experiments.
    - Scientists share information through publications, seminars, meetings, and personal communication.
    - Scientists may be very competitive when focusing on the same research question.
- Science as a whole is embedded in the culture of its times.
    - Recent increases in the proportion of women biologists have had an impact on the research being performed.
    - For instance, the focus in studies of the mating behavior of animals has shifted from competition among males for access to females to the role that females play in choosing mates.
    - Recent research has revealed that females prefer bright coloration that "advertises" a male's vigorous health, a behavior that increases a female's probability of having healthy offspring.
- Some philosophers of science argue that scientists are so influenced by cultural and political values that science is no more objective than other ways of "knowing nature." At the other extreme are those who view scientific theories as natural laws.
    - The reality of science is somewhere in between.
    - The cultural milieu affects scientific fashion, but the need to replicate observations and hypothesis testing distinguishes science from other fields.
- If there is "truth" in science, it is based on a preponderance of the available evidence.

Both science and technology are functions of society.

- Although both science and technology employ similar inquiry patterns, their basic goals differ.

- The goal of science is to understand natural phenomena.
- In contrast, **technology** *applies* scientific knowledge for some specific purpose.

- Biologists and other scientists often speak of "discoveries," while engineers and other technologists more often speak of "inventions."
  - Scientists benefit from inventions as they put new technology to work in their research.
  - Science and technology are interdependent.
- The discovery of the structure of DNA by Watson and Crick sparked an explosion of scientific activity.
  - Many technologies of DNA engineering are transforming applied fields, including medicine, agriculture, and forensics.
- The direction that technology takes depends less on science than on the needs of humans and the values of society.
  - Debates about technology focus more on "*Should* we do it?" than on "*Can* we do it?"
- With advances in technology come difficult choices, informed as much by politics, economics, and cultural values as by science.
- Scientists should educate politicians, bureaucrats, corporate leaders, and voters about how science works and about the potential benefits and hazards of specific technologies.