Mauseth, James D. Botany : An Introduction to Plant Biology. Seventh edition. 2021.

Thinking About Thinking

BOX 3-2 Evidence-Based Decision Making

All of us make decisions every day. What do we use as a basis for making our decisions? Sometimes we just use personal preference, what we like: You might like coffee better than tea, so you decide to buy a cup of coffee this morning. Personal preference works well if you are familiar with the things you are deciding about and if your decision affects only yourself. If we are not very familiar with the things, we might instead decide based on a hunch or by flipping a coin and letting random chance decide. If the decision will affect a group of people, the decision is usually made by voting, and the majority wins. This method is suited for determining the priorities of a group of people; for example, whether they are willing to pay more taxes to fund better schools. But voting on whether xylem conducts water will not help us understand plant physiology at all.

As the scientific method was being developed in the early years of the Renaissance, the importance of evidence became obvious. Previously, many concepts had been based on the writings of ancient Greek and Roman scholars, but after the discovery of America it was realized that the ancients had not known everything after all, and scientists needed to study the world itself to obtain knowledge about it. Some folks felt that pure logic should be used instead, that truth about the world could be obtained through pure reason and logical thinking; this is known as **rationalism**. Unfortunately, if our reasoning is based on too few facts, it is possible to come to multiple logical conclusions that contradict each other. How do we decide which conclusion is correct? We must make observations and do experiments—we must gather evidence—to see which conclusion matches reality.

Using our sense organs to gather information about the world is called **empiricism**; it is also called **evidence-based decision making**. For example, to know whether it is raining, we can look out the window and see the rain or put our hand out and feel it. This empirical evidence will tell us for certain. Alternatively, we could study the relative humidity, the temperature, and other factors, and then use rational logic to determine if it is raining, but that may not be accurate. Here, empiricism is best. On the other hand, rational logic is our only option for deciding if it will probably rain tomorrow: we cannot look out the window today and know if it will rain tomorrow.

Many of our questions about the world are more complex. How is water pulled upward through xylem? How does electron transport in chloroplasts lead to photosynthesis? Which types of species will be at risk of extinction due to climate change? To answer questions like these, we use the evidence we already have as a basis for making rational, logical hypotheses about the phenomenon. Often our reasoning leads us to several hypotheses, and we must decide which is most accurate. Each hypothesis must make predictions that can be tested (if a statement cannot be tested, it is a speculation, not a hypothesis). Using the predictions, we can design observations or experiments that will give us the evidence we need to decide which hypothesis is the best model of reality.

At first, we might not have enough evidence to be confident in our decision. In fact, some evidence may support one hypothesis and other evidence support an alternative hypothesis. These are not "alternative facts" (a phrase invented recently by a politician), it is just that our hypotheses were not sufficiently refined, or perhaps we had misunderstood the phenomenon in the first place. But as more evidence is gathered, one hypothesis will receive more support than the other. In the long run, every hypothesis and theory must match the evidence. The scientific method is an empirical, evidence-based method of analysis.

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presents us with a bit of a dilemma; it is not a natural, simple food, but on the other hand, when we eat TVP instead of real meat, we are reducing the number of animals that must be slaughtered for food and we are also eating lower on the food chain, being primary instead of secondary consumers. An acre of land used to cultivate soy for TVP produces 15 times more protein than if that same land were used for pasture for cattle.

Legumes are also important as feed for domesticated animals. Horses and cattle are fed alfalfa either by letting them graze on fields of it or by mowing it and then drying it to make hay (**FIGURE 3-16**). It can also be compressed to pellets that are easily stored and transported. Alfalfa is especially important for cows while they are lactating and producing several gallons of protein-rich milk every day.

Our own bodies synthesize almost every lipid we need with the exception of the omega-3 and omega-6 fatty acids: Linoleic acid and alpha-linolenic acid are essential fatty acids, and we must obtain them in our food. Plants make these omega fatty acids and other lipids that are beneficial for us, and just as important, plants never make cholesterol or harmful *trans*-fats (see **BOX 3-3**). Consequently lipids obtained from plants tend to be healthful; good sources are nuts such as walnuts, pecans, and almonds; several fruits such as avocados, olives, and coconuts; and certain seeds such as peanuts, sunflower, canola, safflower, and soybeans (**FIGURE 3-17**).

Thinking About Thinking

BOX 8-2 Designing Experiments: Parachutes Don't Increase the Survival Rate of People Who Jump Out of Airplanes

Do you believe that roots really absorb water and minerals from the soil? Could you design an experiment to prove your belief? Be careful, because as you might guess, I am leading you into a trap.

The first part of my trap is the word "believe." It seems reasonable that roots do absorb water and minerals, but to say we "believe" they do means that we have already reached a conclusion before we have even designed an experiment, not to mention that we haven't obtained results yet. It is better to say we "strongly suspect" that roots absorb water and minerals, or "that it seems highly likely" they do. Remember, keeping an open mind—skepticism—is a fundamental principle of the scientific method. On the basis of a great deal of research that gave consistent results many people believed that DNA was the universal information storage molecule of life. But then it was discovered that some viruses that infect plants store their information in RNA, not DNA. It would have been so easy to have not even bothered to check the plant viruses if everyone "believed" that they must have DNA; fortunately, someone was skeptical.

The second part of my trap was to ask if you could "design an experiment to prove" your belief. An experiment should be designed with an open mind. A well-designed experiment must be set up such that it does not improperly favor one outcome over the other. For example, look at the statement in the title of this box: Parachutes do not increase the survival rate of people who jump out of airplanes. This seems ridiculous, but it is possible to design an experiment to give us exactly this result. In fact, the experiment has been performed.[1] A group of people were selected, and then some of them—chosen at random—received good, functional parachutes, whereas the others received empty backpacks. All people then did in fact jump out of airplanes, and everyone survived. Having a parachute did not increase the survival rate over jumping without a parachute: The survival was 100% for both groups. To say the least, that is an unexpected result until you learn that the airplanes were parked on the ground, not moving at all when the people jumped out of them. This experiment was designed with strong bias in order to produce a desired result. It was not designed to produce impartial information that would be useful to someone flying in an airplane.

This experiment was obviously meant to be a humorous teaching tool, but we must be careful not to introduce similar, less extreme biases into our own thinking and experimental design. It is difficult to be certain our experiments or observations do not have biases; we all have blind spots. But every scientific paper has a section called "Materials and Methods" in which the procedures of the research must be described in detail. People reading the paper can examine this section and may see a bias or error that was not obvious to the authors. Also, research is repeated by other scientists, and if the results are inconsistent, then they search for the reason. Eventually, any errors are discovered. This principle of open publication not only of research results but also the materials and methods makes the scientific method a self-correcting process.

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[1] You can read the published results online: Yeh, R. W., Valsdottir, L. R., Yeh, M. W., Shen, C., Kramer, D. B., Strom, J. B., . . . Nallamothu, B. K. (2018). Parachute use to prevent death and major trauma when jumping from aircraft: Randomized controlled trial. *BMJ*, 363, k5094. https://doi.org/10.1136/bmj.k5094. You can also read a report about it at National Public Radio: Harris, R. (2018, December 22). Researchers show parachutes don't work, but there's a catch. *Weekend Edition Saturday*. Retrieved from https://www.npr.org/sections/health-shots/2018/12/22/679083038/researchers-show-parachutes-dont-work-but-there-s-a-catch.

Thinking About Thinking

BOX 11-2 New Knowledge Versus Old Knowledge

What did the ancient Greeks know about photosynthesis? About ATP? Proton pumping? Nothing. They knew that plants do not grow in completely dark caves, but they did not associate that with sunlight, and they had no word for photosynthesis. Plato, Aristotle, and others were brilliant, but we know that their knowledge was limited, and we are not surprised by that.

But imagine that you are a European living in 1000 CE. You can read ancient Greek and Roman works about mathematics, biology, medicine, and cosmology. All doctors are being trained using the 800-year-old writings of Galen. The Sun, Moon, and stars move through the sky as Ptolemy had described in *Almagest*, written about 150 CE. You might have seen the Colosseum in Rome or the Acropolis in Athens, and you might have heard about the Pyramids in Egypt. These were monumental feats of architecture and engineering that cannot be reproduced in the times in which you live.

Imagine if today in our own world we were surrounded by structures that were beyond our technology, if there were ruins of ancient, lost civilizations with libraries that contained books describing concepts of physics, mathematics, and medicine vastly more advanced than what we know today. We would immediately set out to translate those books and attempt to rediscover their lost knowledge, to benefit from the scientific advances they had already made. If you lived in the Middle Ages between about 500 CE and 1492 CE, you lived in just such a world. The past had been a golden age of almost superhuman geniuses and builders. It seemed that the best way to gain knowledge of the world was to study old Greek and Latin texts in an attempt to relearn what had already been discovered. Everything that *could be known* already *had been known* to the Ancients. You would have to be extremely bold to think that by studying the world yourself, by looking at flowers or minerals, you would figure out something that Plato, Aristotle, Hippocrates, or the others had not known.

But everything changed in 1492: Columbus discovered America. This was important for many reasons, of course, but a real shock was that America was something the Ancients had not known. All of a sudden, as Columbus returned with his maps, exotic plants, and never-before-seen animals, in that instant people knew things that had never been known before. There was such a thing as *new knowledge*. It would be impossible to learn about these things by reading old books—instead, one had to go out and explore, observe, measure, think for oneself. To the truly insightful people in 1492, this was more than a breath of fresh air: The world was full of new knowledge that needed to be discovered in the world itself.

The concept can be summarized as "To know the world, study the world." Many people embraced this immediately, and breathtaking new knowledge soon resulted. An early pivotal result was the work of Andreas Vesalius. He dissected human cadavers, examined them closely, and realized that many aspects of Galen's teachings were wrong. In 1543, Vesalius published *De humani corporis fabrica*, and immediately our understanding of human anatomy became more detailed and accurate than ever before. Galileo, using newly invented telescopes, discovered that the Moon had mountains, which demolished the old "knowledge" that the Moon had to be a perfectly smooth sphere because it was part of the heavens. Galileo also discovered four moons orbiting Jupiter: Earth was not the center of everything.

It is so easy for us today, especially for those of us at research universities, to assume that people have always searched for new knowledge. But that is not how it was. Our search for new things is actually a new thing itself.

Environmental and Internal Factors

A plant's photosynthesis is affected by its environment in many ways.

Light

From a plant's viewpoint, light has three important properties: (1) quality, (2) quantity, and (3) duration.

Quality of sunlight refers to the colors or wavelengths it contains. Sunlight is white because it contains the entire visible spectrum. During sunset and sunrise, sunlight passes tangentially through the atmosphere, and a large percentage of the blue light is deflected upward; consequently, light at ground level is enriched in red, which is easily visible. This period of red-enriched light lasts only a few minutes and probably has little effect on photosynthesis. At noon, sunlight passes nearly vertically through the atmosphere, more blue light is transmitted, and even though the blueness of the sky suggests that all reds, greens, and yellows have been blocked, in fact, enough of all of these wavelengths penetrate to Earth's surface to allow rapid photosynthesis. This is true of plants in deserts, grasslands, and the top layer—the canopy—of a forest; however, herbs and shrubs that grow near soil level in a forest are understory plants and the light that they receive has already passed through the leaves of the canopy (**FIGURE 11-20**). As light penetrates

Thinking About Thinking

BOX 11-3 Tabla Rasa, Clean-Sheet Thinking

"Tabla rasa" is an expression we do not hear very often. It is usually translated as "blank slate" or "clean sheet," and it means to start new, from scratch with no preconceived ideas. When Pilâtre de Rozier invented the first hot air balloon in 1873, he designed it tabla rasa: Nothing at all like a hot air balloon existed before his creation. He had to invent every part of it on his own. In contrast, the Wright brothers invented the first powered airplane, but their ideas were based on studies of bird wings, kites, and gliders that many other people had already built and flown.

How does the concept of tabla rasa relate to biology? People have been trying to understand how plants and animals work for thousands of years. Aristotle was a critical thinker, and we are fortunate that many of his writings still exist. Greeks of his time believed the world was composed of only four elements: earth (solid), water (liquid), air (gas), and fire (energy). As they puzzled over the nature of living creatures, they thought in terms of those four elements. For example, plants must be composed of fire, earth, and water: Living plants need sunlight and dead plant material burns; plants will not grow unless rooted in soil; and no plant lives without water. Aristotle and his contemporaries did not approach the explanation of life tabla rasa; that is, they did not try to come up with a completely new explanation of life. If someone had proposed cells, photosynthesis, or DNA, those ideas would have been untestable and unknowable; such concepts would have seemed like magic or mysticism similar to the superstitions that had been proposed earlier by Babylonians and Egyptians.

For over a thousand years, the Greek explanation of life was satisfactory for everyone. Romans were excellent at engineering and building, but were not especially interested in investigating fundamental concepts. During the Dark Ages after the fall of the Roman Empire, people were more interested in the afterlife in heaven (which would be eternal) rather than actual life here on Earth (which rarely lasted longer than 40 years).

But gradually some people did turn to thinking about the world we live in, and slowly the earliest concepts of chemistry and physics were discovered. It was realized that the four elements of earth, water, air, and fire were inadequate to explain many phenomena. New concepts were postulated; some were correct, others were wrong. For example, it was shown that water was not an element after all but rather a compound of two previously unknown new elements, hydrogen and oxygen. On the other hand, one of the new ideas was that life had its unusual characteristics because it contained a new element, a "vital force." Through the use of hypotheses and experiments, it was realized that the earliest version of the vital force theory did not fit many observations, so it was adjusted, tweaked, and refined. The proposal that vital force was an energy that gives life to inanimate chemicals was reasonable: It was compatible with what little was known of chemistry, physics, and biology at the time. But people continued to study the world, and bit by bit new observations were made that were not compatible with the theory of vital force. People started to look for a hypothesis that was better able to explain most of the observations. It was proposed that life is not so special after all; instead, all metabolism could be understood using the principles of chemistry and physics. This was a bold claim, completely outside the box: This theory started from scratch, there was nothing like it, it was not a modification of any previous theory. This was clean-sheet thinking.

But was it correct? Vital force was a familiar concept, and many observations were ambiguous enough to be consistent with it, whereas chemical/physical biology was unfamiliar and it was not immediately obvious how that theory could really be applied to concepts such as growth, reproduction, heredity, or sense organs. Even today we still don't understand how the chemistry and physics of brain cells result in human consciousness and thinking. But finally, in an exquisite series of experiments in the second half of the 1800s, Louis Pasteur explained fermentation in terms of chemistry and disproved spontaneous generation; support for vital force collapsed.

Think of where we are today. Biology—the study of life, the theory of life—is so immense that you can study biology for 4 years in college and yet be only superficially familiar with just a fraction of the basic facts and theories. Within our body of biological knowledge there are many gaps that need to be filled in, many thin areas that need more supporting evidence, and, unfortunately, some parts of our "knowledge" seem sound but are actually erroneous.

How do biologists do clean-sheet thinking now? Someone would have to be very bold to believe that they could ignore all our existing theories and propose a completely new view of life starting from scratch. But rather than thinking about replacing all current biological theories, we can focus on areas in which the results of a set of experiments and observations are not fitting well into a particular current theory. If further research produces even more observations that are not compatible with that theory, someone will eventually decide to look for a completely new explanation: Clean-sheet thinking will be necessary.

Such thinking sometimes requires courage. When Darwin and Wallace proposed natural selection as the driving force of evolution and the fundamental principle of all biology—a profoundly clean-sheet thought—many people did not accept this idea, as you undoubtedly know. Darwin and Wallace had their supporters, but they were also ridiculed by numerous influential people: In many ways their lives became more difficult. But think about the great, famous people in biology or any other scientific field: They are famous because when confronted with confusing observations that did not fit into contemporaneous theories, they started from scratch and came up with new theories—they changed our way of thinking.

Thinking About Thinking

BOX 16-3 Emergent Properties

One plus one equals two, right? One million plus one million equals two million, correct again? The sum is equal to the parts, isn't it? For many things, such as the numbers we learned in arithmetic in grade school, the answer is "Yes": 1 + 1 = 2. But very often, the answer is "No," the sum is *greater* than its parts.

Consider an ordinary brick that is usually twice as long as it is tall, and its thickness is a bit greater than its height. We can count, weigh, measure, and perform a chemical analysis of one brick, and we can do the same for two bricks: 1 + 1 = 2, so far. But with two bricks we can do something that is impossible with only one brick: We can arrange them in patterns relative to each other. Even with just two bricks, the number of patterns is almost infinite. We could use multiple bricks to encode information, to be a message. For example, an upright brick might represent a dot in Morse code, and a brick lying on its side could be a dash, and with many bricks we could write any sort of message, however complicated. The patterns that we can make with multiple bricks is what we call an **emergent property**; it is a property that exists only in a number of units but does not exist at all in any one unit. If we use 1,000 bricks to make a pattern, it is not that each brick contains 1/1,000th of the pattern; instead, each individual brick contains none of the pattern at all. The pattern (or the possibility of a pattern) only comes into existence when multiple units are present.

Emergent properties are central to biology and many other fields. Think about water: The properties of a mass of water molecules are much greater than the properties of any individual molecule. A mass of water can be a solid, liquid, or gas; it can be moved in bulk flow under tension from transpiration or under pressure from a heart; it has surface tension where it meets air (and thus a mass of water does not move easily through a pit membrane in xylem or move out of the air sacs in our lungs, even though an individual molecule can readily do so). All these are emergent properties; no part of these properties exists in any individual water molecule.

We see emergent properties at all levels of biological organization. The conduction of water throughout a plant is the property of xylem but not of any individual xylem cell. Proton pumping, chemiosmotic synthesis of ATP, the reduction of NADP$^+$, and other processes of photosynthesis are emergent properties of intact chloroplasts but not of any individual chloroplast molecule. Sexual reproduction and evolution are the emergent properties of whole organisms but not of any individual cell.

Some definitions or explanations of emergent properties that you will find on the internet state that emergent properties are properties that cannot be predicted from a knowledge of the individual units. That is not true. If we cannot predict an emergent property from knowledge of the units, then that just means that we do not yet know enough about the units. Please think about this carefully. To say that emergent properties cannot be predicted even with complete knowledge would be to say that they are magic, supernatural. If that were true, there would be no reason to study them.

Now let's take one last case of an emergent property: human consciousness. None of our carbon atoms has any trace of our consciousness, none of our self-awareness, and neither do any of our hydrogen atoms, none of our DNA, none of our cells, not even any individual brain cell. Our consciousness is an emergent property of our hundred billion nerve cells being interconnected in complex patterns within our brains. And in each of us, our neurons are interconnected in unique ways: You are an emergent property of your cells; I am an emergent property of mine. At present, we know so little about nerve cells and consciousness that we cannot predict brain biology based on nerve cell biology, but that does not mean that we will never be able to do so, it does not mean that we should stop searching for new knowledge. It means that we biologists, you included, have taken on an enormous task: studying the emergent property called life. This task will keep us busy for a long time.

CRISPR-Cas9 is such an exciting new system, with so much potential, that other modifications are being made. One variation involves inactivating Cas9's cutting ability and instead just using the Cas9–guide RNA complex as a means of bringing various molecules to precise sites on DNA. For example, the Cas9 might carry transcription activators to the DNA: The guide RNA would bring the Cas9 to exactly the correct site of DNA, and then the cargo of activators would bind the DNA and attract the cell's transcription machinery. This should cause the cell to activate a gene that would normally be repressed.

The potential of CRISPR-Cas9 technology seems almost limitless. At this writing, a scientist in China claimed that his team had used CRISPR-Cas9 to genetically modify a human embryo that was then implanted into its mother; reportedly, a healthy baby was born. If this claim is true, it would be the first case of genetically engineering a human being.

Thinking About Thinking

BOX 25-3 Can't See the Forest for the Trees—Reductionist and Holistic Thinking

You might not be familiar with the old-fashioned saying, "Can't see the forest for the trees." Its more complete form is "He can't see the forest because all the trees are in the way." One meaning of this is that a person is looking so closely at the individual details (trees) of something that he doesn't even realize there is a larger concept (the forest) present. The phrase is often reversed as well: "He can't see the trees because the forest is in the way." The point of this is that many concepts can be regarded as either a set of individual components or as a whole.

How does this apply to plant biology? Consider xylem; learning about xylem involves learning about many different things: tracheids, vessels, secondary walls, pit-pairs, pit membranes, perforations, cavitations, embolisms, xylem parenchyma, growth rings, sapwood, heartwood, and so on. It can all seem like a jumble of different concepts. But now think of how these fit together, how each contributes to the safe conduction of water through a plant. These work together, function together, and each fits into the larger concept—"water transport by means of xylem." We can think of "water transport by means of xylem" as the forest made up of the trees. It is also a human model of water movement. The individual facts about xylem can seem endless and confusing, but if we keep in mind the emergent property of water transport, then various facts fit together and begin to make sense. We see how each item contributes to water conduction.

It might help if we think of the pieces of a jigsaw puzzle and how the picture becomes complete once all the pieces are put together correctly. When we first start a puzzle, all the pieces lie scattered at random, and each makes little or no sense. Fortunately, each contains clues about how it might fit with others, but if we haven't looked at the picture on the box, we have no idea what the pieces will combine into. As we progress in fitting some pieces together, part of the picture emerges, and even while it is incomplete, we might be able to guess at what it will be, and that will guide us in assembling the rest of the pieces. As we get close to finishing the puzzle, we see the emergent property of the entire picture that we can understand at a glance.

We could apply this to all other topics in plant biology. Let's use ecology. Many students are inspired by tropical rainforests, and they want to study them. But how do you go about studying a tropical rainforest? We can't put one on a microscope slide, nor can we measure the photosynthesis of an entire forest. Instead, we might study the xylem anatomy of rainforest herbs compared to rainforest trees, or compare photosynthesis on sunny days with that on rainy days. We could study pollinators, seed dispersers, the climate history of the rainforest, and so on. The situation here is that the students have seen the big picture—tropical rainforests—and now they must look into it to see its individual parts. We can start to understand the whole by studying its individual parts (this is called **reductionist thinking** or **reductionism**).

But can we understand a rainforest, or any other complex phenomenon, just by studying its parts? No. Emergent properties exist in biology, the sum is greater than the parts, so to understand the whole, we need to integrate all the parts and think in terms of their relationships (called **holist thinking** or **emergentism**). It is important for us to realize that in addition to actual, physical, tangible tropical rainforests such as those of the Amazon River Basin or Southeast Asia, there are also the concepts, the theoretical models of tropical rainforests. If we want to understand a real rainforest, we must also construct and understand a theory of rainforests, a theory that encompasses all the evidence we have gathered and which goes beyond it. Ultimately, we always want to be able to fit our many facts—our observations and experimental results, our empirical evidence—into a theory or a model. Theories and models give us an understanding of the whole as well as the relationships of the parts. Until we are able to construct a theory or model, we have little more than random facts with little meaning.

You may not realize it, but you have already learned many integrating theories. Let's consider one you know so well you might not realize it is a theory: shoots of seed plants are composed of leaves attached to stems at nodes and separated from each other by internodes. With this theory, you can examine any seed plant in the world and either understand its organization immediately or figure it out with a little observation and rational logic. Just think about this: One simple model organizes and makes sense of millions of observations on more than 200,000 species of plants. Is there an alternative? If so, what is a consequence? Yes, there are several alternatives. For example, the seedless plants known as thallose liverworts do not have leaves or nodes or internodes. A consequence is that if you come across some of them, you will be bewildered by their organization. You cannot be confident of what part is what, how they grow, how they branch, even how they reproduce. We get even further from our model if we examine the bodies of the brown algae known as kelps or the bodies of large red algae. Some parts will fool you because they superficially resemble leaves and internodes, but they had a completely separate evolutionary origin and our model does not apply to them at all. You will

Plants and People

BOX 1-2 The Characteristics of Life

Botany is a subdivision of biology, the study of life. Despite the importance to biology of defining life, no satisfactory definition exists. As we study metabolism, structure, and ecology more closely, we understand many life processes in chemical/physical terms. It is difficult to distinguish between biology and chemistry or between living and nonliving, but the lack of a definition for life does not bother biologists; very few short definitions are accurate, and life is such a complex and important subject that a full understanding gained through extensive experience is more useful than a definition.

Although we cannot define life, it is critically important for us to recognize it and to know when it is absent. Many hospitals use artificial ventilators, blood pumps, and drugs to maintain the bodies of victims of accidents or illness. The person's cells are alive, but is the person alive? On a less dramatic scale, how does one recognize whether seeds are alive or dead? A farmer about to spend $100,000 on seed corn wants to be certain that the seed is alive. How do we recognize that coral is alive? It looks like rock but grows slowly—but stalactites are rock and they also grow.

The ability to recognize life or its absence is important in space exploration also. The surface of Mars is dry, but water may exist within the soil; many bacteria on Earth live below ground, obtaining energy from chemicals in rock. Europa, a moon of Jupiter, has an ocean below a layer of permanent ice; on Earth, worms, clams, and bacteria live in complete, icy darkness near vents on the ocean floor, obtaining enough energy from volcanic gases to thrive, not just survive. When we explore Mars, Europa, and other parts of the solar system, how will we search for life? How will we know whether we have found it?

All living beings have all of the following characteristics; if even one is missing, the material is not alive:

1. *Metabolism involving the exchange of energy and matter with the environment.* Organisms absorb energy and matter, convert some of it into their own bodies, and excrete the rest. Many nonliving systems also do this: Rivers absorb water from creeks, mix it with mud and boulders, and then "excrete" it into oceans.
2. *Nonrandom organization.* All organisms are highly structured, and decay is the process of its molecules returning to a random arrangement; however, many nonliving systems also have this feature: Crystals have an orderly arrangement as do many cloud patterns, weather patterns, and ripple patterns in flowing streams.
3. *Growth.* All organisms increase in size from the time they are formed: Fertilized eggs grow into seeds or embryos, and each in turn grows into an adult. At some point, growth may cease—we stop getting taller at about 25 years of age. This too is not sufficient to distinguish living from nonliving: Mountains and crystals also grow.
4. *A system of heredity and reproduction.* An organism must produce offspring very similar to itself such that when the individual dies life persists within its progeny. Fires reproduce but are not alive.
5. *A capacity to respond to the environment such that metabolism is not adversely affected.* When conditions become dry, an organism can respond by becoming dormant, conserving water, or obtaining water more effectively. Mountains also respond to the environment by growing as geological forces push them upward and by becoming smaller as erosion wears them away.

In addition to these absolute requirements of life, two features are almost certainly associated with all forms of life: (1) Organisms develop, such that young individuals and old ones have distinctive features, and (2) organisms evolve, changing with time as the environment changes.

Although these various features are always present in living creatures, no one characteristic is sufficient to be certain that something is living versus inanimate. We have no difficulty being certain that rivers, fire, and crystals are not living, but when we search for life on other planets or even in some exotic habitats here on Earth, deciding whether we have actually discovered life might be quite problematical.

FIGURE B1-2A Lichens grow extremely slowly and remain dormant for months; almost no sign of life can be detected during their dormant period.

FIGURE B1-2B These seeds of corn (*Zea mays*) are alive and healthy, but inactive metabolically. They will germinate and become obviously alive, but only if given the proper conditions.

Plants Do Things Differently

BOX 3-2 Calcium: Strong Bones, Strong Teeth, but Not Strong Plants

Most plants and animals need hard parts. Wood is strong enough to support the weight of a tree, and bones play a similar role in animals. Seeds are often protected by resistant shells such as those of walnuts and almonds, and animal shells protect clams and oysters. Our teeth are so tough that they can chew through almost anything. Although plants and animals use hard parts for similar roles, plants rely on thick, tough cell walls, whereas animals use calcium salts.

Would it be possible for plants to use bone-like material? We can analyze this as a set of alternatives and their consequences. The present alternative—wood—consists of cellulose and a chemical called lignin. Both are carbohydrates that a plant itself makes through photosynthesis, and thus, they are readily available. And both are remarkably inert, having little impact on other aspects of the plant's metabolism. In contrast, calcium and its salts participate in many metabolic pathways, and building or resorbing shells, bones, or teeth has a broad impact on cell physiology. Shells consist of calcium carbonate, and as animals use carbonate ion (CO_3^{2-}) to build a shell, the acidity of the protoplasm is altered. Furthermore, animals can digest part of their shells if they need the calcium elsewhere, and this liberation of carbonate will again affect the pH. This is tolerable for marine organisms because they use carbonate from the surrounding seawater rather than from their own protoplasm so their pH is not affected. If the shell is resorbed later, the liberated carbonate is likewise dumped outside the animal into the seawater.

Animals like us—with an internal skeleton—use calcium phosphate in our bones and teeth. Calcium carbonate's tendency to alter pH is too dangerous for us, and our skeleton cannot use seawater as a carbonate reservoir. The phosphate ion (PO_4^{2-}) that

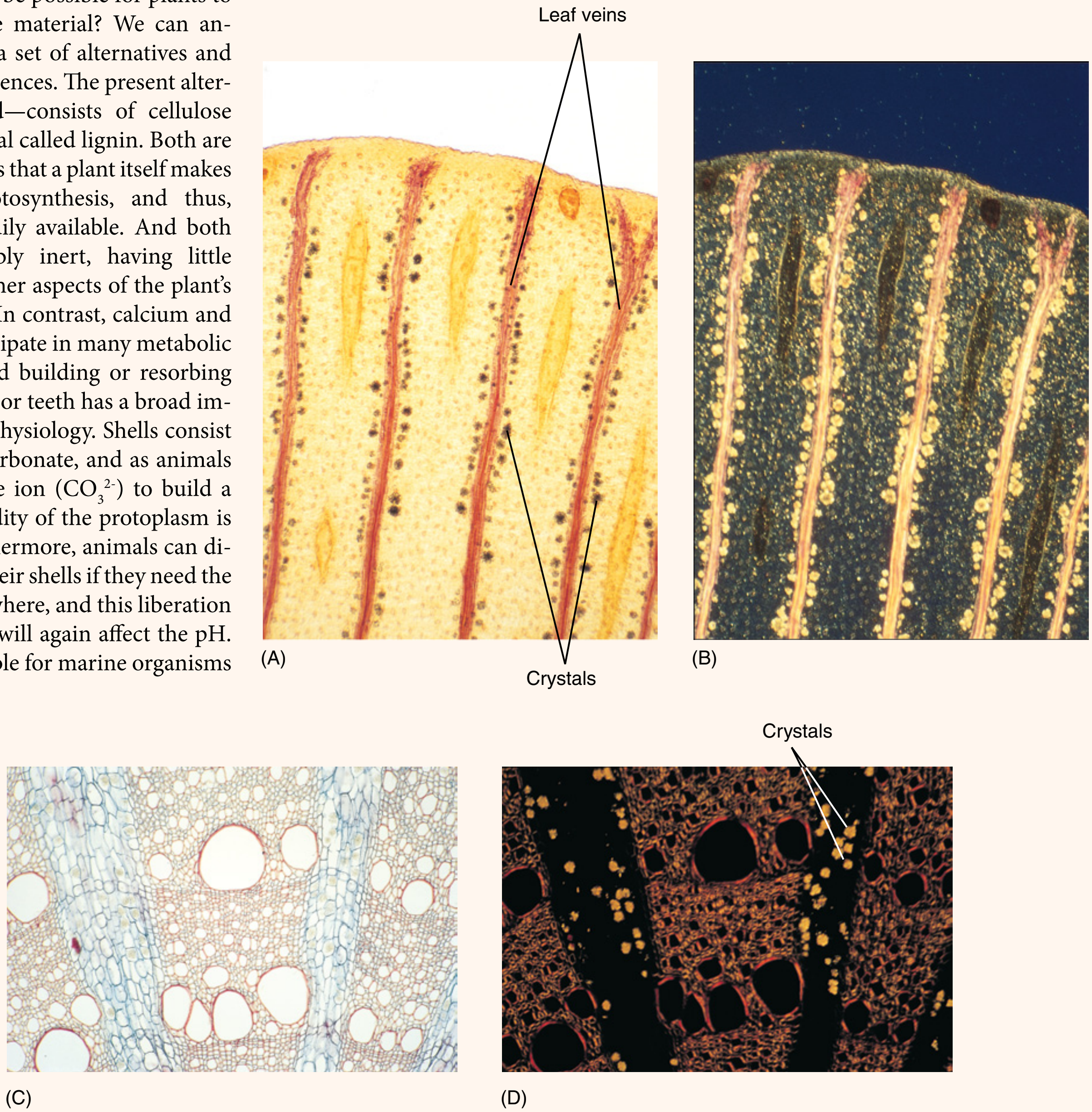

FIGURE B3-2 **(A)** A leaf clearing of maidenhair tree (*Ginkgo*), showing several red-stained leaf veins that conduct sugars out of the leaf. Such veins are the targets of aphids and other sucking insects (× 15). **(B)** The same tissue, in polarized light (× 15). **(C)** A cross-section of *Aristolochia* wood; crystals are present in the two bands of tissue with blue-stained walls, see **(D)**. This is a soft tissue in wood and is the site where sugars and other nutrients are stored (× 50). (D) The same tissue as (C), but with polarized light (× 50).

Plants and People

BOX 4-1 Controlled Growth Versus Cancerous Growth

The actual steps of karyokinesis and cytokinesis must be controlled if cells are to divide properly, but other aspects must be regulated as well. First, the rate and frequency of cell division are important in determining how rapidly or slowly one cell produces a mass of progeny cells. Second, orientation of both cell division and cell growth affects the shape of the growing mass of cells: If all cells divide with their new walls parallel to each other, the mass grows as a column, but if new cell walls occur in any plane, the mass grows in all three dimensions. The mass grows as a sheet if new cell walls can occur in two planes but not in the third. Finally, it is important to control which cells divide: If only some cells undergo cell division, they may produce a lump or outgrowth while the rest of the mass of cells remains unchanged.

These factors are controlled accurately in plants. In a young embryonic plant, all cells divide but later, cells at the tips of roots and shoots become centers of cell division and growth while the rest of the stem and root tissues mature and carry out their functions. By controlling rate, orientation, and location of cell division, plants produce cylindrical stems and roots, thin flat leaves and petals, and massive, three-dimensional fruits.

Plants impose quiescence on certain cells and then reactivate them to growth and division later: Plants produce buds that are forced to remain quiescent for a long time, even years, but can then be stimulated by the plant to grow out as a branch or a flower. In young stems, epidermal cells grow rapidly enough to keep the stem covered, but then they mature and remain mitotically quiescent as they protect the plant. In many species, these can be reactivated years later, undergo cell division, and produce bark cells.

Cell division and growth must be controlled in animals as well. During early stages of fetal development, all cells of human embryos divide and grow. Later, some cells divide more rapidly than others, but basically, most of our cells are mitotically active during much of our growth before birth. Then cells in certain tissues and organs undergo cell cycle arrest; they mature and never divide again such as the cells of our eyes and our brains. Other cells never stop dividing and are active until we die, such as the layer of cells that produces our skin and hair and the bone marrow that generates most of our blood cells. Just as in plants, some of our cells enter a prolonged state of quiescence and later are activated to division. For example, surgical removal of part of the liver causes cells of the remaining portion to divide and restore the organ to an adequate size. Of course, this is not true of most of our organs.

Some of our cells release themselves from cell cycle arrest and begin growing uncontrolled by the rest of the body. This is cancerous growth, and its severity depends on which types of cells and organs are involved, how rapidly the cells divide, and whether the cells can migrate from their original site and invade surrounding tissues. It is well known that certain environmental factors act as carcinogens—agents that cause cancer by interfering with cell cycle arrest. Cigarette smoke is known to cause cancer of the lung and throat, and ultraviolet light triggers skin cancer.

Whereas uncontrolled cancerous growth in humans may be fatal, it does not seem to be a problem in plants. Irregular lumps and growths, called galls, may occur, but these are often caused by insects or microbes, not by the plant's own cells undergoing a spontaneous, self-induced release from cell cycle arrest. It may be that plants do form cancerous growths but that they are not a serious problem for several reasons. First, cells cannot migrate through a plant body the way that our cells migrate through our bodies; consequently, any uncontrolled growth is localized, not invasive. Second, whereas we have many organs that are each critical to our life and which occur singly (heart, brain) or in pairs (kidneys, lungs), plants have many leaves, roots, and flowers, and no single one is indispensable. Damage to one part of the plant may have little effect on the rest of the plant. By lacking the highly differentiated, complex, and tightly integrated body of humans and many animals, plants are not so threatened by diseases involving control of nuclear and cellular division.

microtubules that extend from the opposite pole. The two sets together, overlapping in the center, form a large framework (**FIGURES 4-15** and **4-16**). Other microtubules run from a pole to a centromere. The point of attachment is a **kinetochore**; a structure consisting of two layers of proteins, one layer bound tightly to centromere DNA and the other attached to spindle microtubules. Each centromere has two kinetochore faces, one attached by approximately 15 to 35 microtubules to one end of the spindle and the other face attached by a similar number to the other end of the spindle (Figure 4-15).

Plants Do Things Differently

BOX 7-1 Plants and People and Having a Weight Problem

Most of us probably do not spend too much time worrying about starving to death. However, throughout much of the history of civilization, people had to be careful to store up enough food to last not only through winter but through spring as well. Food supplies had to last until gardens could provide potatoes, beans, wheat, and other staples. Grocery stores are a recent luxury. How did people store food? If dry seeds like wheat and beans are kept free of moisture, they last a long time. Grapes and milk are not dry, but they can be preserved by turning the first into wine and the second into cheese. Meat and fish can be dried, smoked, or salted for long-term storage.

One particular method of storing food is particularly popular with humans and is the only means available to most animals. Eat the food whenever it is available, and store it as fat inside our body. Beans can become moldy. Rats can find our supply of dried meat, but fat in our adipose tissues is safe. For animals that hibernate, getting fat in autumn is the only way to survive. We may regret eating so much at Thanksgiving, but the pilgrims did not. Feasting was a means of storing food that might otherwise spoil during winter.

Plants too must be adapted to the availability—or the scarcity—of food. For plants, "food" is supplied by photosynthesis, and that requires only light, carbon dioxide, and water. In tropical climates where temperatures are always mild and droughts virtually never occur, plants have leaves throughout the year and photosynthesize every day, making all of the carbohydrates they need whenever they need them. Storing food reserves is not a problem. In temperate climates, evergreen trees such as pines and hollies also are able to photosynthesize most days, being inhibited only when it is extremely cold. But deciduous plants—those that drop their leaves and become dormant—are similar to animals in that they need to store food to maintain their metabolism while leafless. When a plant abscises its leaves in autumn, it is almost as if an animal were throwing away its entire digestive tract in anticipation of growing an entire new one in spring. If a plant had no nutrient reserves inside itself when it abscised its leaves, it would not even be able to make new leaves in the following spring. It would starve to death.

Energy reserves can be stored as a variety of chemical compounds. We animals sequester our reserve energy as fats. A little bit of energy is stored as a polymer called glycogen, located in our liver and muscle cells, but that is only enough to keep us going for a few hours as any runner or cyclist knows. Plants virtually never store fats; they rely on starch instead. Why do plants and animals differ on such a simple feature? Let us look at the consequences of each alternative storage molecule.

An energy storage molecule should not be too heavy, and it must be stable enough that it does not "go bad" within the plant or animal's body. Fat is the most lightweight means of storing energy. A pound of fat—whether it is lard, oil, butter, or margarine—stores more energy than a pound of starch or protein. For an organism that needs to move, weight will be less of a problem if it stores fat rather than if it stores the same amount of energy as starch. The next time your bathroom scale reads 10 pounds more than you want, be glad we do not store starch. We would be even more overweight and have even bigger rear ends.

Plants, however, do not move around too much; thus, saving on weight is not a real necessity. For plants, the long-term stability of starch is better than the lightness of fat. Some plants save up energy for years, not just months, and starch will last that long in the plant's body. For example, century plants bloom only once after growing for about 12 to 15 years (but not for an entire century), and fishtail palms may not bloom until they are more than 70 years old. These plants store some starch each year, then use it all at once in a massive flowering. Fat would not last that long because it becomes rancid if exposed to oxygen, and all parts of a plant are well aerated.

Pollen and seeds are exceptions. Many flowers produce pollen with a drop of oil rather than a grain of starch, which makes it lighter and easier for wind or insects to carry it to another flower. Seeds such as peanuts, cashews, and sesame store oil and thus are lighter and smaller and more easily moved by animals. Avocados are very rich in oil, but rather than being an energy storage mechanism, it is a reward that entices an animal to eat the fruit and then spit the seed out somewhere, thereby dispersing the plant's seeds far and wide.

Plants also store a little starch here and there throughout their bodies, some in cortex cells, some in pith cells, and even wood can store a bit. However, when a plant needs to store a lot of starch, it almost always relies on its roots. The enlarged roots of beets, carrots, radishes, sweet potatoes, and similar plants are filled with starch. By using roots as a storage organ, the plants are putting their reserves underground, out of sight of hungry animals. Also, the soil is a more stable environment, being neither as hot during the day nor as cold at night as the air, and similarly, it maintains a more uniform humidity. The storage tissue in roots is usually wood—a type of xylem; thus, just as in adipose tissue of animals, root storage tissues are well vascularized.

Even though plants and animals store energy differently, the reasons are understandable when we consider the consequences of each alternative. Plants favor stability. Animals need mobility.

Plants Do Things Differently

BOX 8-2 Having Multiple Bodies in One Lifetime

Woody plants have two bodies. As the primary body of a woody plant ages, a vascular cambium arises inside it and produces wood and secondary phloem—an entire new body—inside the preexisting body. Think about how different the two bodies are. The primary body has leaves and axillary buds, flowers, fruits, and seeds. It has root hairs and absorbs water and nutrients. The secondary body is just wood and bark. It has no leaves, no buds, no flowers, and so on. The secondary body is, for the most part, nothing more than an ever-growing vascular/skeletal system. The two bodies look completely different and have distinct functions. Growth of the secondary body tears apart and destroys the primary phloem, cortex, and epidermis of the plant's primary body, and these dead remnants are shed as part of the plant's first bark. Shoot tips and root tips continually make more sections of primary body, but they too will be destroyed by formation of more secondary body inside them. It is dramatic for one organism to have two distinct bodies, to have one body form inside another, destroying the first. Does anything like this occur in animals? In us? Yes, and in even more dramatic fashion.

We humans undergo moderate changes in our body. When about 5 or 6 years old, we shed our baby teeth as a new set of permanent teeth forms below them. As the permanent teeth develop and enlarge, they simply push our baby teeth out and we lose them. Parts of our body—teeth with blood vessels, nerves, and living cells—just fall out much the way bark falls off a tree. Later, when we go through puberty, other changes occur. Hair follicles, especially in boys, become active and start producing thicker hair than the type children have. In girls, there is development of glandular and adipose tissue in the breasts. These and other changes, however, are really just modifications of preexisting tissues that were already present in children. There is nothing equivalent to a cambium and the formation of brand new cells.

Our puberty, however, pales in comparison to that of eels. Juvenile eels are just tiny, flat, coin-shaped marine fish that look something like a leaf. As they go through the transformation to being adults, they develop their very long, cylindrical shape and switch to being freshwater fish, migrating up rivers to spawn. Juvenile and adult eels have such different bodies that the juveniles were long considered to be a completely different type of fish. Juvenile and adult *Homo sapiens* are obviously the same species. We do not change that much during puberty.

Other animals go through more significant bodily changes. Crabs, lobsters, and beetles have an exterior exoskeleton that is so hard it cannot grow. The animal periodically produces a new, soft exoskeleton; then the animal molts—that is, it sheds its skin and old exoskeleton—and very quickly grows to a new size before its new exoskeleton hardens and prevents further growth. After some time, the animal will repeat this process so that it can grow even larger. Snakes too periodically shed an old skin, replacing it with a new one. In these examples, entire, complex tissues are being sloughed off and new body parts are formed.

Undoubtedly, the most drastic examples of individuals that have two distinct bodies are insects that go through what is called a complete metamorphosis. Their larval bodies do not look anything at all like the adult bodies. Examples are caterpillars, which metamorphose into moths or butterflies, and maggots, which metamorphose into flies. The larval body is specialized for eating and growing and has neither wings nor sex organs of any kind. In contrast, the adult body does have wings and sex organs, enabling it to fly about and find a mate and then carry out sexual reproduction and dispersal. In some cases, the adult body needs to survive only a day or two until it can mate and die (males) or lay fertilized eggs (females). Such adult bodies have either no digestive system at all or such a simple one that it can only absorb the sugar water of flower nectar. In the complete metamorphosis of caterpillars, the caterpillar spins a cocoon around itself; then its body more or less dissolves except for special sets of cells called imaginal discs. These act like meristems and produce the cells, tissues, and organs of the adult body by using the nutrients from the dissolved larval body. By the time metamorphosis is complete, the body has been completely rearranged; almost nothing exists of the preexisting larval body except that its molecules have been recycled and not wasted.

A plant's primary body differs as greatly from its secondary body as do the caterpillar body and the butterfly body of a particular species. If plants could also digest their primary bodies and rebuild them the way caterpillars do, the transformation in plants would be seen to be just as dramatic as metamorphosis in animals. However, plants do not form cocoons and do not undergo self-digestion, so the activity of a vascular cambium and a cork cambium in the production of an entire new secondary body seems unremarkable. It appears as if the plants are doing nothing more than adding a few new tissues, but the change is really much more fundamental.

Just considering ourselves, the idea of individual plants and animals having several distinct bodies may seem far fetched, but as it turns out, it is a common occurrence with each body carrying out distinct phases of the organism's life activities.

Plants and People

BOX 10-1 Photosynthesis, Global Warming, and Global Climate Change

Our atmosphere is critically important to life on Earth; ironically, its composition is the product of that very life. The free oxygen (O_2) we breathe is produced solely by oxygenic photosynthesis; there is no other source. Oxygenic photosynthesis originated 2.8 billion years ago: We know this because for millions of years the newly produced oxygen reacted with iron, forming a worldwide stratum of rust in ancient rocks. After all iron had been oxidized, free oxygen began accumulating in the atmosphere, and its concentration has been increasing ever since. Simultaneously, photosynthesis pulled carbon dioxide out of the atmosphere, converting it first to 3-phosphoglyceraldehyde and then to all of the other organic compounds that exist. Every single organic molecule started out as carbon dioxide snared by RuBP carboxylase. Most organic molecules are digested and respired by aerobic organisms, a process that returns carbon dioxide back to the atmosphere rather quickly. But millions of tons of trees have died and fallen into stagnant swamps where a lack of oxygen prevented decay: The carbon in their wood—all of the cellulose, hemicellulose, and lignin—was converted to coal and did not return to the atmosphere. Petroleum also is probably derived from photosynthetically fixed carbon dioxide. The point is that respiration does not release all carbon back to the atmosphere; therefore, photosynthesis is gradually causing carbon dioxide concentration in the air to decrease.

Three groups of organisms have had especially important impacts on atmospheric carbon dioxide: coccoliths, mollusks, and humans. Coccoliths are microscopic algae that build shells of calcium carbonate, as do mollusks. When they die, their shells and the carbon they contain sink to the bottom of the ocean and decompose only slowly. All limestone and vast carbonate deposits on the ocean floor represent millions of tons of carbon dioxide removed from the atmosphere by clams, barnacles, and unimaginable numbers of algae.

We humans were no different from any other aerobic organism until we made a fateful discovery: how to use fire. Since then, we not only oxidize food in our mitochondria, but we also oxidize wood, coal, oil, and gas, putting carbon dioxide back into the atmosphere and raising its concentration measurably.

Why does the concentration of atmospheric carbon dioxide matter? Think of carbon dioxide as a pigment; its absorption spectrum is low for visible light but high for infrared wavelengths. Visible light from the sun passes easily through the atmosphere: It is not absorbed by nitrogen, oxygen, or carbon dioxide. As it strikes Earth's surface, some is reflected immediately back out into space, and a small amount is absorbed by biological pigments such as chlorophyll in leaves or rhodopsin in eyes, where it powers photosynthesis or vision; however, most visible light has no effect other than to warm rocks, soil, and water, causing them to radiate the extra energy away as long-wavelength infrared light. Many of these infrared quanta pass directly back through the atmosphere without hitting a carbon dioxide molecule because the concentration of carbon dioxide is so low (0.03% of air), but many quanta are absorbed by atmospheric carbon dioxide molecules, causing them to become warmer. This energy is trapped in the Earth/atmosphere system and warms our world. This is called the **greenhouse effect** because the glass in greenhouses works the same way, as does the glass in a parked car. Carbon dioxide is a **greenhouse gas**.

An important balance exists between the atmospheric concentration of carbon dioxide and life: With less carbon dioxide, more heat would be lost and Earth would be frozen, like Mars. With more, more heat would be trapped and our world would be as hot as Venus, at 800°C, with lakes of molten lead. During the industrial age, we have been adding carbon dioxide to the atmosphere by burning oil, gas, and coal, and we have destroyed forest trees that can remove the carbon dioxide by photosynthesis. The concentration of carbon dioxide is increasing in the atmosphere, and the average temperature is also increasing. This is **global warming**, and it could cause mean temperatures to be 2°C or 3°C (3°F or 4°F) warmer in the next century.

Global warming is having numerous consequences. First, surface water of the oceans is becoming warmer; therefore, more water evaporates into the air. Much of our weather in North America comes as winds blow eastward across the North Pacific. The water is cold and the air picks up only enough moisture to keep the Pacific Northwest wet; by the time it moves to the Central Plains states, it has so little moisture left that only grasses, not forests, thrive. But as surface waters of the Pacific become slightly warmer, vastly more moisture will evaporate into the wind and be carried to the Mississippi drainage basin. This increased rainfall could cause much better farming conditions in the Central Plains, and catastrophic flooding in most river valleys where cities are located. El Niño years show the gigantic flooding that results from slight warming in just one area of an ocean.

Global warming is also causing rapid melting of snow and glaciers in mountains and of ice caps in the Arctic and Antarctic. It is difficult to comprehend, but Antarctica

Plants Do Things Differently

BOX 13-1 Plants Eat Dirt; Animals Eat Protoplasm

At its most fundamental level, plant nutrition is almost identical to that of animals, virtually indistinguishable. All cells depend on the same amino acids, nucleic acids, sugars, and with a few exceptions, the same lipids (plants never use cholesterol). Small molecules such as ATP and vitamins such as thiamin, riboflavin, and folic acid perform exactly the same functions in both types of organisms. At the same time, however, the two types of organisms could hardly differ more. No organism can synthesize mineral elements, of course, so plants and animals share that obvious similarity, but differences abound if we consider how an organism obtains organic molecules. Plants can be described first because they are so easy. They themselves make absolutely everything organic within their own bodies. It might be a bit difficult for zoologists, medical students, and dietitians to truly grasp this point. Every plant itself makes every organic molecule found within its body. A balanced diet for a plant is dirt, dirt, and more dirt, with carbon dioxide and water, morning, noon, and night. Photosynthesis converts carbon dioxide and water into glyceraldehyde-3-phosphate, and starting with just this simple small molecule and some minerals, a plant constructs everything it uses in its life—absolutely everything.

Animals lack many of these synthetic pathways and must obtain many organic compounds in their diet. We humans, like all other organisms, use a universal set of 20 amino acids in our proteins, but we cannot make 9 of these ourselves. We must obtain these 9 in the food we eat or we become ill and could even die. Several fatty acids cannot be synthesized by any tissue, cell, or organelle of our bodies. The list of essential nutrients is especially dramatic when it comes to vitamins, the organic molecules so fundamentally important in such small amounts that they were the first chemicals to be discovered as being essential dietary factors. Thirteen molecules have received this designation so far, and no one would be surprised if others are added to the list with further research. Every plant makes all of its own vitamins; we must get most of ours from our food. If an organic molecule is always reliably present in an animal's food, then mutations that prevent the synthesis of the molecule are actually beneficial. The animal saves energy by not synthesizing compounds it will get in its diet anyway, and that energy can be used to carry out other life activities. If the vitamin is truly always available in the diet, then it is redundant for the animal to synthesize it as well.

The differences in nutritional resources used by plants versus animals are also great. Plants obtain nutrients in the form of elements or as simple compounds present in the environment, such as CO_2, H_2O, K^+, Mg^{2+}, SO_4^{2-}, and so on. An animal begins with food in the mouth, but the nutrients occur as monomers in complex polymers, which in turn are parts of cell structure. Minerals must be digested away from organic molecules; for example, iron must be digested out of hemoglobin and myoglobin before it is absorbed into the blood stream. Although animals save energy by not needing to synthesize many molecules, they must go through much more effort to obtain their food and convert it to forms that can be absorbed. And their food usually also contains indigestible fur, feathers, bones, teeth, and dirt. Plants never take in such debris.

Plants are not completely self-sufficient nutritionally. Most rely on bacteria for converting atmospheric nitrogen gas (N_2) into a chemical form such as nitrate (NO_4^{2-}) or ammonium (NH_4^+) that plants and animals can use. Some plants have gone so far as to actually cultivate these bacteria within their own bodies, within nitrogen-fixing nodules on roots of alfalfa, for example, or within special chambers in liverworts. Although plants can take up phosphorus from the soil on their own, they usually obtain it more efficiently by entering into a symbiotic relationship—called a mycorrhizal association—with certain soil fungi that are more effective at scavenging phosphorus. Other plants have decided that animals have the right idea; the plants either are parasitic on other plants, or they capture and consume animals.

The elements chlorine, magnesium, nitrogen, phosphorus, potassium, and sulfur are **mobile elements**; even after they have been incorporated into a tissue, they can be translocated to younger tissue. After the soil becomes exhausted of one of these elements, older leaves are sacrificed by the plant. The mobile elements are salvaged and moved to growing regions (**FIGURE 13-6B**). The adaptive value of this is easy to understand: A leaf photosynthesizes most efficiently right after it has first expanded and less efficiently as it ages. The plant increases its overall photosynthetic rate by sacrificing old, inefficient leaves and using the minerals to construct new, efficient leaves.

The immobility of certain ions is not understood; boron, calcium, and iron are initially moved upward from roots into shoots, flowers, and fruits, so transport mechanisms do exist for them. Mutations that would result in the degradation of cytochromes in old leaves and the recovery of iron should be selectively advantageous. Animals have trouble with mineral

Plants and People

BOX 14-3 Environmental Stimuli and Global Climate Change

Global climate change is causing our world to rapidly become warmer and wetter, but plant mechanisms for detecting and responding to environmental stimuli are changing more slowly, if at all. As we burn oil, coal, and natural gas and as we convert forests into pasture for cattle, we increase the amount of greenhouse gasses in the atmosphere, causing the air, soil, lakes, and oceans to become warmer. As ocean temperatures rise, their surface waters evaporate faster, making the atmosphere more humid and increasing the amount of rain and snow that later fall on land. Temperatures do not increase uniformly everywhere; instead, circulation patterns in the atmosphere and oceans are affected, so some areas become warmer, others cooler, some wetter, others drier.

Changing climate will have profound effects on all plants, not only on those that respond to temperatures but also on those controlled by day length. Increasing temperatures affect two critically important events for temperate plants: The date of the last frost in spring occurs earlier, and the time of the first frost in autumn comes later. The frost-free growing season in many areas starts earlier and ends later: Plants have a longer growing season.

Plants that germinate or bud out solely based on temperatures can take advantage of this longer growing period, and many seem to be thriving. But for plants controlled by photoperiod, their critical night length does not change, they germinate or bud out at the same time in spring as they have for centuries, and they go dormant at their typical time in autumn. They are not able to take advantage of the extra days of warmth in spring and autumn; instead, they are dormant when they could be photosynthesizing, growing, and reproducing. And, just as bad, their respiration during dormancy is higher than before because it is controlled by environmental temperature: Not only are the plants not producing sugars photosynthetically as long as they could, they are now respiring away their carbohydrates faster. They will have less reserve nutrients available when they resume growth in springtime.

Now consider the interaction of photoperiodic plants and temperature-controlled plants. They occur together in the same habitat and compete with each other for water, minerals, room for their roots, and so on. As warm temperatures occur earlier in spring, the temperature-controlled plants get a head start over the photoperiod-controlled ones, and the same is true in autumn. It is likely that the photoperiod-controlled plants will suffer in this competition, and the ratio of the two types of plants in the ecosystem will change.

As temperature in general increases, the snow-free habitable zone in alpine areas gradually rises to higher elevations. Similarly, habitable zones are expanding northward in the Northern Hemisphere, southward in the Southern. Areas near the North and South Poles are more hospitable. Again, temperature-controlled plants may benefit from this: If their seeds happen to occur in the newly warmer areas, they should be able to grow and reproduce. But the same is only partially true for photoperiod-controlled plants. These should be able to grow higher on any mountain on which they exist already: The critical night length is the same up and down the mountain. But close to the poles, a few days at the beginning of summer (June 20 or 21) have sunlight for 24 hours: There is no night at all for a few days. And at the beginning of winter (December 20 or 21), several days have no sunlight. From early winter to early summer, day length increases from 0.0 to 24 hours. At the equator daylight always lasts for 12 hours and night is also 12 hours, all year long. Between these two extremes, days get slightly longer each day in lower latitudes and much longer each day in high latitudes. For plants that need very long days to bloom (for example, 17 hours, with 7 hours of night), that occurs in May or June in the northern part of the United States and southern Canada, but it occurs in March in northern Alaska and Canada. If a longer growing season would allow that species to grow that far north, its critical night length would occur too early (March) while the plant is still a seedling: It could grow in the new habitat but not reproduce there.

It is important to remember that plants and their control mechanisms do evolve. Hundreds of different plant species differ in their critical night length, and this variation came about through evolution by natural selection. The important question is whether these mechanisms will evolve rapidly enough to allow plants to adapt to the changing climate. We do not know the answer, but, in general, such evolution is slow and we are causing the climate to change rapidly.