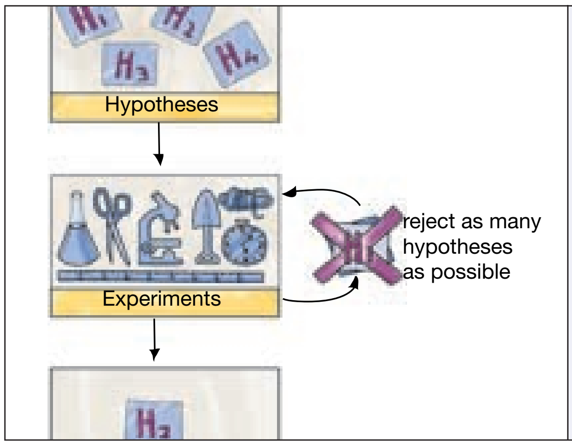
1

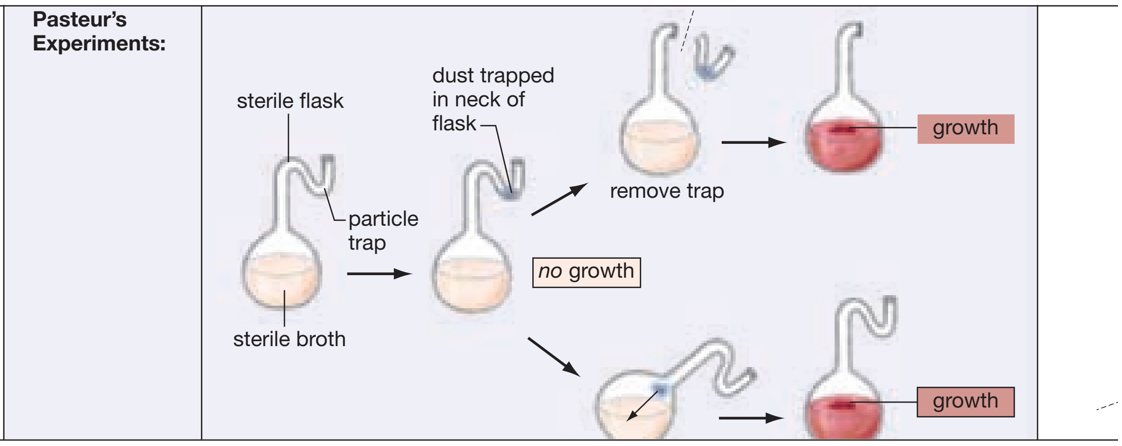
Science as a Way of Learning

A Guide to the Natural World

Essay



How scientists think about the world—
the scientific method.
(Section 1.3, page 8)



A famous experiment by a famous scientist.
(Section 1.3, page 9)

Science has great impact on our lives now and stands to have greater impact on them in the future. Science is both a body of knowledge and a means of acquiring knowledge. Biology, a branch of science, is the study of life.

About 20 years ago, a friend of mine showed me a magazine article which asserted that science and technology were becoming such important parts of our society that people would either have to jump on an approaching technological train or get run over by it. At the time, it just didn't look that way to me. Why, I wondered, would members of my generation have to know any more about science than members of my parents' generation did?

Looking back on this, it's easy to see that the magazine article had it about right. Indeed, the beginning of the 1980s can be seen as about the time when science and technology began knocking on the average person's door with great frequency. The fundamental breakthrough that brought about modern electronics, including the computer, was the invention of the transistor at Bell Labs in 1947. Average American workers then *heard* about computers for 30 years, but by the mid 1980s, they were *using* computers right on their desktops and having other electronic innovations, such as VCRs and CD players, thrust at them from every angle (**see Figure 1.1**). The fundamental breakthrough that brought about the biotechnology industry was the description of the DNA molecule in 1953 by James Watson

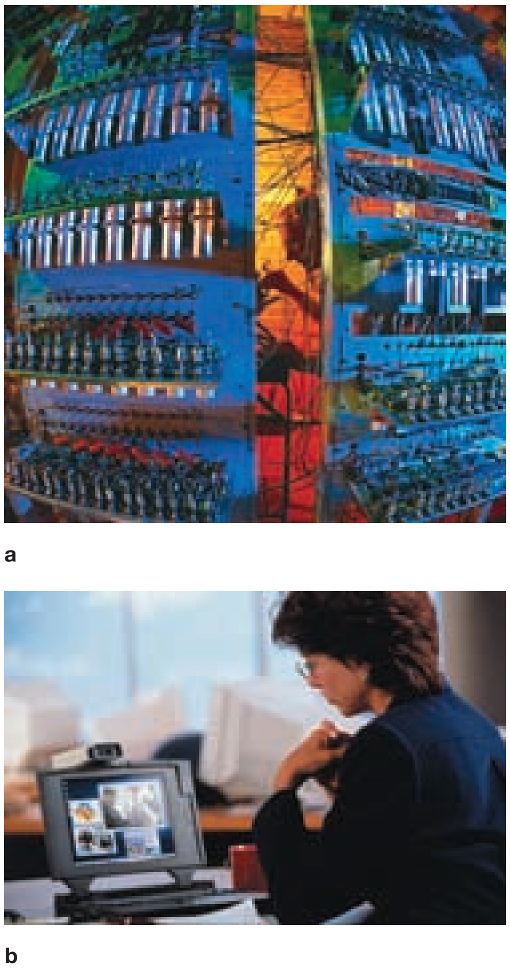
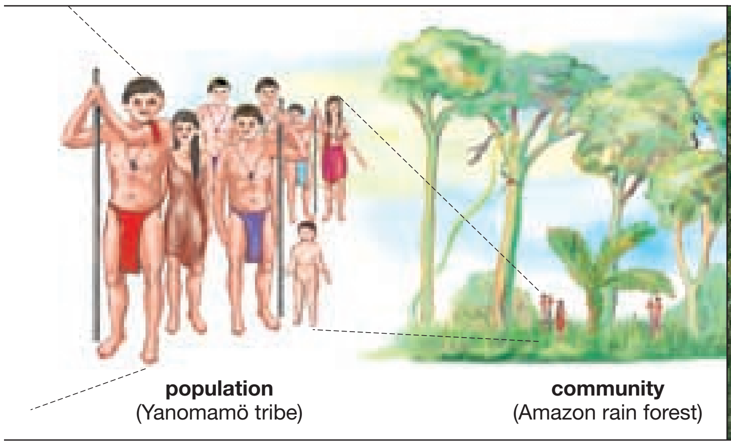


Figure 1.1
Then and Now

a A technician enters data into the world's first programmable computer, run initially in 1948. Called "Baby," the computer was more than 2 meters (6 feet) tall and almost 5 meters (15.5 feet) wide, but had a total memory of only 128 bytes—less than one-ten-thousandth the amount of data that can be put on a common floppy disk today.

b A businesswoman using a laptop computer participates in a video conference while viewing colleagues in a window on her computer screen. A small video camera sits on top of her computer.



From atom to rain forest, the hierarchy of life.
(Section 1.4, page 12)

Nature's finery—it's evolutionary.
(Section 1.5, page 14)

You don't know what this
insect is, but it scares you. Why?
(Section 1.5, page 15)

and Francis Crick. People heard more about genes in subsequent years, but only in 1978 did we get the first genetically engineered medicine (human insulin).

What once was a trickle in both these fields became a stream in the 1980s and a torrent in the 1990s. Indeed, in the 1990s it would have been quite a challenge to *avoid* the technological changes going on all around. (You might decline a computer at home, but try evading one at work.) Strictly biological innovations didn't have this kind of presence for the average person, but it was not hard to see signs of a coming wave. Consider in vitro fertilization ("test-tube babies"), DNA testing for paternity, the wide popularity of new antidepressant drugs such as Prozac, the controversy over genetically modified foods, and genetic testing for such diseases as cystic fibrosis. Then, there was the cloning of Dolly the sheep from a single cell of an adult sheep. Since Dolly, scientists have gone on to clone cows, mice, monkeys, and goats and are working hard to see if cloned pigs might be used to produce human "spare parts," such as hearts and livers. (**see Figure 1.2**). Beyond these things, scarcely a week goes by without an environmental issue being in the news, with scientists being turned to for guidance on how to deal with it.

Figure 1.2
A Step Beyond Dolly
Dolly the sheep was merely the first step in animal cloning. In March 2000, the same British pharmaceutical company that cloned Dolly announced that it had cloned these five healthy piglets from a single cell of an adult sow. Pig-cloning research has a practical goal: the growing of organs, in pigs, that can be transplanted to human beings. Tens of thousands of Americans need organ transplants but cannot get them because of a shortage of human organs. Pig organs are about the same size as human organs and carry out the same functions. Pig cloning is aimed at producing organs that, once transplanted, will not be attacked by the human immune system.

If we ask, then, whether science and technology are becoming ever more important in our society, the answer is plain. To fully participate in the workforce, to make everyday decisions, and to make informed choices at the ballot box, the average person must now be more technologically and scientifically literate than at any time in the past, and this trend only stands to accelerate in coming years.

Given this, it seems worthwhile to take a look at the relationship between science and society. What practical effect does science have on us? What do average citizens think of science and scientists? These questions are examined at the beginning of this chapter. This will be followed by a review of the nature of science and of biology.

1.1 How Does Science Impact the Everyday World?

How is science in general—and biology in particular—likely to be relevant to a person's life in contemporary society?

A Look at the News

To get an idea, let's look at some of the biology-related news that came to Americans through one magazine (*Time*) during one randomly selected period (six months in 2000). More than 60 stories connected to biology appeared in *Time* during this period (**see Figure 1.3**). Six are noted here.

Vitamin Overdose, said the headline in an April 24 *Time* story that reported on the increasingly popular American practice of taking "megadoses" of vitamin C and vitamin E in the hope of living longer, healthier lives. A national Institute of Medicine study threw cold water on the idea, however, saying there is insufficient evidence to conclude that large doses of vitamins can protect people from chronic diseases. Worse, the study said, *really* large doses of these supplements may actually cause health problems. People take large doses of these vitamins, the *Time* story noted, because some studies have raised the possibility that they may serve as "antioxidants," soaking up the "free radicals" that seem to play roles in aging and in such afflictions as heart disease and cancer. But what is a free radical? For that matter, what is an oxidant? *Time* didn't have the space to let its readers know, but readers of this *textbook* who are interested can find out about free radicals in the box "Free Radicals" on **page 29**, while readers who want to know more about oxidation can turn to Chapter 7, on **page 130**.

The Science of Dissent was one article among several in a special "Life on the Mississippi" section *Time* ran in its July 10 issue. The article reported on a public high school teacher in Faribault, Minnesota, who has gone to court to be allowed to teach what his critics say is creationism—the idea that the living world is so diverse and complex it could not have been shaped by the forces of nature alone. The teacher claims, meanwhile, that all he wants to do is teach *evolution* with "an honest look at the difficulties and inconsistencies in the theory." Debates over the teaching of evolution and creationism have raged for decades in America and show no signs of tapering off. In Chapter 16, beginning on **page 320**, you can find an account of why the vast majority of scientists are convinced that all of Earth's life-forms did indeed develop through the process of evolution.

The Big Meltdown was the title *Time* gave to a September 4 story on the effect global warming is having in Earth's far north region, the Arctic. Sea ice in the Arctic is now 40 percent thinner and covers 6 percent less area than in 1980. *Time*'s story provided vivid evidence of the down-to-Earth effects of global warming. In Alaska, for example, much of the "permafrost" is no longer permanently frozen. The result is "power lines tilted at crazy angles and houses sinking up to their window sashes as the ground liquifies." Scientific evidence clearly indicates that Earth is warming, and a scientific consensus appears to be emerging that a human activity—the burning of fossil fuels—is at least partly to blame. But how could human activity cause the Earth to warm? You can find an explanation in "The Worrisome Issue of Global Warming" on **page 708** of Chapter 30.

Battle Pending, *Time* said in an April 17 article that noted what a big business human genes have become. Old-line pharmaceutical companies and newer biotech start-ups are in a feverish race to file patents on newly discovered genes, hoping to cash in should knowledge about the genes lead to products that can be used in medicine, agriculture, manufacturing, or even home lawn care. (Imagine grass that almost never has to be cut because it stays short thanks to genetic programming.) The problem, as the *Time* article pointed out, is that firms are filing patents on genes that merely look like they might be important, while having little idea of what this importance may be. Readers who want to know what a gene is can read Chapter 9, beginning on **page 170**.

Little Hope, Less Help, said a July 24 *Time* article on AIDS in sub-Saharan Africa, which is expected to suffer 23 million AIDS deaths by 2005. By the end of the decade, life expectancy in Botswana, Zimbabwe, and South Africa will plummet to 30; without AIDS, it would have been about 70. AIDS is devastating because it attacks the human body's own defenses—its immune system. How does the immune system work and how can AIDS destroy it? For an account, see "The Immune System: Defending the Body from Invaders" on **page 572**.

Grains of Hope, the cover story in *Time*'s July 31 issue, concerned a new chapter in the debate over genetically modified foods. Until recently, such foods have primarily benefited food *producers*, such as farmers and seed suppliers, by making crops more resistant to pests or to herbicides (the chemicals used to control weeds). Now, however, European researchers have developed a genetically modified rice that contains its own beta carotene, meaning that this rice, unlike the natural variety, can be

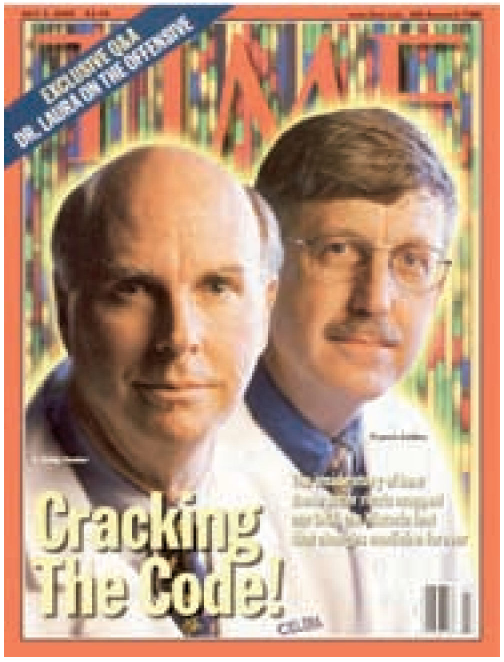


Figure 1.3
Science in the News
The importance of science to everyday life is reflected in the large number of news stories that focus on science. The text contains a summary of six stories concerning biology that appeared in *Time* magazine during a six-month period in 2000. Pictured is a cover story *Time* ran in July on the sequencing of the human genome.

a source of vitamin A. This is no small matter, as at least a million children die each year because they are weakened by vitamin A deficiency. Yet genetically modified foods have numerous critics who charge that they are "Frankenfoods," whose production stands to harm the environment and possibly human beings as well. The newly developed variety of rice certainly is genetically modified, as it contains genes from two other living things (daffodils and a species of bacteria). But how can genes from one species be spliced into another? More generally, what is the promise—and the peril—of biotechnology? To find out, see Chapter 15, beginning on **page 292**.

1.2 What Does the Public Think, and Know, about Science?

Science issues may be thrust upon the public today, but what do Americans think about science, and how "scientifically literate" are they? A wealth of information on these topics was contained in a report titled *Science and Engineering Indicators—1998.* This document was one in a series of reports on the state of science and engineering in America produced by the National Science Foundation (NSF). In a section of the 1998 report that dealt with the American public and its relation to science, two things stood out. One is that Americans are positive about science in many ways; the other is that their *knowledge* of science is uneven—surprisingly high in some areas and surprisingly low in others.

Public Attitudes toward Science

On American attitudes toward science, surveys used in the NSF report revealed that Americans were more interested in science in the late 1990s than at any time in the previous 20 years. They have more confidence in American scientific leadership than they do in the leadership of Congress, corporations, the press, organized religion, even the U.S. Supreme Court. (Only leaders in medicine ranked higher in the public's esteem.) And they believe science has brought much to them already, and that it stands to bring a lot more. More than 85 percent of all Americans believe that the world is a better place because of science.

Public Knowledge of Science

Given Americans' attitudes toward science, it's somewhat surprising to learn what they *know* about science. If you look at **Figure 1.4**, you can see the proportion of a representative sample of adult Americans who could correctly answer some basic scientific questions. Better than 75 percent understand that light travels faster than sound, but only about 20 percent understand what DNA is. Almost 80 percent of Americans know that the continents are moving about the face of the Earth, but less than half know that it takes a year for the Earth to go around the Sun. (The alternatives were that it made the journey in a day or a month.) Meanwhile, another question revealed that more than a quarter of all Americans think the Sun goes around the Earth. With respect to how science works, 27 percent of those questioned were classified as having at least a minimal understanding of scientific inquiry, which is to say they understood that science involves formulating hypotheses and testing them with experiments, a topic you'll learn more about later in this chapter.

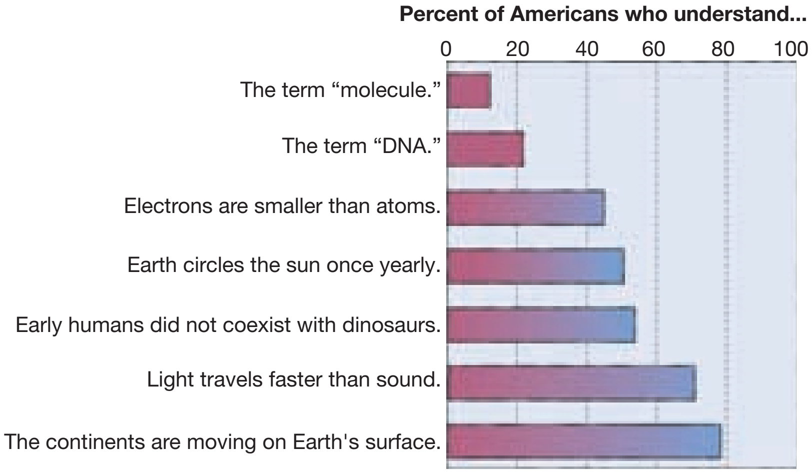


Figure 1.4
What Do Americans Know about Science?
Some results published by the National Science Foundation.

Science Education Makes for Informed Citizens

Connected to the issue of scientific literacy is the question of science education. According to the NSF study, there is a high correlation between how much American adults know about general topics in science and how many science courses they have taken in school. In short, science education is retained in a significant way in that it makes for better-informed citizens.

1.3 What Is Science?

Having looked a little at the ways science affects our everyday world, let's now review something about science in general and about biology as one of its disciplines. The point here is to give you some sense of the underpinnings of science and biology—to review something about the how and why of them before getting to what they have revealed. This discussion starts with the big picture and progressively gets more specific.

Science as a Body of Knowledge

Science is in one sense a process—a *way* of learning. In this respect, it is an activity carried out under certain loosely agreed-to rules, which you'll get to shortly. **Science** is also a body of knowledge, however. It is a collection of unified insights about nature, the evidence for which is an array of facts. The unified insights of science are commonly referred to as *theories.*

It's unfortunate but true that *theory* means one thing in everyday speech and something almost completely different in scientific communication. In everyday speech, a theory can be little more than a hunch. It is an unproven idea that may or may not have any evidence to support it. In science, meanwhile, a **theory** is a general set of principles, supported by evidence, that explains some aspect of nature. There is, for example, a Big Bang theory of the universe. It is a general set of principles that explains how our universe came to be and how it developed. Among its principles are that a cataclysmic explosion occurred 10–15 billion years ago; and that, after it, matter first developed in the form of gases that then coalesced into the stars we can see all around us. There are numerous facts supporting these principles, such as the current size of the universe and its average temperature.

As you might imagine, with any theory this grand some *pieces* of it are in dispute; some facts don't fit with the theory, and scientists disagree about how to *interpret* this piece of information or that. On the whole, though, these general insights have withstood the questioning of critics, and together they stand as a scientific theory.

The Importance of Theories

Far from being a hunch, a scientific theory actually is a much more valued entity than is a scientific fact, for the theory has an *explanatory* power, while a fact is generally an isolated piece of information. That the universe is at least 10 billion years old is a wonderfully interesting fact, but it explains very little in comparison with the Big Bang theory. Facts are important; theories could not be supported or refuted without them. But science is first and foremost in the theory-building business, not the fact-finding business.

Science as a Process: Arriving at Scientific Insights

So how does a body of facts and theories come about? What is the process of scientific investigation, in other words? When **science** is viewed as a process, it could be defined as a means of coming to understand the natural world through the testing of hypotheses. This process generally is referred to as the **scientific method**. The starting state for scientific inquiry is always *observation:* A piece of the natural world is observed to work in a certain way. Then follows the *question,* which broadly speaking is one of three types: a "what" question, a "why" question, or a "how" question. Biologists have asked, for example, What are genes made of? Why does the number of species decrease as we move from the equator to the poles? How does the brain make sense of visual images?

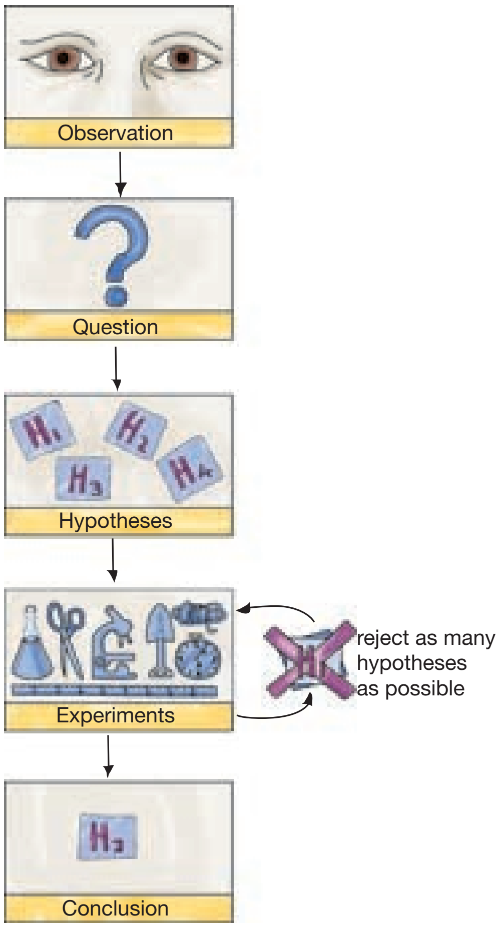
Formulating Hypotheses, Performing Experiments

Following the formulation of the question, various hypotheses are proposed that might answer it. A **hypothesis** is a tentative, testable explanation for an observed phenomenon. In almost any scientific question, several hypotheses are proposed to account for the same observation. Which one is correct? Most frequently in science, the answer is provided by a series of *experiments,* meaning controlled tests of the question at hand (**see Figure 1.5**). It may go without saying that scientists don't regard all hypotheses as being equally worthy of undergoing experimental test. By the time scientists arrive at the experimental stage, they usually have an idea of which is the most promising hypothesis among the contenders, and they then proceed to put that hypothesis to the test. Let's see how this worked in an example from history.

The Test of Experiment: Pasteur and Spontaneous Generation

Does life regularly arise from anything *but* life, or can it be created "spontaneously," through the coming together of basic chemicals? The latter idea had a wide acceptance from the time of the ancient Romans forward, and as late as the nineteenth century it was championed by a number of the leading *scientists* of the day. So how could the issue be decided? The famous French chemist and medical researcher Louis Pasteur formulated a hypothesis to address this question (**see Figure 1.6**). He believed that many purported examples of life arising spontaneously were simply instances of airborne microscopic organisms landing on a suitable substance and then multiplying in such profusion that they could be seen. Life came from life, in other words, not from spontaneous generation. But how could this be demonstrated? In 1860, Pasteur sterilized a meat broth in glass flasks by heating it, while at the same time heating the glass *necks* of the flasks, after which he bent the necks into a "swan" or S-shape. The ends of the flasks remained open to the air, but inside the flasks there was not a sign of life. Why? The broth remained sterile because microbe-bearing dust particles got trapped in the bend of the flask's neck. If Pasteur broke the neck off before the bend, however, the flask soon had a riot of bacterial life growing within it. In another test, Pasteur tilted the flask so that the broth *touched* the bend in the neck, a change that likewise got the microbes growing.

Figure 1.5
Scientific Method
The scientific method enables us to answer questions by testing hypotheses.



Elements in Pasteur's Experiments

Now, note what was at work here. Pasteur had a preconceived notion of what the truth was, and designed experiments to test his hypothesis. Critically, he performed the same set of steps several times in the experiments, keeping all the elements the same each time—except for one. The nutrient broth was the same in each test; it was heated the same amount of time and in the same kind of flask. What *changed* each time was one critical **variable**, meaning an adjustable condition in an experiment. In this case, the variable was either the shape of the flask neck, or the tilt of the flask. Given the fact that all other elements of the experiments were kept the same, the experiments had rigorous controls: All conditions were held constant over several trials, except for a single variable. A **control** can be defined as a comparative condition in an experiment. Pasteur's finding that no life grew in the bent-necked flask is interesting, but tells us very little by itself. We only learn something by comparing this finding to the result in the control condition: that life did grow when the flask neck was straight.

Note also that the idea of spontaneous generation was not banished with this one set of experiments—nor should it have been. Pasteur's experiments provided one of the *facts* mentioned earlier, in this case the fact that flasks of liquid will remain sterile under certain conditions. The idea that life arises only from life is, however, one of the scientific *theories* noted earlier, meaning that it requires the accumulation of many facts pointing in the same direction.

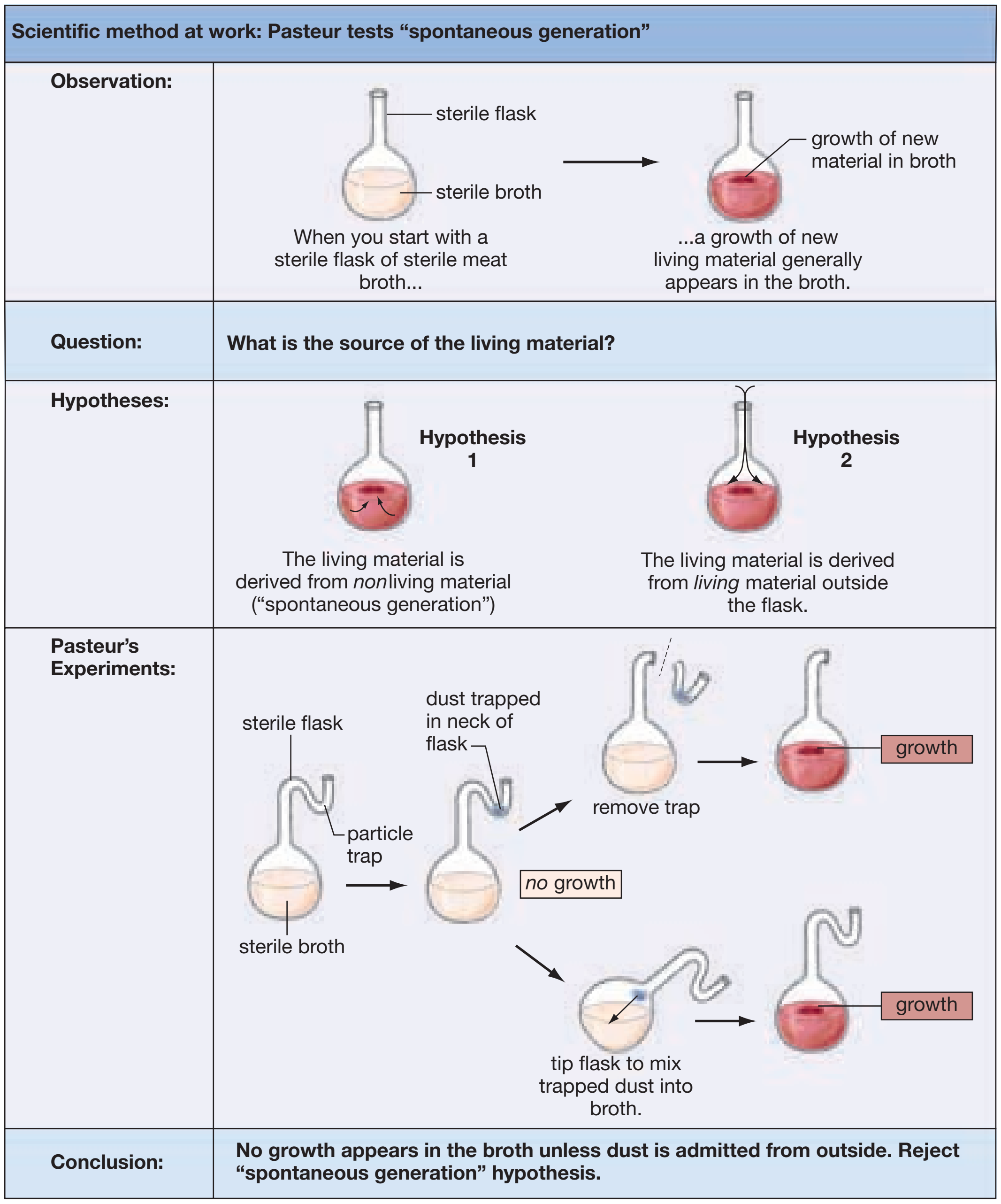
Other Kinds of Support for Hypotheses

Some scientific questions are difficult or impossible to test purely through experiment. For example, there currently is a controversy over whether birds are the direct descendants of dinosaurs. What kind of experiment could be run to test this hypothesis? Certain modern-day evidence is available to us—the DNA of living birds, for example—but examining DNA does not amount to an experiment. Instead it is observation, which is another valid way to test a hypothesis. Evidence from the past can also be observed, of course, which in this case means the observation of dinosaur and bird fossils. Indeed, fossils have been the key evidence in convincing most experts that birds are the descendants of dinosaurs. Joining experiment and observation, statistics is a tool used frequently in science, as you can see in "Lung-cancer, Smoking, and Statistics in Science" on page 10.

From Hypothesis to Theory

When does an idea move from hypothesis to theory? One of the ironies of the orderly undertaking called science is that there's nothing orderly about the change from hypothesis to theory. No scientific supreme court exists to make a decision. Scientists aren't polled for their views on such questions, and even if they were, at what point would we say something had been "proven"? When more than 50 percent of the experts in the field assent to it? When there are no dissenters left?

Tutorial 1.1.1
The Scientific Method (Pasteur's Experiments)



Scientific method at work: Pasteur tests "spontaneous generation"

Observation:

When you start with a sterile flask of sterile meat broth...

...a growth of new living material generally appears in the broth.

Question: **What is the source of the living material?**

Hypotheses:

The living material is derived from *non*living material ("spontaneous generation")

The living material is derived from *living* material outside the flask.

Pasteur's Experiments:

Conclusion: **No growth appears in the broth unless dust is admitted from outside. Reject "spontaneous generation" hypothesis.**

Figure 1.6
Pasteur's Experiments
Pasteur's spontaneous generation experiments and the scientific method. Nineteenth-century observation made clear that life would appear in a medium, such as broth, that had been sterilized. But what was the source of this life? One hypothesis was that it arose through "spontaneous generation," meaning it formed from the simple chemicals in the broth. Conversely, Pasteur hypothesized that it originated from airborne microorganisms. He was able to design an experiment that offered evidence for this hypothesis. The device he used was an S-shaped flask, which enabled air to enter the flask freely while trapping all particles (including invisible microorganisms) in a bend in the neck.

Lung Cancer, Smoking, and Statistics in Science

Valuable as they are, experimental and observational tests often are not enough to provide answers to scientific questions. In countless instances, scientists employ an additional tool in coming to comprehend reality—a mathematical tool—as you'll see in the following example.

The evidence that cigarette smoking causes lung cancer (and heart disease and emphysema and on and on) has been around for so long that most people have no idea why smoking was looked into as a health hazard in the first place. You might think that scientists were suspicious of tobacco decades ago and thus began experimenting with it in the laboratory, but this wasn't the case. Instead, the trail that led to tobacco as a health hazard started with a mystery about disease.

When the lung-cancer pioneer Alton Ochsner was in medical school in 1919, his surgery professor brought both the junior and senior classes in to see an autopsy of a man who had died of lung cancer. The disease was then so rare that the professor thought the young medical students might never see another case during their professional lifetimes. Prior to the 1920s, lung cancer was among the rarest forms of cancer, because cigarette smoking itself was rare before the twentieth century. It did not become the dominant form of tobacco use in the United States until the 1920s. This made a difference in lung-cancer rates because cigarette smoke is inhaled, while pipe and cigar smoke generally are not.

If you look at essay **Figure 1**, you can see the rise in lung-cancer mortality in U.S. males and females from 1930 forward. Note that women show a later rise in lung-cancer deaths; this is because women started smoking en masse later. (Also note that in the 1990s, lung-cancer rates finally began to level off—or drop in the case of men. This was a direct result of a decline in smoking that began in the 1970s.)

Given the lung-cancer trends that were apparent in males by the 1930s forward, the task before scientists was to explain the alarming increase in this disease. What could the cause of this scourge be, the medical detectives wondered? The effects of men being gassed in World War I? Increased road tar? Pollution from power plants? Through the 1940s, cigarette smoking was only one suspect among many.

Laboratory experiment eventually would play a part in fingering tobacco as the lung-cancer culprit, but the original indictment of smoking was written in numbers—in statistical tables showing that smokers were contracting lung cancer at much higher rates than nonsmokers.

It has sometimes been said that "science is measurement," and the phrase is a marvel of compact truth. For centuries, people had an idea that smoking might be causing serious harm, but this information fell into the realm of guessing or of *anecdote,* meaning personal stories. The problem with anecdote is that there is no measurement in it; there is no way of judging the validity of one story as opposed to the next. Related to anecdote is the notion of "common sense," which is valuable in many instances, but which also had us believing for centuries that the Sun moved around the Earth. In the case of smoking, it took the extremely careful measurement provided by a discipline called *epidemiology*—the study of disease distributions—to separate truth from fiction.

Provisional Assent to Findings: Legitimate Evidence and Hypotheses

One of the tenets of science is that nothing is ever finally proven. Instead, every finding is given only *provisional* assent, meaning it is believed to be true for now, pending the addition of new evidence. In practice, some theories are so well established that no one expects them to be overturned . . . but you never know! For years, scientists "knew" that adult human brain cells did not divide, thereby producing new brain cells. But this certainty has now been overturned; at least one area of the adult brain *does* produce new cells. In a similar vein, one of the most established beliefs in biology—that nearly all of Earth's living things derive their energy ultimately from the Sun—is now being called into question by some respected scientists. (It may be that the Earth houses a vast underground world of microbes who derive their energy from chemicals found in soil and rocks.)

Probability in Science

Note that “measurement” in this instance was a matter of calculating *probability,* which is often the case in science. Epidemiologists found a linkage between smoking and lung cancer, in the sense that those who smoked were more likely to get the disease. But having seen this, scientists then had to ask: Could this result be a matter of pure chance? A person tossing a coin might get heads five times in a row, and it might be written off to chance. But would it be the same if the person came up with heads *seventy* times in a row? No; at that point there would be justification for assuming that some force other than chance was in operation (such as a rigged coin). When the epidemiologists looked at their statistical tables and saw so many more smokers than nonsmokers getting lung cancer, they had to ask whether this result fell into the realm of seven heads in a row, or seventy. Even in the earliest studies they concluded that more than chance was at work in the results. After many studies, they concluded that smoking was *causing* lung-cancer. But how did they judge what was probable and what was not in an issue as complicated as this one? The researchers relied on techniques developed in the branch of mathematics called *statistics.*

The importance of probability and statistics to science can hardly be overstated. These tools are used frequently in nearly every scientific discipline. Imagine that 10 experimental plots of land are being compared, five with fertilizer added to them, the other five without. The plots with the added fertilizer end up with more growth but fewer kinds of plants. Could the differences between the two kinds of plots be a matter of chance? Here, as in so many other tests, scientists would use the tools of statistics to get at the truth.

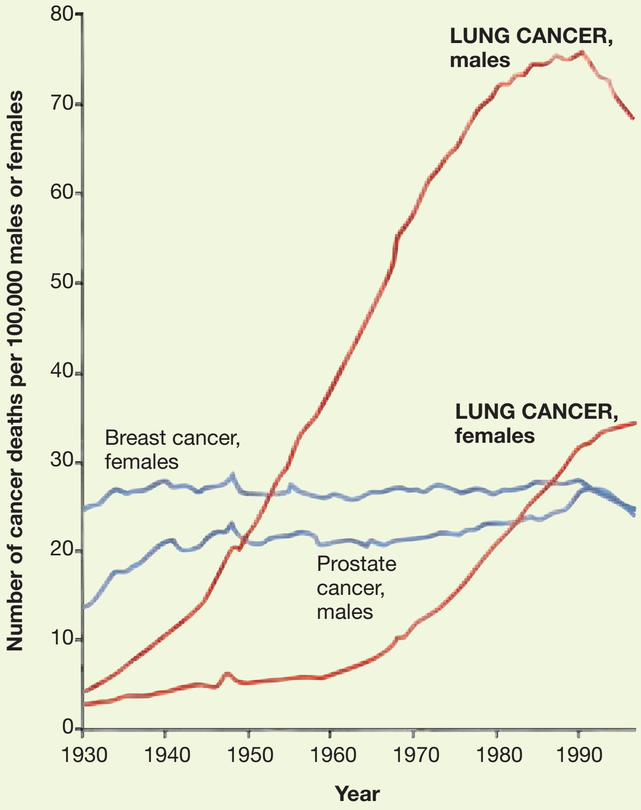


Figure 1
Rise in Lung-Cancer Mortality in U.S. Males and Females from 1930 Forward

So in the final analysis, scientists must always be open to the possibility that what we “know” is wrong. Indeed, this is one of the fundamental principles of science. Here it is, stated another way, along with some other important scientific principles regarding hypotheses and evidence:

- Every assertion regarding the natural world is subject to challenge and revision.
- Results obtained in experiments must be *reproducible.* Different investigators must be able to obtain the same results from the same sets of procedures and materials.
- Any scientific hypothesis or claim must be *falsifiable,* meaning open to negation through means of scientific inquiry. The assertion that “UFOs are visiting the Earth” does not rise to the level of a scientific claim, because there is no way to prove that this is *not* so.

1.4 Biology

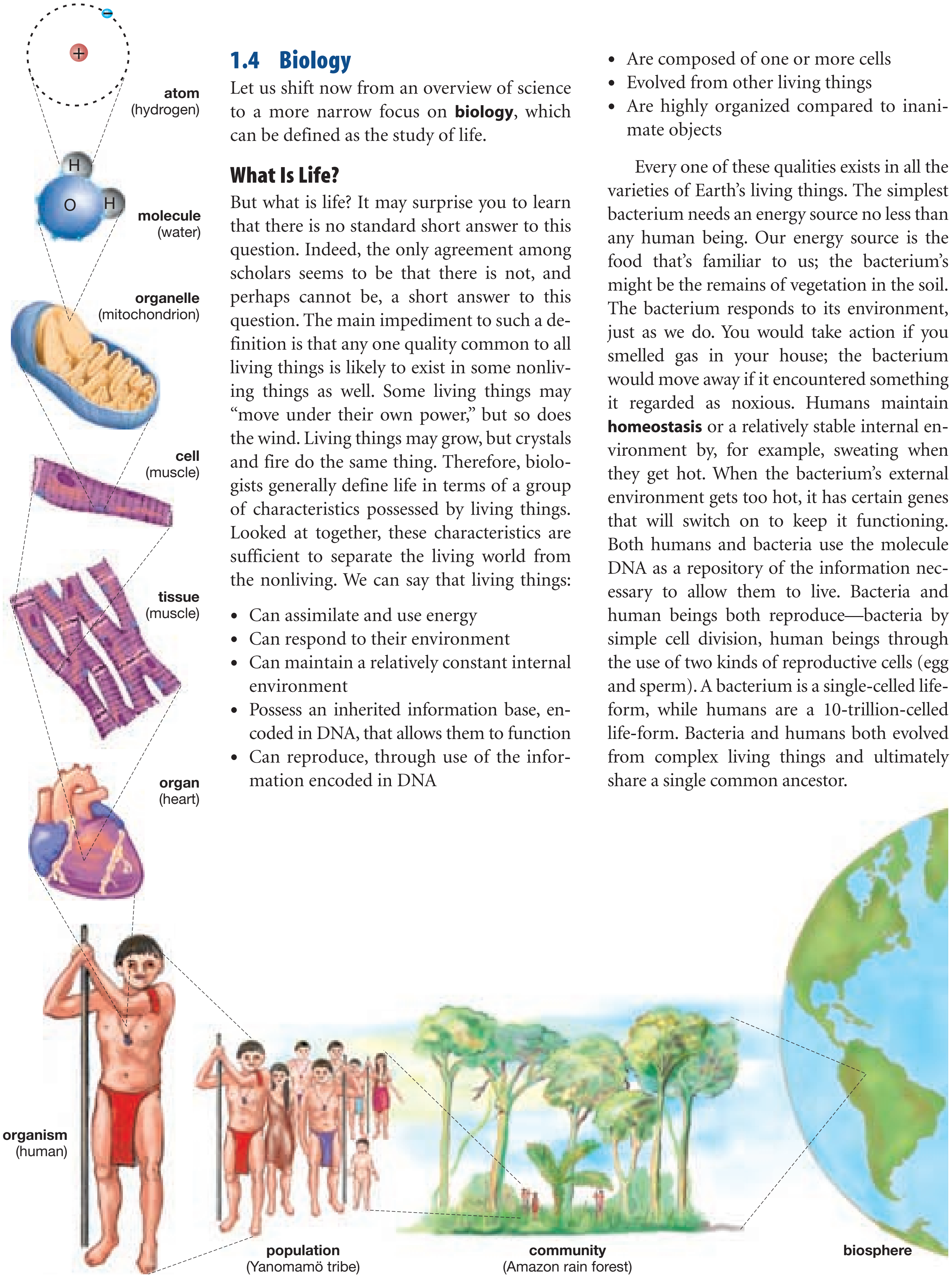
Let us shift now from an overview of science to a more narrow focus on **biology**, which can be defined as the study of life.

What Is Life?

But what is life? It may surprise you to learn that there is no standard short answer to this question. Indeed, the only agreement among scholars seems to be that there is not, and perhaps cannot be, a short answer to this question. The main impediment to such a definition is that any one quality common to all living things is likely to exist in some nonliving things as well. Some living things may "move under their own power," but so does the wind. Living things may grow, but crystals and fire do the same thing. Therefore, biologists generally define life in terms of a group of characteristics possessed by living things. Looked at together, these characteristics are sufficient to separate the living world from the nonliving. We can say that living things:

- Can assimilate and use energy
- Can respond to their environment
- Can maintain a relatively constant internal environment
- Possess an inherited information base, encoded in DNA, that allows them to function
- Can reproduce, through use of the information encoded in DNA
- Are composed of one or more cells
- Evolved from other living things
- Are highly organized compared to inanimate objects

Every one of these qualities exists in all the varieties of Earth's living things. The simplest bacterium needs an energy source no less than any human being. Our energy source is the food that's familiar to us; the bacterium's might be the remains of vegetation in the soil. The bacterium responds to its environment, just as we do. You would take action if you smelled gas in your house; the bacterium would move away if it encountered something it regarded as noxious. Humans maintain **homeostasis** or a relatively stable internal environment by, for example, sweating when they get hot. When the bacterium's external environment gets too hot, it has certain genes that will switch on to keep it functioning. Both humans and bacteria use the molecule DNA as a repository of the information necessary to allow them to live. Bacteria and human beings both reproduce—bacteria by simple cell division, human beings through the use of two kinds of reproductive cells (egg and sperm). A bacterium is a single-celled life-form, while humans are a 10-trillion-celled life-form. Bacteria and humans both evolved from complex living things and ultimately share a single common ancestor.



Tutorial 1.1.2
Hierarchichal Organization of Life

Figure 1.7
Levels of Organization in Living Things

There are some exceptions to these "universals." For example, the overwhelming majority of honeybees and ants are sterile females; they can't reproduce, but no one would doubt that they're alive. In the main, however, if something is living, it has all these qualities.

Life Is Highly Organized, in a Hierarchical Manner

One item on the list of qualities requires a little more explanation. It is that living things are highly organized compared to inanimate matter. More specifically, they are organized in a "hierarchical" manner, meaning one in which lower levels of organization are progressively integrated to make up higher levels. The main levels in this hierarchy could be compared to the organization of a business. In a corporation, there may be individuals making up an office, several offices making up a department, several departments making up a division, and so forth. In life, there is one set of organized "building blocks" making up another (**see Figure 1.7**).

Actually life is not just "highly" organized. Nothing else comes *close* to it in organizational complexity. The Sun is a large thing, but it is an uncomplicated thing compared to even the simplest organism. Consider that you have about 10 trillion cells in your body and that, with some exceptions, each of these cells has in it a complement of DNA that is made up of chemical building blocks. How many building blocks? Three billion of them. Now, you probably know that most cells divide regularly, one cell becoming two, the two becoming four, and so on. Each time this happens, each of the 3 billion DNA building blocks must be faithfully *copied,* so that both of the cells resulting from cell division will have their own complete copy of DNA. And this is just the copying of the molecule, before anything is actually done with it. Complex indeed. Let's see what life's levels of organization are.

Levels of Organization in Living Things

The building blocks of matter, called *atoms,* lie at the base of life's organizational structure. (See Chapter 2 for an account of them.) Atoms come together to form *molecules,* meaning entities consisting of a defined number of atoms in a defined spatial relationship to one another. A molecule of water is one atom of oxygen bonded to two atoms of hydrogen, with these atoms *arranged* in a very precise way. Molecules in turn form what are called *organelles,* meaning "tiny organs" in a cell. Each of your cells has, for example, hundreds of organelles in it, called *mitochondria,* that transform the energy from food into an energy form your body can use. Such an organelle is not just a collection of molecules that exist close to one another. It is a highly organized structure, as you can tell just from looking at the rendering of it in Figure 1.7.

At the next step up the organizational chain are entities that are actually *living,* as opposed to entities that are components of life. *Cells* are units that can do all of the things listed earlier: assimilate energy, reproduce, react to their environment, and so forth. Indeed, most experts would agree that cells are the *only* place that life exists. You may say: But isn't there a lot of material in between my cells? The answer is yes; it's mostly water with a good number of other molecules in the mix. But if all the cells were removed from this watery milieu, there would be nothing resembling life left in it.

The next step up is to a *tissue,* meaning a collection of cells that serve a common function. Your body contains collections of muscle cells that serve the same function (contraction). Each concentration of these cells constitutes muscle tissue. Several *kinds* of tissues can come together to form a functioning unit known as an *organ.* Your heart, for example, is a collection of nerve tissue and muscle tissue, among other types. An assemblage of cells, tissues, and organs can then form a multicelled *organism.* (Of course, back down at the cell level, a one-celled bacterium is also an organism; it's just not one with organs and so forth.)

From here on out, life's levels of organization all involve *many* organisms. Members of a single type of living thing (a species), living together in a defined area, make up what is known as a *population.* When you look at *all* the kinds of living things in a given area, you are looking at a *community.* Finally, all the communities of the Earth—and the physical environment with which they interact—make up the *biosphere.*

1.5 Special Qualities of Biology

Almost all scientific disciplines can trace their origins to the ancient Greeks, and biology is no exception. In the work of such Greeks as Hippocrates and Galen, we can find the origins of modern medical science. In the work of Aristotle and others, we can find the origins of "natural history," which led to what we think of today as mainstream biology and the larger category of the **life sciences**, which includes not only biology, but medicine, forestry, and the like.

Despite these ancient origins, biology is, in a sense, a much younger science, than, say, physics, which is one of the **physical sciences**, meaning the natural sciences not concerned with life. Western Europe's revolution in the physical sciences probably can be dated from the sixteenth century, when Nicholas Copernicus published his work *On the Revolution of Heavenly Spheres,* which demonstrated that Earth moves around the Sun. Meanwhile, biology did not come into its own as a science until the *nineteenth* century.

Prior to the 1800s, biology was almost purely *descriptive,* meaning that the "naturalists" that we would today call biologists largely confined themselves to describing living things—what kinds there were, where they lived, what features they had, and so forth. Beginning in about the 1820s, however, biologists began to formulate biological *theories* as that term was defined earlier. They began to postulate that all life exists within cells, that life comes only from life, that life is passed on through small packets of information that we now call genes, and so forth. To put this another way, biologists in the nineteenth century began describing the *rules* of the living world, whereas before they were largely describing *forms* in the living world.

This change moved biology closer to the same scientific footing as physics. But biology was then, and remains now, a very different kind of science from any of the physical sciences, with physics being a clear case in point. One reason for this difference is that the constituent parts of physics are very uniform and far fewer in number than is the case in biology. Physics deals with only 92 stable elements, such as hydrogen and gold, and to a first approximation, if you've seen one electron, you've seen them all.

Meanwhile, in biology, if you've seen one species you've seen just that—one species. Each species is at least marginally different from another, and many are greatly dissimilar. Moreover, there are thought to be at least 10 million species on Earth. And each of these species has all the organizational levels of elements in physics *and more.* (They not only have electrons and atoms, they have organelles, cells, tissues, and so on.) Biology is concerned with the rules that govern all species, and you've seen that there are some biological "universals." But when cancer researchers are looking for the principles that underlie cell division, they are likely to be looking at only one of two main kinds of cells; when ecologists are looking at what causes dry grassland to turn into desert, their findings are likely to have little relevance to the rain forest. Put simply, the living world is tremendously diverse compared to the nonliving world, and such diversity means that universal rules in biology are likely to be few

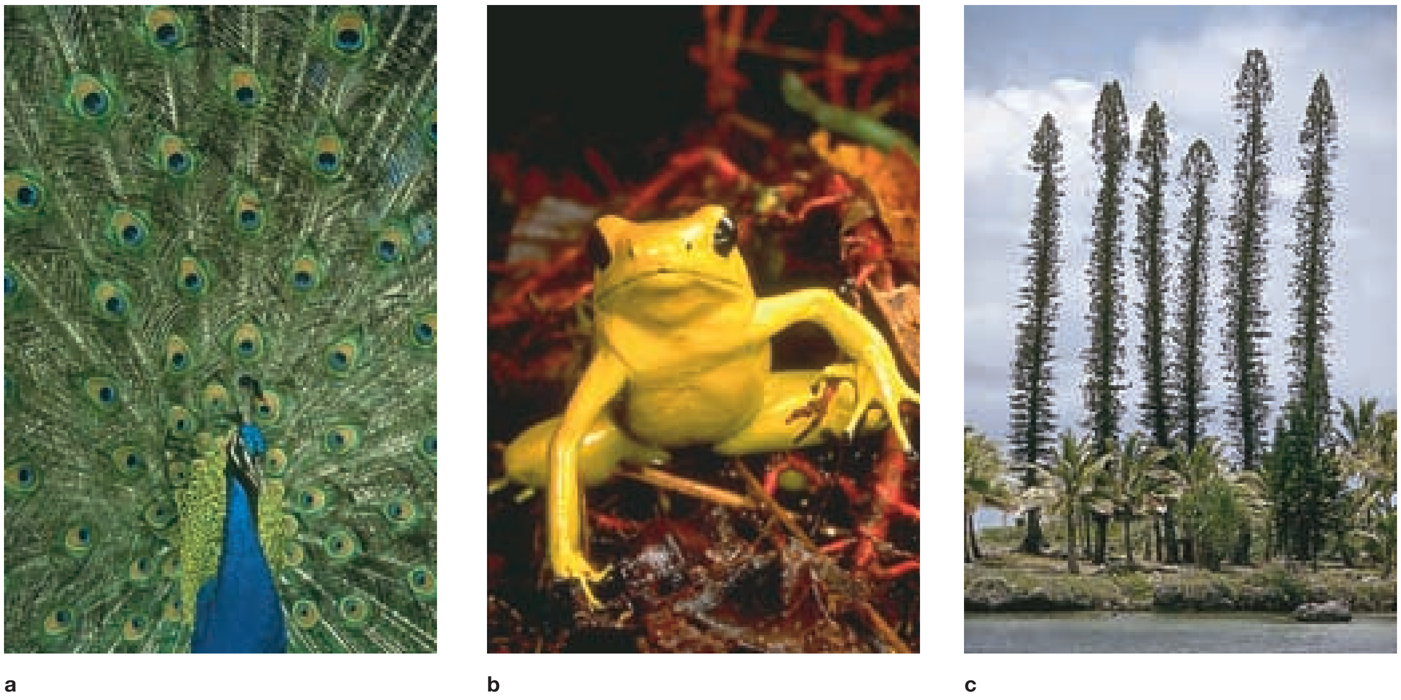


Figure 1.8
Evolution Has Shaped the Living World

a A peacock displaying his plumage

b A poison dart frog in Colombia

c New Caledonia pine trees towering above palm trees in the New Caledonia islands, east of Australia and far between. Biology is concerned with the *particular* to a far greater degree than is the case in the physical sciences. Note also that "universals" in biology may not apply beyond Earth; we don't know if life even exists anywhere else, much less what its rules are. Meanwhile, the rules of physics truly are universal in that they are equally applicable on Earth or in the farthest reaches of the cosmos.

Biology's Chief Unifying Principle

Almost all biologists would agree that the most important thread that runs through biology is **evolution**, meaning the gradual modification of populations of living things over time, with this modification sometimes resulting in the development of new species. Evolution is central to biology, because every living thing has been *shaped* by evolution. (There are no exceptions to this universal.) Given this, the explanatory power of evolution is immense. Why do peacocks have their finery, or frogs their coloration, or trees their height (**see Figure 1.8**)? All these things stand as wonders of nature's diversity, but with knowledge of evolution they are wonders of diversity that *make sense.* For example, why do so many unrelated stinging insects look alike? Evolutionary principles suggest they *evolved* to look alike because of the general protection this provides from predators. Think of yourself for a moment as a bee predator. Having once gotten stung, would you annoy *any* roundish insect that had a black-and-yellow-striped coloration? You probably learned your lesson about this in connection with one species, but *many* species of insects are now protected from you simply by virtue of the coloration they share with the others (**see Figure 1.9**). Thus, there were reproductive benefits to individuals who, through genetic chance, happened to get a slightly more striped coloration: They left more offspring, because they were bothered less by predators. Over time, entire populations moved in this direction. They evolved, in other words.

The means by which living things can evolve is a topic this book takes up beginning in Chapter 16. Suffice it to say for now that a consideration of evolution is never far from most biological observations. So strong is evolution's explanatory power that, in uncovering something new about, say, a sequence of DNA or the life cycle of a given organism, one of the first things a biologist will ask is: Why would evolution shape things in this way?

The Organization of This Book

This book has something in common with the levels of organization you looked at earlier, in that it too goes from constituent parts to the larger whole. It begins with atoms, moves on to the biological molecules that atoms make up, and then goes to cells. The end of the book covers the highest levels of biological organization, which is to say natural communities and Earth's biosphere. In between, however, are tours of such facets of life as energy, DNA-encoded information, and reproduction. Even here, however, you'll be moving in a general way from the small to the large, because much of the first part of the book is given over to **molecular biology**—meaning the study of individual molecules (such as DNA) as they affect living things. Then you'll move into evolution, which touches on **organismal biology**, meaning the study of whole organisms. Next is the **physiology** or physical functioning of plants and animals, which largely concerns tissues and organs. Finally there is **ecology**, which is the study of the interactions of organisms with each other and with their physical environment. And so, let's begin to look at biology—as a body of knowledge and a way of learning.

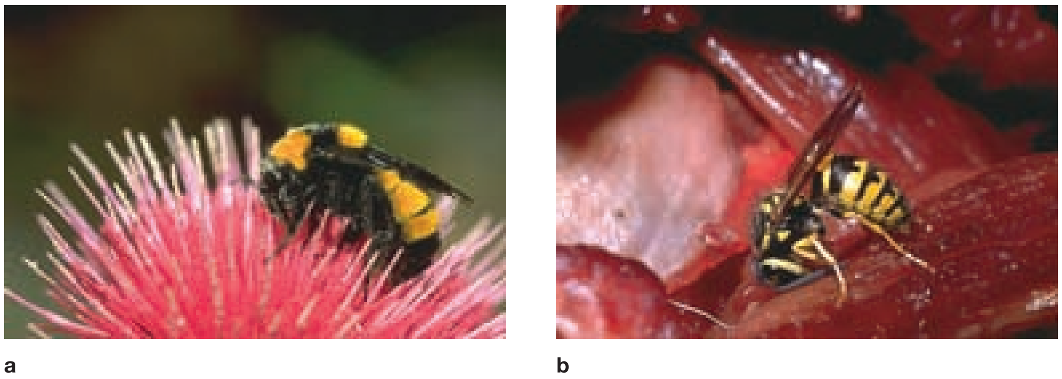


Figure 1.9
Similar Enough to Yield a Benefit

a The golden northern bumblebee

b The Sandhills hornet

These are two of the many stinging insects that have the black-and-yellow-striped coloration that offers protection from predators.

Chapter Review

Summary

1.1 How Does Science Impact the Everyday World?

- Science is playing an increasingly important role in the everyday lives of Americans, as evidenced by weekly news regarding such issues as genetically modified food, disease, and the biotech industry.

1.2 What Does the Public Think, and Know, about Science?

- Americans are interested in science, have a great deal of confidence in American scientific leadership, and overwhelmingly believe that the world is a better place because of science.
- Americans have an uneven knowledge about science. Almost 80 percent of adult Americans know that the continents are moving about the face of the Earth, for example, but more than a quarter think the Sun goes around the Earth.

1.3 What Is Science?

- Science is a body of knowledge, a collection of unified insights about nature, the evidence for which is an array of facts.
- The unified insights of science are known as theories. A theory is a general set of principles, supported by evidence, that explains some aspect of nature.
- Science can also be defined as a way of learning: a process of coming to understand the natural world through the testing of hypotheses.
- Science works through the scientific method, in which an observation leads to the formulation of a question about the natural world. Then comes a hypothesis—an explanation that has not been proven to be true. The hypothesis may be tested through observation, through a series of experiments, or by statistical means.
  TUTORIAL 1.1.1: The Scientific Method (Pasteur's Experiments)
- Every assertion regarding the natural world is subject to challenge and revision. Results obtained in experiments must be reproducible. Any scientific hypothesis or claim must be falsifiable, meaning open to negation through means of scientific inquiry.

1.4 Biology

- Biology is the study of life. Life is defined by a group of characteristics possessed by living things. Living things can assimilate energy, respond to their environment, maintain a relatively constant internal environment, and possess an inherited information base, encoded in DNA, that allows them to function. Living things can also reproduce, are composed of one or more cells, are evolved from other living things, and are highly organized compared to inanimate objects.
- Life is organized in a hierarchical manner, running in increasing complexity from atoms to molecules and then in sequence to organelles, cells, tissues, organs, organisms, populations, communities, and the biosphere.
  TUTORIAL 1.1.2: Hierarchichal Organization of Life

1.5 Special Qualities of Biology

- Until the early nineteenth century, biology was largely a descriptive science, meaning it largely catalogued and described the Earth's living things. Beginning about the 1820s, however, life science researchers began to formulate biological theories, such as that life comes only from life and exists only within cells.
- Biology's subject matter—the living world—is notable for its diversity.
- Biology's chief unifying principle is evolution, which can be defined as the gradual modification of populations of living things over time, with this modification sometimes resulting in the development of new species.

Key Terms

biology	12
control	8
ecology	15
evolution	15
homeostasis	12
hypothesis	7
life science	14
molecular biology	15
organismal biology	15
physical science	14
physiology	15
science	7
scientific method	7
theory	7
variable	8

Understanding the Basics

Multiple-Choice Questions

1. Which of the following statements best describes the nature of a scientific hypothesis?
  a. A hypothesis is an idea that is widely accepted as a description of objective reality by a majority of scientists.
  b. A hypothesis must stand alone, and not be based on prior knowledge.
  c. A scientific hypothesis must be testable through experimentation, observation, or mathematical demonstration.
  d. Experiments can be designed that will prove the validity of a hypothesis.
  e. A hypothesis when accepted becomes a scientific law.

2. Those who wish to berate a scientific theory sometimes say, “that’s only a theory.” The use of the word *theory* for a biological concept means that
  a. There is absolute certainty about the validity of the concept.
  b. Most scientists would agree that there is a preponderance of evidence in support of the concept.
  c. The concept is in doubt among most scientists.
  d. The concept is no more than a hypothesis.
  e. The concept has no basis in fact.

3. It may be argued that an automobile constitutes living matter because the burning of gasoline represents metabolism. Also, because a car picks up speed when the accelerator is depressed, one might claim it is responding to stimuli. Which of these reasons would you give for definitively concluding that a car is a nonliving entity?
  a. It does not store or use energy.
  b. It does not reproduce by transmitting genetic information through DNA.
  c. Carbon is not a major component of its chemical makeup.
  d. It exhibits cellular organization.
  e. It breaks down sometimes.

4. Evolution is a central, unifying theme in biology because
  a. Evolution is a falsifiable hypothesis.
  b. Humans have evolved from ancestors we share with present-day monkeys.
  c. Evolution has occurred in the past, even though it no longer operates today.
  d. The enormously diverse forms of life on Earth have all been shaped by evolution.
  e. Almost all biologists believe in it.

5. Biologists generally define life in terms of a group of characteristics possessed by living things. Which of the following is not a characteristic of living things?
  a. All living things possess an inherited information base, encoded in DNA, that allows them to function.
  b. All living things can respond to their environment.
  c. All living things can maintain a relatively constant internal environment.
  d. All living things evolved from other living things.
  e. All living things are composed of two or more cells.

Brief Review

1. What is science? In what ways is science similar to, and different from, belief systems such as religious faith?

2. What is a controlled experiment? Why is it important to keep all variables but one constant in a scientific experiment?

3. How did Louis Pasteur cast doubt on the idea of spontaneous generation?

4. Describe the defining features of life as we know it on the Earth.

5. Living systems can be described at various hierarchical levels. List as many levels of biological organization as you can think of, from the microscopic to the largest levels imaginable.

Applying Your Knowledge

1. Would you agree that it is valuable for a nation to have a citizenry that is reasonably well versed in science? Give reasons for your answer. Would you say this need has become especially urgent in the last two decades? If so, why?

2. Is it harder to prove a hypothesis than to disprove it? Imagine you wanted to establish that cheetahs are the fastest land animals, and assume you have the ability to clock any animal moving at its top speed. Now, what would it take to disprove the idea that cheetahs are the fastest land animals? What would it take to prove that cheetahs are the fastest land mammals, meaning no other land mammal could run faster than they?

3. If you were sent on an interplanetary mission to investigate the presence of life on Mars, what would you look for? Would you explore the land and the atmosphere? Imagine you discover an entity you suspect is a living being. Realizing that life elsewhere in the universe may not be organized by the same rules as on Earth, which of the features of life on Earth, if any, would you insist that the entity display before you would declare it living?