The biggest problems associated with the control of the human population are not biological problems; rather, they require the efforts of philosophers, theologians, politicians, and sociologists. As the population increases, so do political, social, and biological problems; individual freedom diminishes, intense competition for resources intensifies, and famine and starvation become more common. The knowledge and technology necessary to control the human population are available, but the will is not. What will eventually limit the size of our population? Will it be lack of resources, lack of energy, accumulated waste products, competition among ourselves, or rational planning of family size?

Studies of the changes in the population growth rates of various countries indicated that a major factor in determining the size of families is the educational status of women. Regardless of other cultural differences, as girls and women become educated, they have fewer children. Several reasons have been suggested for this trend. Higher levels of education enable women to get jobs with higher pay, which makes them less dependent on males for their support. Being able to read may lead to better comprehension of how methods of birth control work. Regardless of the reasons, increasing the educational levels of women has become a major technique used by rapidly growing countries that hope to control their populations.

17.8 CONCEPT REVIEW

20. How does human population growth differ from the population growth of other kinds of organisms?
21. What forces will ultimately lead to the control of human population growth?

Summary

A population is a group of organisms of the same species in a particular place at a particular time. Populations differ from one another in gene frequency, age distribution, sex ratio, population distribution, and population density. Organisms typically have a reproductive capacity that exceeds what is necessary to replace the parent organisms when they die. This inherent capacity to overreproduce causes a rapid increase in population size when a new area is colonized. A typical population growth curve consists of a lag phase, in which the population rises very slowly, followed by an exponential growth phase in which the population increases at an accelerating rate, followed by a leveling off of the population during the deceleration phase, which leads to a relatively constant population size in a stable equilibrium phase as the carrying capacity of the environment is reached. In some populations, a fifth phase, the death phase, occurs.

The carrying capacity is the maximum sustainable number of organisms an area can support. It is set by a variety of limiting factors. The availability of energy, the availability of raw materials, the accumulation of wastes, and interactions with other organisms are limiting factors. Because organisms are interrelated, population changes in one species sometimes affect the size of other populations. This is particularly true when one organism uses another as a source of food. Some limiting factors operate from outside the population and are known as extrinsic limiting factors; others are properties of the species itself and are called intrinsic limiting factors. Some limiting factors become more intense as the density of the population increases; these are known as density-dependent limiting factors. Limiting factors that are more accidental and unrelated to population density are called density-independent limiting factors.

Humans as a species have the same limits and influences that other organisms do. Our current problems of food production, energy needs, pollution, and habitat destruction are outcomes of uncontrolled population growth. However, humans can reason and predict, thus offering the possibility of population control through conscious population limitation.

Key Terms

Use the interactive flash cards on the ***Concepts in Biology, 14/e*** *website to help you learn the meaning of these terms.*

age distribution 374
carrying capacity 384
death phase 381
deceleration phase 379
density-dependent limiting factors 381
density-independent limiting factors 381
environmental resistance 380
exponential growth phase 379
extrinsic limiting factors 380
intrinsic limiting factors 381
lag phase 379
limiting factors 380
mortality 379
natality 379
population 374
population density 377
population distribution 377
population growth curve 379
population pressure 377
reproductive capacity (biotic potential) 378
sex ratio 376
stable equilibrium phase 380

Basic Review

1. The number of reproducing adults in a population compared with the number of juveniles is the
   a. population density.
   b. age distribution.
   c. population distribution.
   d. gene frequency.
2. The period of time when a population is growing rapidly is known as the _____.

3. Populations grow
   a. because most species have a high reproductive capacity.
   b. when birthrates are greater than death rates.
   c. when there are high numbers of reproductive and juvenile individuals in the population.
   d. All of the above are correct.
4. The maximum size of a population is set by limiting factors of the environment. (T/F)
5. A limiting factor that becomes more intense as the size of a population increases is known as a density-independent limiting factor. (T/F)
6. The carrying capacity
   a. for the human population has been reached.
   b. is determined by the limiting factors of the environment.
   c. is the same for all organisms.
   d. None of the above is correct.
7. When the size of a population is caused to stop growing because of competition among its members, there are _____ in action.
   a. extrinsic limiting factors
   b. density-independent limiting factors
   c. intrinsic limiting factors
   d. population distribution factors
8. The populations of all species eventually reach a stable equilibrium phase. (T/F)
9. Which one of the following populations would grow most rapidly?
   a. a population of mice in which there were twice as many males as females
   b. a population of mice that had reached its carrying capacity
   c. a population of mice in which density-dependent limiting factors were acting strongly
   d. a population that was in the lag phase
10. The human population has been increasing rapidly for the past 200 years because
    a. humans have displaced other organisms.
    b. humans have controlled many disease organisms.
    c. humans have developed improvements in agriculture.
    d. All of the above are correct.
11. Gene flow occurs when individuals _____ to new places.
12. Pollution can be considered to be a waste product. (T/F)
13. Which of the following is an extrinsic limiting factor?
    a. the number of siblings in a bird nest
    b. competition among individuals for food
    c. rainstorms that kill many plant seedlings
    d. None of the above is correct.
14. A K-strategist
    a. lives a short time.
    b. gives care to its young.
    c. is always a tiny organism.
    d. None of the above is correct.
15. The lag phase of a population growth curve results in
    a. a reduction in the size of the population.
    b. little increase in the size of the population.
    c. a rapidly growing population.
    d. None of the above is correct.

Answers
1. b 2. exponential growth phase 3. d 4. T 5. F 6. b 7. c 8. F 9. d 10. d 11. travel/migrate/move 12. T 13. c 14. b 15. b

Thinking Critically

Understanding Human Population Growth
Review figure 17.14; note that this population growth curve has very little in common with the population growth curve shown in figure 17.8. What factors have allowed the human population to grow so rapidly? What natural limiting factors will eventually bring our population under control? What is the ultimate carrying capacity of the world? What alternatives to the natural processes of population limitation could bring human population under control? Consider the following in your answers: reproduction, death, diseases, food supply, energy, farming practices, food distribution, cultural biases, and anything else you consider relevant.

CHAPTER 18

Evolutionary and Ecological Aspects of Behavior

CHAPTER OUTLINE

Urban Coyotes Kill Pets

What can be done to solve the problem?

Coyotes have adapted to urban and suburban locations where there are natural areas such as parks, golf courses, drainage ditches, and similar places that provide suitable habitat. Reports of coyotes killing pets, particularly cats and small dogs, are common throughout the United States. What has happened to make this wary animal lose its fear of humans?

Humans have contributed to this problem by providing several sources of food that are attractive to wild animals. Animals like coyotes learn to associate food with humans. The three most common sources of food are (1) garbage that is not in a secure container; (2) pet food provided outdoors; and (3) bird feeders. Coyotes are scavengers as well as carnivores and will use these sources of food. Once coyotes become habituated to finding food around homes, they are likely to encounter pets that are outside the home. Cats that roam at night are particularly vulnerable to predation by coyotes.

- **Why do coyotes lose their fear of humans?**
- **Can coyotes be trained to avoid humans?**
- **In areas with a coyote problem, should homeowners be required to place garbage in a secure container, stop feeding birds, and keep their pets indoors?**

Background Check

Concepts you should already know to get the most out of this chapter:
- How natural selection shapes the evolution of organisms (chapter 13)
- The difference between a scientific test of a hypothesis and an opinion (chapter 1)

18.1 Interpreting Behavior

Behavior is how an animal acts—what it does and how it does it. When you watch a bird, a squirrel, or any other animal, its activities appear to have a purpose. Birds search for food, take flight as you approach, and build nests in which to raise young. Usually, the nests are inconspicuous or placed in difficult-to-reach spots. Likewise, squirrels collect and store nuts and acorns, "scold" when you get too close, and learn to visit sites where food is available.

Discovering the Significance of Behavior

It is not always easy to identify the significance of a behavior without careful study of the behavior pattern and its impact on other organisms. For example, a baby herring gull pecks at a red spot on its parent's bill. What possible value can this behavior have for either the chick or the parent? If we watch, we see that, when the chick pecks at the spot, the parent regurgitates food onto the ground, and feeds it to the chick (figure 18.1). This looks like a simple behavior, but there is more to it than meets the eye. Why did the chick peck to begin with? How did it "know" to peck at that spot? Why did the pecking cause the parent to regurgitate food? These questions are not easy to answer. Many people assume that the actions have the same motivation and direction as similar human behaviors, but this is not necessarily a correct assumption. For example, when a little girl points to a piece of candy and makes appropriate noises, she is indicating to her parent that she wants some candy. Is that what the herring gull chick is doing? We don't know. Although both kinds of young may get food, we don't know what the baby gull is thinking because we can't ask it.

FIGURE 18.1 Understanding Behavior
A herring gull chick causes its parent to regurgitate food onto the ground by pecking at the red spot on its parent's bill. This behavior is instinctive. The parent then picks up the food and feeds it to the chick.

Behavior Is Adaptive

When we observe behavior, we must keep in mind that behavior is adaptive just like any other characteristic displayed by an animal. Behaviors are important for survival and appropriate for the environment in which an animal lives. As with animals' highly adaptive structural characteristics, behaviors are the result of a long evolutionary process. Birds that do not take flight at the approach of another animal are eaten by predators. Squirrels that do not find deposits of food are less likely to survive, and birds that build obvious nests on the ground are more likely to lose their young to predators.

Because the nervous system of animals is the product of genes, many aspects of behavior have a genetic component. In this respect, behavioral characteristics are no different from physical characteristics, such as eye structure, wing shape, or tail length. However, the evolution of behavior is much more difficult to study than structural characteristics. This is because behavior is temporary, and it is difficult to find fossils that show the development of behavior, the way fossils allow us to follow changes in structures. Fossils of footprints, nests, and specific structures such as teeth adapted for grinding give clues about the behavior of extinct animals (How Science Works 18.1). However, these examples represent only a few fragments of the total behavior that must have been a part of the lives of extinct animals. When scientists compare the behavior of closely related animals living today, they can see inherited behaviors that are slightly different from one another. This strongly suggests that these behaviors have evolved, just as the wings of different species of birds have evolved for different kinds of flight. In both cases (structural and behavioral) a basic pattern has been modified as the organisms adapted to their environments.

18.1 CONCEPT REVIEW

1. Why is it more difficult to study the evolution of behavior than the evolution of structural characteristics?
2. List two animal behaviors and state their significance to the animal's reproductive success.

HOW SCIENCE WORKS 18.1

Males Raised the Young in Some Species of Dinosaurs

Sometimes it is possible to use fossils to gain insight into the behavior of extinct animals. In 2008, scientists published a study that suggests that some kinds of theropod dinosaurs (*Oviraptor, Troodon, Citipati*) had a mating system in which the male dinosaurs were the primary caregivers for young. The male dinosaurs guarded the eggs in the nest and cared for the young after the eggs hatched. They based their assertion on several lines of evidence. Fossils of adult dinosaurs have been found associated with nests of eggs and the position of the adult is consistent with it protecting the nest. The dinosaurs that show this behavior show many birdlike characteristics and are closely related to species of birds that show male brooding of young—kiwi, ostrich, and emu. The number of eggs in the nest is large. Birds in which males brood the eggs and raise the young have large numbers of eggs. They compared the number of eggs in the nest of the dinosaurs with that of modern dinosaur relatives—crocodiles, alligators, and birds—and found that the number of eggs in the nest closely matched that of birds in which males brood the eggs. Finally, they compared the bone structure of the dinosaurs found guarding the nest and determined that the bones lacked a layer of spongy bone inside their long bones. Female birds produce this spongy bone during reproduction. The absence of this feature strengthens the argument that the individual guarding the nest were males.

This has significant implications for our understanding of the evolution of bird behavior. Perhaps the first birds were those in which males cared for the young, and the common pattern we see today—both parent birds caring for the young—has evolved from the more primitive condition found in ostriches and their relatives.

18.2 The Problem of Anthropomorphism

Anthropomorphism is the idea that we can assign human feelings, meanings, and emotions to the behavior of animals (figure 18.2). Poets, composers, and writers have often described birdsong as the act of a "joyful songster," but is a bird singing on a warm, sunny spring day making a beautiful sound because it is happy? Students of animal behavior do not accept this idea and have demonstrated that a bird sings primarily to attract mates and to tell other birds to keep out of its territory. The barbed stinger of a honeybee remains in your skin after you are stung, and the bee tears the stinger out of its body when it flies away. The damage to its body is so great that it dies. Has the bee performed a noble deed of heroism and self-sacrifice? Was it defending its hive from you? Scientists need to know a great deal more about the behavior of bees to understand the value of such behavior to the success of the bee species. The fact that bees are social animals, like humans, makes it tempting to think that they are doing things for the same reasons we are.

If you chase a squirrel in a park it will run up a tree and chatter at you. This is often referred to as scolding; however, this is a human interpretation based on what we might do if someone disturbed us. We might yell at the other person to go away and leave us alone. However, several other possible interpretations are equally reasonable. Perhaps the purpose of the squirrel's noise-making is directed at driving you away. Or perhaps its vocalizations warn other squirrels of the presence of a predator. Or perhaps it is simply a nervous reaction to

FIGURE 18.2 Anthropomorphism
It is tempting to think that both the girl and the dog are having the same experience. However, that would be anthropomorphic thinking. We really don't know what the dog is experiencing. We can't ask the dog what it is thinking.

being disturbed. We cannot crawl inside the brain of another animal and see what it is thinking.

In order to evaluate behavior objectively, we need to avoid anthropomorphic assumptions. A scientific study of this scolding behavior would attempt to determine what triggers the behavior, rather than jump to a conclusion that it must be for the same reasons we humans do things. Furthermore, a scientific study of this behavior would seek to determine the effect of the behavior. A scientific study of an organism's behavior looks at the behavior of an animal during its lifetime and seeks to determine the behavior's value to the animal and how that behavior may have evolved. This scientific way of thinking requires the testing of hypotheses; an anthropomorphic approach does not.

18.2 CONCEPT REVIEW

3. Why do students of animal behavior reject the idea that a singing bird is happy?
4. Define *anthropomorphism*.

18.3 Instinctive and Learned Behavior

There are two major kinds of behaviors: instinctive and learned. **Instinctive behavior** is behavior that is inherited, automatic, and inflexible. **Learned behavior** is behavior that changes as a result of experience. Both are involved in the behavior patterns of most organisms. Learning allows an organism to generate a completely new behavior or to slightly modify existing behavior patterns. Most animals (e.g., jellyfish, clams, insects, worms, frogs, turtles) have a high proportion of instinctive behavior and very little learning. Others, such as many birds and mammals, have a great deal of learned behavior in addition to many instinctive behaviors.

The Nature of Instinctive Behavior

Instinctive behavior makes up most of the behavior in animals that have short life cycles, simple nervous systems, and little contact with their parents. These behaviors are performed correctly the first time without previous experience. Such behaviors are found in a wide range of organisms, from simple, one-celled protozoans to complex vertebrates.

Stimulus and Response

Instinctive behaviors occur as a result of a specific *response* to a particular *stimulus*. A **stimulus** is a change in the organism's internal or external environment that an animal is able to detect. A **response** is an organism's reaction to a stimulus.

In our example of the herring gull chick, the red spot on the parent's bill serves as a stimulus for the chick. The chick responds to this spot in a genetically programmed way. The behavior is instinctive—it is done correctly the first time without prior experience. The chick's pecking behavior, in turn, is the stimulus for the adult bird to regurgitate food. Obviously, these behaviors have adaptive value for the survival of the young, because they leave little to chance. The young will get food automatically from the adult. Instinctive behavior has great value to a species, because it allows correct, appropriate, and necessary behavior to occur without prior experience.

An organism can respond only to stimuli it can recognize. For example, it is difficult for humans to appreciate what the world is like to a bloodhound. The bloodhound is able to identify individuals by smell, whereas we have great difficulty detecting, let alone distinguishing among, many odors. Some animals, such as dogs, deer, and mice, can see only shades of gray. Others, such as honeybees, see ultraviolet light, which is invisible to us. Some birds and other animals are able to detect the magnetic field of the Earth. And some, such as rattlesnakes, are able to detect infrared radiation (heat) from distant objects.

Instinctive Behavior Cannot Be Modified

Instinctive behaviors can be very important for the survival of individuals of a species. This is especially true for fundamental, essential activities that do not require modification. The major drawback of instinctive behavior is that it cannot be modified when a new situation presents itself.

Over long periods of evolutionary time, genetically determined behaviors have been selected for and have been useful to most individuals of the species. However, instances of inappropriate behavior may be generated by unusual stimuli or unusual circumstances in which the stimulus is given. For example, many kinds of insects fly toward a source of light. Over the millions of years of insect evolution, this has been a valuable, useful behavior. It allows them easily to find their way to open space. However, the human species invented artificial lights and transparent windows, which cause the animals to engage in totally inappropriate behavior. We have all seen insects drawn to lights at night or insects inside houses, constantly flying against window panes through which sunlight is entering. This mindless, mechanical behavior seems incredibly stupid to us. Although *individual* animals die, the general behavior pattern of flying toward light is still valuable because *most* of the individuals of the species do not encounter artificial lights or get trapped inside houses, and they complete their life cycles normally.

Geese and other birds sit on nests. This behavior keeps the eggs warm and protects them from other dangers. During this incubation period, the eggs may roll out of the nest as the parents get on and off the nest. When this happens, certain species of geese roll the eggs back into the nest. If the developing young within the egg are exposed to extremes of heat or cold, they are killed; thus, the egg-rolling behavior has a significant adaptive value. If, however, the egg is taken from

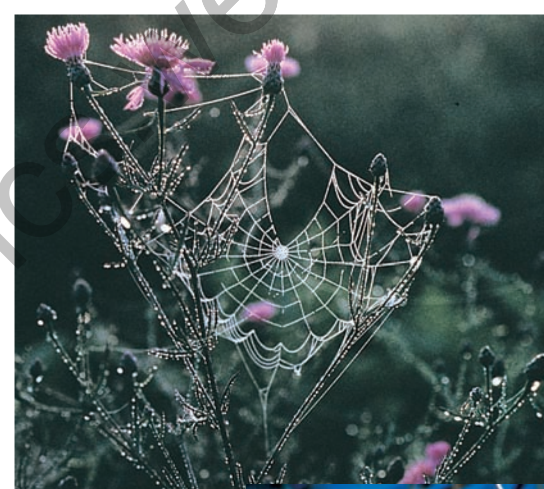
FIGURE 18.3 Inflexible Instinctive Behavior
Geese use a specific set of head movements to roll any reasonably round object back to the nest. There are several components of this instinctive behavior, including recognition of the object and head-tucking movements. If the egg is removed during the head-tucking movements, the behavior continues as if the egg were still there. This demonstrates the inflexible nature of instinctive behavior.

the goose when it is in the middle of egg-rolling behavior, the goose will continue its egg rolling until it gets back to the nest, even though there is no egg to roll (figure 18.3). This is typical of the inflexible nature of instinctive behaviors. It has also been found that many other, somewhat egg-shaped structures can stimulate egg-rolling behavior. For example, beer cans and baseballs trigger egg-rolling behavior. Thus, not only are the birds unable to stop the egg rolling in midstride, but also nonegg objects can generate inappropriate behavior because they resemble eggs.

Instinctive Behavior Can Be Complex

Some activities are so complex that it seems impossible for an organism to be born with such abilities. For example, a spider web is not just a careless jumble of silk threads; it is so precisely made that scientists can recognize what species of spider made it by the pattern of threads in the web. However, web spinning is not a learned ability. A spider has no opportunity to learn how to spin a web, because it never observes others doing it. Furthermore, spiders do not practice several times before they get a proper, workable web. It is as if a "program" for making a particular web were in the spider's "computer" (figure 18.4).

Might these behavior patterns be the result of natural selection? Many kinds of behaviors are controlled by genes. The "computer" in our example is really the spider's DNA, and the "program" is a specific package of genes. Through the millions of years that spiders have been in existence, natural selection has modified the web-making program to refine the process. Certain genes of the program have undergone mutation, resulting in changes in behavior. Imagine various ancestral spiders, each with a slightly different program. The inherited program that gives individuals the best chance of living long enough to produce a new generation is the program selected for, and the most likely to be passed on to the next generation.



(a)

(b)

FIGURE 18.4 Complex Instinctive Behavior
(a) The kind of web constructed by a spider is determined by instinctive behavior patterns. *(b)* Instinctive behavior by this masked weaver is responsible for its construction of this complex nest.

TABLE 18.1 Comparison of Instinct and Learning

Instinct	Learning
The animal is born with the behavior.	The animal is not born with the behavior.
Instinctive behavior is genetically determined.	Learned behavior is not genetically determined, but the way in which learning occurs is at least partly hereditary.
No experience is required; the behavior is done correctly the first time.	Performance improves with experience; learning the behavior requires practice.
The behavior cannot be changed.	The behavior can be changed.
Memory is not important.	Memory is important.
New instinctive behavior can evolve as gene frequencies change and new species evolve.	The *ability* to learn can evolve as gene frequencies change and new species evolve. However, changes in the actual behaviors learned are not the result of genetic changes.
Instinct is more common in simple animals with short lives and little contact with their parents.	Learning is typical of more complex animals with long lives and extensive contact with parents.
Instinctive behaviors can be passed from parents to offspring only by genetic means.	Learning allows acquired behaviors to be passed from parents to offspring by cultural means.

The Nature of Learned Behavior

The alternative to preprogrammed, instinctive behavior is learned behavior. **Learning** is a change in behavior as a result of experience.

Learning is very significant in long-lived animals that care for their young. Animals that live many years are highly likely to benefit from an ability to recognize previously encountered situations and to modify their behavior accordingly. Furthermore, because the young spend time with their parents, they can imitate their parents and develop behaviors that are appropriate to local conditions. These behaviors take time to develop but have the advantage of adaptability. For learning to become a dominant feature of an animal's life, the animal must also have a memory, which requires a relatively large brain in which to store new information. This is probably why learning is a major part of the lives of only a few kinds of animals, such as the vertebrates. Nearly all human behavior is learned. Even such important behaviors as walking, communicating, feeding oneself and sexual intercourse must be learned. Table 18.1 compares instinctive and learned behaviors.

18.3 CONCEPT REVIEW

5. List two ways in which learned and instinctive behaviors differ.
6. Briefly describe an example of unlearned behavior in a particular animal. Explain why you know it is unlearned.
7. Briefly describe an example of learned behavior in a particular animal. Explain why you know it is learned.

FIGURE 18.5 Habituation
These elephants in a national park are habituated to the presence of vehicles containing tourists.

18.4 Kinds of Learning

Scientists who study learning recognize that there are various kinds of learning: *habituation, association, exploratory learning, imprinting,* and *insight.*

Habituation

Habituation is a change in behavior in which an animal ignores an insignificant stimulus after repeated exposure to it. There are many examples of this kind of learning. Typically, wild animals flee from humans. Under many conditions, this is a valuable behavior. Wild animals that frequently encounter humans and never experience negative outcomes may learn to ignore humans. Many wild animals, such as the deer, elk, and bears in parks, have been habituated to the presence of humans and behave in a way that would be totally inappropriate in areas near the park where hunting is allowed (figure 18.5).

Similarly, loud noises usually startle humans and other animals. However, constant exposure to such sounds cause the individuals to ignore them. As a matter of fact, the sound may become so much a part of the environment that the stopping of the sound causes a response. Habituation is valuable because the animal does not waste time and energy responding to a stimulus that does not have a beneficial or negative impact on the animal. Animals that respond continually to inconsequential stimuli have less time to feed and may miss other, more important stimuli.

Association

Association occurs when an animal makes a connection between a stimulus and an outcome. Associating a particular outcome with a particular stimulus is important to survival, because it allows an animal to avoid danger or take advantage of a beneficial event. If association allows the animal to get more food, avoid predators, or protect its young more effectively, this kind of learning is advantageous to the species. The association of certain shapes, colors, odors, or sounds with danger is especially valuable. There are three common kinds of association: *classical conditioning, operant* (*instrumental*) *conditioning,* and *observational learning* (*imitation*).

Classical Conditioning

Classical conditioning occurs when an involuntary, natural, reflexive response to a natural stimulus is transferred from the natural stimulus to a new stimulus. The response provoked by the new stimulus is called a **conditioned response.** During the period when learning is taking place, the new stimulus is given *before* or *at the same time as* the normal stimulus.

A Russian physiologist, Ivan Pavlov (1849–1936), was investigating the physiology of digestion when he discovered that dogs can transfer a natural response to a new stimulus. He was studying the production of saliva by dogs and knew that a natural stimulus, such as the presence or smell of food, would cause the dogs to start salivating. Then, he rang a bell just before presenting them with food. After a training period, the dogs began to salivate when the bell was rung even though no food was presented. The natural response (salivating) was transferred from the natural stimulus (the smell or taste of food) to a new stimulus (the sound of a bell).

Animals can also be conditioned unintentionally. Many pets anticipate their mealtimes because their owners go through a certain set of behaviors, such as going to a cupboard or opening a can of pet food prior to putting food in a dish. It is doubtful that this kind of learning is common in wild animals, because it is hard to imagine such tightly controlled sets of stimuli in nature.

Operant (Instrumental) Conditioning

Operant (**instrumental**) **conditioning** also involves the association of a particular outcome with a specific stimulus, but it differs from classical conditioning in several ways. First, during operant conditioning, the animal learns to repeat acts that bring good results and avoid those that bring bad results. Second, the animal receives a reward or punishment *after* engaging in a particular behavior. Third, the animal's response is typically a more complicated behavior than a simple reflex. A reward that encourages a behavior is known as positive reinforcement, and a punishment that discourages a behavior is known as negative reinforcement.

The training of many kinds of animals involves this kind of conditioning. If a dog being led on a leash is given the command *heel* and is then vigorously jerked into the correct position, it eventually associates the word *heel* with assuming the correct position slightly behind and to the side of the trainer. This is negative reinforcement, because the animal avoids the unpleasantness of being jerked about if it assumes the correct position. Similarly, petting or giving food to a dog when it has done something correctly will positively reinforce the desired behavior. For example, placing the dog into the sitting position on the command *sit* and rewarding the dog when it performs the behavior on command is positive reinforcement.

Wild animals have many opportunities to learn through positive or negative reinforcement. As animals encounter the same stimulus repeatedly, there is an opportunity to associate the stimulus with a particular outcome. For example, many kinds of birds eat berries and other small fruits. If a distinctly colored berry has a good flavor, birds will return repeatedly to eat them. Pigeons in cities have learned to associate food with people in parks. They can even identify specific individuals who feed them regularly. Their behavior is reinforced by being fed. Many birds in urban areas have associated automobiles with food and are seen picking smashed insects from the grills and bumpers of cars. When a car drives into the area, birds immediately examine it for food.

In some national parks, bears have associated backpacks with food. In some cases, attempts have been made to use negative reinforcement to condition the bears to avoid humans. Usually, the bears are exposed to loud or painful stimuli if they approach backpacks. Some bears that cannot be trained to avoid humans and their "equipment" are killed. Conversely, in areas where bears are hunted, they have generally been conditioned to avoid contact with humans. Similarly, if certain kinds of fruits or insects have unpleasant tastes, animals learn to associate the bad tastes with the colors and shapes of the offending objects and avoid them in the future (figure 18.6). Each species of animal has a distinctive smell. If a deer or rabbit has several bad experiences with a predator that has a particular smell, it can avoid places where the smell of the predator is present.

Animals also engage in trial-and-error learning, which includes some elements of conditioning. When confronted with a problem, they try one option after another until they achieve a positive result. Once they have solved the problem, they can use the same solution repeatedly. For example, if a squirrel has a den in a hollow tree on one side of a stream and is attracted to a source of food on the other side, it may explore several routes to get across the stream. It may jump from a tree on one side of the stream to another on the opposite side. It may run across a log that spans the stream. It may wade a shallow portion of the stream. Once it has found a

(a) Positive reinforcement

(b) Negative reinforcement

FIGURE 18.6 Association Learning Positive and Negative Reinforcement
(a) These geese have frequently received food from people who come to the water's edge. Therefore, they have associated people with the food. *(b)* The monarch butterfly this blue jay is eating contains a chemical that makes the blue jay sick. After one or two such experiences, blue jays learn not to eat monarchs.

good pathway, it is likely to use the same pathway repeatedly. Similarly, many hummingbirds visit many different flowers during the course of a day. When they have found a series of nectar-rich flowers, they follow a particular route and visit the same flowers several times a day.

FIGURE 18.7 Observational Learning
By following and observing their mother, these cubs will learn how to fish for salmon.

Observational Learning (Imitation)

Observational learning (imitation) is a form of association; it consists of a complex set of associations formed while watching another animal being rewarded or punished after performing a particular behavior. The animal does not receive the reward or punishment itself but, rather, observes the positive outcomes of the other's behavior. Subsequently, the observing animal may show behaviors that receive rewards and avoid behaviors that lead to punishment. It is likely that conditioning is involved in imitation, because an animal that imitates a beneficial behavior is rewarded. Observing a negative outcome to another animal is also beneficial, because it allows the observer to avoid negative consequences. Many kinds of young birds and mammals follow their parents and sample the same kinds of foods their parents eat (figure 18.7). If the foods taste good, they are positively reinforced. They may also observe warning and avoidance behaviors associated with particular predators and mimic these behaviors when the predators are present. For example, crows will mob predators, such as hawks and owls. As young crows observe older ones cawing loudly and chasing an owl, they learn the same behavior. They associate a certain kind of behavior (mobbing) with a certain kind of stimulus (owl or hawk).

Exploratory Learning

Animals are constantly moving about and sampling their environment. For animals that rely primarily on instinctive behaviors, this movement increases the likelihood that they will find food or other valuable resources but does not result in learning because they do not increase their efficiency at finding resources. Animals that have a significant amount of memory can store information about their surroundings as they wander about. In some cases, the new information may have immediate value—for example, many kinds of birds and mammals remember where certain physical features are located in their environment. They may find a food source during their wanderings and can return to it repeatedly in the future.

When you put up a bird feeder, it does not take very long before many birds are visiting the feeder on a regular basis (figure 18.8). Birds certainly find suitable nesting sites by exploring; then, they store the location in memory. Even invertebrate animals with limited ability to store information engage in exploratory learning. For example, in spring, a queen bumblebee will fly about, examining holes in the ground. Eventually, she will find a hole in which she will lay eggs and begin to raise her first brood of young. Once she has selected a site, she must learn to recognize that spot so that she can return to it each time she leaves to find food, or her young will die.

In other cases, the information learned is not used immediately but might be of use in the future. If an animal has an inventory of its environment, it can call on the inventory to solve problems later in life. Many kinds of animals hide food items when food is plentiful and are able to find them later when food is scarce. Even if they don't remember exactly where the food is hidden, if they always hide food in a particular kind of place, they are likely to find it later. (For example, if you needed to drive a car that you have never seen before, you would know that you need to use a key, and you would search in a particular place in the car to insert the key.) Having a general knowledge of its environment is very useful to an animal.

FIGURE 18.8 Exploratory Learning
As a result of traveling about, these goldfinches located this bird feeder. Once they found this food source, they could return repeatedly to obtain food.

Many kinds of small mammals, such as mice and ground squirrels, avoid predators by scurrying under logs or other objects or into holes in the ground. Experiments with mice and owl predators show that mice that are familiar with their surroundings are more likely to escape predators than are those that are not.

Imprinting

Imprinting is a special kind of irreversible learning in which a very young animal is genetically primed to learn a specific behavior in a very short period during a specific time in its life. The time during which imprinting is possible is known as the **critical period.** This type of learning was originally recognized by Konrad Lorenz (1903–1989) in his experiments with geese and ducks. He determined that, shortly after hatching, goslings and ducklings would follow an object if the object was fairly large, moved, and made noise. The critical period was short—minutes to hours immediately following hatching.

Imprinting is irreversible. Ducklings will follow only the object on which they are originally imprinted. Under normal conditions, the first large, noisy, moving object newly hatched ducklings see is their mother. Imprinting ensures that the immature birds will follow her and may learn appropriate feeding, defensive tactics, and other behaviors by example. Because they are always near their mother, she can also protect them from enemies or bad weather. If animals imprint on the wrong objects, they are not likely to survive (figure 18.9a).

Since these experiments by Lorenz in the early 1930s, scientists have discovered that many young animals can be imprinted on several types of stimuli and that there are responses other than following. The way song sparrows learn their song appears to be a kind of imprinting. The young birds must hear the correct song during a specific part of their youth, or they will never be able to perform the song correctly as adults. This is true even if later in life they are surrounded by other adult song sparrows that are singing the correct song. Furthermore, the period of time when they learn the song is before they begin singing. Recognizing and performing the correct song is important, because it has a particular meaning to other song sparrows. For males, it conveys that a male song sparrow has reserved a space for himself. For females, the male's song is an announcement of the location of a male of the correct species that is a possible mate.

Mother sheep and many other kinds of mammals imprint on the odor of their offspring. They are able to identify their

(a) Following response

(b) Imprinted on odor

FIGURE 18.9 Imprinting
Imprinting is irreversible learning that occurs during a very specific part of the life of an animal. *(a)* Ducklings exhibit the "following response" to their mother. *(b)* Female sheep imprint on the odor of their lambs and will only let their lambs nurse.

offspring among a group of lambs and allow only their own lambs to suck milk (figure 18.9b). Shepherds have known for centuries that they can sometimes get a mother that has lost her lambs to accept an orphan lamb if they place the skin of the mother's dead lamb over the orphan.

Many fish appear to imprint on odors in the water. Salmon are famous for their ability to return to the freshwater streams where they were hatched. Fish that are raised in artificial hatcheries can be imprinted on minute amounts of specific chemicals and be induced to return to any stream that contains the chemical.

Insight

Insight is learning in which past experiences are reorganized to solve new problems. When faced with a new problem, whether it is a crossword puzzle, a math problem, or any other, everyday problem, we sort through our past experiences to find those that apply. We may not even realize we are doing it, but we put these past experiences together in a new way that may solve the current problem. Because this process is internal and can be demonstrated only through a response, it is very difficult to understand exactly what goes on when insight occurs. Behavioral scientists have explored this area for many years, but the study of insight is still in its infancy.

Insight is very difficult to study, because it is impossible to know for sure whether a novel solution to a problem is the result of thinking it through or simply an accident. For example, a small group of Japanese macaques (monkeys) was studied on an island. They were fed by simply dumping food, such as sweet potatoes or wheat, onto the beach. Eventually, one of the macaques discovered that she could get the sand off the sweet potato by washing it in a nearby stream. She also discovered that she could sort the wheat from the sand by putting the mixture into water because the wheat would float. Are these examples of insight? We will probably never know, but it is tempting to think so. In addition, in the colony of macaques, the others soon began to display the same behavior, probably imitating the female that had first made the discovery. Table 18.2 summarizes the characteristics and significance of each of the kinds of learning discussed here.

18.4 CONCEPT REVIEW

8. Give an example of a conditioned response. Describe one that is not mentioned in this chapter.
9. How are classical conditioning and operant conditioning different?
10. What is imprinting, and what value does it have to an organism?
11. Give an example of habituation in a wild animal.
12. In what kinds of animals is observational learning common?
13. Why is insight difficult to demonstrate in animals?
14. Give an example of the value of exploratory learning.

18.5 Instinct and Learning in the Same Animal

It is important to recognize that all animals have both learned and instinctive behaviors, and that a single behavior pattern can include both instinctive and learned elements. For example, biologists have raised young song sparrows in the absence of any adult birds, so that there was no song for the young birds to imitate. These isolated birds sang a series of notes similar to the normal song of the species, but not exactly correct. Birds from the same nest that were raised with their parents developed a song nearly identical to that of their parents. If birdsongs were totally instinctive, there would be no

TABLE 18.2 Kinds of Learning

Kind of Learning	Defining Characteristic	Ecological Significance	Example
Habituation	An animal ignores a stimulus to which it is subjected continually.	An animal does not waste time or energy by responding to unimportant stimuli.	Wild animals raised in the presence of humans lose their fear of humans.
Association	An animal learns that a particular outcome is connected with a particular stimulus.	An animal can avoid danger or anticipate beneficial events by connecting a particular outcome with a specific stimulus when that stimulus is frequently tied to a particular outcome.	Many mammalian predators associate prey with high-pitched, squealing sounds.
Classical conditioning	A new stimulus is presented in combination with a natural stimulus. The animal transfers its response from the natural stimulus to the new stimulus.	Classical conditioning probably does not happen in natural settings.	Pets can anticipate when they will be fed, because their owners' food-preparation behavior occurs shortly before food is presented.
Operant (instrumental) conditioning	An animal responds to a new stimulus. It is rewarded or punished following its response. Eventually, the animal associates the reward or punishment with the stimulus and responds appropriately to the stimulus.	Animals can avoid harmful situations that are associated with particular stimuli. They can learn to repeat behaviors that bring benefits.	Animals that associate a shape, color, smell, or sound with a predator can take refuge. Animals that associate a shape, color, smell, or sound with the presence of food will find food more readily.
Observational learning (imitation)	An animal imitates the behaviors of others.	The animal can acquire the knowledge of others by watching. This can be more rapid than learning by trial and error.	Young animals run when their mothers do and feed on the food their parents do.
Exploratory learning	An animal moves through and observes the elements of its environment.	Information stored in memory may be valuable later.	An awareness of hiding places can allow an animal to escape a predator.
Imprinting	An animal learns specific, predetermined activity at a specific time in life.	The animal quickly gains a completely developed behavior that has immediate value to its survival.	Many kinds of newborn animals follow their mothers.
Insight	An animal understands the connection between things it had no way of experiencing previously.	Information stored in an animal's memory can be used to solve new problems.	The manufacture and use of tools by humans and some other primates suggests insight is involved.

difference between these two groups. It appears that all these birds inherited the ability to produce appropriate notes but the refinements of the song's melody came from experience. Therefore, the characteristic song of that species is partly learned behavior (a change in behavior as a result of experience) and partly unlearned (instinctive). This is probably true of the behavior of many organisms; they show complex behaviors that are a combination of instinct and learning. It is important to note that many kinds of birds learn most of their songs with very few innate components. Mockingbirds are very good at imitating the songs of a wide variety of bird species in their region. They even imitate the sounds made by inanimate objects, such as the screeching of a rusty hinge.

This mixture of learned and instinctive behavior is not the same for all species. Many invertebrate animals rely on instinct for most of their behavior patterns, whereas many of the vertebrates (particularly birds and mammals) make use of a great deal of learning (figure 18.10).

When a behavior pattern has both instinctive and learned components, typically the learned components have particular

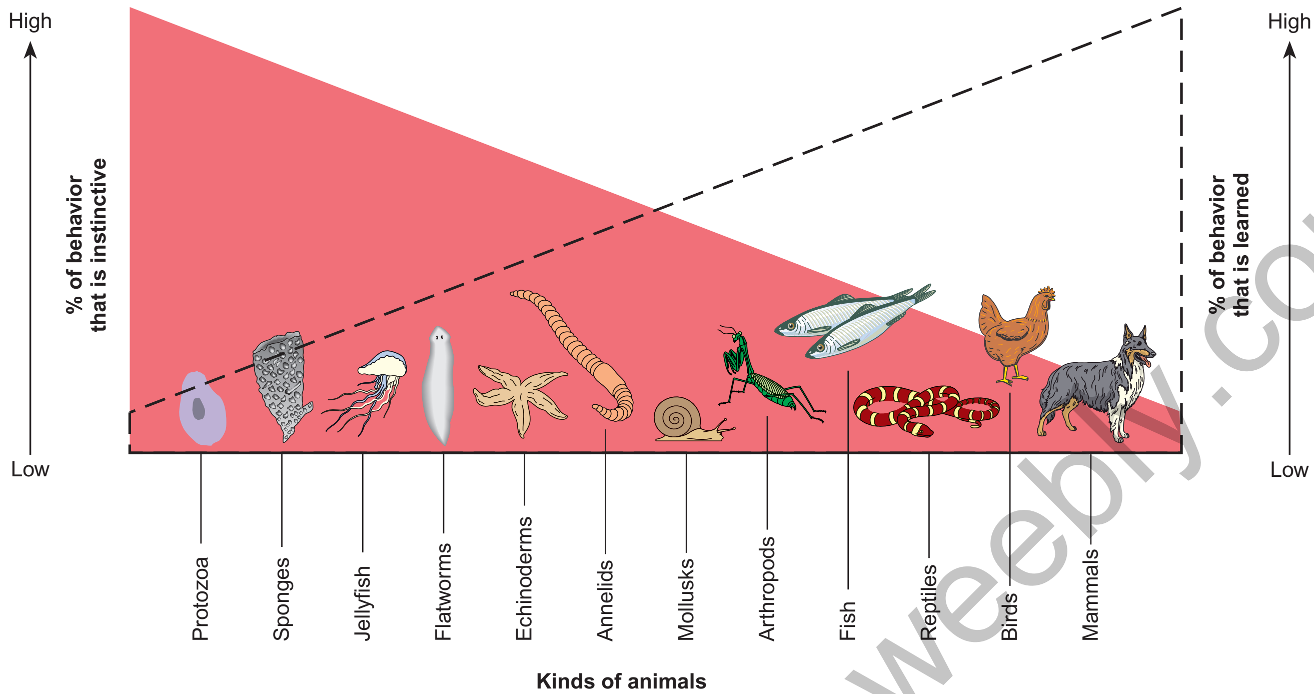


FIGURE 18.10 The Distribution of Learned and Instinctive Behaviors
Different groups of animals show different proportions of instinctive and learned behaviors in their behavior patterns.

value for the animal's survival. For example, most of a honeybee's behavior is instinctive; however, when it finds a new food source, it can remember the route between the hive and the food source. A bird's style of nest is instinctive, but the skill with which it builds may improve with experience. Birds' food-searching behavior is probably instinctive, but the ability to modify the behavior to exploit unusual food sources, such as bird feeders, is learned. On the other hand, honeybees cannot be taught to make products other than honey and beeswax, a robin will not build a nest in a birdhouse, and most insect-eating birds will not learn to visit bird feeders.

18.5 CONCEPT REVIEW

15. Which one of the following animals—goose, shark, or grasshopper—is likely to have the highest proportion of learning in its behavior? List two reasons for your answer.

18.6 Human Behavior

We tend to think of human behavior as different from that of other animals, and it is. However, we are different only in the degree to which we demonstrate different kinds of behavior.

1. *Instinctive behavior* is rare in humans. We certainly have reflexes that cause us to respond appropriately without thinking. Touching a hot object and rapidly pulling your hand away is a good example. Newborns grasp objects and hang on tightly with both their hands and feet. This kind of grasping behavior in our primitive ancestors would have allowed the child to hang onto its mother's hair as the mother and child traveled from place to place. But do we have more complicated instinctive behaviors? Newborns display several behaviors that can be considered instinctive. If you stroke the side of an infant's face, the child will turn its head toward the side touched and begin sucking movements. This is not a simple reflex behavior but, rather, requires the coordination of several sets of muscles and involves the brain. It is hard to see how this is a learned behavior, because the child does the behavior without prior experience. Therefore, it is probably instinctive. This behavior may be associated with nursing, because carrying the baby on its back would place the child's cheek against the mother's breast. Other mammals, even those whose eyes do not open for several days following birth, are able to find nipples and begin nursing shortly after birth.
2. *Habituation* is a common human experience. We readily ignore sounds that are continuous, such as the sound of air conditioning equipment or the background music in shopping malls. Teachers recognize that it is important to change activities regularly to keep their students' attention.
3. *Association* is extremely common in humans. We associate smells with certain kinds of food, sirens with emergency vehicles, and words with their meanings. Much of the learning we do is by association. We also use positive and negative reinforcement to change behavior. We seek

FIGURE 18.11 Negative Reinforcement
The reprimand this recruit is receiving is an example of negative reinforcement.

to reward appropriate behavior and punish inappropriate behavior (figure 18.11). We can experience positive and negative reinforcement without actually engaging in a behavior, because we can visualize its possible consequences. Adults routinely describe consequences for children, so that they will not experience harm: "If you don't study for your biology exam, you'll probably fail it."

4. *Exploratory learning* is extremely common in humans. Children wander about and develop a mental picture of where things are in their environment. Exploration also involves behaviors such as picking things up, tasting things, and making sounds. Even adults explore new ideas and activities.
5. *Imprinting* in humans is more difficult to demonstrate, but there are instances in which imprinting may be taking place. Bonding between mothers and infants is thought to be an important step in the development of the mother-child relationship. Most mothers form very strong emotional attachments to their children; likewise, children are attached to their mothers, sometimes literally, as they seek to maintain physical contact with them. However, it is very difficult to show what is actually happening at this early time in the life of a child.

   Language development in children may also be an example of imprinting. All children learn whatever languages are spoken where they grow up. If multiple languages are spoken, they learn them all and they learn them easily. However, adults have more difficulty learning new languages, and many find it impossible to "unlearn" languages they spoke previously, so they speak new languages with an accent. This appears to meet the definition of imprinting. Learning takes place at a specific time in life (critical period), the kind of learning is preprogrammed, and what is learned cannot be unlearned. Recent research using brain-imaging technology shows that those who learn a second language as adults use two different parts of the brain for language—one part for the native language or languages they learned as children and a different part for their second language.
6. *Insight* is what our species prides itself on. We are *thinking* animals. **Thinking** is a mental process that involves memory and an ability to reorganize information. A related aspect of our thinking nature is our concept of self. We can project ourselves into theoretical situations and measure our success by thinking without needing to experience a situation. For example, we can look at the width of a small stream and estimate our ability to jump across it without needing to do the task. We are mentally able to measure our personal abilities against potential tasks and decide if we should attempt them. In the process of thinking, we come up with new solutions to problems. We invent new objects, new languages, new culture, and new challenges to solve. However, how much of what we think is really completely new, and how much is imitation? As mentioned earlier, association is a major core of our behavior, but we also are able to use past experiences, stored in our large brains, to provide clues to solving new problems.

18.6 CONCEPT REVIEW

16. Give examples of instinct, habituation, association, and imprinting in humans.

18.7 Selected Topics in Behavioral Ecology

The science of animal behavior is a broad one, drawing on information from several fields of study, and it can be used to explore many kinds of questions. Of the examples so far in this chapter, some involved laboratory studies, some were field studies, and some included aspects of both. Often, these studies overlap with the field of psychology. This is particularly true for many of the laboratory studies. The topics that follow concentrate on the significance of behavior from ecological and evolutionary points of view. Now that we have some understanding of how organisms generate behavior, we can look at a variety of behaviors in several kinds of animals and see how they are significant for their ecological niches.

Communication

Communication is the use of signals to convey information from one animal to another. Animals communicate in many ways and for a variety of purposes.

FIGURE 18.12 Communication by Sound
This tree frog is calling. The inflated vocal sac amplifies the sound he produces.

FIGURE 18.13 Maintaining Social Order
Many kinds of body postures and actions are used for communication that reinforces the social status of animals. The wolf on the left is the dominant wolf. It has its ears up, head in an elevated position, and is staring. The wolf on the right is in a submissive position. Its ears are back and its head is lowered. Both wolves are showing aggression with exposed teeth.

Sensory Systems

The senses of hearing, sight, taste, smell, and touch are all involved in communication. Regardless of the sensory system used, communication involves the production of signals that can be received and interpreted by others of the same species. For most animals, the communication system is instinctive. However, in humans language is a learned behavior.

1. *Sound* is used by many kinds of animals for communication. Birds, frogs, alligators, crickets, wolves, and many other animals use sound to communicate information.
2. *Sight* is used to communicate in many ways. Colors, lights, body postures, and movements are all involved in communication.
3. *The chemical senses of taste and smell* are important in the communication system of many kinds of animals. **Pheromones** are chemicals produced by animals and released into the environment that trigger behavioral or developmental changes in other animals of the same species. For example, honeybees produce a pheromone that smells like bananas to humans. This pheromone triggers aggressive behavior in the bees of the hive. Many kinds of animals produce odors that communicate information about their reproductive status. Licking or touching with antennae is a way to obtain chemical information about other animals.
4. *Touch* is probably involved in the communication systems of nearly all organisms. If nothing else, the touch of one animal by another announces its presence.

Often, several of the senses are used at the same time in the process of communication. For example, when two dogs meet for the first time, they are likely to communicate by sound, sight, smell, touch, and taste. They bark or growl. They assume special body postures or bare their teeth, which are visual signals. They sniff one another. They may push one another, or one may put a leg over the other's body. Finally, if they are friendly, they are likely to lick one another.

Purposes of Communication

Animals communicate for several purposes.

1. *Advertising location* is an important function of communication. Information about location can be used to gather individuals together. The calls of frogs in the spring bring animals together at a breeding site (figure 18.12). The calls of crows can call attention to a predator or food source. Many birds use sounds to attract potential mates to their location. The same sounds can be used to tell others of the same species that a particular piece of the habitat is occupied and to stay away.
2. *Social structure* among animals that live in groups is maintained through communication. The elaborate greeting activities of wolves are an example. There is much posturing, touching, smelling, licking, and vocalization, all of which help reinforce the status of each individual in the group (figure 18.13).
3. *Alarm signals* alert animals to potential danger. The alarm pheromone of honeybees mentioned earlier is an example. The raised tail of a white-tailed deer is a similar signal, but deer also snort and stamp their forefeet when they are disturbed by something in their surroundings.

And many birds and mammals use alarm calls to alert others to the presence of danger.

4. *Reproduction* requires communication. Information about the location and reproductive readiness of individuals is important for reproduction to be successful.

Reproductive Behavior

The reproductive behavior of many kinds of animals has been studied a great deal. Although each species has its own behaviors, some components of reproductive behavior are common to nearly all animals. In order for an animal to produce offspring that reach adulthood, several events must occur. A suitable mate must be located, mating and fertilization must take place, and the young must be provided for.

Finding Each Other

To reproduce, an animal must find individuals of the same species that are of the opposite sex. Various species use different methods, but most send signals that can be interpreted by others of the same species. Depending on the species, any of the senses (sound, sight, touch, smell, or taste) may be used to identify the species, sex, and sexual receptiveness of another animal. For instance, different species of frogs produce distinct calls. The call produced by male frogs, which both male and female frogs can hear, results in frogs of both sexes congregating in a limited area. Once they gather in a small pond, it is much easier to have the further communication necessary for mating to take place. Many other animals, including most birds, insects (e.g., crickets), reptiles (e.g., alligators), and some mammals, produce sounds that are important for bringing individuals together for mating.

Chemicals can have the same effect as the sounds made by frogs or birds; they are just a different code system. For example, many kinds of female moths release a chemical into the air. The large, fuzzy antennae of the male moths can receive the chemical in unbelievably tiny amounts. The males fly upwind to the source of the pheromone, which is a female (figure 18.14).

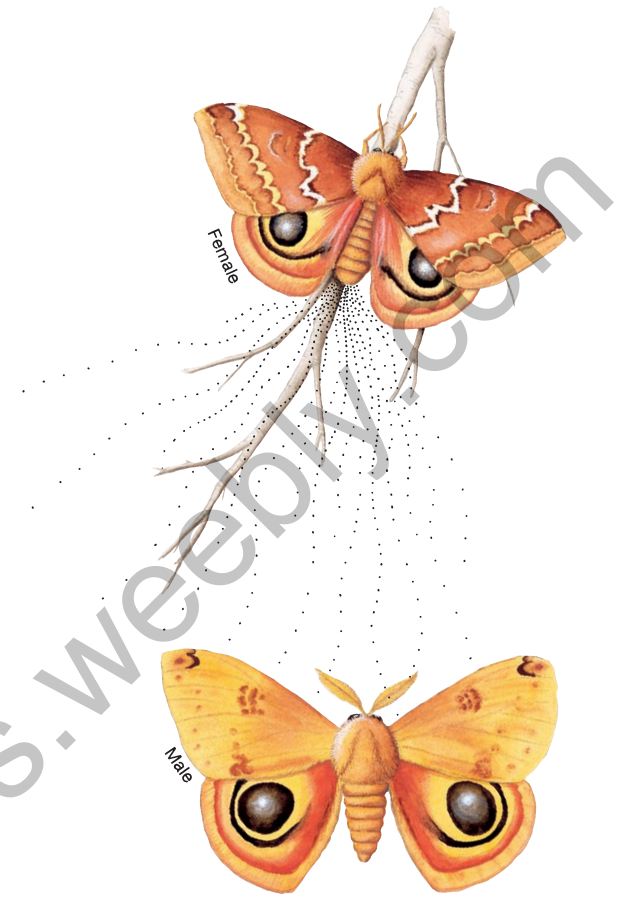


FIGURE 18.14 Chemical Communication
The female moth signals her readiness to mate and attracts males by releasing a pheromone, which attracts males from long distances downwind.

Most mammals rely on odors. Females typically produce distinct odors when they are in breeding condition. When a male happens on such an odor trail, he follows it to the female. Many reptiles also produce distinctive odors that are attractants.

Visual cues are also important for many species. Brightly colored birds, insects, fish, and many other animals use specific patches of color for species identification. Conspicuous movements can also be used to attract the attention of a member of the opposite sex.

The firefly is probably the most familiar organism that uses light signals to bring males and females together. Several species may live in the same area, but each species flashes its own code. The code is based on the length of the flashes, their frequency, and their overall pattern (figure 18.15). There is also a difference between the signals given by males and those given by females. For the most part, males are attracted to and mate with females of their own species. Once male and female animals have attracted one another's attention, the second stage in successful reproduction takes place. However, in one species of firefly, the female has the remarkable ability to signal the correct answering code to species other than her own. After she has mated with a male of her own species, she continues to signal to passing males of other species. She is not hungry for sex, just hungry. The luckless male who responds to her "come-on" will be her dinner.

Assuring Fertilization

The second important activity in reproduction is fertilizing eggs. Many marine organisms simply release their gametes into the sea simultaneously and allow fertilization and further development to take place without any input from the parents. Sponges, jellyfishes, and many other marine animals fit into this category. Other aquatic animals congregate, so that the chances of fertilization are enhanced by the male and female being near one another as the gametes are shed. This is typical of many fish and some amphibians, such as frogs. Internal fertilization, in which the sperm are introduced into

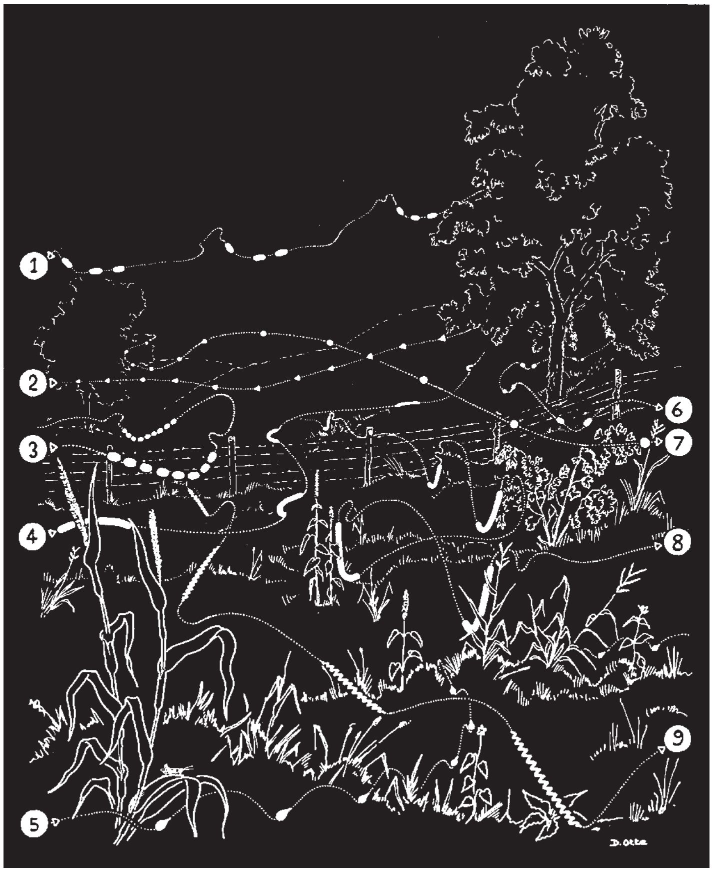


FIGURE 18.15 Firefly Communication
The pattern of light flashes, their location, and their duration all help fireflies identify members of the opposite sex who are of the appropriate species.
Courtesy of James E. Lloyd.

FIGURE 18.16 No Parental Care
The mother of these caterpillars does not provide any care for her offspring. The only provision she has made for her offspring is to lay her eggs on a suitable food plant. Most of these larvae will die.

the female's reproductive tract, occurs in most terrestrial animals. Some spiders and other terrestrial animals produce packages of sperm, which the female picks up with her reproductive structures. Many of these mating behaviors require elaborate, species-specific communication prior to the mating act.

Raising Young

The third element in successful reproduction is providing the young with the resources they need to live to adulthood. Many invertebrate animals spend little energy on the care of the young, leaving them to develop on their own. Usually, the young become free-living larvae, which eat and grow rapidly. Many insects lay their eggs on the particular species of plant that the larva will feed on as it develops. Parasitic species seek out the required host in which to lay their eggs. The eggs of others may be placed in spots that provide safety until the young hatch from the egg (figure 18.16). Turtles, many fish, and some insects fit into this category. In most of these cases, however, the female lays large numbers of eggs, and most of the young die before reaching adulthood. This is an enormously expensive process: The female invests considerable energy in producing eggs but has a low success rate. Nevertheless, most species use this strategy, and it has proven to be very successful.

An alternative strategy to this "wasteful" loss of potential young is to produce fewer young but invest large amounts of energy in their care. This is not necessarily a more efficient system, because it still requires large investments by the parents in the production and care of the young. This strategy is typical of birds and mammals. Parents build nests, share in the feeding and protection of the young, and often assist the young in learning appropriate behaviors. Caring for the young requires many complex behavior patterns (figure 18.17). Most of the animals that feed and raise young are able to distinguish their own young from those of other nearby families and may even kill the young of another family unit. Elaborate greeting ceremonies are usually performed when animals return to the nest or the den. Perhaps this has something to do with being able to identify individual young. Often, this behavior is shared among adults as well. This is true for many colonial nesting birds, such as gulls and penguins, and for many carnivorous mammals, such as wolves, dogs, and hyenas.

Care of the young also occurs in several species of fish and reptiles, such as alligators. Certain kinds of insects, such as bees, ants, and termites, have elaborate social organizations in which one or a few females (queens) produce large numbers of young, which are cared for by the queen's sterile offspring. Most of the offspring are sterile workers, but a few become new queens.

(a)

(b)

FIGURE 18.17 Parental Care
Mammals and birds typically invest a great deal of energy in caring for their young. *(a)* Zebras protect their young and provide food in the form of milk. *(b)* Robins and other birds build nests away from most predators, and provide food until the young are able to fend for themselves.

Territorial Behavior

A **territory** is the space used for food, mating, or other purposes, that an animal defends against others of the same species. **Territorial behaviors** are activities performed to secure and defend a space. These behaviors are widespread in the animal kingdom and can be seen in such diverse groups as insects, spiders, fish, reptiles, birds, and mammals (figure 18.18).

FIGURE 18.18 Territorial Behavior
This clown fish lives with a sea anemone. It will defend its small territory against other clown fish.

On the other hand, many kinds of animals do not establish fixed territories. For example, most insects, worms, and many other invertebrates do not form territories. In addition, many kinds of migratory animals, such as tuna and wildebeest, do not establish territories or do so only during the breeding season.

Territorial Behavior Reduces Conflict

When territories are first being established, there is often much conflict among individuals. However, this eventually gives way to their use of signals that define the territory and communicate to others that the territory is occupied. For example, the male redwing blackbird has red shoulder patches, but the female does not. The male will perch on a high spot, flash his red shoulder patches, and sing to other males that venture into his territory. Most other males get the message and leave his territory; those that do not leave are attacked. He will also attack other red objects such as people wearing red caps. Clearly, the spot of red is the characteristic that stimulates the male to defend his territory. Once the initial period of conflict is over, the birds tend to respect one another's boundaries. All that is required is to frequently announce that the territory is still occupied. They do so by singing from a conspicuous position in the territory. After territorial boundaries have been established, little time is required to prevent other males from venturing close. Thus, the animal may spend a great deal of time and energy securing the territory initially, but doesn't need to expend much to maintain it.

Territorial Behavior Involves Special Signals

For redwing blackbirds, singing in a conspicuous location and flashing red shoulder patches is a signal warning other male blackbirds to stay away. The use of signals replaces the need for fighting. Much of the singing behavior of other species of birds is also territorial. Many carnivorous mammals, such as foxes, weasels, cougars, coyotes, and wolves, use urine

FIGURE 18.19 Territory Size
Colonial nesting seabirds typically have very small nest territories. Each territory is just out of pecking range of the neighbors.

FIGURE 18.20 Advertising One's Territory
The howling of this wolf has several functions. One is to advertise its presence in its territory.

or other scents to mark the boundaries of their territories. Territorial fish use color patterns and threat postures to defend their territories. Crickets use sound and threat postures. Male bullfrogs engage in shoving matches to displace males that invade their small territories along the shoreline.

Territorial Behavior Allocates Resources

A territory has great importance, because it reserves exclusive rights to the use of a certain space for an individual or small group of individuals, such as a pair of robins or a wolf pack. These resources may include sources of food or water, nest or den sites, or access to potential mates. Thus, establishing and maintaining a territory is a way to allocate resources among the members of a species. This is also likely to have an effect on population size, because animals that are not able to establish a territory or are forced to accept poor-quality territories will be less likely to survive and reproduce.

Territory Size

Different species of animals maintain territories for different purposes. Some species maintain small territories of a few square meters, whereas others maintain territories of several square kilometers. For example, many seabirds build nests in colonies. Each pair of birds maintains an extremely small nesting territory of about 1 square meter within the colony. Each territory is just beyond the reach of the bills of the neighbors (figure 18.19). When one bird invades the nesting territory of another, the resident bird uses threat postures to drive the intruder away. If the intruder does not take the hint, it is attacked. Many kinds of fish also maintain small territories.

Many other birds maintain territories for both nesting and gathering food resources. These territories range from a few hundred square meters, such as for robins, to several square kilometers, such as for owls.

Many large carnivores have territories that cover several square kilometers. In such cases, the signals they use must be perceived over great distances or last for a long time. The howling of wolves and the roaring of lions are signals that can be heard over long distances (figure 18.20). The use of scent posts—places where animals urinate, defecate, or deposit other scents, transmits long-lasting signals. The "owner" of the territory does not need to be present all the time to defend its territory, but it must visit these sites regularly to renew the signal.

Dominance Hierarchy

In social animals, a kind of organization known as a *dominance hierarchy* is often observed. A **dominance hierarchy** is a relatively stable, mutually understood order of priority within the group. One individual in the group dominates all the others. A second-ranking individual dominates all but the highest-ranking individual, and so forth; the lowest-ranking individual must give way to all others within the group. Generally, the initial establishment of a dominance hierarchy involves fighting. The best fighters take the top places. However, once the hierarchy is established, it results in a more stable social unit with little conflict, because the positions of the individuals within the hierarchy are reinforced by various kinds of threats without the need for fighting. This kind of behavior is seen in barnyard chickens and is known as a *pecking order.* Figure 18.21 shows a dominance hierarchy; the lead animal has the highest rank and the last animal has the lowest rank.

A dominance hierarchy gives certain individuals preferential treatment when resources are scarce. The dominant individual has first choice of food, mates, shelter, water, and other resources because of its position. Animals low in the hierarchy may be malnourished or fail to mate in times of scarcity. In many social animals, such as wolves, usually only the dominant male and female reproduce. If the dominant male and female have achieved their status because they have superior characteristics, their favorable genes will probably be passed on to the next generation. Poorly adapted animals

FIGURE 18.21 A Dominance Hierarchy
Many animals maintain order within their groups by establishing a dominance hierarchy. For example, in a group of cows or sheep walking in single file, the dominant animal is probably at the head of the line and the lowest-ranking individual is at the end.

with low rank may never reproduce. Such a hierarchy frequently results in low-ranking individuals emigrating from the area. Such migrating individuals are often subject to heavy predation.

Behavioral Adaptations to Seasonal Changes

Most animals live in environments that change from time to time. There may be differences in temperature, rainfall, or availability of food. In some areas, the dry part of the year is the most stressful. In temperate areas, winter reduces many sources of food and forces organisms to adjust. Animals have several behavioral means for coping with these changes.

1. *Metabolic changes* allow many animals to avoid seasonal changes or times of environmental stress. Where drought occurs, many animals become inactive until water becomes available. Frogs, toads, and many insects remain inactive (*estivate*) underground during long periods of drought and emerge to mate when it rains. *Hibernation* in mammals is a response to cold, seasonal temperatures in which the body temperature drops and all the body processes slow down. The slowing of body processes allows an animal to survive on the food it has stored within its body as fat prior to the onset of severe environmental conditions and low food availability. Hibernation is typical of bats, marmots, and some squirrels. Animals such as insects, reptiles, and amphibians are not able to regulate their temperatures the way birds and mammals do. Because their body temperatures drop when the environmental temperature drops, their activities are slowed during the winter and they require less food.
2. *Migration* allows many animals simply to move to areas that are less stressful. Migratory birds fly hundreds or thousands of kilometers. Many birds that nest in the north avoid winter by migrating to more southerly regions (figure 18.22). Many migratory mammals move from drier areas where food has been depleted to other moister areas where food is more available. In many cases, the migrations are triggered by instinctive responses to environmental clues, and the same migration routes are used generation after generation.
3. *Storing food* during seasons of plenty for periods of scarcity is a common behavior pattern. These behaviors are instinctive and are seen in a variety of animals. Squirrels bury nuts, acorns, and other seeds. (They also

(a)

(b)

FIGURE 18.22 Seasonal Migration
(a) Snow geese and many other birds migrate from their northern breeding grounds to milder climates during the winter. In this way, they are able to use the north for breeding and avoid the harsh winter climate. *(b)* Wildebeest migrate annually to find better grazing.

plant trees because they never find all the seeds they bury.) Chickadees stash seeds in cracks and crevices when food is plentiful and spend many hours during the winter exploring similar places for food. Some of the food they find is food they stored. Honeybees store honey, which allows them to live through the winter when nectar is not available. This requires a rather complicated set of behaviors that coordinates the activities of thousands of bees in the hive.

Navigation and Migration

Because animals move from place to place to meet their needs, it is useful for them to be able to return to a nest, water hole, den, or favorite feeding spot. This requires some memory of their surroundings (a mental map) and a way of determining direction. Direction can be determined by such things as magnetic fields, landmarks, scent trails, or reference to the Sun or stars. If the Sun or stars are used for navigation, some sort of time sense is also needed because these bodies move in the sky. It is valuable to have information about distance as well.

Animals often use the ability to sense changes in time to prepare for seasonal changes. Away from the equator, the length of the day—the **photoperiod**—changes as the seasons change. Many birds prepare for migration and have their migration direction determined by the changing photoperiod. For example, in the fall, many birds instinctively change their behavior, store up fat, and begin to migrate from northern areas to areas closer to the equator. This seasonal migration allows them to avoid the harsh winter conditions signaled by the shortening of days. The return migration in the spring is triggered by the lengthening photoperiod. This migration requires a lot of energy, but it allows many birds to exploit temporary food resources in the north during the summer months.

In honeybees, navigation also involves communication among the various individuals that are foraging for nectar. The bees are able to communicate information about the direction and distance of the nectar source from the hive. If the source of nectar is some distance from the hive, the scout bee performs a "wagging dance" in the hive. The bee walks in a straight line for a short distance, wagging its rear end from side to side. It then circles around back to its starting position and walks the same path as before (figure 18.23). This dance is repeated many times. The direction of the straight-path portion of the dance indicates the direction of the nectar relative to the position of the Sun. For instance, if the bee walks straight upward on a vertical surface in the hive, this tells the other bees to fly directly toward the Sun. If the path is 30° to the left of vertical, the source of the nectar is 30° to the left of the Sun's position.

The duration of the entire dance and the number of waggles in its straight-path portion are positively correlated with the length of time the bee must fly to get to the nectar source. So the dance communicates the duration of flight as well as the direction. Because the recruited bees have picked up the scent of the nectar source from the dancer, they also have information about the kind of flower to visit when they

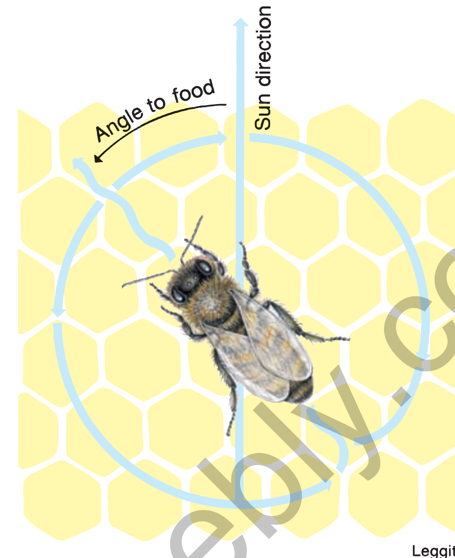


FIGURE 18.23 Honeybee Communication and Navigation
The direction of the straight, tail-wagging part of the dance of the honeybee indicates the direction to a source of food. The angle that this straight run makes with the vertical is the same angle the bee must fly in relation to the Sun to find the food source. The length of the straight run and the duration of each dance cycle indicate the flying time necessary to reach the food source.

arrive at the correct spot. Because the Sun is not stationary in the sky, the bee must constantly adjust its angle to the Sun. It appears that they do this with an internal clock. Bees that are prevented from going to the source of nectar or from seeing the Sun still fly in the proper direction sometime later, even though the position of the Sun is different.

Like honeybees, some daytime-migrating birds use the Sun to guide them. For nighttime migration, some birds use the stars to help them find their way. In one interesting experiment, warblers, which migrate at night, were placed in a planetarium. The pattern of stars as they appear at any season could be projected onto a large, domed ceiling. In autumn, when these birds would normally migrate southward, the stars of the autumn sky were shown on the ceiling. The birds responded with much fluttering activity at the south side of the cage, as if trying to migrate southward. Then, the experimenters projected the stars of the spring sky, even though it was autumn. The birds then attempted to fly northward, although there was less unity in their efforts to head north; the birds seemed somewhat confused. Nevertheless, the experiment showed that the birds recognized star patterns and were influenced by them.

Some birds navigate by compass direction—that is, they fly as if they had a compass in their heads. They seem to be able to sense magnetic north. Their ability to sense magnetic fields was proven at the U.S. Navy's test facility in Wisconsin. The weak magnetism radiated from this test site has changed the flight patterns of migrating birds, but it is yet to be proved that birds use the Earth's magnetism to guide their migration. Homing pigeons are famous for their ability to find their way home. They make use of a wide variety of clues, but it has been shown that one of the clues they use is magnetism. In one study, birds with tiny magnets glued to the sides of their heads were very poor navigators; others, with nonmagnetic objects attached to the sides of their heads, did not lose their ability to navigate.

Social Behavior

A **society** is a group of animals of the same species that interact with one another and in which there is a division of labor.

Animal societies exhibit many levels of complexity, and the types of social organization differ from species to species. Some societies show little specialization of individuals other than that determined by sexual differences and differences in physical size and endurance. The African wild dog illustrates such a flexible social organization. These animals are nomadic and hunt in packs. Although an individual wild dog can kill prey about its own size, groups are able to kill fairly large animals if they cooperate in the chase and kill. Young pups are unable to follow the pack. When adults return from a successful hunt, they regurgitate food if the proper begging signal is presented to them (figure 18.24). Therefore, the young and the adults that remained behind to guard the young are fed by the returning hunters. The young are the responsibility of the entire pack, which cooperates in their feeding and protection. While the young are at the den site, the pack must give up its nomadic way of life. Therefore, the young are born during the time of year when prey are most abundant. Only the dominant female in the pack has young each year. If every female had young, the pack couldn't feed them all. At about 2 months of age, the young begin to travel with the pack, and it can return to its nomadic way of life.

FIGURE 18.24 African Wild Dog Society
African wild dogs hunt in groups and share food, which they take back to the den. Only the dominant male and female mate and raise offspring.

Honeybees have a social organization with a high degree of specialization. A hive may contain thousands of individuals, but under normal conditions only the queen bee and the male drones are capable of reproduction. None of the thousands of workers, who are also females, reproduce. The large number of sterile female worker honeybees collect food, defend the hive, and care for the larvae. As they age, the worker honeybees move through a series of tasks over a period of weeks. When they first emerge from their wax cells, they clean the cells. Several days later, their job is to feed the larvae. Next, they build cells. Later, they become guards, challenging all insects that land near the entrance to the hive. Finally, they become foragers, finding and taking back nectar and pollen to the hive to feed the other bees and to be stored for the winter. Foraging is usually the workers' last job before they die. Although this progression of tasks is the normal order, workers can shift from their main task to others if there is a need. Both the tasks performed and the progression of the tasks are instinctively (genetically) determined (figure 18.25).

Altruism

Altruism is behavior in which an individual animal gives up an advantage or puts itself in danger to aids others. In honeybee societies, the workers give up their right to reproduce and help raise their sisters. Is this a kind of self-sacrifice by the workers, or is there another explanation? In general, the workers are the daughters or sisters of the queen and, therefore, share a large number of her genes. This means that they are helping a portion of their genes get to the next generation by helping raise their own sisters, some of whom will become new queens. This argument has been used to partially explain behaviors in societies that might be bad for the individual but advantageous for the society as a whole.

In other cases, it is not clear that there is any advantage to altruistic behavior. Alarm calls may alert others to a danger

FIGURE 18.25 Honeybee Society
Within the hive, the queen lays eggs, which the sterile workers care for. The workers also clean and repair the hive and forage for food.

FIGURE 18.26 **Tree-Climbing Lions**
In most of Africa, lions do not climb trees; however, in some areas, they do. The difference is cultural.

but do not benefit the one who gives the alarm. In fact, the one giving the alarm may call attention to itself.

Culture

Culture often develops among social organisms. Extensive contact between parents and offspring allows the offspring to learn certain behavior patterns from their parents. Thus, there are behavioral differences among groups within species. This is obvious in humans, who have various languages, patterns of dress, and many other cultural characteristics. But it is even possible to see similar differences in other social animals. Different groups of chimpanzees use different kinds of tools to get food. Some groups of lions climb trees; others do not (figure 18.26).

Sociobiology

In many ways, honeybee and African wild dog societies are similar. Not all the females reproduce, raising the young is a shared responsibility, and there is some specialization of roles. The analysis and comparison of animal societies has led to the thought that there may be fundamental processes that shape all societies. **Sociobiology** is the systematic study of all forms of social behavior, both human and nonhuman.

How did various types of societies develop? What selective advantage does a member of a social group have? In what ways are social groups better adapted to their environment than nonsocial organisms? How does social organization affect the way populations grow and change? These are difficult questions because, although evolution occurs at the population level, it is individual organisms that are selected. Thus, new ways of looking at evolutionary processes are needed when describing the evolution of social structures.

The ultimate step is to analyze human societies according to sociobiological principles. Such an analysis is difficult and controversial, however, because humans have a much greater ability to modify behavior than do other animals. However, there are some clear parallels between human and nonhuman social behaviors. This implies that there are certain fundamental similarities among social organisms, regardless of their species. Do we see territorial behavior in humans? "No trespassing" signs and fences between neighboring houses seem to be clear indications of territorial behavior in our social species. Do groups of humans have dominance hierarchies? Most business, government, and social organizations have clear dominance hierarchies, in which those at the top get more resources (money, prestige) than those lower in the organization. Do human societies show division of labor? Our societies clearly benefit from the specialized skills of certain individuals. Do humans treat their own children differently than other children? Studies of child abuse indicate that abuse is more common between stepparents and their nongenetic stepchildren than between parents and their biological children. Although these few examples do not prove that human societies follow certain rules typical of other animal societies, it bears further investigation. Sociobiology will continue to explore the basis of social organization and behavior and will continue to be an interesting and controversial area of study.

18.7 CONCEPT REVIEW

17. Describe why communication is important to successful reproduction.
18. Describe two alternative strategies for assuring that some offspring will survive to continue the species.
19. How do territorial behavior and dominance hierarchies provide certain individuals with an advantage?
20. What distinguishes societies from simple aggregations of individuals?
21. How do animals use chemicals, light, and sound to communicate?
22. What is sociobiology?

Summary

Behavior is how an organism acts, what it does, and how it does it. The kinds of responses organisms make to environmental changes (stimuli) include simple reflexes, very complex instinctive behavior patterns, or learned responses.

From an evolutionary viewpoint, behaviors represent adaptations to the environment. They increase in complexity and variety the more highly specialized and developed the organism is. All organisms have inborn, or instinctive, behavior, but higher animals also have one or more ways of learning. These include habituation, association, exploratory learning, imprinting, and insight. Communication for purposes of courtship and mating is accomplished through sounds, visual displays, touch, and chemicals, such as pheromones. Many animals have behavior patterns that are useful in the care and raising of their young.

Territorial behavior is used to obtain exclusive use of an area and its resources. Both dominance hierarchies and territorial behavior are involved in the allocation of scarce resources. To escape from seasonal stress, some animals estivate or hibernate, others store food, and others migrate. Migration to avoid seasonal extremes requires a timing sense and a way of determining direction. Animals navigate by means of sound, celestial light cues, and magnetic fields.

Societies consist of groups of animals in which individuals specialize and cooperate. Sociobiology attempts to analyze all social behavior in terms of evolutionary principles, ecological principles, and population dynamics.

Key Terms

*Use the interactive flash cards on the **Concepts in Biology**, 14/e website to help you learn the meaning of these terms.*

altruism 411
anthropomorphism 393
association 397
behavior 392
classical conditioning 397
communication 404
conditioned response 397
critical period 399
dominance hierarchy 408
habituation 396
imprinting 399
insight 400
instinctive behavior 394
learned behavior 394
learning 396
observational learning (imitation) 398
operant (instrumental) conditioning 397
pheromones 404
photoperiod 410
response 394
society 411
sociobiology 412
stimulus 394
territorial behaviors 407
territory 407
thinking 403

Basic Review

1. Instinctive behavior differs from learned behavior in that instinctive behavior
   a. is inherited.
   b. is flexible.
   c. is found only in simple animals.
   d. is less valuable than learned behavior.
2. The thought that your dog is happy to see you is an example of _____.
3. Imprinting is different from other kinds of learning in that imprinting
   a. is of little value to an organism.
   b. is not reversible.
   c. can be changed easily.
   d. can occur at any time during the life of an individual.
4. Learning is a change in behavior as a result of experience. (T/F)
5. All of the following are typical of territorial behavior EXCEPT
   a. territorial behavior reserves resources for particular individuals or groups.
   b. territorial behavior involves the use of signals to denote territorial boundaries.
   c. territorial behavior is found only in higher animals, such as birds and mammals.
   d. territorial behavior reduces conflict after territories are established.
6. Social behavior typically involves individuals assuming specialized roles. (T/F)
7. Most methods of communication used by animals are learned. (T/F)
8. A social system in which each animal has a particular ranking in the group is a(n) _____.
9. Most kinds of animals provide no care for their offspring. (T/F)
10. Which of the following provide navigational clues to migrating animals?
    a. landmarks, such as rivers and shorelines
    b. the magnetic fields of the Earth
    c. the stars
    d. All of the above are correct.
11. Instinctive behaviors are simple. (T/F)
12. Humans do not learn through association. (T/F)

13. The concept of sociobiology
    a. supposes that social behavior has common characteristics in all animals, including humans.
    b. does not apply to humans.
    c. is applied only to birds and mammals.
    d. None of the above is correct.
14. If an organism has instinctive behavior, it probably also has the ability to learn. (T/F)
15. Exploratory learning
    a. provides information that an animal can use later in life.
    b. is evidence of imprinting.
    c. is instinctive.
    d. None of the above is correct.

Answers

1. a 2. anthropomorphism 3. b 4. T 5. c 6. T 7. F 8. dominance hierarchy 9. T 10. d 11. F 12. F 13. c 14. T 15. a

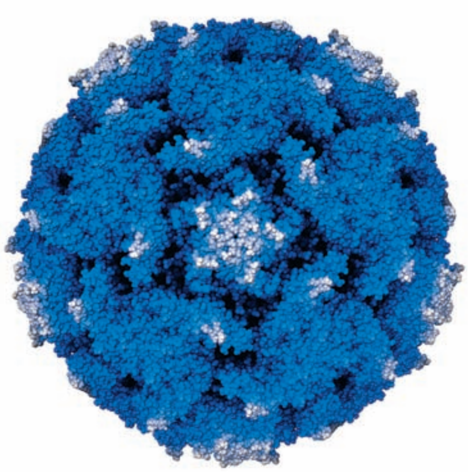
Thinking Critically

Talk to the Animals

If you were going to teach an animal to communicate a message new to that animal, what message would you select? How would you teach the animal to communicate the message at the appropriate time?

CHAPTER 19

The Origin of Life and the Evolution of Cells



CHAPTER OUTLINE

Scientists Create Virus from Simple Chemicals

Could this be a step toward creating life in a test tube?

In 2004, scientists used off-the-shelf chemicals to synthesize the poliovirus. They had to use several highly technical procedures, but they were able to create a poliovirus from scratch. The process involved several steps. The genetic code of the poliovirus is in the form of RNA and the sequence of RNA nucleotides is known. The first step involved using this known RNA sequence to assemble a DNA molecule from individual DNA nucleotides. RNA viruses, like the poliovirus, do not make copies of their RNA from RNA but use the enzymes and other structures of the host cell to make a DNA copy of its RNA. The DNA copy is then transcribed in the host cell to produce multiple copies of the poliovirus RNA.

Because polioviruses are normally parasites in human cells, the researchers then placed the newly synthesized RNA into a culture made from human cells. The cells were ground up and large structures, such as nuclei, were removed. However, the ribosomes, enzymes, amino acids, and other materials necessary for protein synthesis were still present. When the newly synthesized viral RNA was placed in this juice, it was able to direct the synthesis of the protein coat that surrounds the RNA of the virus. To show that the poliovirus they produced was functional, they infected mice with the virus and the mice developed the disease.

The scientists started with individual chemical units they obtained from chemical suppliers and produced a functional poliovirus. Although viruses are not cells, they show some similarities to living things and may be similar to some of the earliest forms of life.

- **What conditions on Earth billions of years ago could have allowed for the creation of the first living thing?**
- **What additional steps would be necessary to get *cells* from simple chemicals?**
- **Do you think it is ethical for scientists to go one step further and try to create living cells from scratch?**

Background Check

Concepts you should already know to get the most out of this chapter:
- Carbohydrates, lipids, proteins, and nucleic acids are components of living things (chapter 3)
- Chemical reactions are either exothermic or endothermic (chapter 2)
- Basic cell structure of both prokaryotic and eukaryotic cells (chapter 4)

19.1 Early Thoughts About the Origin of Life

For centuries, people have asked the question "How did life originate?" Scientists are still trying to answer that question today. One hypothesis for the origin of life is *spontaneous generation*. **Spontaneous generation** is the concept that living things arise from nonliving material. Aristotle (384–322 B.C.) proposed this concept and it was widely accepted until the seventeenth century. People believed that maggots arose from decaying meat; mice developed from wheat stored in dark, damp places; lice formed from sweat; and frogs originated from damp mud. However, as time passed, people began to question this long-held belief and proposed an alternative idea, called *biogenesis*. **Biogenesis** is the concept that living things develop only from other living things and not from nonliving matter. For several hundred years, proponents of these two alternative concepts about how life originated argued and performed scientific experiments to test their ideas.

In 1668, Francesco Redi, an Italian physician, performed an experiment that challenged the concept of spontaneous generation. He set up a controlled experiment to test the hypothesis that maggots arose spontaneously from rotting meat (figure 19.1). He used two sets of jars that were identical except for one aspect. Both sets of jars contained decaying meat, and both were exposed to the atmosphere. However, one set of jars was covered by gauze while the other was uncovered. Redi observed that flies settled on the meat in the open jars, but the gauze blocked their access to the meat in the covered jars. When maggots appeared on the meat in the uncovered jars but not on the meat in the covered ones, Redi concluded that the maggots arose from the eggs of the flies (biogenesis), not from spontaneous generation in the meat.

However, Redi's experiment did not settle the question. Eighty years later, in 1748, John T. Needham, an English priest, performed an experiment that led him to conclude that spontaneous generation did happen. He placed a solution of boiled mutton broth in containers, which he sealed with corks. Needham reasoned that boiling would kill any organisms in the broth and that the corks would prevent any living thing from entering. Thus, if the broth was found to contain living things, it must be the result of spontaneous generation. Conversely, if no life appeared, the concept of biogenesis would be supported. When, after several days, the broth became cloudy with a large population of microorganisms, he concluded that life in the broth was the result of spontaneous generation.

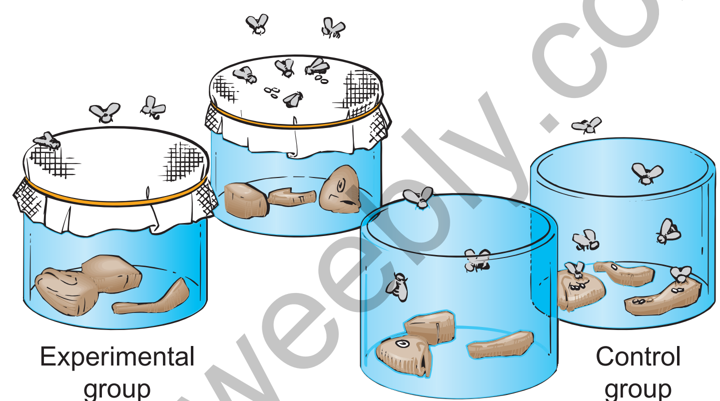


FIGURE 19.1 Redi's Experiment
Francesco Redi performed an experiment in which he prepared two sets of jars that were identical in every way except one. One set of jars had a gauze covering. The uncovered set was the control group; the covered set was the experimental group. Any differences seen between the control and the experimental groups were the result of a single variable—being covered by gauze. In this manner, Redi concluded that the presence of maggots in meat was due to flies laying their eggs on the meat and not spontaneous generation.

A short time later, in 1767, another Italian scientist and Catholic priest, Abb'e Lazzaro Spallanzani, challenged Needham's findings. He thought that Needham's experimental design may have allowed something to enter the broth and devised a slightly different experiment that made certain that nothing accidentally entered the broth. Spallanzani boiled a meat and vegetable broth, placed this mixture in clean glass containers, and sealed the openings by melting the glass over a flame. This would prevent anything from entering the flask. He placed the sealed containers in boiling water to kill any living things that might have been in the broth. As a control, he set up the same conditions but did not seal the necks, allowing air to enter the flasks (figure 19.2). Two days later, the open containers had a large population of microorganisms, but there were none in the sealed containers. He concluded that spontaneous generation did not occur and that something had entered the unsealed flasks from the air that caused the growth in the broth.

Spallanzani's experiment did not completely disprove spontaneous generation to everyone's satisfaction, however. The supporters of spontaneous generation attacked Spallanzani by stating that he excluded air from his sealed flasks, a factor believed necessary for spontaneous generation. Supporters of spontaneous generation also argued that

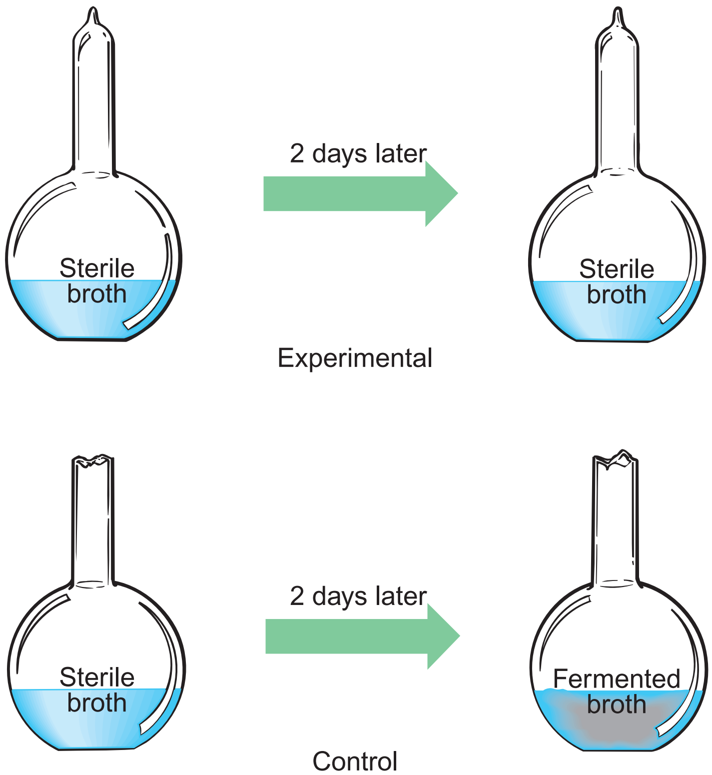


FIGURE 19.2 Spallanzani's Experiment
Spallanzani boiled a meat and vegetable broth and placed this mixture into clean flasks. He sealed one and put it in boiling water. As a control, he subjected another flask to the same conditions, except he left it open. Within 2 days, the open flask had a population of microorganisms. Spallanzani maintained that this demonstrated that spontaneous generation did not occur and that something from the air was responsible for the growth in the broth.

boiling had destroyed a "vital element." In 1774, when Joseph Priestly discovered oxygen, the proponents of spontaneous generation claimed that oxygen was the "vital element" that Spallanzani had excluded from his sealed containers.

In 1861, French chemist Louis Pasteur convinced most scientists that spontaneous generation could not occur. He designed an experiment that would allow air to enter a flask but would prevent tiny living things from entering. He placed a fermentable sugar solution and yeast mixture in a flask that had a long swan neck. The mixture and the flask were boiled for a long time. The flask was left open to allow oxygen, the "vital element," to enter, but no organisms developed in the mixture. Organisms did not enter the part of the flask with the sugar mixture because they settled on the bottom of the curved portion of the neck and could not reach the sugar-water mixture. As a control, he cut off the swan neck (figure 19.3). This allowed microorganisms from the air to fall into the flask, and within 2 days the fermentable solution was supporting a population of microorganisms. In his address to the French Academy, Pasteur stated, "Never will the doctrine of spontaneous generation arise from this mortal blow."

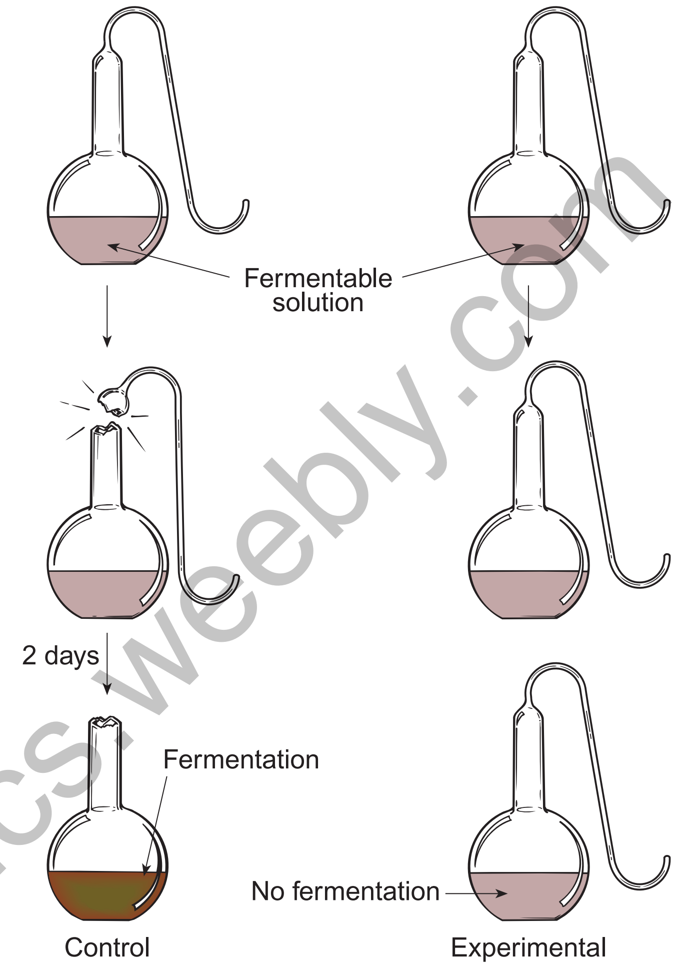


FIGURE 19.3 Pasteur's Experiment
Louis Pasteur conducted an experiment designed to test the idea that a "vital element" (oxygen) from the air was necessary to produce life. He boiled a mixture of sugar and yeast in swan-neck flasks that allowed oxygen, but not airborne organisms, to enter them. He left some flasks intact (the experimental group) and broke the neck off others (the control group). Within 2 days, there was growth in the flasks that had their swan necks removed but none in the intact flasks. Thus, Pasteur concluded that it was not oxygen in the air that caused growth in the flasks but that the growth resulted from living things, which entered the flask when the swan neck was broken off. This supported the concept of biogenesis and argued against the concept of spontaneous generation.

19.1 CONCEPT REVIEW

1. What is meant by the term *spontaneous generation*?
2. What is meant by the term *biogenesis*?
3. Describe the contribution of each of the following scientists to the biogenesis/spontaneous generation debate: Redi, Needham, Spallanzani, and Pasteur.

19.2 Current Thinking About the Origin of Life

Today, it is clear that current living things are the result of biogenesis. New living things come from other living things as a result of either sexual or asexual reproduction. But that does not answer the question of how the *first* living thing developed. Because the evidence is strong that the universe had a time of origin, life must have originated spontaneously from nonliving material at least once. It is clear that we will never really know how the first living thing developed, because we cannot repeat the "original" experiment that led to the first living thing. However, that does not prevent scientists from speculating on the origin of life and evaluating relevant scientific information. There are many different hypotheses that have some supporting evidence.

An Extraterrestrial Origin for Life on Earth

Early in the 1900s, Swedish scientist Svante Arrhenius popularized the idea of *panspermia*. **Panspermia** is the concept that life arose outside Earth and that living things were transported to Earth to seed the planet with life. However, this idea does not explain *how* life arose originally. It sees Earth as similar to one of Spallanzani's or Pasteur's open flasks. Although Arrhenius's ideas had little scientific support at that time, his basic concept has since been revived and modified as a result of new evidence gained from examinations of meteorites and space explorations.

Evidence from Meteorites

Since all life forms that we know about are based on organic molecules, the presence of organic molecules in space and in extraterrestrial objects such as meteorites suggest that life or the conditions necessary for life may have existed in other worlds.

In 1996, a meteorite found in Antarctica generated excitement about the possibility of life on other planets. Its chemical makeup suggested it had been a portion of the planet Mars that had been ejected from that planet as a result of a collision with an asteroid. Analysis of the meteorite showed the presence of complex organic molecules and tiny, microscopic objects that were thought to be ancient microorganisms. While scientists no longer think these objects are microorganisms or were formed by living things, many still think conditions on Mars may have been able to support life in the past.

Evidence from Mars and Beyond

In June and July 2003, two spacecrafts were launched by the National Aeronautics and Space Administration (NASA) to explore the surface of Mars. One of the important goals of these missions is to search for signs of present or past life. The robotic rover vehicles from these two spacecrafts have gathered much information about the surface of Mars. One important piece of information is that it is highly likely that in the past, liquid water existed in large enough quantities to form rivers, lakes, and perhaps salty oceans. In 2009 it was discovered that methane (a simple organic molecule) exists on Mars. However, methane can be produced by either geochemical or biological means and, at this point, it is not clear which processes are responsible.

In recent years, astronomers have been able to detect the presence of planets in other solar systems. By 2010 over 400 such planets have been identified orbiting stars in other solar systems. Although many are large gas planets like Jupiter, a few appear to be smaller rocky planets like Earth or Mars.

Although none of these discoveries proves that life exists or existed elsewhere in the universe, they keep open the possibility that life may have originated elsewhere and arrived on Earth.

An Earth Origin for Life on Earth

A popular alternative explanation for the origin of life on Earth focuses on chemical evolution. This hypothesis proposes that chemical reactions between simple, inorganic chemicals produced complex, carbon-containing organic molecules. These organic molecules, in turn, combined to form the first living cell. Furthermore, it is possible to perform experiments that test scientists' hypotheses about these processes. Several pieces of evidence support the idea that life could have arisen on Earth.

1. The temperature range on Earth allows for water to exist as a liquid on its surface. This is important, because water is the most common compound of living things.
2. Analysis of the atmospheres of the other planets in our solar system shows that they all lack oxygen. The oxygen in Earth's current atmosphere is the result of photosynthesis by living organisms. Therefore, before there was life on Earth, the atmosphere probably lacked oxygen.
3. Experiments demonstrate that organic molecules can be generated in an atmosphere that lacks oxygen.
4. Because it is assumed that all of the planets have been cooling off as they age, it is very likely that Earth was much hotter in the past. The large portions of Earth's surface that are of volcanic origin strongly suggest a hotter past.
5. The discovery of specialized Bacteria and Archaea that live in extreme environments of high temperature, high salinity, low pH, or the absence of oxygen suggests that they may have been adapted to life in a world that is very different from today's Earth. These kinds of organisms are found today in unusual locations, such as hot springs and around thermal vents in the ocean floor, and may retain characteristics that were essential to the first organisms formed on the primitive Earth.

19.2 CONCEPT REVIEW

4. Provide two kinds of evidence that support the idea that life could have originated on Earth.
5. Provide two kinds of evidence that support the idea that life could have arrived on Earth from space.

19.3 The "Big Bang" and the Origin of the Earth

An understanding of how Earth formed and what conditions were like on early Earth will help us think about how life may have originated.

The "Big Bang"

Astronomers note that the current stars and galaxies are moving apart from one another. This and other evidence has led to the concept that our universe began as a very dense mass of matter that had a great deal of energy. This dense mass of matter exploded in a "big bang" about 13 billion years ago, resulting in the formation of simple atoms, such as hydrogen and helium. When huge numbers of these atoms collected in one place, stars formed. Stars consist primarily of hydrogen and helium atoms. The light from stars is the result of nuclear fusion, in which these atoms combine to form larger atoms. According to this theory, all of the chemical elements were formed as a result of nuclear fusion.

The Formation of the Planet Earth

Many scientists believe that Earth—along with other planets, meteors, asteroids, and comets—was formed at least 4.6 billion years ago. The *protoplanet nebular model* proposes that the solar system was formed from a large cloud of gases and elements produced by previously existing stars (figure 19.4). The simplest and most abundant gases were hydrogen and helium, but other, heavier elements had been formed by nuclear fusion and were present as well. A gravitational force was created by the collection of particles within this cloud, which caused other particles to be pulled from the outer edges to the center. As the particles collected into larger bodies, gravity increased and more particles were attracted to the bodies. Ultimately, a central body (the Sun) was formed, with several other bodies (planets) moving around it. Like other stars, the Sun consists primarily of hydrogen and helium atoms that are being fused together to form larger atoms, with the release of large amounts of thermonuclear energy.

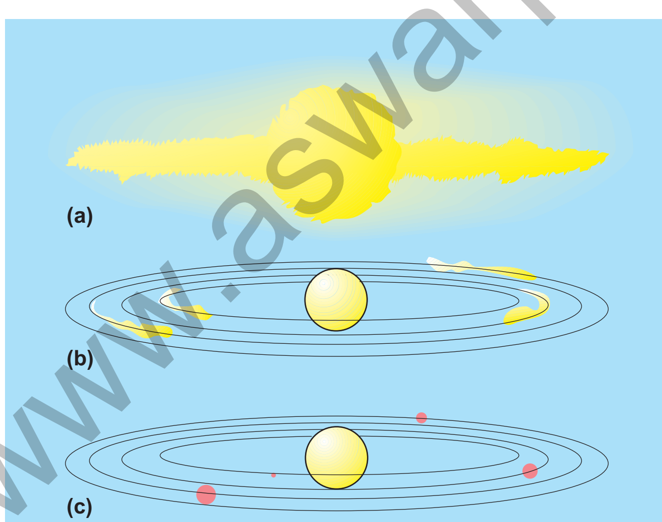


FIGURE 19.4 The Formation of Our Solar System
(a) As gravity pulled gases and other elements toward the center, the accumulating matter resulted in the formation of the Sun. *(b)* In other regions, smaller gravitational forces caused the formation of the Sun's planets. *(c)* Finally, the solar system was formed.

Thermonuclear reactions also occurred as the particles became concentrated to form Earth. Thus, the early Earth would have been a very hot place. Geologically, this period in the history of Earth is called the "Hadean Eon." The term *Hadean* means "hellish." Although not as hot as the Sun, the material of Earth formed a molten core, which became encased by a thin outer crust as it cooled. (How Science Works 19.1). In Earth's early stages of formation, about 4 billion years ago, there probably was a considerable amount of volcanic activity.

Conditions on the Early Earth

The high temperature of the early Earth would have prevented an atmosphere from forming, because light gases such as hydrogen and helium would have escaped into space. Over hundreds of millions of years, Earth is thought to have changed slowly. As it cooled, volcanic activity would have released gases, and an atmosphere would have formed. Studies of current volcanoes show that they release water vapor (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen (N_2), ammonia (NH_3), hydrochloric acid (HCl), and various sulfur compounds. These gases would have formed a **reducing atmosphere**—an atmosphere that did not contain molecules of oxygen (O_2). Any oxygen would have quickly combined with other atoms to form compounds. Further cooling enabled the water vapor in the atmosphere to condense into droplets of rain, which ran over the land and collected to form oceans.

19.3 CONCEPT REVIEW

6. How did the atmosphere, the temperature, and the surface of the newly formed Earth differ from what exists today?
7. What is the approximate age of Earth?

19.4 The Chemical Evolution of Life on Earth

When we consider the nature of the simplest forms of life today, we find that living things have certain characteristics. They have an outer membrane, which separates the cell from its surroundings; genetic material in the form of nucleic acids; and many kinds of enzymes, which control the activities of the cell. Therefore, when we speculate about the origin of life

HOW SCIENCE WORKS 19.1

The Oldest Rocks on Earth

Determining events that happened in Earth's distant past are difficult to achieve. The early Earth would have been molten and, as it cooled, the outer layer of Earth would have solidified into a thin crust of igneous rock. Earth is not static—it consists of geologic plates that are moving across the surface and in many places are being forced below the surface where they melt to reemerge at some other place. Thus, finding really old rock is rare.

In September 2008, scientists at McGill University in Montreal, Canada, announced they had found, on the eastern shore of Hudson Bay in northern Canada, the oldest Earth rocks yet discovered. To determine the age of the rocks they compared the amounts of specific isotopes of the element neodymium. This analysis led them to conclude that the rocks are about 4.28 billion years old. Since Earth is thought to have originated about 4.57 billion years ago, these rocks would have formed about 290 million years after the origin of Earth. These rocks are presumed to be some of the first formed on Earth as it cooled. The age of these rocks also suggests that Earth cooled faster than previously thought.

As with all new discoveries, other scientists are being cautious about accepting this new information. They would like to see additional evidence to confirm the date.

from inorganic material, it seems logical that several events or steps were necessary:

1. Simple organic molecules must first have been formed from inorganic molecules.
2. Simple organic molecules must have combined to form larger organic molecules, such as RNA, proteins, carbohydrates, and lipids.
3. A molecule must have served as genetic material.
4. Genetic material must have become self-replicating.
5. Some molecules must have functioned as enzymes.
6. The molecules serving as genetic material and other large organic molecules must have been collected and segregated from their surroundings by a membrane.
7. The first life-forms would have needed a way to obtain energy from their surroundings in order to maintain their complex structure.

The Formation of the First Organic Molecules

In the 1920s, a Russian biochemist, Alexander I. Oparin, and a British biologist, J. B. S. Haldane, working independently, proposed that the first organic molecules were formed spontaneously in the reducing atmosphere thought to be present on the early Earth. According to their theory, inorganic molecules in the primitive atmosphere supplied the atoms of carbon, hydrogen, oxygen, and nitrogen needed to build organic molecules. Lightning, heat from volcanoes, and ultraviolet radiation furnished the energy needed for the synthesis of simple organic molecules from inorganic molecules (figure 19.5).

It is important to understand the significance of a reducing atmosphere to this proposed mechanism for the origin of life. The absence of oxygen in the atmosphere would have allowed these organic molecules to remain and combine with one another. This does not happen today because organic molecules are either consumed by organisms or oxidized to simpler inorganic compounds because of the oxygen present in our atmosphere. For example, today many kinds of organic air pollutants (hydrocarbons) eventually oxidize into smaller molecules in the atmosphere. Unfortunately, they participate in the formation of photochemical smog as they are broken down.

Recognize that all the ideas discussed so far in this section cannot be confirmed by direct observation, because we cannot go back in time. However, several assumptions central to this model for the origin of life have been laboratory tested.

In 1953, Stanley L. Miller conducted an experiment to test the idea that organic molecules can be synthesized in a reducing environment. He constructed a simple model of the early Earth's atmosphere (figure 19.6). In a glass apparatus, he placed distilled water to represent the early oceans. Adding hydrogen (H_2), methane (CH_4), and ammonia (NH_3) to the water (H_2O) simulated the reducing atmosphere. Electrical sparks provided the energy needed to produce organic compounds. By heating parts of the apparatus and cooling others, he simulated the rains that are thought to have fallen into the early oceans. After a week of operation, he removed some of the water from the apparatus. When he analyzed this water, he found that it contained many simple organic compounds.

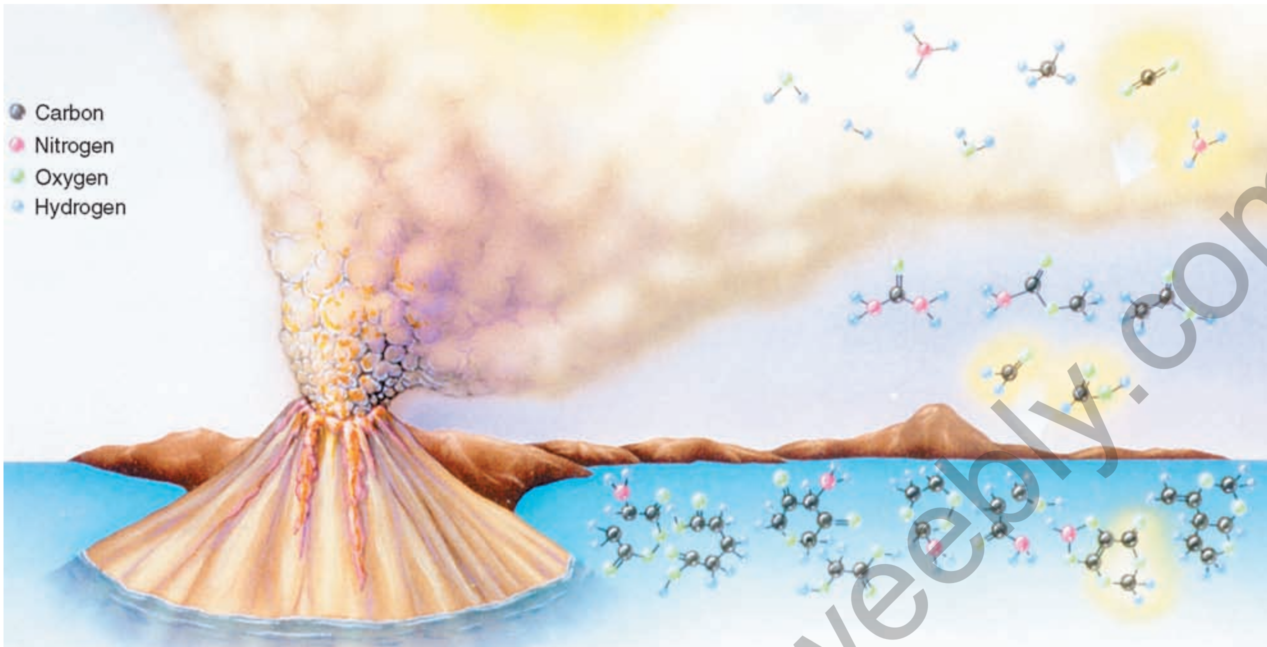


FIGURE 19.5 The Formation of Organic Molecules in the Atmosphere
The environment of the primitive Earth was harsh and lifeless. But many scientists believe that it contained the necessary molecules and sources of energy to fashion the first living cell. The energy furnished by volcanoes, lighting, and ultraviolet light could have broken the bonds in the simple inorganic molecules in the atmosphere. New bonds could have formed as the atoms from the smaller molecules were rearranged and bonded to form simple organic compounds in the atmosphere. Rain and runoff from the land would have carried these chemicals into the oceans, where they could have reacted with each other to form more complex organic molecules.

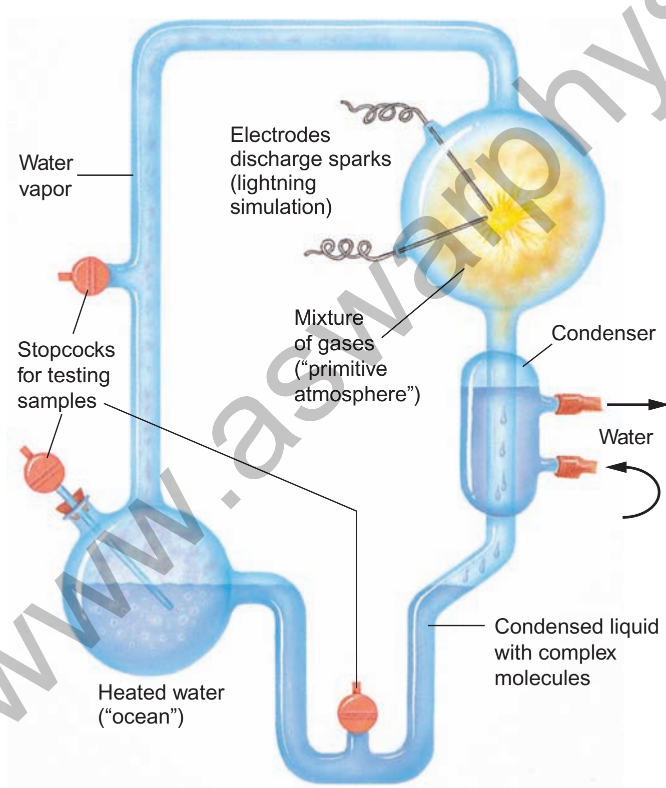


FIGURE 19.6 Miller's Apparatus
Stanley Miller developed this apparatus to demonstrate that the spontaneous formation of organic molecules from inorganic molecules could take place in a reducing atmosphere.

The idea that organic molecules could have formed on Earth is further supported by the discovery of many kinds of organic molecules in interstellar clouds and in the structure of meteorites. These pieces of evidence show that organic molecules form without the presence of living things.

The Formation of Macromolecules

Although Miller demonstrated the nonbiological synthesis of simple organic molecules, such as amino acids and simple sugars, his results did not account for complex organic molecules, such as proteins and nucleic acids (e.g., DNA).

After simple organic molecules were formed in the atmosphere, they probably would have been washed from the air and carried into the newly formed oceans by rain and runoff from the land. There, the molecules could have reacted with one another to form the more complex molecules of simple sugars, amino acids, and nucleic acids. The accumulation of larger organic molecules is thought to have occurred over half a billion years, resulting in oceans that were a dilute organic soup.

Several ideas have been proposed to explain how simple organic molecules could have been concentrated and caused to combine to form larger macromolecules. One hypothesis suggests that a portion of the early ocean could have been separated from the main ocean by geologic changes. The evaporation of water from this pool could have concentrated the molecules, which might have led to the formation of macromolecules by dehydration synthesis. Second, it has been proposed that freezing may have been the means of concentration. When a mixture of alcohol and water is placed in a freezer, the water freezes solid and the alcohol becomes concentrated into a small portion of liquid. A similar process could have occurred on Earth's early surface, resulting in the concentration of simple organic molecules. In this concentrated solution, dehydration synthesis in a reducing atmosphere could have occurred, resulting in the formation of macromolecules. A third theory proposes that clay particles may have been a factor in concentrating simple organic molecules. Small particles of clay have electrical charges, which can attract and concentrate organic molecules, such as proteins, from a watery solution. Once the molecules became concentrated, it would have been easier for them to interact to form larger macromolecules.

RNA May Have Been the First Genetic Material

As you know from chapter 8, the genetic system of most current organisms involves the replication of DNA and the distribution of the copied DNA to subsequent cells. Furthermore, DNA is responsible for the manufacture of RNA, which is responsible for the manufacture of proteins. Some of the proteins produced serve as enzymes that control chemical reactions. However, it is difficult to see how this complicated sequence of events, which involves many steps and the assistance of several enzymes, could have been generated spontaneously, so scientists have looked for simpler systems that could have led to the current DNA system.

In recent years many people have come to look at RNA as the prime candidate for the first genetic material. In order to serve as genetic material, a molecule must store information, mutate, and make copies of itself:

1. **RNA can store genetic information**. Scientists involved in studying the structure and function of viruses discovered that many viruses do not contain DNA but, rather, store their genetic information in the structure of RNA. In order for these RNA-viruses to reproduce, they must enter a cell. The cell makes copies of the RNA and the proteins necessary to make more of the virus. Certain plant diseases are caused by pieces of naked RNA known as viroids, which enter cells and cause the cells to make copies of the RNA. In other words, in both of these cases, RNA serves as genetic material.
2. **RNA can mutate**. Scientists who study viral diseases find that it is difficult to develop vaccines for many viral diseases because their genetic material mutates easily. Because of this, researchers have been studying the nature of viral DNA or RNA to see what causes the high rate of mutation.
3. **RNA can make copies of itself**. RNA can be assembled from simpler subunits that could have been present on the early Earth. Scientists have also shown that RNA molecules are able to make copies of themselves without the need for enzymes, and they can do so without being inside cells. Furthermore, some RNA molecules serve as enzymes for specific reactions. Such molecules are called *ribozymes*. Because RNA is a much simpler molecule than DNA, contains genetic information, can mutate, and can make copies of itself without the aid of enzymes, perhaps it was the first genetic material. Once a primitive life-form had the ability to copy its genetic material, it would be able to reproduce. Reproduction is one of the most fundamental characteristics of living things.

If RNA was the first genetic material, many subsequent changes would have been necessary to get to the kind of genetic system we see in most organisms today:

1. DNA must have replaced RNA as the self-replicating genetic material of the cell.
2. DNA must have become the molecule responsible for making RNA.
3. RNA must have taken over control of protein synthesis.
4. Proteins must have become the catalysts (enzymes) of the cells.
5. Membranes and other cellular structures involved in cell reproduction and protein synthesis would have developed.

Obviously, there is much still to learn about the how this genetic system developed.

The Development of Membranes

One of the defining features of any living thing is the presence of a membrane surrounding its cells which regulates what enters and leaves them. Consider the formation of bubbles in water. Bubbles are particularly common when organic molecules are present in water. Perhaps the first membranes were formed because of an interaction between water and organic molecules similar to the formation of bubbles. There are several theories about what the first membranes were like. Some suggest that they were made of proteins, others that they were lipids or other organic molecules. Several kinds of experiments have sought to clarify what the first membrane might have been like. Alexander I. Oparin mentioned earlier, speculated that a structure could have formed consisting of a collection of organic macromolecules surrounded by a film of water molecules. This arrangement of water molecules, although not a membrane, could have functioned as a physical barrier between the organic molecules and their surroundings. He called these structures *coacervates*.

Coacervates have been synthesized in the laboratory (figure 19.7). They can selectively absorb molecules from the surrounding water and incorporate them into their structure. Also, the chemicals within coacervates have a specific arrangement—they are not random collections of molecules. Some coacervates contain proteins (enzymes) that direct a specific type of chemical reaction. Because they lack a definite membrane, no one claims that coacervates are alive, but these structures do exhibit some lifelike traits: They can increase in size and can split into smaller particles if the right conditions exist.

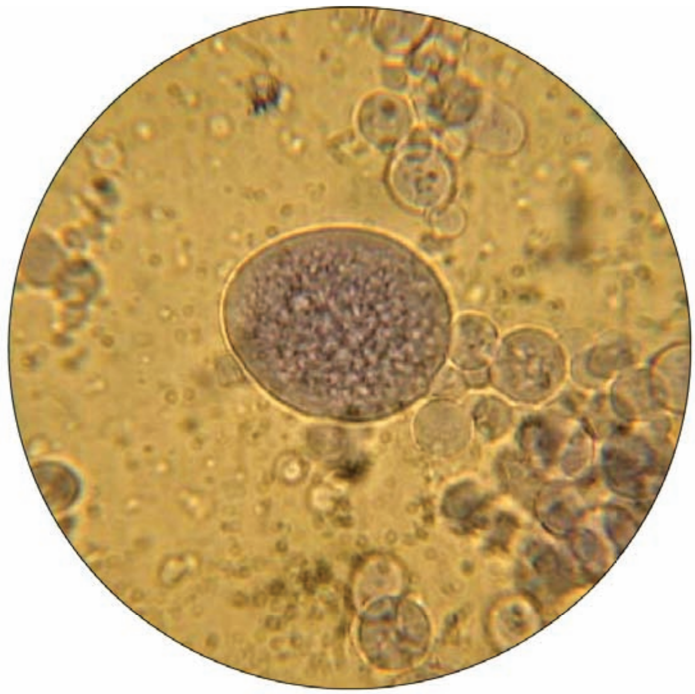


FIGURE 19.7 Coacervates
One hypothesis proposes that a film of water, which acted as a primitive cell membrane, could have surrounded organic molecules, forming a structure that resembles a living cell. Such a structure can easily be produced in the lab. This view shows one large and several small spherical coacervates.

An alternative hypothesis is that the early, cell-like structure could have consisted of a collection of organic macromolecules with a double-layered outer boundary. These structures have been called *microspheres*. Microspheres can be formed in the laboratory by heating simple, proteinlike compounds in boiling water and slowly cooling them. Some of the protein material produces a double-boundary structure enclosing the microsphere. Although these boundaries do not contain lipids, they exhibit some membranelike characteristics and suggest the structure of a cellular membrane.

Microspheres swell or shrink, depending on the osmotic potential in the surrounding solution. They also display a type of internal movement (streaming) similar to that exhibited by living cells and contain some molecules that function as enzymes. Using ATP as a source of energy, microspheres can direct the formation of polypeptides and nucleic acids. They can absorb material from the surrounding medium and form buds, resulting in a second generation of microspheres.

A third possibility is that a membrane forms as a result of lipid materials interacting with water. Lipids do not dissolve in water and whenever lipids are mixed with water, spherical structures form, as in vinegar and oil salad dressing.

There is no way to know if any of these models represents what really happened in the origin of living things. However, some kind of structure was necessary to separate the complex, organized molecules from the watery environment in which they were dissolved. Once organic molecules were separated from their watery surroundings by a membrane, these structures were similar to primitive cells.

The Development of Metabolic Pathways

Fossil evidence indicates that there were primitive forms of life on Earth about 3.5 billion years ago. Regardless of how they developed, these first primitive cells would have needed a way to add new organic molecules to their structures as previously existing molecules were lost or destroyed. There are two ways to accomplish this. Heterotrophs capture organic molecules, such as sugars, amino acids, or organic acids, from their surroundings, which they use to make new molecules and provide themselves with energy. Autotrophs use an external energy source, such as sunlight or the energy from inorganic chemical reactions, to combine simple inorganic molecules, such as water and carbon dioxide, to make new organic molecules. These new organic molecules can then be used as building materials for new cells or can be broken down at a later date to provide energy.

The Heterotroph Hypothesis

Many scientists support the idea that the first living things on Earth were heterotrophs, which lived off organic molecules in the oceans. There is evidence to suggest that a wide variety of compounds were present in the early oceans, some of which could have been used, unchanged, by primitive cells. The earliest cells appear in the fossil record over 2 billion years before there is evidence of oxygen in the atmosphere. Therefore, these early heterotrophs would have been anaerobic organisms. However, as their populations increased through reproduction, they would have begun to consume organic molecules faster than they were being spontaneously produced in the atmosphere.

The compounds that could be used easily by these cells would have been the first to become depleted. However, some of the heterotrophs may have contained a mutated form of nucleic acid, which allowed them to convert previously unusable material into something they could use. Heterotrophic cells with such mutations could have survived, whereas those without such mutations would have become extinct as the compounds they used for food became scarce. It has been suggested that, through a series of mutations in the early heterotrophic cells, a more complex series of biochemical reactions originated within some of the cells. Such cells could use chemical reactions to convert unusable chemicals into usable organic compounds. Thus, additional steps would have been added to their metabolic processes, and new metabolic pathways would have evolved.

The Autotroph Hypothesis

The heterotroph hypothesis for the origin of living things was the prevailing theory for many years. However, recent discoveries have caused many scientists to consider an alternative—that the first organisms were autotrophs. Several kinds of information support this theory. There is much evidence that Earth was a much hotter place in the past. Today, many different kinds of prokaryotic organisms are autotrophic and live in extremely hostile environments resembling the conditions that may have existed on the early Earth. These organisms are found in hot springs—such as those found in Yellowstone National Park; in Kamchatka, Russia (Siberia); and near thermal vents—areas where hot, mineral-rich water enters seawater from the deep ocean floor. They use energy released from inorganic chemical reactions to synthesize organic molecules from inorganic components. Because of this, they are called *chemoautotrophs*. If their ancient ancestors had similar characteristics, the first organisms may have been autotrophs.

If the first organisms were autotrophs, there would have been competition among different cells for the inorganic raw materials they needed for their metabolism, and there would have been changes in the metabolic processes as mutations occurred. There could have been subsequent evolution of a variety of cells, both autotrophic and heterotrophic, which could have led to the diversity of prokaryotic organisms seen today.

Summary

As a result of this discussion you should understand that we do not know how life on Earth originated. Scientists look at many kinds of evidence and continue to explore new avenues of research. Thus, currently there are three competing theories of the origin of life on Earth:

1. Life arrived here from an extraterrestrial source.
2. Life originated on Earth as a heterotroph.
3. Life originated on Earth as an autotroph.

Figure 19.8 summarizes the steps that are thought to have been necessary for primitive cells to evolve from inorganic molecules.

19.4 CONCEPT REVIEW

8. List two kinds of evidence that suggest that organic molecules could have formed before there were living things.
9. List two kinds of evidence that suggest that RNA was the first genetic material.
10. Describe two models that suggest how collections of organic molecules could have been segregated from other molecules.
11. Why must the first organism of Earth have been anaerobic?
12. How do heterotrophs and chemoautotrophs differ in how they obtain organic molecules?

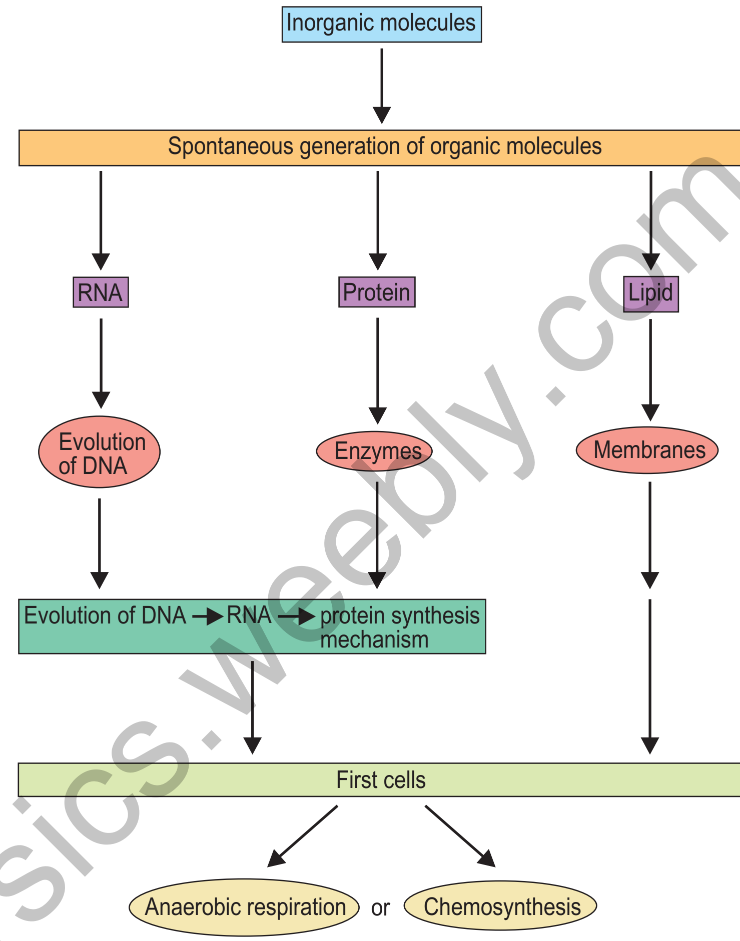


FIGURE 19.8 The Chemical Evolution of Life
This diagram summarizes the steps necessary for primitive cells to evolve from inorganic molecules.

19.5 Major Evolutionary Changes in Early Cellular Life

Once living things had genetic material that stored information and could mutate, they could evolve. Thus, living things could have proliferated into a variety of kinds that were adapted to specific environmental conditions. Remember that Earth has not been static but has been changing as a result of its cooling, volcanic activity, and encounters with asteroids. In addition, the presence of living organisms has had an impact on the way in which Earth has developed. Regardless of the way in which life originated on Earth, there have been several major events in the subsequent evolution of living things.

The Development of an Oxidizing Atmosphere

Since its formation, Earth has undergone constant change. In the beginning, it was too hot to support an atmosphere. Later, as it cooled and as gases escaped from volcanoes, a reducing atmosphere (one lacking oxygen) was likely to have been formed. The earliest life-forms would have lived with a reducing atmosphere. However, now we have an **oxidizing atmosphere** which contains 20 percent oxygen. Today, most organisms use the oxygen to extract energy from organic molecules through a process of aerobic respiration. But what caused the atmosphere to change? It is clear that the oxygen in our current atmosphere is the result of the process of photosynthesis.

The Origin of Photosynthesis

Today, we find that several kinds of Bacteria perform some form of photosynthesis in which sunlight is used to synthesize organic molecules from inorganic molecules. Several of these perform a type of photosynthesis that does not result in the release of oxygen. However, one major group, the cyanobacteria, use a form of photosynthesis that results in the release of oxygen. Therefore, it seems plausible that the first organisms, regardless of whether they were heterotrophs or chemoautotrophs, accumulated many mutations over time, resulting in photosynthetic autotrophs. Because oxygen is released from the most common form of photosynthesis, this would have resulted in the development of an oxidizing atmosphere.

The development of an oxidizing atmosphere created an environment *unsuitable* for the continued spontaneous formation of organic molecules. Organic molecules tend to break down (oxidize) when oxygen is present. The presence of oxygen in the atmosphere would make it impossible for life to spontaneously originate in the manner described earlier in this chapter because an oxidizing atmosphere would not allow the accumulation of organic molecules in the seas. However, once living things existed, new life could be generated through reproduction, and new *kinds* of life could be generated through mutation and evolution. The presence of oxygen in the atmosphere had one other important outcome: It opened the door for the evolution of aerobic organisms.

Geologic evidence suggests that oxygen was present in small amounts in the atmosphere about 2.4 billion years ago. However, oxygen-releasing photosynthesis would have been present some time earlier, since the first oxygen produced would have immediately combined with elements in Earth's crust to form oxides of various kinds. Once oxygen became a significant component of the atmosphere, the oxygen molecules also would have reacted with one another to form ozone (O_3). Ozone collected in the upper atmosphere and acted as a screen to prevent most of the ultraviolet light from reaching Earth's surface. The reduction of ultraviolet light diminished the spontaneous formation of complex organic molecules. It also reduced the number of mutations in cells. In an oxidizing atmosphere, it was no longer possible for organic molecules to accumulate over millions of years to be later incorporated into living material.

The Origin of Aerobic Respiration

The appearance of oxygen in the atmosphere also allowed for the evolution of aerobic respiration. Because the first heterotrophs were, of necessity, anaerobic organisms, they did not derive large amounts of energy from the organic materials available as food. With the evolution of aerobic heterotrophs, there could be a much more efficient conversion of food into usable energy. Aerobic organisms would have a significant advantage over anaerobic organisms. They could use the newly generated oxygen as a final hydrogen acceptor and, therefore, generate many more adenosine triphosphates (ATPs) from the food molecules they consumed.

The Establishment of Three Major Domains of Life

Biologists have traditionally divided organisms into kingdoms, based on their structure and function. However, because of their small size, it is very difficult to do this with microscopic organisms. However, advances in the ability to decode the sequence of nucleic acids made it possible to look at the genetic nature of organisms without being confused by their external structures. Biologist Carl Woese studied the sequences of nucleotides in the ribosomal RNA of many kinds of prokaryotic cells commonly known as bacteria and compared their similarities and differences. As a result of his studies and those of many others, a new concept of the relationships between various kinds of organisms has emerged. It is now clear that the bacteria that previously had been considered a group of similar organisms, are actually two very different kinds of organisms: the Bacteria and the Archaea. Furthermore, the Archaea have unique characteristics that differentiate them from other living things and share some characteristics with eukaryotic organisms.

Thus, today biologists recognize three main kinds of living things—Bacteria, Archaea, and Eucarya—that are called domains. The domains Bacteria and Archaea are both prokaryotic organisms that lack a nucleus. The domain Eucarya contains organisms that have eukaryotic cells. Within each domain are several kingdoms. In the domain Eucarya, there are four kingdoms: Animalia, Plantae, Fungi, and Protista. The process of identifying kingdoms within the Bacteria and Archaea is currently ongoing.

Cell types:	Prokaryote ↙	↘	Eukaryote ↓
Domains:	Bacteria	Archaea	Eucarya ↓
			Kingdoms 1. Protista 2. Fungi 3. Plantae 4. Animalia

The oldest living things gave rise to two major types of prokaryotic organisms (Bacteria and Archaea). Strangely, the domains Archaea and Eucarya share many characteristics, suggesting that they are more closely related to each other than either is to the domain Bacteria.

It appears that each domain developed specific abilities. The Archaea have very diverse metabolic abilities. Some are chemoautotrophic and use inorganic chemical reactions to generate the energy they need to make organic matter. Often, these reactions result in the production of methane (CH_4), and these organisms are known as methanogens. Others use sulfur and produce hydrogen sulfide (H_2S). Others use reactions with ammonia, hydrogen gas, or metals to provide themselves with energy. Some do a form of photosynthesis but do not release oxygen. Many of these organisms are found in extreme environments, such as hot springs, or in extremely salty or acidic environments. However, it is becoming clear that they also inhabit soil, the guts of animals, and are particularly abundant in the ocean.

The Bacteria developed many different metabolic abilities. Today, many Bacteria are heterotrophic and use organic molecules as a source of energy. Some of these heterotrophs use anaerobic respiration, whereas others use aerobic respiration. Other Bacteria are autotrophic. Some, such as the cyanobacteria, carry on photosynthesis, whereas others are chemosynthetic and get energy from inorganic chemical reactions similar to Archaea.

The Eucarya are the most familiar and appear to have exploited the metabolic abilities of other organisms by incorporating them into their own structure. Chloroplasts and mitochondria are both bacteria-like structures found inside eukaryotic cells.

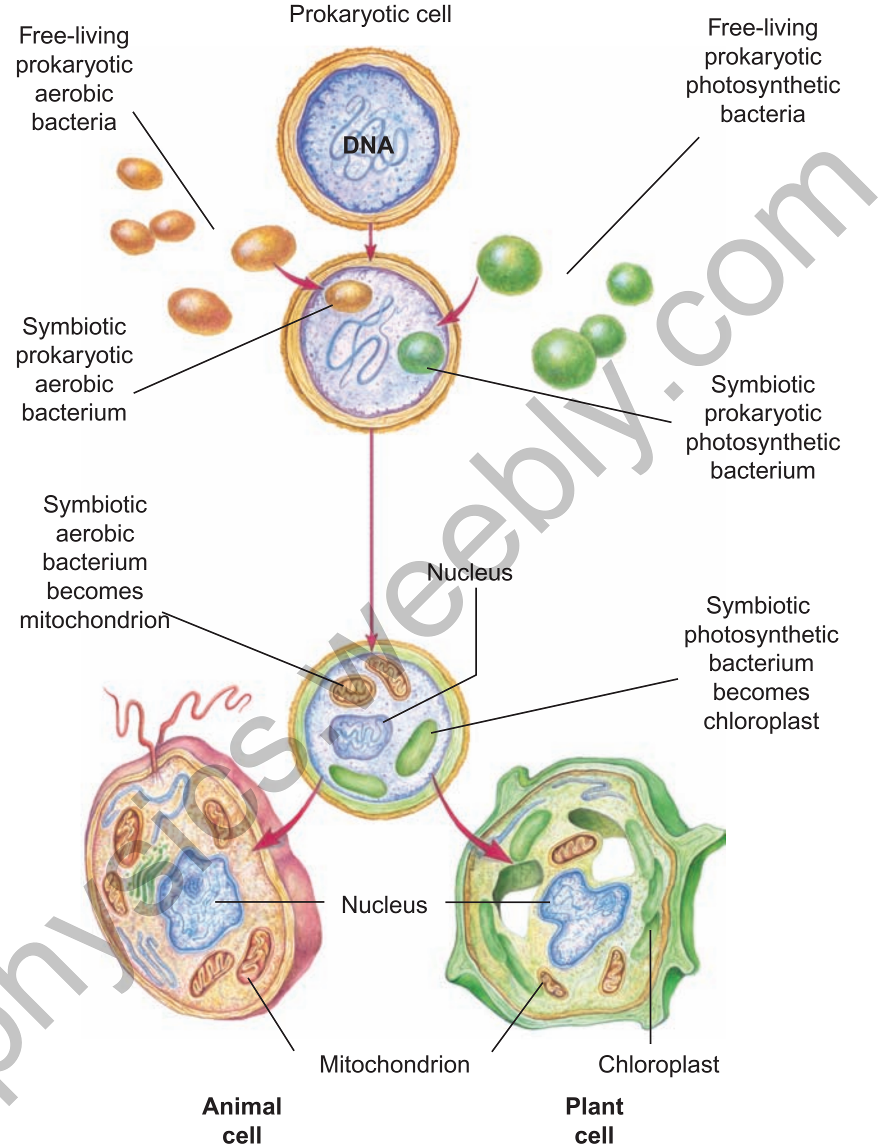


FIGURE 19.9 The Endosymbiotic Theory
This theory proposes that some free-living prokaryotic bacteria entered a host cell and a symbiotic relationship developed. Mitochondria appear to have developed from certain aerobic bacteria and chloroplasts from photosynthetic cyanobacteria. Once eukaryotic cells were present, the subsequent evolution of more complex protozoa, algae, fungi, plants, and animals could take place.

The Origin of Eukaryotic Cells

Biologists generally believe that eukaryotes evolved from prokaryotes. Two major characteristics distinguish eukaryotic cells from prokaryotic cells. Eukaryotic cells have their DNA in a nucleus surrounded by a membrane and have many kinds of membranous organelles. The most widely accepted theory of how eukaryotic cells originated is the *endosymbiotic theory*. The **endosymbiotic theory** states that present-day eukaryotic cells evolved from the uniting of several types of primitive prokaryotic cells. It is thought that some organelles found in eukaryotic cells may have originated as free-living prokaryotes. For example, mitochondria and chloroplasts contain DNA and ribosomes that resemble those of bacteria. They also reproduce on their own and synthesize their own enzymes. Therefore, it has been suggested that mitochondria were originally free-living prokaryotes that carried on aerobic respiration and chloroplasts were free-living photosynthetic prokaryotes. If the combination of two different cells in this symbiotic relationship were mutually beneficial, the relationship could have become permanent (figure 19.9).

Although endosymbiosis explains how many of the membranous organelles may have arisen in eukaryotic cells, the origin of the nucleus is less clear. There are currently two ideas about how the nucleus came to be. One suggests that the nucleus formed in the same way as other organelles. An invading cell with a membrane around it became the nucleus when it took over the running of the cell from the cell's original DNA. The alternative hypothesis is that prokaryotic cells developed a nuclear membrane on their own from membranes in the cell. In other words, an increase in the number of membranes within prokaryotic cells could have produced an envelope that enclosed the DNA of the cell.

When the endosymbiotic theory was first suggested, it met with a great deal of criticism. However, continuing research has uncovered several other instances of the probable joining of two different prokaryotic cells to form one. In addition, it appears that endosymbiosis occurred among eukaryotic organisms as well. Several kinds of eukaryotic red and brown algae contain chloroplast-like structures, which appear to have originated as free-living eukaryotic cells.

The endosymbiotic theory is further supported by DNA studies. It is now clear that over their long evolutionary history, the genes within any one species of organism may appear to have arisen from several sources. We know that viruses carry genes from one organism to another, different species of bacteria can exchange genetic information, and parasitic organisms use their DNA to manipulate their hosts. The incorporation of entire cells with their DNA into other cells would also bring about the transfer of genes from one species to another and result in cells that have DNA from a variety of sources. Figure 19.10 summarizes current thinking about how endosymbiosis has been involved in the evolution of various kinds of organisms. Table 19.1 summarizes the major characteristics of these three domains.

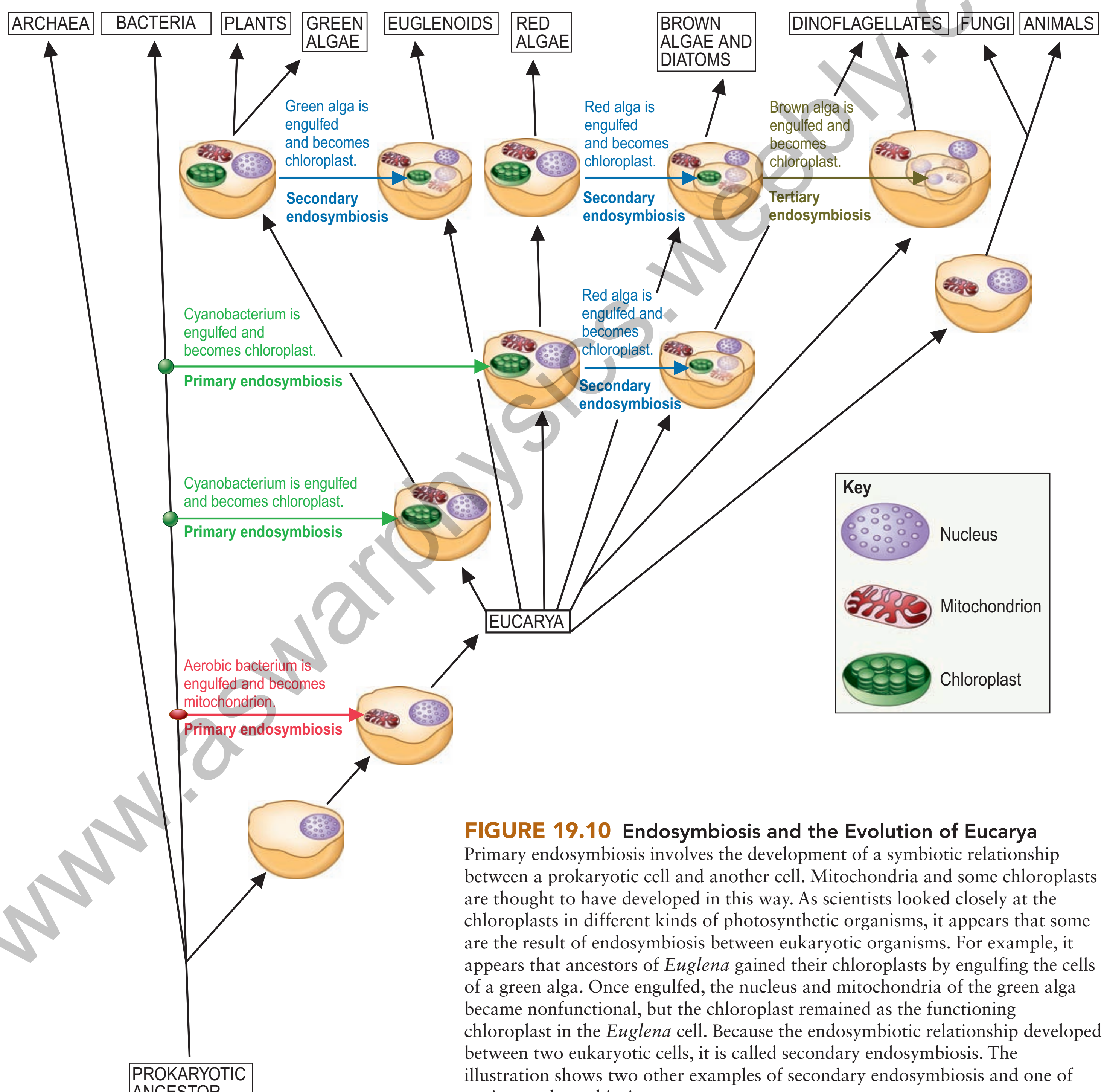


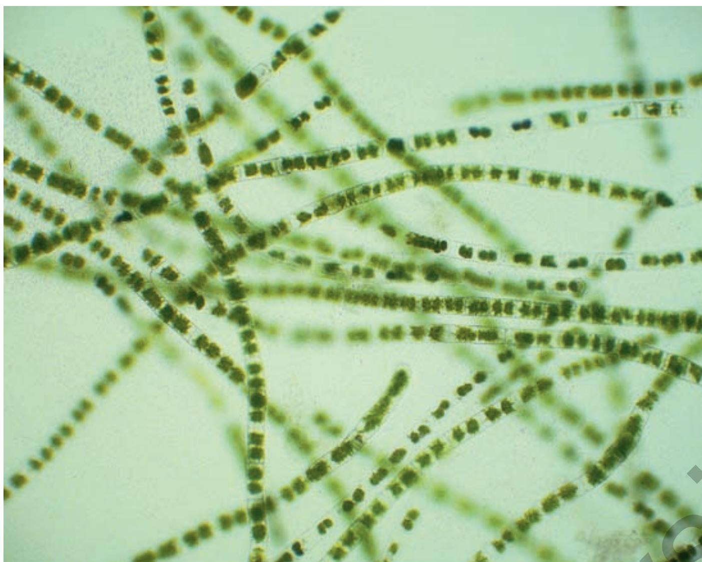
FIGURE 19.10 Endosymbiosis and the Evolution of Eucarya
Primary endosymbiosis involves the development of a symbiotic relationship between a prokaryotic cell and another cell. Mitochondria and some chloroplasts are thought to have developed in this way. As scientists looked closely at the chloroplasts in different kinds of photosynthetic organisms, it appears that some are the result of endosymbiosis between eukaryotic organisms. For example, it appears that ancestors of *Euglena* gained their chloroplasts by engulfing the cells of a green alga. Once engulfed, the nucleus and mitochondria of the green alga became nonfunctional, but the chloroplast remained as the functioning chloroplast in the *Euglena* cell. Because the endosymbiotic relationship developed between two eukaryotic cells, it is called secondary endosymbiosis. The illustration shows two other examples of secondary endosymbiosis and one of tertiary endosymbiosis.

TABLE 19.1 Summary of Characteristics of the Three Major Domains of Life

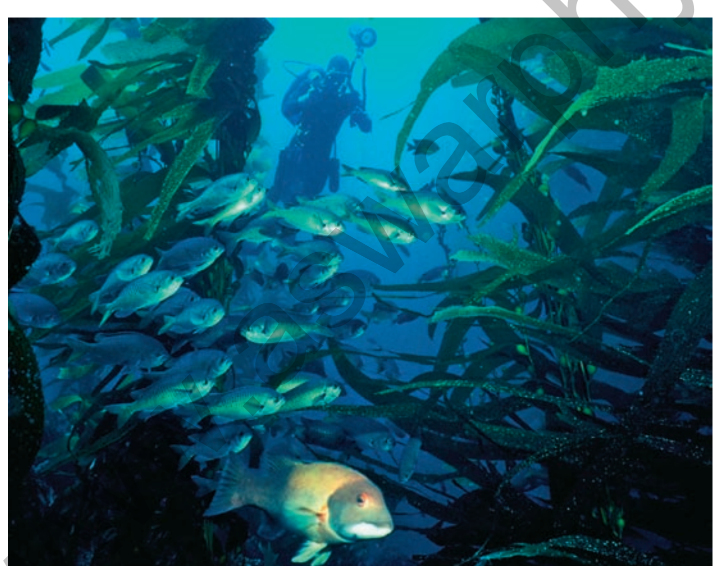
Characteristics	DOMAIN Bacteria	Archaea	Eucarya
Cell Structure	Few membranous structures	Few membranous structures	Many kinds of membranous organelles are present in cells.
	There is no nuclear membrane.	There is no nuclear membrane.	A nuclear membrane is present.
			Chloroplasts are probably derived from cyanobacteria and entered cells through endosymbiosis.
			Mitochondria are probably derived from certain aerobic bacteria and entered cells through endosymbiosis.
Metabolic Activity	Some Bacteria are chemoautotrophs that use energy from inorganic chemical reactions to produce organic molecules.	Most Archaea are chemoautotrophs that obtain energy from inorganic reactions to make organic matter.	
	Most Bacteria are anaerobic heterotrophs.	There are few heterotrophs.	A few Eucarya use only anaerobic respiration—fungi, some protozoa Many Eucarya have tissues that use anaerobic respiration—muscle
	Some Bacteria are aerobic heterotrophs.		Nearly all Eucarya have mitochondria and use aerobic respiration.
	Chlorophyll-based, oxygen-generating photosynthesis was an invention of the cyanobacteria.		Plants and algae have chloroplasts and use photosynthesis in addition to aerobic respiration.
Evolutionary Status	Probably related to the first living thing		
	Some live at high temperatures and are probably ancestral to Archaea.	Probably derived from Bacteria	
		Archaea probably have a common ancestor with Eucarya.	Eucarya probably have a common ancestor with Archaea.
			The common evolutionary theme is the development of complex cells through endosymbiosis of other organisms.
Ecological Status	Major role as photosynthesizers in aquatic environments		Major role as photosynthesizers on terrestrial and in aquatic environments
	Major category of decomposers	Archaea are typically found in extreme environments.	Dominant form of life today
	Many are pathogenic.	None have been identified as pathogenic.	Various eukaryotes fill ecological roles of producer, consumer, pathogen, and decomposers.

The Development of Multicellular Organisms

Following the development of eukaryotic cells, there was a long period in which single-celled organisms (both prokaryotic and eukaryotic) were the only ones on Earth. Eventually, organisms developed that consisted of collections of cells. At first, these collections may have been very similar to modern algae in which there was very little specialization of cells (figure 19.11a). However, eventually some cells within organisms became specialized for specific tasks, and the many kinds of multicellular algae, fungi, plants, and animals developed (figure 19.11b).



(a) *Zygnema*



(b) Kelp

FIGURE 19.11 Simple and Complex Algae
(a) Zygnema is a simple alga, which forms long, hairlike strands a few millimeters long, in which all the cells are identical. *(b)* The kelp, *Macrocystis,* is a much more complex alga, with specialized structures, such as stalks, leaf-like blades, and gas-filled bladders. It can be several meters long.

19.5 CONCEPT REVIEW

13. What organisms were probably responsible for the development of an oxygen-containing atmosphere?
14. What evidence supports the theory that eukaryotic cells arose from the development of an endosymbiotic relationship between primitive prokaryotic cells?
15. Why is it unlikely that organic molecules would accumulate in the oceans today?
16. List two significant biologically important effects caused by the increase of oxygen in Earth's atmosphere.
17. In what sequence did the following things happen: living cell, oxidizing atmosphere, respiration, photosynthesis, reducing atmosphere, first organic molecule?
18. List two distinguishing characteristics of each of the following domains: Bacteria, Archaea, and Eucarya.

19.6 The Geologic Timeline and the Evolution of Life

A geologic timeline shows a chronological history of living organisms based on the fossil record. The largest geologic time units are called *eons*. From earliest to most recent, the geologic eons are the Hadean, Archaean, Proterozoic, and Phanerozoic. The Phanerozoic eon is divided into the *eras* Paleozoic, Mesozoic, and Cenozoic. Each of these eras is subdivided into smaller time units called *periods*. For example, Jurassic is the period of the Mesozoic era that began 208 million years ago (figure 19.12).

Note on the geological time chart in figure 19.12 that its divisions are associated with the major events in the evolutionary history of living things. For example, the Ordovician period is characterized by the appearance of the first primitive land plants and a major extinction of marine animals. The Carboniferous period is characterized by large swamps of primitive plants and cone-bearing plants, and reptiles arose by the end of the period. The Tertiary period is the time when most forms of modern terrestrial organisms arose. In each instance, the dominance of a particular plant or animal group resulted from adaptive radiation. It is also important to note that the ends of many geologic time designations are associated with major extinctions. These extinctions appear to be related to major changes in climate or sea level or asteroid impacts. Following each major extinction, a new group of organisms became dominant.

Eon	Era	Period	Epoch	Million Years Ago	Major Events and Characteristics
Phanerozoic	Cenozoic	Quaternary	Holocene (Recent)	0.01 to present	Dominance of modern humans Much of Earth modified by humans
			Pleistocene	1.8–0.01	Extinction of many large mammals Most recent period of glaciation
		Tertiary	Pliocene	5–1.8	Cool, dry period Grasslands and grazers widespread Origin of ancestors of humans
			Miocene	23–5	Warm, moist period Grasslands and grazers common
			Oligocene	38–23	Cool period—tropics diminish Woodlands and grasslands expand
			Eocene	54–38	All modern forms of flowering plants present All major groups of mammals present
			Paleocene	65–54	Warm period Many new kinds of birds and mammals
	Mesozoic	Cretaceous		144–65	Meteorite impact causes mass extinction Dinosaurs dominant Many new kinds of flowering plants and insects
		Jurassic		208–144	Giant continent begins to split up Dinosaurs dominant First flowering plants and birds
		Triassic		245–208	Giant continent—warm and dry Explosion in reptile and cone-bearing plant diversity First dinosaurs and first mammals
	Paleozoic	Permian		286–245	90% of species go extinct at end of Permian New giant continent forms Modern levels of oxygen in atmosphere Gymnosperms, insects, amphibians, and reptiles dominant
		Carboniferous		360–286	Gymnosperms and reptiles present by end Vast swamps of primitive plants—formed coal Amphibians and insects common
		Devonian		408–360	Glaciation the probable cause of extinction of many warm-water marine organisms Abundant fish, insects, forests, coral reefs
		Silurian		436–408	Melting of glaciers caused rise in sea level Numerous coral reefs First land animals (arthropods), jawed fish, and vascular plants
		Ordovician		505–436	Sea level drops causing major extinction of marine animals at end of Ordovician Primitive plants present—jawless fish common
		Cambrian		540–505	Major extinction of organisms at end of Cambrian All major phyla of animals present Continent splits into several parts and drift apart
Proterozoic	This period of time is also known as the Precambrian			2,500–540	First multicellular organisms about 1 billion years ago First eukaryotes about 1.8 billion years ago Increasing oxygen in atmosphere Single large continent about 1.1 billion years ago
Archaean				3,800–2,500	Continents form—no oxygen in atmosphere Fossil prokaryotes—about 3.5 billion years ago
Hadean				4,500–3,800	Crust of Earth in process of solidifying Origin of the Earth

FIGURE 19.12 A Geologic Time Chart
This chart shows the various geologic time designations, their time periods, and the major events and characteristics of each time period.

An Aquatic Beginning

Recent evidence suggests that the first living thing most likely came into existence in the ocean approximately 3.8 billion years ago during the Archaean eon. Prokaryotic cell types (domain Bacteria) appear about 3.5 billion years ago in the fossil record. One of the common fossils is of stromatolites, photosynthetic Bacteria that grew in layers and formed columns in shallow oceans. Modern-day stromatolites still exist in western Australia (figure 19.13). Also about this time, the Archaea diverged from the Bacteria. For approximately 2 billion years, the only organisms on Earth were Bacteria and Archaea that lived in the ocean. For most of its existence Earth was dominated by prokaryotic organisms. The photosynthetic cyanobacteria are thought to have been responsible for the production of the molecular oxygen (O_2) that began to accumulate in the atmosphere about 2.4 billion years ago. The presence of oxygen made conditions favorable for the evolution of other types of cells. The first members of the Domain Eucarya, the eukaryotic organisms, appeared approximately 1.8 billion years ago.

There is fossil evidence of multicellular algae at about 1 billion years ago and multicellular animals at about 0.6 billion years ago. During the Cambrian period of the Paleozoic era, an evolutionary explosion of multicellular animals occurred. Examples of most of the present-day kinds of marine invertebrate animals (e.g., echinoderms, arthropods, mollusks) are found in the fossil record at this time.

Several other "evolutionary explosions," or *adaptive radiations,* followed.

FIGURE 19.13 Stromatolites in Australia
This photo of stromatolites was taken at Hamelin Pool, Western Australia, a marine nature preserve. The dome-shaped structures are composed of cyanobacteria and materials they secrete, they grow to 60 centimeters tall. Similar structures are known from the fossil record. Taking samples from fossil stromatolites and cutting them into thin slices produces microscopic images that show some of the world's oldest cells.

Adaptation to a Terrestrial Existence

For about 90% of Earth's history, life was confined to the sea. Primitive land plants probably arose about 430 million years ago and the first land animals (ancestors to present-day centipedes and millipedes) at about 420 million years ago. In order to live on land, organisms needed several characteristics:

1. an ability to exchange gases (particularly oxygen and carbon dioxide) with the air,
2. a way to prevent dehydration,
3. some sort of skeleton for support, and
4. an ability to reproduce out of water.

Modern plants exchange gases through openings in their leaves. Plants with vascular tissue were able to obtain water from the soil and regulate its loss with a waxy coating on their exterior. The cellulose cell walls allowed for support. The development of pollen grains allowed sperm to be transferred to the egg through the air. More primitive plants like mosses and ferns have swimming sperm and need water for sexual reproduction.

The first major group of land animals to become abundant was the insects, followed by vertebrates. Both groups are very successful but solved the problems associated with life on land in different ways. The marine ancestors of insects already had two characteristics that were valuable. They had an external skeleton and they had legs that they could use to walk on the ocean bottom or on land. In this sense they were somewhat preadapted for life on land. Marine ancestors of insects would have had gills, and some terrestrial arthropods (spiders and land crabs) have modified gills that work on land. However, modern insects have a system of tubes that permeate their bodies and carry oxygen to each cell. A waxy coating on the exterior reduces water loss and internal fertilization and an egg that resists drying allow for reproduction on land.

The conquest of a terrestrial environment by vertebrates appears to have involved several steps. Among the vertebrates, the first land animals most likely evolved from a lobe-finned fish of the Devonian period. They possessed two important adaptations: lungs and paired, lobed fins which had a skeletal structure. The lobe fins allowed the organisms to pull themselves onto land and travel to new water holes during times of drought. They were probably the ancestors of the first amphibians. Early amphibians would have found a variety of unexploited terrestrial niches, resulting in the rapid evolution of new amphibian species and their dominance during the Carboniferous period. Although early amphibians had a skeleton with legs and could breathe air, they probably lost water through their skin and returned to water to reproduce as modern amphibians do.

Reptiles are the first truly terrestrial vertebrate organisms. In addition to having lungs and a supportive skeleton like their amphibian ancestors, they also had a relatively impermeable skin that reduced water loss and two reproductive adaptations that allowed for reproduction on land. One change allowed males to deposit sperm directly within females. Because the sperm could directly enter females and remain in a moist interior, it was no longer necessary for the animals to return to the water to mate, as the amphibians still had to do. However, the developing young still required a moist environment for early growth. A second modification, the amniotic egg, solved this problem. An amniotic egg, such as a chicken egg, protected the developing young from injury and dehydration while allowing for the exchange of gases with the external environment. See chapter 23 for a discussion of the nature of an amniotic egg. With these adaptations, the reptiles were able to outcompete the amphibians in most terrestrial environments. The amphibians that did survive were the ancestors of present-day frogs, toads, and salamanders. With extensive adaptive radiation, the reptiles took to the land, sea, and air. A particularly successful group of reptiles was the dinosaurs, which were the dominant terrestrial vertebrates for more than 100 million years.

Both birds and mammals are descendants of reptiles. They have a relatively impermeable skin and internal fertilization but have diverged somewhat in the way they reproduce. All birds lay eggs and most mammals have a uterus in which the young develop prior to birth. A more complete discussion of terrestrial adaptations can be found in chapter 22 for plants and chapter 23 for animals.

19.6 CONCEPT REVIEW

19. Describe four problems organisms had to overcome to be successful on land.
20. For each of the following pairs of terms, select the one that is the earliest in geologic time.
    a. eukaryote—prokaryote
    b. marine—terrestrial
    c. vertebrate—invertebrate
    d. flowering plant—cone-bearing plant
    e. aerobic respiration—photosynthesis
    f. plants—animals

Summary

Current theories on the origin of life speculate that either the primitive Earth's environment led to the spontaneous organization of organic chemicals into primitive cells or primitive forms of life arrived on Earth from space.

The spontaneous origin of living things on Earth would require:

- the formation of organic molecules,
- a genetic system,
- a membrane that separated the organic molecules from their surroundings, and
- a method of obtaining energy.

There are two different theories about the way in which the first living things would have obtained energy. They were either anaerobic heterotrophs or chemosynthetic autotrophs. Regardless of how the first living things came to be on Earth, these basic units of life were probably similar to present-day prokaryotes. The primitive cells could have changed through time as a result of mutation. A changing environment would have selected for new combinations of characteristics.

The recognition that prokaryotic organisms can be divided into two distinct types has led to the development of the concept that there are three major domains of life: the Bacteria, the Archaea, and the Eucarya. The Bacteria and Archaea are similar in structure, but the Archaea have metabolic processes that are distinctly different from those of the Bacteria.

The origin of the Eucarya is more clear-cut. Similarities between cyanobacteria and chloroplasts and between aerobic bacteria and mitochondria suggest that they have a common origin. The endosymbiotic theory proposes that eukaryotic cells are the result of combining two or more ancient cell ancestors into one cellular unit and that both of the original separate cells benefit from the new combination.

The accumulation of geologic information has allowed several key events in the history of life to be placed in sequence (figure 19.14).

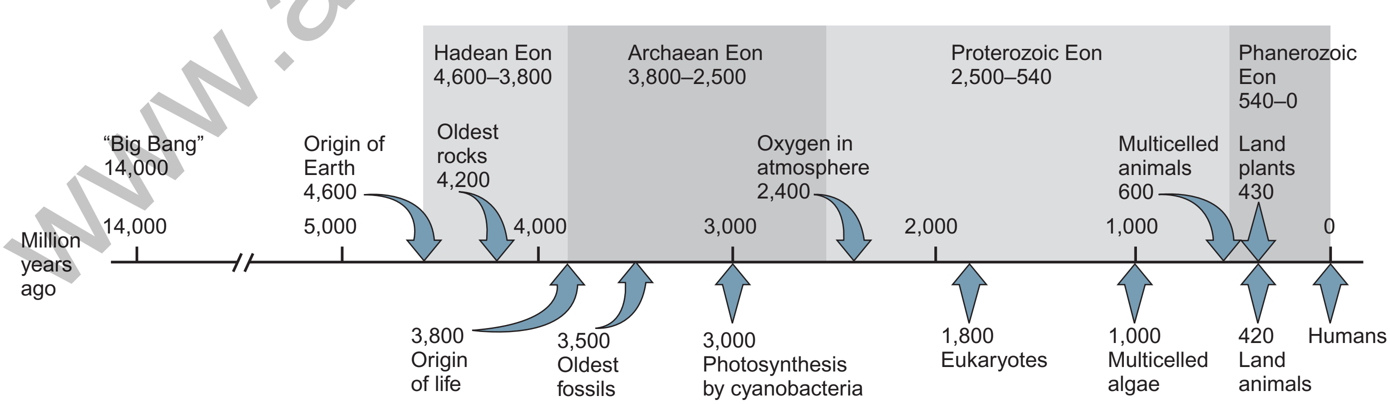


FIGURE 19.14 An Evolutionary TimeLine
This chart displays how science sees the order of major, probable events in the origin and evolution of life from the "Big Bang" to the present day.

Key Terms

Use the interactive flash cards on the ***Concepts in Biology, 14/e*** *website to help you learn the meaning of these terms.*

biogenesis 416
endosymbiotic theory 426
oxidizing atmosphere 425
panspermia 418
reducing atmosphere 419
spontaneous generation 416

Basic Review

1. The reproduction of an apple tree by seeds is an example of
   a. spontaneous generation.
   b. biogenesis.
   c. endosymbiosis.
   d. None of the above is correct.
2. The first organisms on Earth would have carried on aerobic respiration. (T/F)
3. Endosymbiosis involves one cell invading and living inside another cell. (T/F)
4. Which of the following suggests that organic molecules may have formed on Earth from inorganic molecules?
   a. Experiments that simulated the early Earth's atmosphere have produced organic molecules.
   b. Organic molecules have been detected in interstellar gases in space.
   c. Meteorites contain organic molecules.
   d. All of the above are correct.
5. Oxygen in today's Earth atmosphere is the result of the process of _____.
6. The oldest fossils of living things are about _____ years old.
   a. 3.5 million c. 4.5 billion
   b. 3.5 billion d. 4.5 million
7. The first genetic material was probably
   a. protein. c. RNA.
   b. DNA. d. enzymes.
8. An organism that requires organic molecules for food is known as a(n) _____.
9. A prokaryotic organism that is a chemoautotroph and lives in a very hot environment is probably in the domain
   a. Archaea. c. Eucarya.
   b. Extremophile. d. Any of these are correct.
10. Which one of the following evolved before all of the others?
    a. terrestrial plants and animals
    b. prokaryotic cells
    c. eukaryotic cells
    d. multicellular organisms
11. The first terrestrial organisms were
    a. vertebrates. c. simple plants.
    b. insects. d. amphibians.
12. Chloroplasts are probably derived from
    a. Archaea.
    b. cyanobacteria.
    c. Eucarya.
    d. None of the above is correct.
13. Louis Pasteur performed an experiment that showed that _____ did not occur.
14. Stanley Miller performed an experiment that showed that
    a. life originated on Earth.
    b. life originated in outer space.
    c. membranes form around cells.
    d. organic molecules can be formed from inorganic molecules in a rather than a reducing atmosphere.
15. In order to be successful as a terrestrial organism, any organism must be able to retain water. (T/F)

Answers
1. b 2. F 3. T 4. d 5. photosynthesis 6. b 7. c 8. heterotroph 9. a 10. b 11. c 12. b 13. spontaneous generation 14. d 15. T

Thinking Critically

Thinking Like an Astrobiologist
Imagine that there is life on another planet in our galaxy (Planet X). Using the following data concerning the nature of this life, determine what additional information is necessary and how you would verify the additional data needed to develop a theory of the origin of life on Planet X.

1. The age of the planet is 5 billion years.
2. Water is present in the atmosphere.
3. The planet is farther from its Sun than our Earth is from our Sun.
4. The molecules of various gases in the atmosphere are constantly being removed.
5. Chemical reactions on this planet occur at approximately half the rate at which they occur on Earth.

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CHAPTER 20

The Classification and Evolution of Organisms

CHAPTER OUTLINE

Taxonomists Needed

Taxonomists are important in medical discoveries.

Many scientists are concerned that there is a lack of scientific specialists who identify and classify living things. Although this may seem like a skill with limited value to the general public, it is extremely important to medicine and many other aspects of our modern society. Many of our medicines were originally discovered in other living organisms. Digitalis, which is used to stimulate the heart, comes from the foxglove plant. Chemicals in marijuana are used to treat nausea. Many kinds of antibiotics are derived from fungi. Taxol, which is used to treat ovarian and other forms of cancer, is an extract from the bark of the Pacific yew, *Taxus brevifolia* (see photo) which has a rather limited distribution along the northwest coast of the United States.

Proper identification of organisms is important because the beneficial chemical may be found in only one species within a group of closely related species that basically all look alike to the general public. Initially taxol was produced by harvesting Pacific yews and extracting taxol from the bark. This was not sustainable and an alternative source of the drug was sought. It was logical to look at closely related but more common species of yews to see if they also produced the drug. Eventually, it was discovered that the common yew, *Taxus baccata*, which is widely grown throughout the world as an ornamental, produced a compound similar to taxol that could be modified to produce taxol. This discovery greatly increased the source of supply for this valuable drug and protected the Pacific yew from overharvesting. Subsequently, a cell culture method was developed that allows for the production of the drug without harvesting trees.

- **Why is precise identification of organisms important?**
- **What tools do taxonomists use to classify organisms?**
- **Should governments subsidize the education of taxonomists?**

Background Check

Concepts you should already know to get the most out of this chapter:

- The processes of natural selection and evolution (chapter 13)
- Prokaryotic organisms have a simpler cellular structure than eukaryotic organisms (chapter 4)

20.1 The Classification of Organisms

In order to talk about items in our world, we must have names for them. As new items come into being or are discovered, we devise new words to describe them. For example, the words *laptop, palm pilot,* and *text message* describe technology that did not exist 30 years ago. Similarly, in the biological world, people have given names to newly discovered organisms so they can communicate to others about the organism.

The Problem with Common Names

The common names people use vary from culture to culture. For example, *dog* in English is *chien* in French, *perro* in Spanish, and *cane* in Italian. Often different names are used in different regions within a country to identify the same organism. For example, the common garter snake is called a garden snake or gardner snake, depending on where you live (figure 20.1). Actually, there are several species of garter snakes that have been identified as distinct from one another. Thus, common names can be confusing, so scientists sought a more acceptable way to name organisms, one that all scientists would use that would eliminate confusion.

FIGURE 20.1 Names for the Common Garter Snake Depending on where you live, you may call this organism a garter snake, a garden snake, or a gardner snake. These common names can lead to confusion. However, the scientific name (*Thamnophis sirtalis*) is recognized worldwide by the scientific community.

The naming of organisms is a technical process, but it is extremely important. When biologists are describing their research, common names, such as robin or maple tree, or garter snake are not good enough. They must be able to identify the organisms involved accurately, so that everyone who reads the report, wherever they live in the world, knows what organism is being discussed. The scientific identification of organisms involves two different but related activities. One, *taxonomy,* is the naming of organisms; the other, *phylogeny,* involves showing how organisms are related evolutionarily. In reality, no taxonomic decisions are made without considering the evolutionary history of the organism.

Taxonomy

Taxonomy is the science of naming organisms and grouping them into logical categories. The root of the word *taxonomy* is the Greek word *taxis,* which means arrangement.

During the Middle Ages, Latin was widely used as the scientific language. As new species were identified, they were given Latin names, often using as many as 15 words to describe a single organism. Although using Latin meant that most biologists, regardless of their native language, could understand a species name, it did not completely do away with duplicate names. Because many of the organisms were found over wide geographic areas and communication was slow, there could still be two or more Latin names for a species. To make the situation even more confusing, ordinary people used common local names.

The Binomial System of Nomenclature

The modern system of classification began in 1758, when Carolus Linnaeus (1707–1778), a Swedish doctor and botanist, published his tenth edition of *Systema Naturae* (figure 20.2). (Linnaeus's original name was Carl von Linné, which he "latinized" to Carolus Linnaeus.) In the previous editions of his book, Linnaeus had used the polynomial Latin system of classification, which required many words to identify a species. However, in the tenth edition, he introduced the *binomial system of nomenclature*. The **binomial system of nomenclature,** uses only two Latin names—the *genus* name and the *specific epithet* (*epithet* = descriptive word) for each species of organism. Recall that a species is a population of organisms capable of interbreeding and producing fertile offspring. Individual organisms are members of a species. A **genus** (plural, *genera*) is a group of closely related organisms. The **specific epithet** is a word added to the genus name to identify which one of several species within the genus is being referred to.

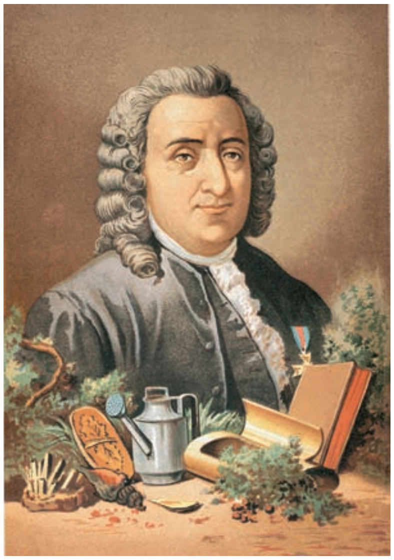


FIGURE 20.2 Carolus Linnaeus (1707–1778)
Carolus Linnaeus, a Swedish doctor and botanist, originated the modern system of taxonomy known as binomial nomenclature.

This is similar to the naming system we use with people. When we look in the phone book, we look for a last name (surname), the correct general category. Then, we look for a first name (given name) to identify the specific individual we wish to call. The unique name given to an organism is its species name, or scientific name. In order to clearly distinguish the scientific name from other words, binomial names are either *italicized* or underlined. The first letter of the genus name is capitalized. The specific epithet is always written in lowercase. For example, *Thamnophis sirtalis* is the binomial name for the common garter snake.

When biologists adopted Linnaeus's binomial method, they simplified the names of organisms and eliminated the confusion of using common local names. Since the adoption of Linnaeus's system, international rules have been established to assure that an orderly system is maintained. The three primary sets of rules are the International Rules for Botanical Nomenclature, the International Rules for Zoological Nomenclature, and the International Bacteriological Code of Nomenclature. Although approximately 1.5 million species have been named, no one knows how many species of organisms live on Earth, but most biologists estimate that several million are yet to be identified.

The Organization of Species into Logical Groups

In addition to assigning a specific name to each species, Linnaeus recognized a need for placing organisms into groups. He originally divided all organisms into two broad groups, which he called the plant and animal kingdoms, and subdivided each kingdom into smaller units. Since Linneaus's initial attempts to place all organisms into categories, there have been many changes. One of the most fundamental is the recent recognition that there are three major categories of organisms, called *domains*.

Recall that a domain is the largest category into which organisms are classified, and there are three domains: Bacteria, Archaea, and Eucarya (figure 20.3). Organisms are separated into these three domains based on the specific structural and biochemical features of their cells. The Bacteria and Archaea are prokaryotic and the Eucarya are eukaryotic.

A **kingdom** is a subdivision of a domain. There are several kingdoms within the Bacteria and Archaea based primarily on differences in the metabolism and genetic composition of

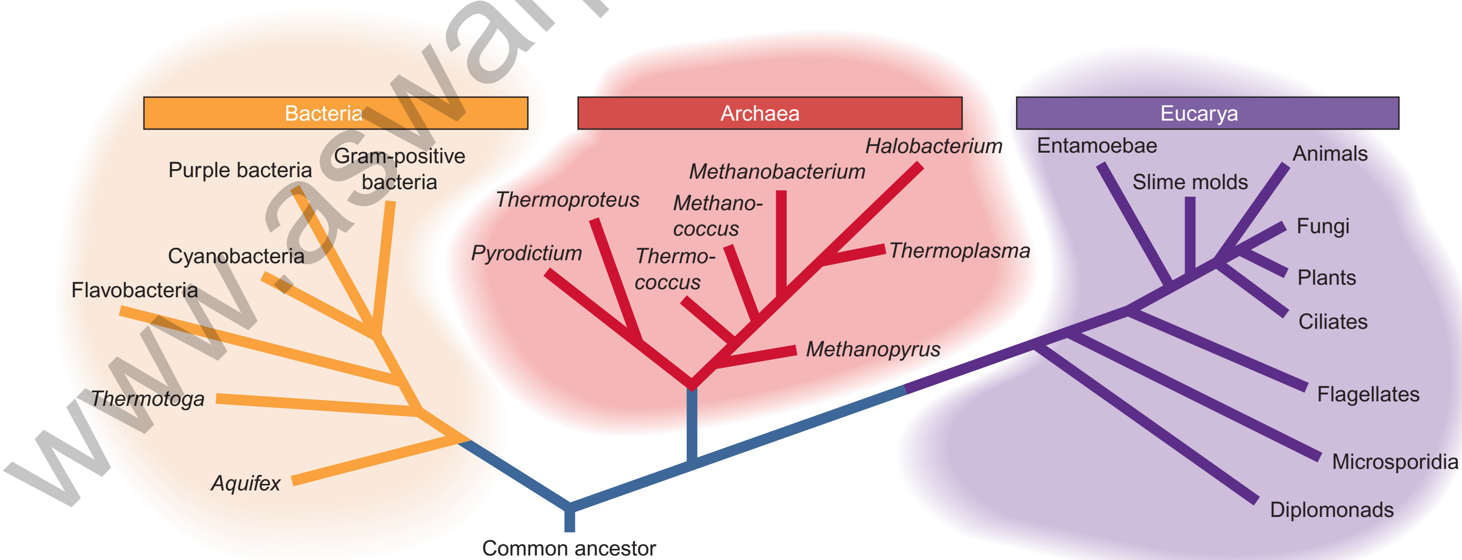
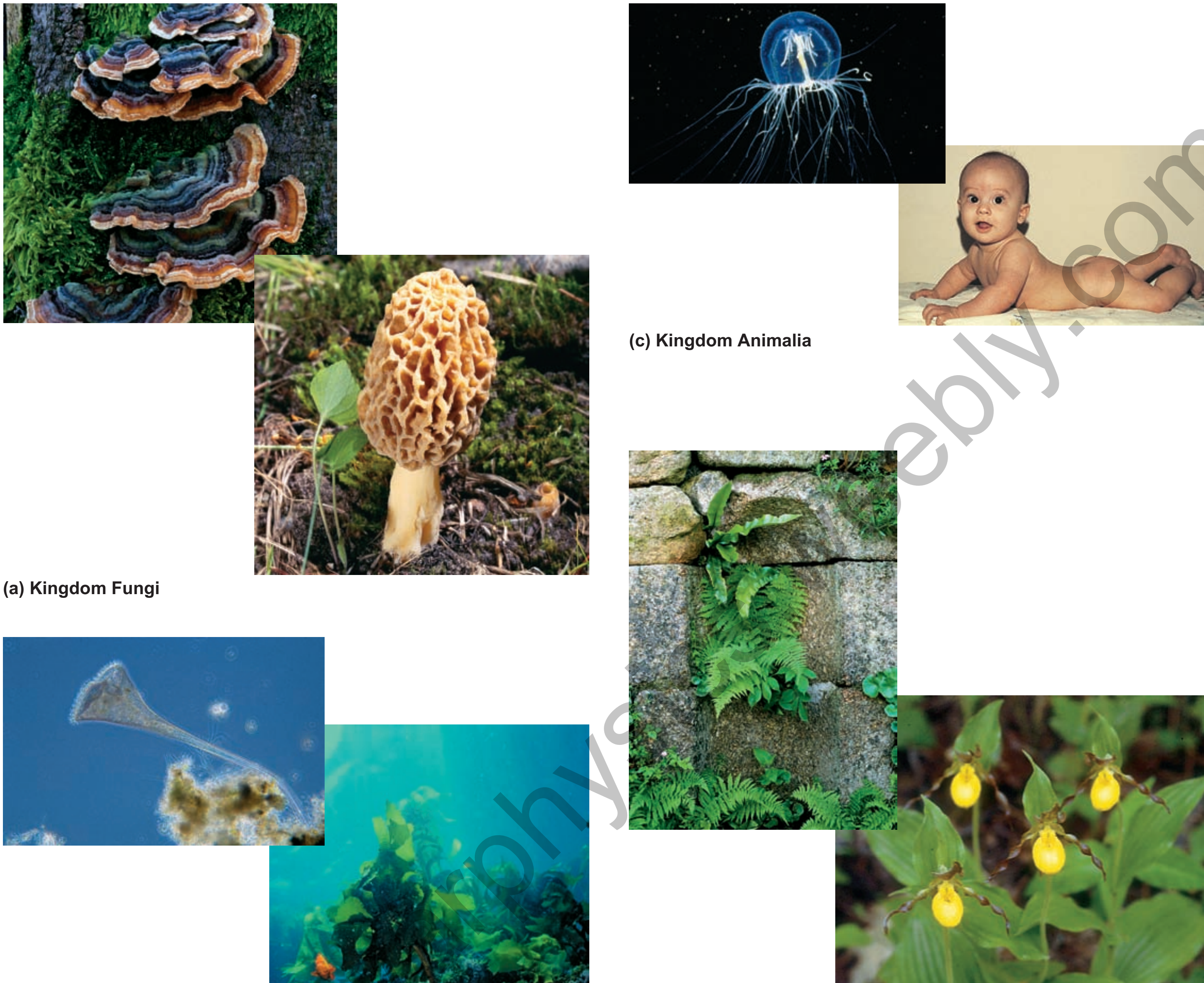


FIGURE 20.3 The Three Domains of Life
The three domains of living things are related to one another evolutionarily. The domain Bacteria is the oldest group. The domains Archaea and Eucarya are derived from the Bacteria.



(a) Kingdom Fungi

(b) Kingdom Protista

(c) Kingdom Animalia

(d) Kingdom Plantae

FIGURE 20.4 Representatives of the Domain Eucarya
There are four kingdoms in the domain Eucarya, represented by the following organisms: *(a)* The bracket fungus *Trametes versicolor,* and the edible mushroom *Morchella esculenta* of the kingdom Fungi; *(b)* The protozoan *Stentor* and the a large alga of the kingdom Protista; *(c)* The moon jellyfish, and *Homo sapiens* of the kingdom Animalia; and *(d)* Ferns and the orchid *Cypripedium calceolus* of the kingdom Plantae.

the organisms. Within the domain Eucarya, there are four kingdoms: Plantae, Animalia, Fungi, and Protista (protozoa and algae) (figure 20.4).

A **phylum** is a subdivision of a kingdom. However, microbiologists and botanists often use the term *division* rather than *phylum*. All kingdoms have more than one phylum. For example, the kingdom Plantae contains several phyla that include flowering plants, conifer trees, mosses, ferns and several other less-common groups. Organisms are placed in phyla based on careful investigation of the specific nature of their structure, metabolism, and biochemistry. An attempt is made to identify natural groups, rather than artificial or haphazard arrangements. For example, although nearly all plants are green and carry on photosynthesis, only flowering plants have flowers and produce seeds; conifers lack flowers but have seeds in cones; ferns lack flowers, cones, and seeds; and mosses are so simple in structure that they even lack tissues for transporting water.

A **class** is a subdivision within a phylum. For example, within the phylum Chordata within the kingdom Animalia, there

TABLE 20.1 Classification of Humans

Taxonomic Category	Taxonomic Name	Characteristics	Other Representatives
Domain	Eucarya	Cells containing a nucleus and many other kinds of organelles	Plants, animals, fungi, protozoa, algae
Kingdom	Animalia	Eukaryotic heterotrophs that are usually motile and have specialized tissues	Sponges, jellyfish, worms, clams, insects, snakes, cats
Phylum	Chordata	Animals with a stiffening rod down their back	Fish, amphibians, reptiles, birds, mammals
Class	Mammalia	Animals with hair and mammary glands	Platypus, kangaroos, mice, whales, skunks, monkeys
Order	Primates	Mammals with a relatively large brain and opposable thumbs	Monkeys, gorillas, chimpanzees, baboons
Family	Hominidae	Primates that lack a tail and have upright posture	Humans and extinct relatives in several genera (*Australopithecus, Paranthropus, Homo*)
Genus	*Homo*	Hominids with large brains	Humans and extinct relatives such as *Homo erectus* and *Homo neanderthalensis*
Species	*Homo sapiens*	Humans	

are seven classes: mammals, birds, reptiles, amphibians, and three classes of fishes.

An **order** is a category within a class. The order Carnivora is an order of meat-eating animals within the class Mammalia. There are other orders of mammals, including horses and their relatives, cattle and their relatives, rodents, rabbits, bats, seals, whales, humans, and many others.

A **family** is a subdivision of an order that consists of a group of closely related genera, which in turn are composed of groups of closely related species. Felidae is a family composed of various kinds of cats within the order Carnivora. It includes many species in several genera, including the Canada lynx and bobcat (genus *Lynx*); the cougar (genus *Puma*); the leopard, tiger, jaguar, and lion (genus *Panthera*); the house cat (genus *Felis*); and several other genera. Thus, in the present-day science of taxonomy, each organism that has been classified has a unique binomial name. In turn, it is assigned to larger groupings that are thought to have a common evolutionary history. Table 20.1 classifies humans to show how the various categories are used.

Phylogeny

Phylogeny is the science that explores the evolutionary relationships among organisms, seeking to reconstruct evolutionary history. Taxonomists and phylogenists work together, so that the products of their work are compatible. A taxonomic ranking should reflect the phylogenetic (evolutionary) relationships among the organisms being classified. New organisms and new information about organisms are discovered constantly. Therefore, taxonomic and phylogenetic relationships are constantly being revised. During this revision process, scientists often have differences of opinion about the significance of new information.

The Evidence Used to Establish Phylogenetic Relationships

Phylogenists use several lines of evidence to develop evolutionary histories: fossils, comparative anatomy, life cycle information, and biochemical and molecular evidence.

1. *Fossils* are physical evidence of previously existing life. There are several forms of fossils. Some fossils are preserved whole and relatively undamaged. For example, mammoths and humans have been found frozen in glaciers, and bacteria and insects have been preserved after becoming embedded in plant resins. Other fossils are only parts of once living organisms. The outlines or shapes of extinct plant leaves are often found in coal deposits, and individual animal bones that have been chemically altered over time are often dug up. Animal tracks have also been discovered in the dried mud of ancient riverbeds (figure 20.5).

   When looking for fossils it is important to understand how various kinds of rocks were formed. Sedimentary rocks are formed by the depositing of eroded particles in layers on the bottom of an ocean, lake, or river. Sedimentary rock is not subject to high temperatures and is usually relatively undisturbed. Thus, sedimentary rock can contain evidence of organisms that were covered by sediments and modified into fossils. Igneous rocks are formed from molten material that cooled and solidified. Metamorphic rocks are formed when a previously existing rock (igneous, metamorphic, or sedimentary) is subjected to high temperature and pressure, causing the form of the rock to change. Thus, fossils are not found in igneous or metamorphic rock.

   It is important to understand that some organisms are more easily fossilized than others. Those that have hard parts, such as cell walls, skeletons, and shells, are

(a) (b) (c)

FIGURE 20.5 Fossil Evidence
A fossil is any evidence of previously existing life. Fossils can be the intact, preserved remains of organisms, as in *(a)* the remains of an ancient fly preserved in amber or the preserved parts of an organism, as in *(b)* the fossilized skeleton and body outline of a bony fish. It is even possible to have evidence of previously existing living things that are not the remains of organisms, as in *(c)* a dinosaur footprint.

more likely to be preserved than are tiny, soft-bodied organisms. Aquatic organisms are more likely to be buried in the sediments at the bottom of the oceans or lakes than are their terrestrial counterparts. Later, when sedimentary rock is pushed up by geologic forces, aquatic fossils are found in layers of sediments on dry land.

Evidence obtained from the discovery and study of fossils allows biologists to place organisms in a time sequence. This can be accomplished by comparing the sedimentary layers in which a fossil is found. As geologic time passes and new layers of sediment are laid down, the older organisms should be in deeper layers, assuming that the sequence of layers has not been disturbed (figure 20.6). In addition, it is possible to age-date certain kinds of rocks by comparing the amounts of certain radioactive isotopes they contain. Older rocks have less of these specific radioactive isotopes than do younger rocks. Fossils associated with rocks of a known age are usually of a similar age to the rocks.

It is also possible to compare subtle changes in particular kinds of fossils over time. For example, in studies of a certain kind of fossil plant, the size of the leaf changed extensively through long geologic periods. If one only looked at the two extremes, they would be classified into different categories. However, because there are fossil links that show intermediate stages between the extremes, scientists conclude that the younger plant is a descendant of the older.

2. *Comparative anatomy studies* of fossils or currently living organisms can be very useful in developing a phylogeny. Because the structures of an organism are determined by its genes, organisms having similar structures are thought to be related. For example, plants can be divided into several categories: All plants that have flowers are thought to be more closely related to one another than they are to plants that do not have flowers, such as ferns. In the animal kingdom, all organisms that have hair and mammary glands are grouped together, and all animals in the bird category have feathers, wings, and beaks.

FIGURE 20.6 Rock Layers and the Age of Fossils
Because new layers of sedimentary rock are formed on top of older layers of sedimentary rock, it is possible to determine the relative ages of fossils found in various layers. The layers of rock shown here represent millions of years of formation. The fossils of the lower layers are millions of years older than the fossils in the upper layers.

3. *Life cycle information* is another line of evidence useful to phylogenists and taxonomists. Many organisms have complex life cycles, which include many completely different stages. After fertilization, some kinds of organisms grow into free-living developmental stages that do not resemble the adults of their species. These are called *larvae* (singular, *larva*). Larval stages often provide clues to the relatedness of organisms. For example, adult barnacles live attached to rocks and other solid marine objects and look like small, hard cones. Their outward appearance does not suggest that they are related to shrimp; however, the larval stages of barnacles and shrimp are very similar. Detailed anatomical studies of mature barnacles confirm that they share many structures with shrimp, such as legs and an external skeleton; their outward appearance tends to be misleading (figure 20.7).

   Both birds and reptiles lay eggs with shells. However, reptiles lack feathers and have scales covering their bodies. The fact that these two groups share this fundamental eggshell characteristic implies that they are more closely related to each other than they are to other groups, but they can be divided into two groups based on their anatomical differences.

   This kind of evidence also applies to the plant kingdom. Many kinds of plants, such as peas, peanuts, and lima beans, produce large, two-parted seeds in pods. Even though peas grow as vines, lima beans grow as bushes, and peanuts have their seeds underground, all these plants are considered to be related.

4. *Biochemical and molecular studies* are recent additions to the toolbox of phylogenists. Like all aspects of biology, the science of phylogeny is constantly changing as new techniques develop. Recent advances in DNA analysis are being used to determine genetic similarities among species. In the field of ornithology, the study of birds, there are those who believe that storks and flamingos are closely related; others believe that flamingos are more closely related to geese. An analysis of the DNA points to

(a) Barnacle

(b) Shrimp

(c) Nauplius larva of barnacle

(d) *Nauplius* larva of shrimp

FIGURE 20.7 Developmental Stages and Phylogeny
The adult barnacle *(a)* and shrimp *(b)* are very different from each other, but their early larval stages *(c* and *d)* look very much alike.

a closer evolutionary relationship between flamingos and storks than between flamingos and geese.

There are five kinds of chlorophyll found in algae and plants: chlorophyll *a, b, c, d,* and *e*. Most photosynthetic organisms contain a combination of two of these chlorophyll molecules. Members of the kingdom Plantae have chlorophyll *a* and *b*. The large seaweeds, such as kelp, superficially resemble terrestrial plants, such as trees and shrubs. However, a comparison of their chlorophylls shows that kelp has chlorophyll *a* and *d*. Another group of algae, called the *green algae,* has chlorophyll *a* and *b*. Along with other anatomical and developmental evidence, this biochemical information has helped establish an evolutionary link between the green algae and plants. All the kinds of evidence (fossils, comparative anatomy, life cycle information, and biochemical evidence) have been used to develop phylogenetic relationships and taxonomic categories.

A Current Phylogenetic Tree

Given all the sources of evidence, biologists have developed a picture of how they think all organisms are related (figure 20.8). The three domains—Bacteria, Archaea, and Eucarya—diverged early in the history of life. Subsequently, many new kinds of organisms have evolved. It is important to remember that this diagram is a work in progress. As new information is discovered, there will be changes in the way biologists think organisms are related (How Science Works 20.1). Biologists have also developed new techniques that help in determining phylogenies. One such technique is cladistics (How Science Works 20.2).

20.1 CONCEPT REVIEW

1. List two ways that scientific names are different from common names for organisms.
2. Who designed the present-day system of classification? How does this system differ from the previous system?
3. What are the goals of taxonomy and phylogeny?
4. Name the categories of the classification system.
5. Describe four kinds of evidence scientists use to place organisms into a logical phylogeny.

20.2 A Brief Survey of the Domains of Life

Members of the domains Bacteria and Archaea are all tiny, prokaryotic cells that are difficult to distinguish from one another. Because of this, in the past it was assumed that the members of these groups were closely related. However, recent evidence gained from studying DNA and RNA nucleotide sequences and a comparison of the amino acid sequences of proteins indicate that there are major differences between the Bacteria and Archaea. The Bacteria evolved first and then gave rise to the Archaea; finally, the Eucarya evolved.

The Domain Bacteria

The Bacteria are small, prokaryotic, single-celled organisms ranging in size from 1 to 10 micrometers (μm). Their cell walls contain a complex organic molecule known as peptidoglycan. Peptidoglycan is found only in the Bacteria and is composed of two kinds of sugars linked together by amino acids. One of these sugars, muramic acid, is found only in the cell walls of Bacteria. The most common shapes of the cells are spheres, rods, and spirals.

Because they are prokaryotic, Bacteria have no nucleus. Their genetic material consists of a single loop of DNA. When Bacteria reproduce, the loop of DNA replicates to form two loops, and the cell divides into two, each having one copy of the DNA loop. This method of reproduction is known as binary fission (figure 20.9). Since the two cells have the same DNA, this is a form of asexual reproduction. Many Bacteria are also known to show a kind of sexual reproduction, in which two bacteria exchange pieces of DNA. Although no additional individuals were formed, both individuals have new combinations of genes.

Some Bacteria move by secreting a slime that glides over their surface, causing them to move through the environment.

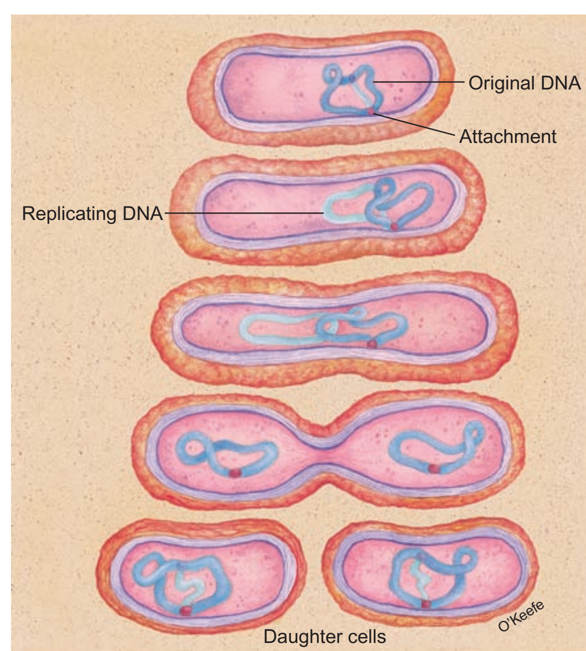


FIGURE 20.9 Asexual Reproduction (Binary Fission) in Bacteria and Archaea
When Bacteria and Archaea reproduce, the loop of DNA replicates and the cell divides, with each cell having one of the two loops of DNA. This form of asexual reproduction is known as binary fission.

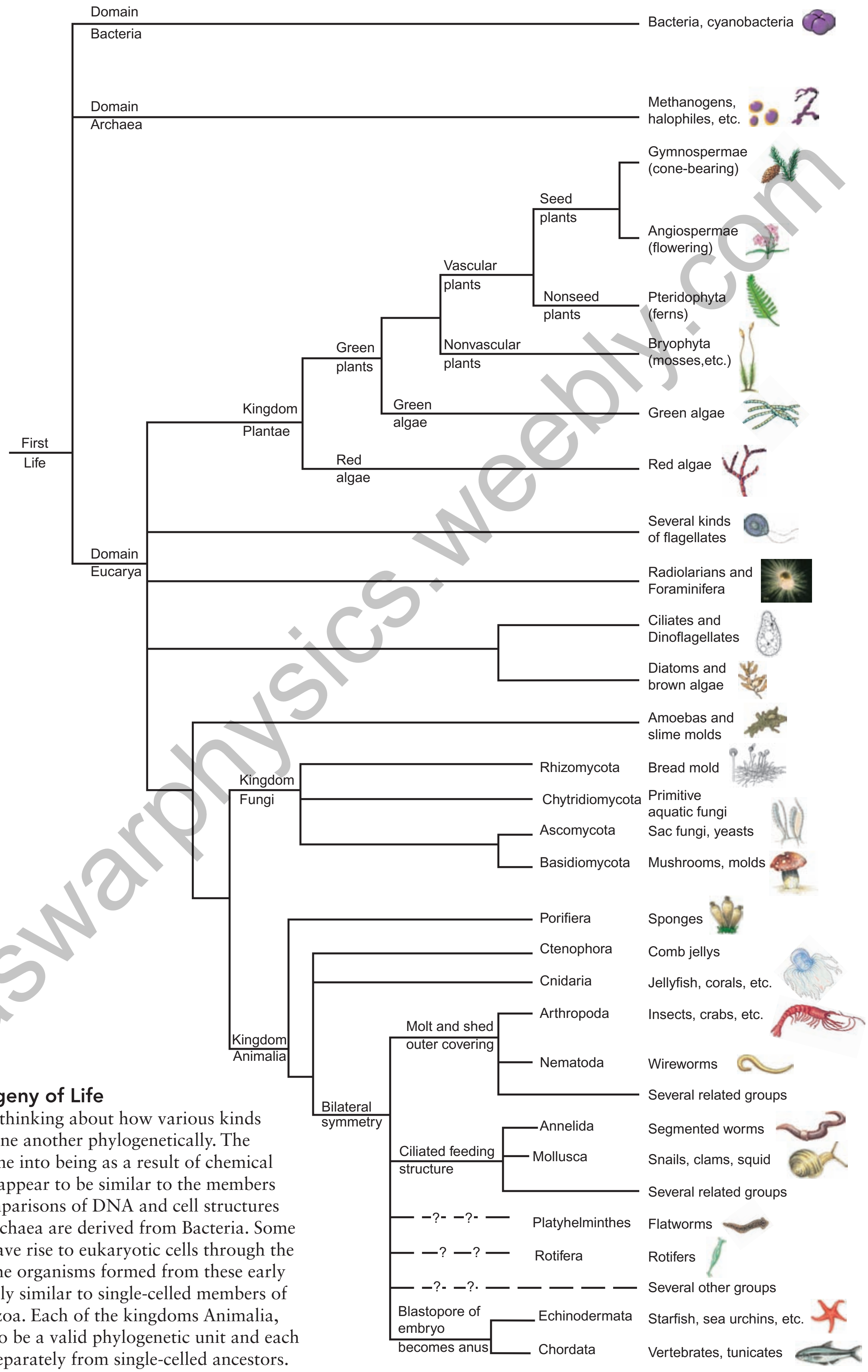


FIGURE 20.8 A Phylogeny of Life
This diagram shows current thinking about how various kinds of organisms are related to one another phylogenetically. The first living cells probably came into being as a result of chemical evolution. The oldest fossils appear to be similar to the members of the domain Bacteria. Comparisons of DNA and cell structures supports the idea that the Archaea are derived from Bacteria. Some prokaryotic cells probably gave rise to eukaryotic cells through the process of endosymbiosis. The organisms formed from these early eukaryotic cells were probably similar to single-celled members of present-day algae and protozoa. Each of the kingdoms Animalia, Plantae, and Fungi appears to be a valid phylogenetic unit and each appears to have originated separately from single-celled ancestors.

HOW SCIENCE WORKS 20.1

New Information Causes Changes in Taxonomy and Phylogeny

The taxonomy and phylogeny of groups of organisms are constantly changing as new information and new tools become available. In his initial classification of organisms, Linnaeus identified two kingdoms—the plant and animal kingdoms. Plants included all kinds of organisms that were not motile and had cell walls. Animals lacked cell walls and moved. Several major scientific and technical developments over the intervening years allowed for a better understanding of the nature of organisms and how they are related. These developments led to changes in taxonomy:

- Advances in the development of microscopes that could look at the smallest of cells made it clear that some of the smallest organisms previously called bacteria and classified as plants, lacked a nucleus. They were, therefore, reclassified into a separate kingdom, Monera.
- A better understanding of the chemical nature of cell walls led to the discovery that a major group of "plants" had cell walls containing chitin and did not have cellulose. Those with chitin in their cell walls were reclassified into the kingdom Fungi.
- Based on the cellular specialization of organisms, multicellular plants and animals that have specialized groups of cells were separated from protozoa and algae that do not have specialized groups of cells. The protozoa and algae were placed in a separate kingdom, Protista.
- Studies of the structure of DNA and ribosomes led to the development of an entirely new way of looking at living things. A new category—domain—was established above the kingdom level. The prokaryotic organisms, "bacteria," which had formerly been in the kingdom Monera, were divided into two major groups, the domains Bacteria and Archaea, and all the remaining kinds of living things that were eukaryotic were placed in the domain Eucarya.
- Although most people agree that kingdoms Plantae and Animalia are valid collections of organisms with a common ancestry, most people recognize that the kingdom Protista is not a valid phylogenetic unit. In the future, this group of organisms will be divided into distinct categories that will be more phylogenetically meaningful.
- The kingdom Fungi will probably undergo some revision. Some organisms are likely to be moved to other kingdoms or placed in an entirely new kingdom.
- The recognition that endosymbiosis occurs and that many organisms of widely different evolutionary backgrounds have shared genes has further complicated the science of taxonomy.
- Stay tuned.

Changes in Taxonomy with Increase in Knowledge

Introduced in 1735		Introduced in 1969		Introduced in 1990		Future Developments
Two Kingdoms		Five Kingdoms		Three Domains		
Kingdom	Kinds of Organisms	Kingdom	Kinds of Organisms	*Domain/* Kingdom	Kinds of Organisms	
Plantae	Bacteria	**Monera**	Bacteria	***Bacteria***	Bacteria	Kingdoms currently being developed
	Archaea		Archaea	***Archaea***	Archaea	Kingdoms currently being developed
				Eucarya		
	Plants	**Plantae**	Plants	**Plantae**	Plants	Probably a valid group—little change
	Fungi	**Fungi**	Fungi	**Fungi**	Fungi	Some reclassification to other kingdoms
	Algae	**Protista**	Algae Protozoa	**Protista**	Algae Protozoa	Will be reorganized into several kingdoms
Animalia	Protozoa Animals	**Animalia**	Animals	**Animalia**	Animals	Probably a valid group—little change

HOW SCIENCE WORKS 20.2

Cladistics: A Tool for Taxonomy and Phylogeny

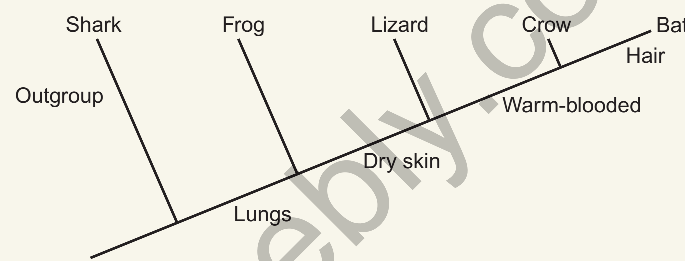
Classification, or taxonomy, is one part of the much larger field of phylogenetic systematics. Classification involves placing organisms into logical categories and assigning names to those categories. Phylogeny, or *systematics,* is an effort to understand the evolutionary relationships of living things in order to interpret the way in which life has diversified and changed over billions of years of biological history. Phylogeny attempts to understand how organisms have changed over time. *Cladistics* (*klados* = branch) is a method biologists use to evaluate the degree of relatedness among organisms within a group, based on how similar they are genetically. The basic assumptions behind cladistics are that

1. Groups of organisms are related by descent from a common ancestor.
2. The relationships among groups can be represented by a branching pattern, with new evolutionary groups arising from a common ancestor.
3. Changes in characteristics occur in organisms over time.

Several steps are involved in applying cladistics to a particular group of organisms. First, you must select characteristics that vary and collect information on the characteristics displayed by the group of organisms you are studying. The second step is to determine which expression of a characteristic is ancestral and which is more recently derived. Usually, this involves comparing the group in which you are interested with an *outgroup* that is related to, but not a part of, the group you are studying. The characteristics of the outgroup are then considered to be ancestral. Finally, you must compare the characteristics displayed by the group you are studying and construct a diagram known as a *cladogram*. For example, if you were interested in studying how various kinds of terrestrial vertebrates are related, you could look at the following characteristics:

Characteristic / Organism	Lungs Present	Skin Dry	Warm-Blooded	Hair Present
Shark	0	0	0	0
Frog	+	0	0	0
Lizard	+	+	0	0
Crow	+	+	+	0
Bat	+	+	+	+

In this example, the shark is the outgroup, and the ancestral conditions are lungs absent, skin not dry, cold-blooded, and hair absent. Using this information, you could construct the following cladogram.



All of the organisms, except sharks, have lungs. Lizards, crows, and bats have dry skin, as well as lungs and so on. Crows and bats share the following characteristics; they have lungs, they have dry skin, and they are warm-blooded. Because they share more characteristics with each other than with the other groups, they are considered to be more closely related.

It is important to recognize that cladistics is a tool and, like any tool, it can be used appropriately or inappropriately. The choice of the outgroup and the characteristics chosen to be evaluated are important to the validity of the process. If a person mistakenly used a whale as the outgroup, they would come to completely different conclusions about how the various kinds of terrestrial vertebrates are related.

It is also important to carefully select the characteristics to be used in making the comparison. Two organisms may share many characteristics but not be members of the same evolutionary group if the characteristics being compared are not from the same genetic background. For example, if you were to compare butterflies, birds, and squirrels using the presence or absence of wings and the presence or absence of bright colors as your characteristics, you would conclude that butterflies and birds are more closely related than birds and squirrels. However, this is not a valid comparison, because the wings of birds and butterflies are not of the same evolutionary origin.

Others move by means of a kind of flagellum. The structure of the flagellum is different from the flagellum found in eukaryotic organisms.

Because the early atmosphere is thought to have been a reducing atmosphere, the first Bacteria were probably anaerobic organisms. Today, there are both anaerobic and aerobic Bacteria. Many heterotrophic Bacteria are **saprophytes,** organisms that obtain energy by the decomposition of dead organic material; others are parasites that obtain energy and nutrients from living hosts and cause disease (Outlooks 20.1); still others are mutualistic and have a mutually beneficial relationship with their host; finally, some are commensalistic and derive benefit from a host without harming it. Several kinds of Bacteria are autotrophic. Many are called cyanobacteria because they contain a blue-green pigment, which allows them to capture sunlight and

OUTLOOKS 20.1

A Bacterium that Controls Animal Reproduction

Wolbachia is a small kind of bacterium called a rickettsia. It is an intracellular parasite that only lives in the cells of its hosts—many kinds of insects, other arthropods, and nematode worms. *Wolbachia* is extremely common—at least 20% of all insects are infected with this parasite. Because it is an intracellular parasite, it is most easily transmitted from one generation of its host to the next during reproduction. Since the eggs of the host species carry *Wolbachia* but the sperm do not, *Wolbachia* is passed from one generation of its host to the next only in the egg of the host as if it were an organelle in the egg. *Wolbachia* manipulates the reproductive biology of its host in several ways that enhance the likelihood that *Wolbachia*-infected female hosts will produce large numbers of *Wolbachia*-infected female offspring.

1. **Egg/sperm incompatibility**
   When a female insect ***uninfected*** with *Wolbachia* mates with a male ***infected*** with *Wolbachia*, some or all of her fertilized eggs die. This means that ***uninfected*** female insects produce fewer offspring than ***infected*** females. Thus, there is a bias toward producing *Wolbachia*-infected offspring.
2. **Killing of host males**
   In some cases, infected male hosts are killed by the presence of the parasite. The killing of male hosts means that only infected females are produced.
3. **Changing the sex of genetic male hosts**
   In some cases, genetic male host offspring that are infected with *Wolbachia* are converted to females. If they are fertile females, they will produce *Wolbachia*-containing eggs. If they are infertile pseudofemales, they do not reproduce.
4. **Parthenogenetic development**
   In certain species of wasps, it appears that infection with *Wolbachia* has resulted in the complete elimination of males. The female wasps reproduce by parthenogenesis, which is a form of reproduction in which unfertilized eggs develop into only female offspring. Thus, all of the female wasps offspring are infected with *Wolbachia*.
5. **Mutualism**
   Some species of nematode worms are unable to reproduce without the presence of *Wolbachia*.

These examples suggest that the *Wolbachia* DNA has taken over some of the functions of its host. In fact, examination of the DNA of the eukaryotic host species shows that they contain *Wolbachia* genes in their nucleus.

carry on photosynthesis. They can become extremely numerous in some polluted waters where nutrients are abundant. Others use inorganic chemical reactions for their energy sources and are called chemosynthetic.

The Domain Archaea

The term *archaea* comes from the Greek word *archaios*, meaning ancient. This is a little misleading, because the Archaea are thought to have branched off from the Bacteria between 2 and 3 billion years ago.

The Archaea are similar to the Bacteria in that they both have a prokaryotic cell structure. However, the Archaea differ from the Bacteria in several fundamental ways. The Archaea do not have peptidoglycan in their cell walls, and the structure of their DNA is different from that of the Bacteria. Although the DNA of the Archaea is a loop, like that of the Bacteria, the DNA of the Archaea appears to have a large proportion of genes that are different from either the Bacteria or the Eucarya. Archaea reproduce asexually by binary fission, as do the Bacteria. They also exchange pieces of DNA between individuals, as do Bacteria. Also, the cell membranes of the Archaea have a unique chemical structure, found in neither the Bacteria nor the Eucarya. Members of the Archaea exist in many shapes, including rods, spheres, spirals, filaments, and flat plates.

Because many members of the Archaea are found in extreme environments, they have become known as *extremophiles*. However, as more species are discovered and organisms that were once thought to be Bacteria are reclassified as Archaea, it is becoming clear there are many that do not live in extreme environments. Archaea use a variety of ways of obtaining energy. Many are autotrophs that use inorganic chemical reactions (chemoautotrophs) or light (photoautotrophs) as sources of energy and carbon dioxide as a source of carbon. Some are heterotrophs and use organic molecules as a source of energy and carbon.

Members of the Archaea are extremely diverse. Based on the particular habitats they occupy and the kind of metabolism they display, Archaea are divided into several functional groups:

1. *Methanogens* are anaerobic, methane-producing organisms. They can be found in sewage, swamps, and the intestinal tracts of termites and ruminant animals, such as cows, sheep, and goats. They are even found in the intestines of humans.
2. *Halobacteria* (*halo* = salt) live in very salty environments, such as the Great Salt Lake (Utah), salt ponds, and brine solutions. Many have a reddish pigment and can be present in such high numbers that they color the water red. Some contain a special kind of chlorophyll and are therefore capable of generating their ATP by a kind of photosynthesis but they do not release oxygen.
3. *Thermophilic* Archaea live in environments that normally have very high temperatures and high concentrations of sulfur (e.g., hot sulfur springs and around deep-sea hydrothermal vents). Over 500 species of thermophiles

have been identified at the openings of hydrothermal vents in the open oceans. One such thermophile, *Pyrolobus fumarii,* grows in a hot spring in Yellowstone National Park (figure 20.10). It grows best at 106°C and can grow at temperatures up to 113°C but will not grow below 90°C. Another species that survives at 122°C has been discovered. Some of these heat-loving Archaea also live in extremely acid conditions.

4. *Marine*, *freshwater*, and *soil Archaea* have recently been discovered to be extremely abundant, but little is yet known about their role in these habitats.
5. Recently an archeon has been discovered that appears to be parasitic on another archeon.

The Domain Eucarya

Most biologists now believe that eukaryotic cells evolved from prokaryotic cells through endosymbiosis (see chapter 19). This hypothesis proposes that structures such as mitochondria, chloroplasts, and several other membranous organelles found in eukaryotic cells were originally separate living organisms that were incorporated into another cell. Once inside another cell, these structures and their functions became integrated with the host cell and ultimately became essential to its survival. This new type of cell was the forerunner of present-day eukaryotic cells.

Eukaryotic cells are usually much larger than prokaryotic cells, typically having more than a thousand times the volume of prokaryotic cells. Their larger size was made possible by the presence of specialized membranous organelles, such as the endoplasmic reticulum, mitochondria, chloroplasts, and nuclei.

Kingdom Protista

The changes in cell structure that led to eukaryotic organisms probably gave rise to single-celled organisms similar to those currently grouped in the kingdom Protista.

There is a great deal of diversity among the approximately 60,000 known species of Protista. Many species live in freshwater; others are found in marine or terrestrial habitats, and some are parasitic, commensalistic, or mutualistic. All species can undergo mitosis, resulting in asexual reproduction. Some species can also undergo meiosis and reproduce sexually. Many are autotrophs that have chloroplasts and carry on photosynthesis. These are commonly called algae. Others are heterotrophs that require organic molecules as sources of energy. These are commonly called protozoa. Both autotrophs and heterotrophs have mitochondria and respire aerobically.

Because members of this kingdom are so diverse with respect to details of cell structure, metabolism, and reproductive methods, most biologists do not think that the Protista form a valid phylogenetic unit and should be divided into several distinct kingdoms. However, it is still a convenient taxonomic grouping. By placing these organisms together in this group, it is possible to gain a useful perspective on how they relate to other kinds of organisms. After the origin of eukaryotic organisms, evolution proceeded along several pathways. Three major lines of evolution within the Protista can be seen. There are plantlike autotrophs (algae), animal-like heterotrophs (protozoa), and funguslike heterotrophs (slime molds). *Amoeba* and *Paramecium* are commonly encountered examples of protozoa. Many seaweeds and pond scums are collections of large numbers of algal cells. Slime molds are seen less frequently, because they live in

FIGURE 20.10 Habitat for Thermophilic Archaea
Thermophilic Archaea are found in hot springs like these at Yellowstone National Park and around thermal vents on the ocean floor.

and on the soil in moist habitats; they are most often encountered as slimy masses on decaying logs. Figure 20.11 shows some examples of this diverse group of organisms.

Kingdom Fungi

Fungus is the common name for members of the kingdom Fungi. The ancestors of fungi were probably related to some of the heterotrophic protozoa. They have evolved several distinct characteristics. Most fungi are nonmotile. They have a rigid, thin cell wall, which contains chitin, a complex carbohydrate containing nitrogen. The members of the kingdom Fungi are nonphotosynthetic, eukaryotic organisms. Most of the approximately 70,000 species (mushrooms and molds) are multicellular, but a few, such as yeasts, are single-celled. In the multicellular fungi, the basic structural unit is a network of multicellular filaments.

Because all of these organisms are heterotrophs, they must obtain nutrients from organic sources. Most are saprophytes and secrete enzymes that digest large molecules into smaller units, which are absorbed as food for the organism. They are very important as decomposers in all ecosystems. They feed on a variety of nutrients ranging from dead organisms to such products as shoes, foodstuffs, and clothing. Most synthetic organic molecules are not attacked as readily by fungi; this is why plastic bags and foam cups are slow to decompose.

Some fungi are parasitic. Many of the parasitic fungi are important plant pests. Some (e.g., chestnut blight, Dutch elm disease) attack and kill plants; others injure the fruit, leaves, roots, or stems. In crop plants, fungi are important pests that kill or weaken plants and reduce yields. The fungi that are human parasites are responsible for athlete's foot, vaginal yeast infections, valley fever, "ringworm," and other diseases.

Other fungi are mutualistic. Lichens are common organisms that consist of a mutualistic relationship between fungal and algal cells. Another important group of mutualistic fungi form an association with the roots of plants and improve the nutrient and water capturing capacity of plants. Indeed many species of plants will not grow without their fungal associates. Figure 20.12 shows examples of several kinds of fungi.

Kingdom Plantae

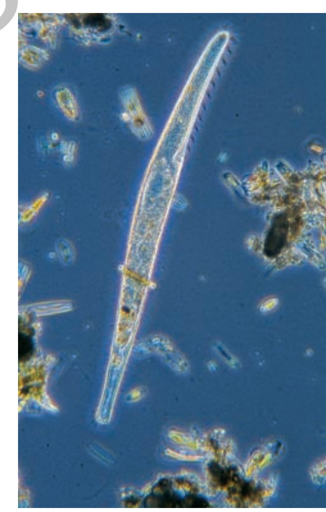
The members of the kingdom Plantae are nonmotile, terrestrial (mostly), multicellular organisms that contain chlorophyll and produce their own organic compounds by photosynthesis. All plant cells have a cellulose cell wall.

Most biologists believe that the evolution of this kingdom began nearly 500 million years ago, when the green algae gave rise to nonvascular plants, such as mosses. The development of vascular (water-transporting) tissue was a major step in the evolution of plants, because it allowed plants to increase in size and to live in drier environmental conditions. Ferns, cone-bearing plants, and flowering plants all have vascular tissue. Some of the vascular plants evolved into seed-producing plants, which today are the cone-bearing and flowering plants, whereas the ferns never developed seeds (figure 20.13). Over 300,000 species of plants have been classified; about 85% are flowering plants, 14% are mosses and ferns, and the remaining 1% are cone-bearers and several other small groups within the kingdom.

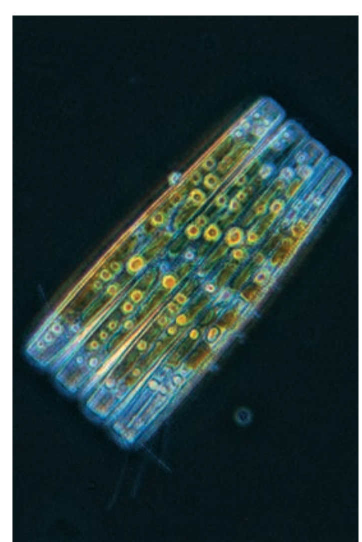
Green Algae

Kelp

Slime mold



Protozoan



Diatom

FIGURE 20.11 A Diversity of Protista
The kingdom Protista includes a wide variety of organisms that are simple in structure. They are not a phylogenetic group.

FIGURE 20.12 Examples of Fungi
Molds, mushrooms, and puffballs are common examples of this kingdom.

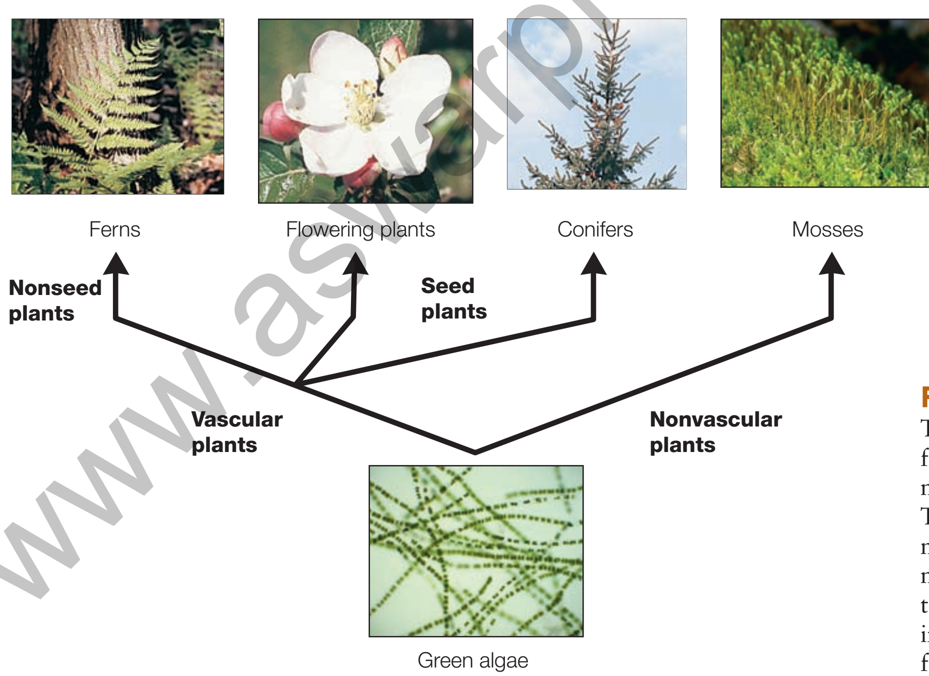


FIGURE 20.13 Plant Evolution
Two lines of plants are thought to have evolved from the green algae of the kingdom Protista. The nonvascular mosses evolved as one type of plant. The second type, the vascular plants, evolved into more complex plants. The early vascular plants did not produce seeds, like present-day ferns. Eventually, the evolution of the ability to produce seeds resulted in two distinct lines: the cone-bearing plants and the flowering plants.

A major unifying theme in the plants and their green alga ancestors is the presence of a unique life cycle with two distinct generation or stages. They have a haploid **gametophyte generation**, which produces haploid sex cells by mitosis. The sex cells unite to form a diploid zygote that grows into a diploid **sporophyte generation**. The sporophyte generation produces haploid spores by meiosis and the haploid spores germinate and grow into the gametophyte generation. This kind of life cycle is referred to as **alternation of generations**. In addition to sexual reproduction, plants are able to reproduce asexually.

Kingdom Animalia

Over a million species of animals have been classified, ranging from microscopic types, such as mites and the aquatic larvae of marine animals, to huge animals, such as elephants and whales. All animals have some common traits. All are composed of eukaryotic cells and all species are heterotrophic and multicellular. All animals are motile, at least during some portion of their lives, although some, such as the sponges, barnacles, mussels, and corals, are sessile (i.e., nonmotile) as adults. All animals are capable of sexual reproduction, but many of the less complex animals also reproduce asexually.

The ancestors of the kingdom Animalia are thought to be certain kinds of flagellated protozoa. It is thought that colonies of flagellated protozoa gave rise to simple, multicellular forms of animals such as the ancestors of present-day sponges. These first animals lacked specialized tissues and organs. As cells became more specialized, organisms developed special tissues, organs, and systems of organs, and the variety of kinds of animals increased (figure 20.14).

Sponge

Sea anemone

Earthworm

Insect

Mammal and bird

FIGURE 20.14 Animal Diversity
Animals range in complexity from simple, marine sponges and sea anemones to complex, terrestrial insects, birds, and mammals.

20.2 CONCEPT REVIEW

6. List two ways that Bacteria and Archaea differ.
7. Describe two distinctly different ways that Bacteria obtain energy.
8. Describe two distinctly different ways that Archaea obtain energy.
9. List the four kingdoms of the domain Eucarya and give two distinguishing characteristics for each.
10. Which of the following groups of organisms contain members that are autotrophic: Bacteria, Archaea, Protista, Fungi, Plantae, Animalia?

20.3 Acellular Infectious Particles

All of the groups discussed so far are cellular forms of life. They all have at least the following features in common. They have (1) cells that have an outer plasma membrane and contain organelles, (2) DNA as genetic material that is involved in reproduction, (3) enzyme-controlled metabolic pathways, (4) an ability to reproduce, and (5) an ability to adapt to their environment physiologically and evolutionarily.

However, some particles show some characteristics of life and cause disease but do not have a cell structure and cannot perform some life functions without the assistance of living cells. Because they lack a cell structure, they are referred to as *acellular* (*a* = lacking). Because they enter cells, cause disease, and can be passed from one organism to another, they are often called infectious particles. In causing disease, they make copies of themselves. There is no clear explanation of how these particles came to be. Therefore, they are not included in the classification system for cellular organisms. There are three kinds of acellular infectious particles: *viruses*, *viroids*, and *prions*.

Viruses

A **virus** is an acellular infectious particle consisting of a nucleic acid core surrounded by a coat of protein (figure 20.15). Viruses are often called *obligate intracellular parasites*, which means they are infectious particles that can function only when inside a living cell. Viruses are not considered to be living because they are not capable of living and reproducing by themselves and because they show some characteristics of life only when inside living cells.

Viruses vary in size and shape, which helps in classifying them. Some are rod-shaped, others are spherical, and still others are in the shape of a coil or helix. Most are too small to be visible through a light microscope and require an electron microscope to make them visible. Most viruses are identified by the disease symptoms they cause when they infect cells. It is very likely that all species on Earth serve as hosts to viruses (table 20.2).

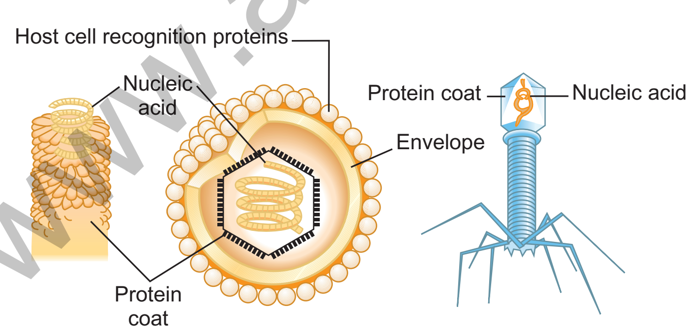


FIGURE 20.15 Typical Viruses
Viruses consist of a core of nucleic acid, either DNA or RNA, surrounded by a protein coat. Some have an additional layer, called an envelope, surrounding the protein coat.

How Did Viruses Originate?

Soon after viruses were discovered in the late nineteenth century, biologists began to speculate on how they originated. One early hypothesis was that they were descendents of the first precells that did not evolve into cells. This idea was discarded as biologists learned more about the complex relationship between viruses and host cells. The recent discovery of a giant virus—mimivirus—in amoebas has added evidence that in their evolutionary past, viruses were more complex. The mimivirus is as large as some bacteria and has as many genes. It has both DNA and RNA. All other known viruses have only DNA or RNA as genetic material—not both. However, its structure is similar to that of other viruses and it shows a typical virus life cycle.

A second hypothesis was that viruses developed from intracellular parasites that became so specialized that they needed only their nucleic acid to continue their existence. Once inside a cell, this nucleic acid can take over and direct the host cell to provide for all of the virus's needs.

A third hypothesis is that viruses are runaway genes that have escaped from cells and must return to a host cell to replicate. Regardless of how the viruses came into being, today they are important as parasites in all forms of life.

TABLE 20.2 Viral Diseases

Type of Virus	Disease
Papovaviruses	Warts in humans
Paramyxoviruses	Mumps and measles in humans; distemper in dogs
Adenoviruses	Respiratory infections in most mammals
Poxviruses	Smallpox
Wound-tumor viruses	Diseases in corn and rice
Potexviruses	Diseases in potatoes
Bacteriophage	Infections in many types of bacteria

How Do Viruses Cause Disease?

Viruses are typically host-specific, which means that they usually attack only one kind of cell. The host is a specific kind of cell that provides what the virus needs to function. Viruses can infect only the cells that have the proper receptor sites to which the virus can attach. This site is usually a glycoprotein molecule on the surface of the cell membrane. For example, the virus responsible for measles attaches to the membranes of skin cells, hepatitis viruses attach to liver cells, and mumps viruses attach to cells in the salivary glands. Host cells for the human immunodeficiency virus (HIV) include some types of human brain cells and several types belonging to the immune system.

Once it has attached to the host cell, the virus either enters the cell intact or injects its nucleic acid into the cell. If it enters the cell, the virus loses its protein coat, releasing the nucleic acid. Once released into the cell, the virus's nucleic acid may remain free in the cytoplasm, or it may link with the host's genetic material. Some viruses contain as few as 3 genes; others contain as many as 500. A typical eukaryotic cell contains tens of thousands of genes. Most viruses need only a small number of genes, because they rely on the host to perform most of the activities necessary for viral multiplication.

Some viruses have DNA as their genetic material but many have RNA. Many RNA viruses can be replicated directly, but others must have their RNA reverse-transcribed to DNA before they can reproduce. Reverse transcriptase, the enzyme that accomplishes this has become very important in the new field of molecular genetics, because its use allows scientists to make large numbers of copies of a specific molecule of DNA.

Viruses do not divide like true cells; they are *replicated*. Virus particles are replicated by using a set of genetic instructions from the virus and new building materials and enzymes from the host cell. Viral genes take command of the host's metabolic pathways and use the host's available enzymes and ATP to make copies of the virus. When enough new viral nucleic acid and protein coat are produced, complete virus particles are assembled and released from the host (figure 20.16). In many cases, this process results in the death of the host cell. When the virus particles are released, they can infect adjacent cells and the infection spreads. The number of viruses released ranges from 10 to thousands. The virus that causes polio affects nerve cells and releases about 10,000 new virus particles from each human host cell. Some viruses remain in cells and are only occasionally triggered to reproduce, causing symptoms of disease. Herpes viruses, which cause cold sores, genital herpes, and shingles, reside in nerve cells and occasionally become active.

Some viruses cause serious disease; others cause mild symptoms. It is also highly likely that there are viruses that require cells for reproduction but go unrecognized because they do not cause the death of cells or cause disease symptoms.

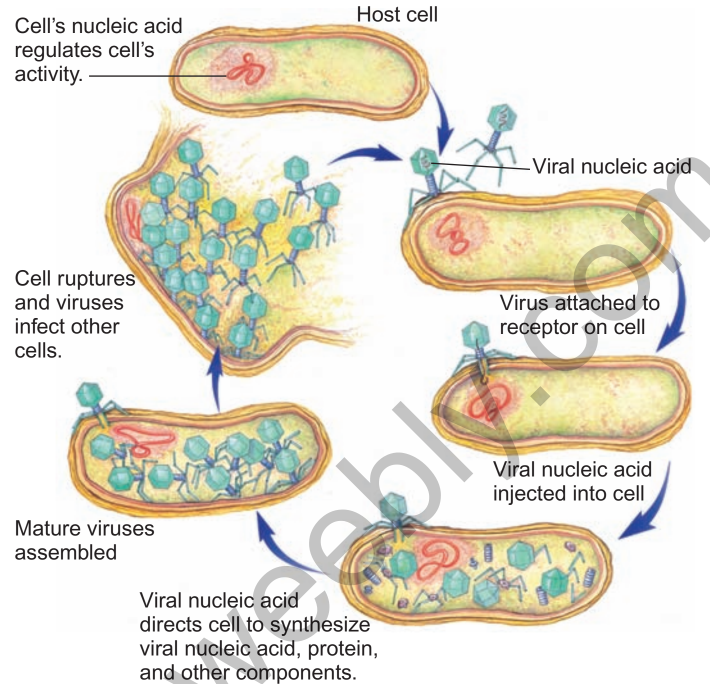


FIGURE 20.16 Viral Invasion of a Bacterial Cell
The viral nucleic acid takes control of the activities of the host cell. Because the virus has no functional organelles of its own, it can become metabolically active only while it is within a host cell. The viral genetic material causes the host cell to make copies of the virus, ultimately resulting in the destruction of the host cell.

Viroids: Infectious RNA

A **viroid** is an infectious particle composed solely of a small, single strand of RNA in the form of a loop. To date, no viroids have been found to infect animal cells. The hosts in which they have been found are cultivated crop plants, such as potatoes, tomatoes, and cucumbers. Viroid infections result in stunted or distorted growth and may cause the plant to die. Pollen, seeds, and farm machinery can transmit viroids from one plant to another. Some scientists believe that viroids are parts of normal RNA from plant cells that have gone wrong.

Prions: Infectious Proteins

Prions are thought to be proteins that can be passed from one organism to another and cause disease. All the diseases of this type cause changes in the brain that result in a spongy appearance called spongiform encephalopathies. Because these diseases can be transmitted from one animal to another, they are often called transmissible spongiform encephalopathies. The symptoms typically involve abnormal behavior and eventually death. There are many scientists who are still cautious about accepting prions as a cause of disease. Although it appears that proteins are involved in these diseases, they suggest that environmental factors may be causing changes in the proteins rather than having the proteins passed from organism to organism.

Examples of Prion Diseases

In animals, the most common examples are scrapie in sheep and goats and mad cow disease in cattle. Scrapie got its name because one of the symptoms of the disease is an itching of the skin associated with nerve damage that causes the animals to rub against objects and scrape their hair off.

In humans, there are several similar diseases. Kuru is a disease known to have occurred in the Fore people of the highlands of Papua New Guinea. The disease was apparently spread because the people ate small amounts of the brain tissue of dead relatives. (This ritual was performed as an act of love and respect for their relatives.) When the Fore people were encouraged to discontinue this ritual, the incidence of the disease declined. Creutzfeldt-Jakob disease (CJD) is found throughout the world. Its spread is associated with medical treatment; contaminated surgical instruments and tissue transplants, such as corneal transplants, are the most likely causes of transfer from infected to uninfected persons.

The occurrence of mad cow disease (bovine spongiform encephalopathy—BSE) in Great Britain in the 1980s and 1990s was apparently caused by the spread of prions from sheep to cattle. This occurred because of the practice of processing unusable parts of sheep carcasses into a protein supplement that was fed to cattle. It now appears that the original form of BSE has changed to a variety that is able to infect humans. This new form is called vCJD; scientists believe that BSE and CJD are, in fact, caused by the same prion.

A form of transmissible spongiform encephalopathy called *chronic wasting disease* is present in elk and deer in parts of the United States and Canada. It is called chronic wasting disease because the animals lose muscle mass and weight as a result of the prion infection. Similar diseases occur in mink, cats, and dogs.

How Prions Cause Disease

How are prions formed and how do they multiply? Prion multiplication appears to result from the disease-causing prion protein coming in contact with a normal body protein and converting it into the disease-causing form, a process called *conversion*. Because this normal protein is produced as a result of translating a DNA message, scientists looked for the genes that make the protein and have found it in a wide variety of mammals. The normal allele produces a protein that does not cause disease but is able to be changed by the invading prion protein into the prion form. Prions do not reproduce or replicate as do viruses and viroids. A prion protein (pathogen) presses up against a normal (not harmful) body protein and may cause it to change shape to that of the dangerous protein. When this conversion happens to a number of proteins, they stack up and interlock, as do the individual pieces of a Lego toy. When enough link together, they have a damaging effect—they form plaques (patches) of protein on the surface of nerve cells, disrupting the flow of the nerve impulses and eventually causing nerve cell death. Brain tissues taken from animals that have died of such diseases appear to be full of holes, thus the name spongiform encephalopathy.

A person's susceptibility to acquiring a prion disease, such as CJD, depends on many factors, such as his or her genetic makeup. If a person produces a functional protein with a particular amino acid sequence, the prion may not be able to convert it to its dangerous form. Other people may produce a protein with a slightly different amino acid sequence that can be converted to the prion form. Once formed, these abnormal proteins resist being destroyed by enzymes and most other agents used to control infectious diseases. Therefore, individuals with the disease-causing form of the protein can serve as the source of the infectious prions. There is still much to learn about the function of the prion protein and how the abnormal, infectious protein can cause copies of itself to be made. A better understanding of the alleles that produce proteins that can be transformed by prions will eventually lead to the prevention and effective treatment of these serious diseases in humans and other animals.

20.3 CONCEPT REVIEW

11. Why do viruses invade only specific types of cells?
12. Describe how viruses reproduce.
13. Describe how viruses and viroids differ in structure.
14. What is the chemical structure of a prion?
15. How does a prion cause disease?

Summary

To facilitate accurate communication, biologists assign a specific name to each species that is cataloged. The various species are cataloged into larger groups on the basis of similar traits.

Taxonomy is the science of classifying and naming organisms. Phylogeny is the science of trying to figure out the evolutionary history of a particular organism. The taxonomic ranking of organisms reflects their evolutionary relationships. Fossil evidence, comparative anatomy, developmental stages, and biochemical evidence are used in taxonomy and phylogeny.

The first organisms thought to have evolved were prokaryotic, single-celled organisms of the domain Bacteria. Current thinking is that the domain Archaea developed from the Bacteria and, ultimately, more complex, eukaryotic, many-celled organisms evolved. These organisms have been classified into the kingdoms Protista, Fungi, Plantae, and Animalia within the domain Eucarya.

There are three kinds of acellular infectious particles: viruses, viroids, and prions. Viruses consist of pieces of genetic material surrounded by a protein coat. Viroids consist of naked pieces of RNA. Prions are proteins. Viruses and viroids can be replicated within the cells they invade. Prions cause already existing proteins within an organism to deform, resulting in disease.

Key Terms

*Use the interactive flash cards on the **Concepts in Biology, 14/e** website to help you learn the meaning of these terms.*

Basic Review

1. In the binomial system for naming organisms, an organism is given two names: the _____ and the specific epithet.
2. The most inclusive group into which an organism can be classified is the
   a. phylum.
   b. genus.
   c. domain.
   d. kingdom.
3. Phylogeny is the study that attempts to
   a. name organisms.
   b. organize organisms into groups based on how they evolved.
   c. decide on the names of phylums.
   d. classify organisms.
4. Closely related organisms should have very similar reproductive stages. (T/F)
5. Fossils
   a. provide information about when organisms lived.
   b. are found in sediments that form rock.
   c. of soft-bodied animals are rare, compared with those with hard body parts.
   d. All of the above are true.
6. The Bacteria and Archaea are prokaryotic. (T/F)
7. Which one of the following organisms has not been placed in the kingdom Protista?
   a. protozoa
   b. algae
   c. yeast
   d. slime mold
8. Which one of the following kinds of plants does not have seeds?
   a. ferns
   b. pine trees
   c. roses
   d. apple trees
9. All viruses have DNA. (T/F)
10. Prions are proteins. (T/F)
11. The kingdom Protista is a valid phylogenetic category. (T/F)
12. All of the following are members of the domain Eucarya EXCEPT
    a. cows
    b. mushrooms
    c. algae
    d. Bacteria
13. The Archaea
    a. are eukaryotic.
    b. have ribosomes.
    c. have a nucleus.
    d. All of the above are correct.
14. Plants have a life cycle that shows alternation of _____.
15. All animals and fungi are heterotrophs. (T/F)

Answers
1. genus 2. c 3. b 4. T 5. d 6. T 7. c 8. a 9. F 10. T 11. F 12. d 13. b 14. generations 15. T

Thinking Critically

Examine Life
A minimum estimate of the number of species of insects in the world is 750,000. Perhaps, then, it would not surprise you to see a fly with eyes on stalks as long as its wings, a dragonfly with a wingspread greater than 1 meter, an insect that can revive after being frozen at −35°C, and a wasp that can push its long, hairlike, egg-laying tool directly into a tree. Only the dragonfly is not presently living, but it once was. What other curious features of this fascinating group can you discover? Have you looked at a common beetle under magnification? It will hold still if you chill it.