

# CELL BIOLOGY AND GENETICS

*Starr and Taggart*

BIOLOGY  
The Unity and  
Diversity of Life

NINTH EDITION



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CECIE STARR / RALPH TAGGART

## BIOLOGY

*The Unity and Diversity of Life*

NINTH EDITION



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# Preface

Teachers of introductory biology know all about the Red Queen effect, whereby one runs as fast as one can to stay in the same place. New and modified information from hundreds of fields of inquiry piles up daily, and somehow teachers are expected to distill it into Biology Lite, a one-course zip through the high points that still manages to help students deepen their understanding of a world of unbelievable richness.

Restricting textbook content runs the risk of splintering understanding of that world, as when an emphasis on human biology inadvertently reinforces archaic notions that everything on Earth is here in the service of Us; or when a molecular focus excludes knowledge of whole organisms. (Here I am reminded of the well intentioned but lethal blanketing of habitats with DDT and of Jacques Monod's first clueless encounters with *E. coli*.)

We offer this book as a coherent account of the sweep of life's diversity and its underlying unity. Through its examples of problem solving and experiments, it shows the power of thinking critically about the natural world. It highlights key concepts, current understandings, and research trends for major fields of biological inquiry. It explains the structure and function of a broad sampling of organisms in enough detail so students can develop a working vocabulary about life's parts and processes.

The book starts with an overview of the basic concepts and scientific methods. Three units on the principles of

biochemistry, inheritance, and evolution follow. They are the conceptual framework for exploring life's unity and diversity, starting with an evolutionary survey of each kingdom. Units on comparative anatomy and physiology of plants, then animals, are next. The last unit focuses on patterns and consequences of organisms interacting with one another and with the environment. This conceptual organization parallels the levels of biological organization.

**TOPIC SPREADS** Ongoing feedback from teachers of more than three million students helped us refine our approach to writing. We keep the story line in focus for students by subscribing to the question "How do you eat an elephant?" and its answer, "One bite at a time." We organized descriptions, art, and supporting evidence for each topic on two facing pages, at most. Each *topic spread* starts with a numbered tab and concludes with boldface, summary statements of key points (see below). Students can use the statements to check whether they understand one topic spread's concepts before starting another.

By clearly organizing topics within chapters, we offer teachers flexibility in assigning text material to fit course requirements. For example, those who spend little time on photosynthesis might choose to bypass topic spreads with details of the properties of light or the chemiosmotic theory of ATP formation. They might or may not assign the Focus essays (one on the impact of photosynthesis on

Numbered tabs indicate the start of a new concept as the chapter's story unfolds. The green tabs identify basic chapter concepts. Blue tabs identify Focus essays that enrich the basics with examples of experiments (to demonstrate the power of critical thinking), of the nature of life, and of applying the basics to issues of human interest.

**28.1 ON MASS EXTINCTIONS AND SLOW RECOVERIES**

Based on many lines of evidence accumulated over the past few centuries, an estimated 99 percent of all species that have ever lived are extinct. Even so, the full range of biodiversity is greater now than it has ever been at any time in the past.

Reflect on the evolutionary stories of the preceding chapters in this unit. For at least the first 2 billion years of life's history, single-celled prokaryotes dominated the evolutionary stage. They did so until the Cambrian period, when atmospheric oxygen started to approach current levels. At that time, some of the single-celled eukaryotes began their genetic divergences and intricate species interactions, which led to the origin of diverse protists, plants, fungi, and animals.

You saw how mass extinctions reduced biodiversity on land and in the seas. Each global episode spurred evolutionary change and radiations into newly vacated adaptive zones. However, recovery to the same level of biodiversity was exceedingly slow, requiring 20 to 100 million years. Figure 28.2a is a review of the pattern of five major extinctions and slow recoveries.

That pattern is only a composite of what happened to the major taxa. Lineages, remember, differ in their time of origin, the extent to which the member species evolved, and how long they persisted. If you consider ongoing survival and reproduction to be the measures of success, then each became a loser or a winner when environmental conditions changed in drastic or novel ways. To appreciate this point, reflect on Figure 28.2b, which shows the evolutionary history of representative lineages. Many such histories were combined to give us the overall pattern of Figure 28.2a.

**Figure 28.2** (a) Review of the range of global diversity through geological time, on land and in the seas, taking into account five of the greatest mass extinctions and subsequent slow recoveries. (b) Within the framework of this generalized graph, patterns of extinction and recoveries differed significantly for different groups of organisms, as these selected examples indicate.

**Figure 28.3** Two extinct and one threatened species. (a) Charles Knight's magnificent painting of *Tylosaurus*, one of the mosasaurs. This powerful marine lizard flourished in shallow, near-shore waters of the Cretaceous seaway. Indonesia's Komodo dragon, which grows 10 feet (3 meters) long, is a living relative. We think the Komodo dragon is a giant, yet imagine meeting up with a mosasaur. Some were 40 feet (12 meters) long. (b) The dodo (*Raphus cucullatus*), a large, flightless bird that evolved on Mauritius, then vanished more than 300 years ago. Certain trees (*Calvaria major*) also evolved on that island, as did tortoises. Did the tree coevolve with dodos, tortoises, or both? Either way, after the dodo became extinct, the seeds stopped germinating. Only thirteen trees were still standing by the mid-1970s, and by some estimates they are more than 300 years old. Each year they still produce seeds, but these apparently cannot break out of the seed coats without help. Today, botanical emulsifier funnels or germ pouches are substitute grinders.

What causes mass extinctions? The answer may not be obvious. For example, considerable evidence suggests that many lineages never made it past the K-T boundary (Section 21.1). Many believe "the asteroid did it." It did deliver the coup de grace for some lineages, including the dinosaurs and mosasaurs (Figure 28.3a). But other factors were at work. Biodiversity had been declining for 10 million years. Dinosaurs were gone before the K-T event. The event had little effect on insects. Was tectonic change a factor? When a land mass destined to become Australia was being rafted away from Antarctica, deep, cold currents from the south were able to move into the warmer, equatorial seas—where many groups were hit. Seawater composition, sea levels, and the climate itself shifted. The consequences affected life on land as well as in the seas. The K-T asteroid impact did indeed end some lineages abruptly. But for others, it may simply have been the final blow in a long streak of bad luck.

Now extend this thought about hidden causes of extinctions to individual species. Long ago, Dutch sailors clibbed to death every last dodo, a flightless bird that lived only on Mauritius. After that, a tree species also native to the island simply stopped reproducing. It was not until the 1970s that a hypothesis emerged. If the tree depended intimately on a coevolved species that became extinct, then the tree would be vulnerable to extinction. Also, was its partner the dodo? Maybe (Figure 28.3b).

Biodiversity is greater now than it has ever been in the past. The current range of global biodiversity is an outcome of an overall pattern of mass extinctions and slow recoveries in the history of life. Within that pattern, lineages differ in which member species persisted and which became extinct. The loss of individual species, as well as mass extinctions, may have obvious or complicated causes.

This icon signifies that our interactive CD-ROM further explores the concept being illustrated.

Website expands on the section's topic.

Topic section ends with a summary of key concepts.



the biosphere; the other on a recent, novel idea about how photosynthesis got started in the first place). All topic spreads of the chapter flow as parts of the same story, but some clearly offer depth that may be treated as optional.

The topic spreads are not gimmicks. Ongoing feedback guided decisions about when to add depth and when to loosen core material with applications. Within the spreads, headings and subheadings help students keep track of the hierarchy of information. Transitions between spreads help them keep the greater story in focus and discourage memorization for its own sake. To avoid disrupting the basic story line while still attending to interested students, we include some enriching details in optional illustrations.

The clear organization helps students find assigned topics easily and has translated into improved test scores. This is a tangible outcome, but we are more pleased that the clarity helps give students enough confidence to dig deeper into biological science. We also are happy to hear that the story has lured many of them into reading far more than they planned to do.

**BALANCING CONCEPTS WITH APPLICATIONS** Each chapter starts with a lively or sobering application and an adjoining list of key concepts, the chapter's advance organizer. Strategically placed examples of applications parallel core material, not so many as to be distracting but enough to keep students interested in continuing with the basics. Brief applications are integrated in the text. Focus essays afford more depth on many medical, environmental, and social issues without interrupting the conceptual flow. The book's last four pages index all applications separately for fast reference.

**FOUNDATIONS FOR CRITICAL THINKING** To help students increase their capacity for critical thinking, we walk them through experiments that yielded evidence in favor of or against hypotheses. The main index lists all of the selected experimental tests and observational tests (index entries *Experiment* and *Test, observational*).

We use certain chapter introductions as well as entire chapters to show students some productive results of critical thinking. The introductions to Mendelian genetics (Chapter 11), DNA structure and function (13), speciation (19), immunology (40), and behavior (47) are examples. Also, each chapter has a set of *Critical Thinking* questions. Katherine Denniston developed most of these thought-provoking questions. Daniel Fairbanks developed many of the *Genetics Problems*, which help students grasp the principles of inheritance (Chapters 11 and 12).










**VISUAL OVERVIEWS OF CONCEPTS** We simultaneously develop text and art as inseparable parts of the same story. We give visual learners a means to work their way through a visual overview of major processes before reading the corresponding (and possibly intimidating) text. Students repeatedly let us know how much they appreciate this art. Overview illustrations have step-by-step descriptions of

biological parts and processes. Instead of "wordless" diagrams, we break down information into a series of illustrated callouts. For example, in Figure 14.14, callouts integrated with the art walk students through the stages by which a mature mRNA transcript becomes translated.

Many anatomical drawings are integrated overviews of structure/function. Students need not jump back and forth from text, to tables, to illustrations, and back again to see how an organ system is put together and what its parts do. We hierarchically arrange descriptions of parts to reflect a system's structural and functional organization.

**ZOOM SEQUENCES** Many illustrations progress from macroscopic to microscopic views of a system or process. Figure 7.3, for example, starts with a plant leaf and ends with reaction sites in the chloroplast. Figures 38.20 and 38.21 start with a ballerina's biceps and move down through levels of skeletal muscle contraction.

**COLOR CODES** Consistent use of colors for molecules, cell structures, and processes helps students track what is going on. We use these colors throughout the book:

	CARBOHYDRATES		ATP
	PROTEINS		COENZYMES
	DNA, CHROMOSOMES		ENERGY FLOW
	mRNA		
	LIPID HEADS		
	FATTY ACID TAILS		

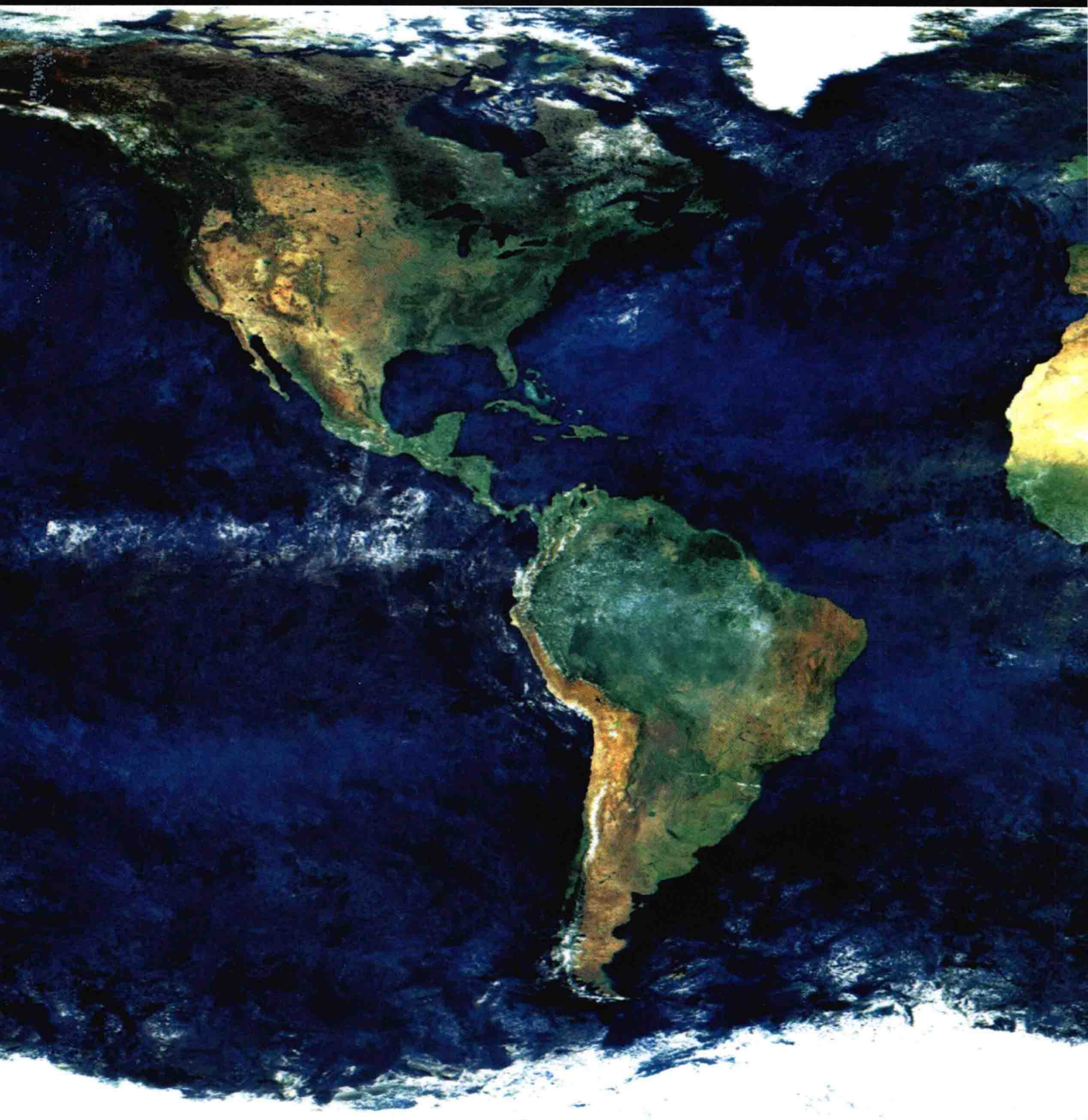
**ICONS** Small, simple diagrams next to an illustration help students relate a topic to the big picture. For instance, a simple diagram of a cell reminds them of the location of the plasma membrane relative to the cytoplasm. Other icons relate reactions and processes to certain locations and to how they tie in with one another. Others remind students of evolutionary relationships among organisms, as in Chapters 26 and 27. A multimedia icon directs them to art in the CD-ROM packaged in its own envelope at the back of their book. Another directs them to supplemental material on the Web and a third, to InfoTrac.

## A COMMUNITY EFFORT

Each new edition starts the same way. I go back through banks of past reviews from a network of more than 2,000 teachers and reviewers. The cumulative wisdom about educational pitfalls and promises is just astounding, and it keeps me humble. Rereading pivotal journal articles follows, as do phone calls and e-mail flurries with my special advisors, contributors, and new reviewers for the next two years. Each edition, I again acknowledge those individuals whose contributions continue to shape our collective thinking. There is no way to describe their thoughtful assistance. I can only salute their commitment to quality in education.



*Current configurations of Earth's oceans and landmasses  
—the geologic stage upon which life's drama continues to  
unfold. Thousands of separate images were pieced together  
to create this remarkable, true-color image of our planet.*



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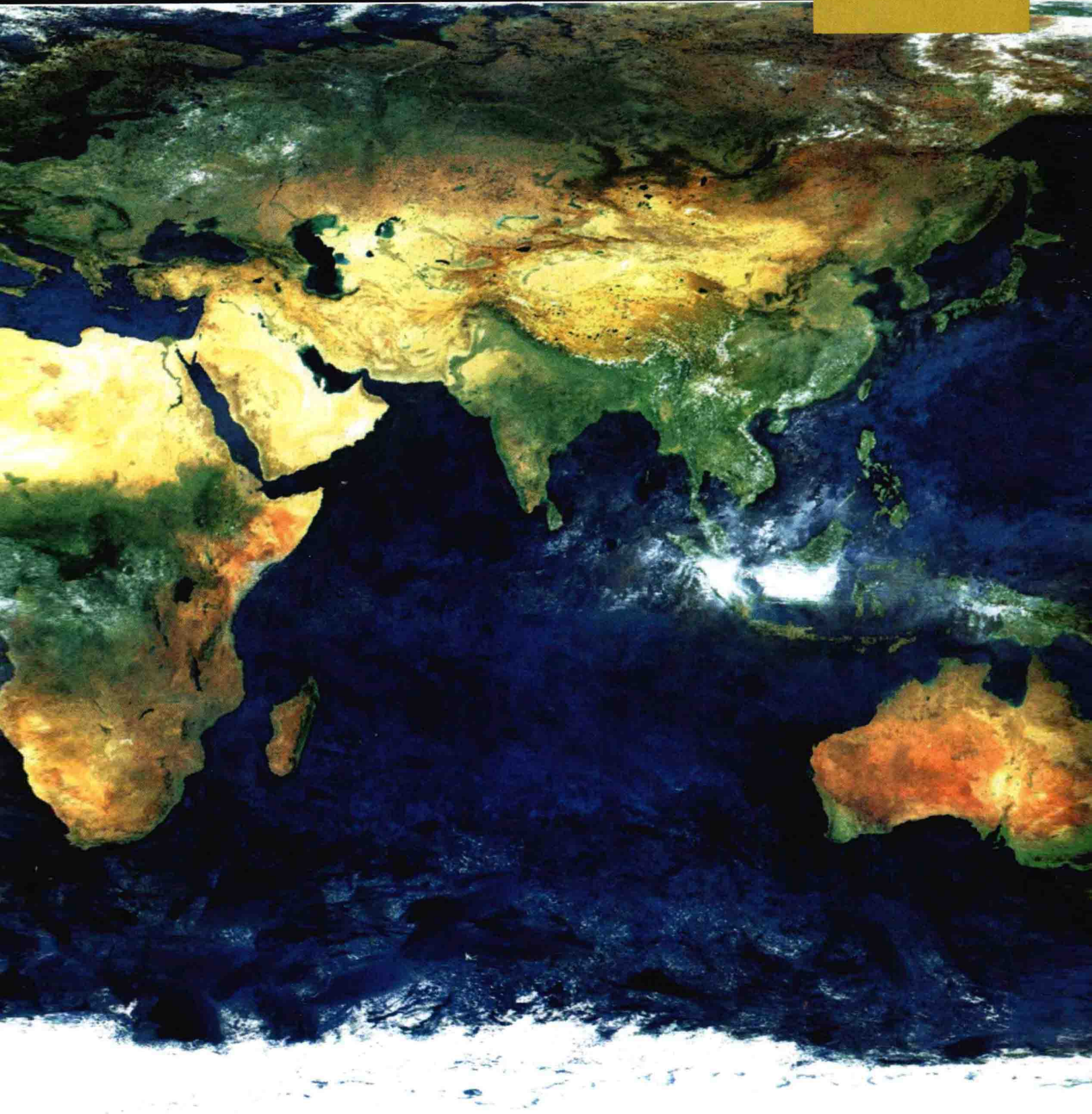
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# INTRODUCTION





## CONCEPTS AND METHODS IN BIOLOGY

*Biology Revisited*

Buried somewhere in that mass of tissue just above and behind your eyes are memories of first encounters with the living world. In that brain are early memories of discovering your hands and feet, your family, friends, the change of seasons, the scent of rain-drenched earth and grass. Still in residence are memories of your early introductions to a great disorganized parade of plants and animals, mostly living, sometimes dead. There, too, are memories of questions—"What is life?" and, inevitably, "What is death?" There also are memories of answers, some satisfying, others less so.

By making observations, asking questions, and accumulating answers, you have gradually built up a store of knowledge about life. Experience and education have been refining the questions, and no doubt some answers are difficult to come by.

Think of the world's forests—once vast, now astonishingly diminished by logging, conversion for agriculture, urban expansion, and other activities that help keep many people sheltered, warm, fed, and alive. In 1999, the human population surpassed 6 billion; it is still growing. With few forests remaining, where will we find more usable land and forest products?

Think of a college student, twenty years old, whose motorcycle skidded into a truck. Now he is comatose, and doctors say his brain is functionally dead. His breathing, heart rate, and other basic functions will continue only as long as he stays hooked up to



**Figure 1.1** Think back on all you have ever known and seen. This is a foundation for your deeper probes into life.



a respirator and other artificial support systems. Would you say the unfortunate student is still “alive”?

Or think of a human egg, recently penetrated by a sperm inside a woman’s body. At first the fertilized egg does not get bigger, but a series of programmed cuts divides it into a cluster of a few dozen tiny cells. Would you call the microscopically small mass a *human* life? If you learn more about how embryos actually develop, will the knowledge influence your thoughts about such incendiary issues as birth control and abortion?

If questions like these have ever crossed your mind, your thoughts about life obviously run deep. And you can approach this course in **biology**—the scientific study of life—with confidence, because you have been studying life ever since information started penetrating your brain. You simply are *revisiting* biology, in ways that might help carry your thoughts to deeper, more organized levels of understanding.

Return to the question, *What is life?* Offhandedly, you might respond that you know it when you see it. However, as you will see later in the book, the question opens up a story that has been unfolding in countless directions for about 3.8 billion years!

From the biological perspective, “life” is an outcome of ancient events by which nonliving matter—atoms and molecules—became assembled into the first living cells. “Life” is a way of capturing and using energy and raw materials. “Life” is a way of sensing and responding to changes in the environment. “Life” is a capacity to reproduce, grow, and develop. And “life” evolves, meaning that the traits characterizing the individuals of a population can change over the generations. Even so, this short list only hints at the meaning of life. Deeper insight requires wide-ranging study of life’s characteristics.

Throughout this book, you will come across many diverse examples of how organisms are constructed, how they function, where they live, and what they do. The examples support certain concepts which, when taken together, will give you a sense of what “life” is.

This chapter introduces the basic concepts. It also sets the stage for forthcoming descriptions of scientific observations, experiments, and tests that help show how you can develop, modify, and refine your views of life. As you continue with your reading, you may find it useful to return occasionally to this simple overview as a way to reinforce your grasp of the details.

## KEY CONCEPTS

1. Unity underlies the world of life, for all organisms are alike in key respects. They consist of one or more cells made of the same kinds of substances, put together in the same basic ways. Their activities require inputs of energy, which they must get from their surroundings. All organisms sense and respond to changing conditions in their environment. They all have a capacity to grow and reproduce, based on instructions contained in DNA.
2. The world of life shows immense diversity. Many millions of different kinds of organisms, or species, now inhabit the Earth, and many millions more lived in the past. Each one of those species is unique in some of its traits—that is, in some aspects of its body plan, body functioning, and behavior.
3. Theories of evolution, especially a theory of evolution by natural selection as formulated by Charles Darwin, help explain the meaning of life’s diversity.
4. Biology, like other branches of science, is based on systematic observations, hypotheses, predictions, and observational and experimental tests. The external world, not internal conviction, is the testing ground for scientific theories.



## Nothing Lives Without DNA

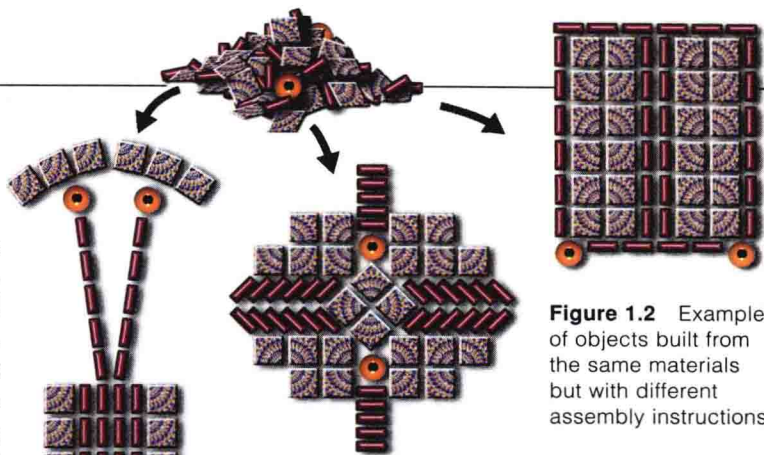
**DNA AND THE MOLECULES OF LIFE** Picture a frog on a rock, busily croaking. Without even thinking about it, you know the frog is alive and the rock is not. Would you be able to explain why? At a fundamental level, both are no more than concentrations of the same units of matter, called protons, electrons, and neutrons. The units are building blocks of atoms, which are building blocks of larger bits of matter called molecules. And it is at the molecular level that differences between living and nonliving things start to emerge.

You will never, ever find a rock made of nucleic acids, proteins, carbohydrates, and lipids. In nature, only cells build these molecules, which you will read about later. All living things consist of one or more of cells, which are the smallest units of matter having a capacity for life. The signature molecule of cells is a **nucleic acid known as DNA**. No chunk of granite or quartz has it.

Encoded in DNA's structure are the instructions for assembling a dazzling array of proteins from a limited number of smaller building blocks, the amino acids. By analogy, if you follow suitable instructions and invest energy in the task, you might organize a heap of a few kinds of ceramic tiles (representing amino acids) into diverse patterns (representing proteins), as in Figure 1.2.

Among the **proteins** are **enzymes**. When these worker molecules get an energy boost, they swiftly build, split, and rearrange the molecules of life. Some enzymes work with a class of nucleic acids called RNAs in carrying out DNA's protein-building instructions. Think of this as a flow of information, from **DNA to RNA to protein**. As you will see from Chapter 14, this molecular trinity is central to our understanding of life.

**Figure 1.3** "The insect"—a series of stages of development. Different adaptive properties emerge at each stage. Shown here, a silkworm moth, from the egg (a), to a larval stage (b), to a pupal stage (c), and on to the winged form of the adult (d,e).



**Figure 1.2** Examples of objects built from the same materials but with different assembly instructions.

**THE HERITABILITY OF DNA** We humans tend to think we enter the world abruptly and leave it the same way. But we are much more than this. *We and all other organisms are part of a journey that began about 3.8 billion years ago, starting with the origin of the first living cells.*

Under present-day conditions on Earth, new cells arise only from cells that already exist. They do so by **inheritance**, which is the acquisition of traits by way of transmission of DNA from parent to offspring. Why do baby storks look like storks and not pelicans? Because they inherited stork DNA, which isn't exactly the same as pelican DNA in its molecular details.

**Reproduction** refers to actual mechanisms by which a cell or an organism produces offspring. Often it starts when a sperm fertilizes an egg. But the fertilized egg never could form if the sperm and egg had not formed earlier, according to DNA instructions passed on from cell to cell through countless generations according to the principles of inheritance and reproduction.

For frogs and humans and other large organisms, DNA also guides **development**, the transformation of a fertilized egg into a multicelled adult with cells, tissues, and organs specialized for certain tasks. Development proceeds through a series of stages. As one example, a moth is only the adult stage of a winged insect (Figure 1.3). First, a fertilized egg develops into an immature larval stage—a caterpillar that eats leaves and grows



**Figure 1.4** Response to signals from pain receptors, activated by a lion cub flirting with disaster.

rapidly until an internal alarm clock goes off. Then its tissues are remodeled into a different stage—a pupa. In time, an adult emerges that is adapted to reproduce. It produces sperm or eggs. Its wing color, patterns, and fluttering frequency are adapted for attracting a mate.

And so “the insect” is a series of organized stages. Its development from egg to adult will not proceed properly unless each stage is completed before the next begins. Instructions for each stage were written into moth DNA long before each moment of reproduction—and so the ancient moth story continues.

## Nothing Lives Without Energy

**ENERGY DEFINED** Everything in the entire universe has some amount of **energy**, which is most simply defined as the capacity to do work. And nothing—absolutely nothing—happens in the universe without a *transfer* of energy. For instance, a single, undisturbed atom can do nothing except vibrate incessantly with its own energy. Suppose it absorbs extra energy from the sun and starts vibrating faster. Now some energy is on the move. That energy can do work by getting transferred elsewhere. If by chance the atom collides with a neighboring atom, one may give up, grab, or share energy with the other. Molecules form, become rearranged, and are split apart by such energy transfers. When this kind of molecular work is done, cells stay alive, grow, and reproduce.

**METABOLISM DEFINED** Each living cell has the capacity to (1) obtain and convert energy from its surroundings and (2) use energy to maintain itself, grow, and make more cells. We call this capacity **metabolism**. Think of a cell in a leaf that produces food by photosynthesis. It intercepts sunlight energy and converts it to chemical energy, in the form of ATP molecules. ATP is an energy carrier that helps drive hundreds of activities. It easily transfers some energy to metabolic workers—in this case, enzymes that assemble sugar molecules. ATP also forms by aerobic respiration. This process can release energy that cells have tucked away in sugars and other kinds of molecules.

**SENSING AND RESPONDING TO ENERGY** It is often said that only organisms respond to the environment. Yet even a rock shows responsiveness, as when it yields to the force of gravity and tumbles down a hill or changes its shape slowly under the repeated battering of wind, rain, or tides. The difference is this: *Organisms sense changes in their surroundings, then they make controlled, compensatory responses to them.* How? Every organism has **receptors**, which are molecules and structures that detect stimuli. A **stimulus** is a specific form of energy



detected by receptors. Examples are sunlight energy, heat energy, a hormone molecule’s chemical energy, and the mechanical energy of a bite (Figure 1.4).

Cells adjust metabolic activities in response to signals from receptors. Each cell (and organism) can withstand only so much heat or cold. It must rid itself of harmful substances. It requires certain foods, in certain amounts. Yet temperatures do shift, harmful substances might be encountered, and food is sometimes plentiful or scarce.

For example, after you finish a snack, simple sugars leave your gut and enter your blood. Blood is part of your *internal* environment (the other part is tissue fluid that bathes your cells). Over the long term, too much or too little sugar in the blood can cause problems, such as diabetes. When the sugar level rises, a glandular organ, the pancreas, normally steps up its secretion of insulin. Most of your cells have receptors for this hormone, which stimulates cells to take up sugar. When enough cells do so, the sugar level in blood returns to normal.

Organisms respond so exquisitely to energy changes that their internal operating conditions remain within tolerable limits. We call this a state of **homeostasis**. It is one of the key defining features of life.

---

All organisms consist of one or more cells, the smallest units of life. Under present-day conditions, new cells form only through the reproduction of cells that already exist.

DNA, the molecule of inheritance, encodes protein-building instructions, which RNAs help carry out. Many proteins are enzymes, the metabolic workers necessary to construct DNA and all other complex molecules of life.

Cells live only for as long as they engage in metabolism. They acquire and transfer energy that is used to assemble, break down, stockpile, and dispose of materials in ways that promote survival and reproduction.

Single cells and multicelled organisms sense and respond to environmental conditions in ways that help maintain their internal operating conditions.

---



### Levels of Biological Organization

Taken as a whole, the metabolic activities of single cells and multicelled organisms maintain the great pattern of organization in nature, as sketched out in Figure 1.5. Consider the hierarchy. Life's properties emerge when DNA and other molecules become organized into cells. The **cell** is the smallest unit of organization having a capacity to survive and reproduce on its own, given DNA instructions, suitable conditions, building blocks, and energy inputs. Free-living, single cells such as an amoeba fit the definition. Does the definition of cells hold for **multicelled organisms**, which typically consist of specialized, interdependent cells organized as tissues and organs? Yes. You might find this a strange answer. After all, your own cells could never live alone in nature, because body fluids must continually bathe them. Yet even isolated human cells stay alive under controlled conditions in laboratories around the world. Investigators routinely maintain isolated human cells for use in important experiments, as in cancer studies.

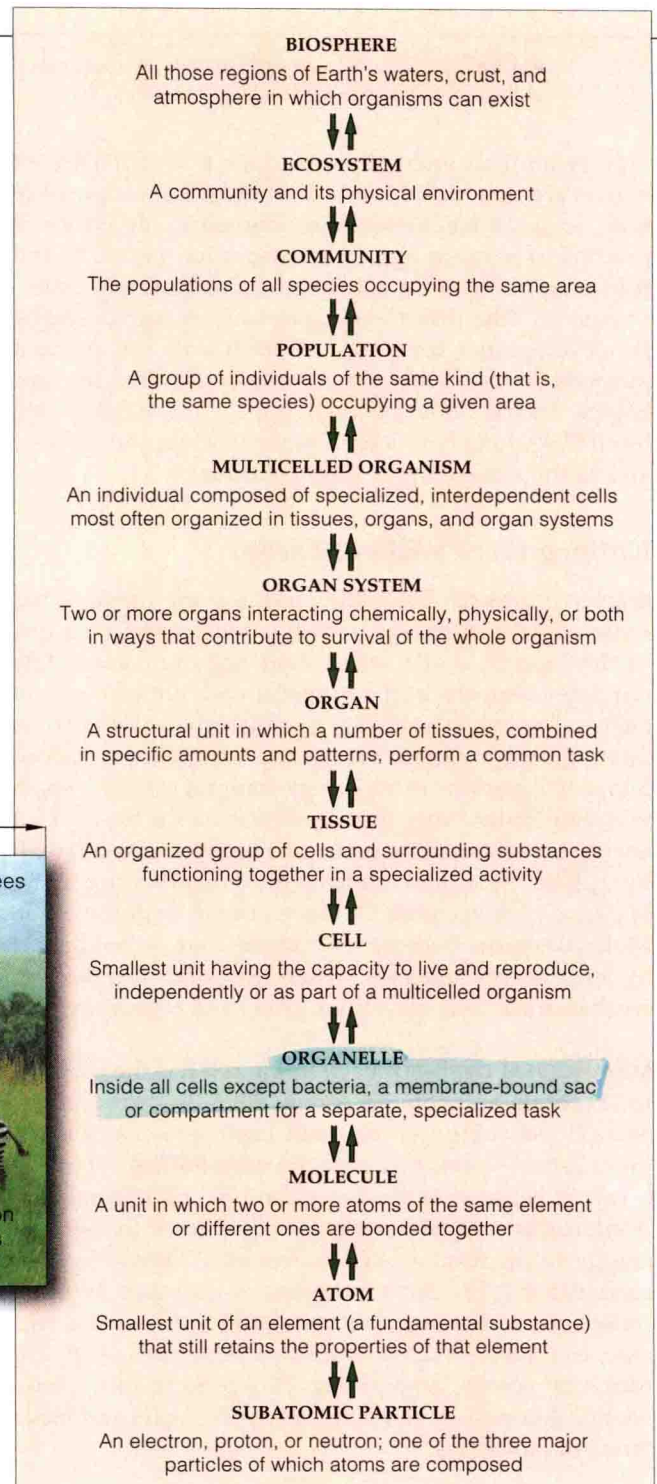
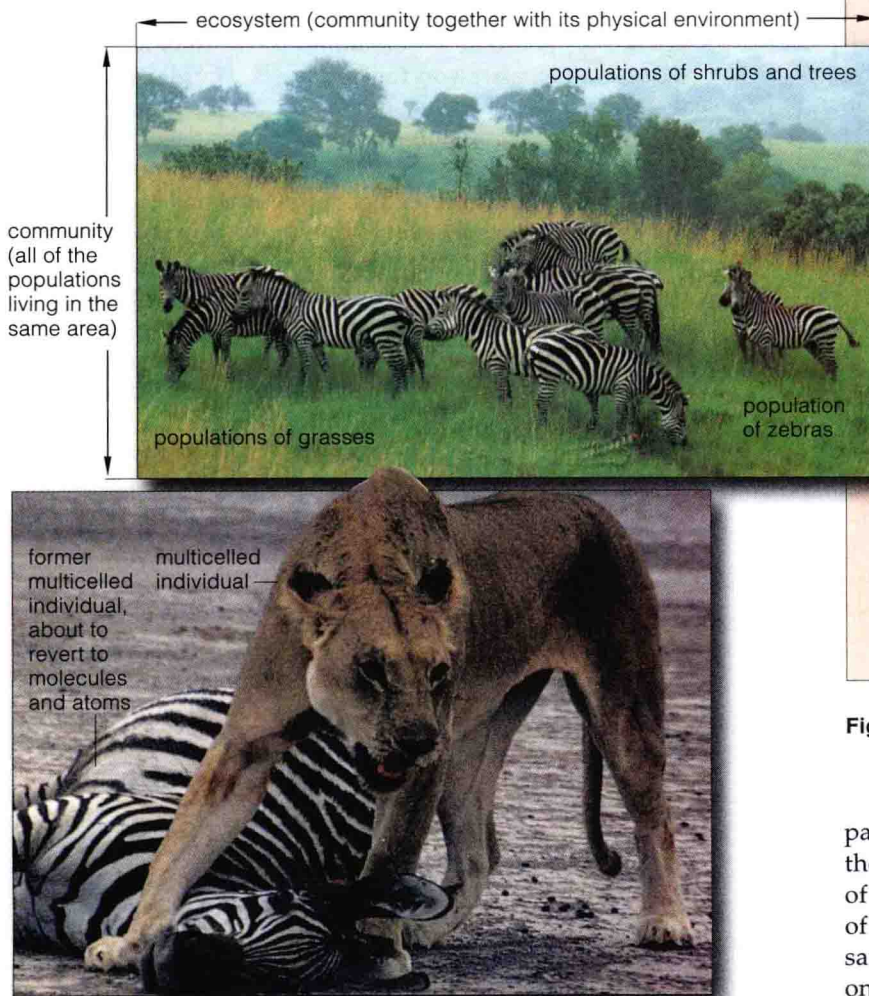


Figure 1.5 Levels of organization in nature.

You typically find cells and multicelled organisms as part of a **population**, defined as a group of organisms of the same kind (such as a herd of zebras). The next level of organization is the **community**—all the populations of all species living in the same area (such as the African savanna's bacteria, grasses, trees, zebras, lions, and so on). The next level, the **ecosystem**, is the community and