12.1 Adaptation

EXPECTATIONS

- **Explain the process of adaptation of individual organisms to their environments.**
- **Describe the relationship between natural selection and adaptation.**
- **Describe different types of adaptations, explain how complex adaptations might have evolved, and describe exaptation.**

The broad, flat leaves of a maple tree and the spines of a cactus are features that enable these plants to live in environments that have different conditions. A species of broad-leafed tree would not survive in the hot, dry desert or in the cold, dry tundra of northern Canada. In these environments, such trees would lose too much water across the large surface of their leaves. In contrast, the spines (which are modified leaves) of cacti, along with other characteristics, reduce water loss. With respect to absorption of light, the broad maple leaf provides a large area to absorb the moderate amounts of sunlight present in a temperate climate. In contrast, cacti live in an environment with an abundance of strong sunlight and a generally dry atmosphere, so they can absorb enough light through their small leaves or through their stems without losing moisture. Leaf shape is an important trait with respect to survival in plants. The sharp canine teeth of cougars and other carnivores; the agile, flexible hooves of mountain goats; and the ability of Arctic char to withstand near-freezing water temperatures are all traits that are important to survival (see Figure 12.1). Any trait that enhances an organism's fitness or that increases its chance of survival and probability of successful reproduction is called an **adaptation**. How exactly do adaptations arise?

Adaptation is essentially a product of natural selection. Organisms become adapted to their immediate environment over a period of time through natural selection. As populations are subjected to the vagaries of their environment, the genetic characteristics that are best adapted or well-suited to the environment are selected. For instance, populations living in cold areas will have a variety of features and behaviours that make them better adapted to withstand the cold. Those individuals that possess characteristics that enable them to survive in the cold will reproduce and may pass on these favourable adaptations to their offspring. Natural selection can, along with selective pressures, affect the number of individuals with particular traits. The result may be an adaptation of the population.

When discussing adaptations, it is important to note that the environment is more than just the immediate surroundings of an organism. Environment includes all the factors, other than genetic make-up, that can affect whether or not an organism lives through the embryo, juvenile, and adult stages to reproduce. For example, whether a plant successfully resists the selective pressure of its environment depends on many factors. These factors include the speed and normality of its germination, whether bacteria or fungi infect it as a seedling, and whether the soil in which it grows can support it. To complicate matters further, selective pressures can be contradictory. For example, warm or hot temperatures may increase the rate of plant growth, but they can also dry out the soil, thus impeding proper root growth.

Figure 12.1 The Arctic char (*Salvelinus alpihus*) has adapted to cold Arctic waters.

Adaptations may occur as particular variations increase in frequency within a population of organisms. However, variation and adaptation are not the same. A variation may improve fitness, but it may also have no effect on or even reduce fitness. Any variations that are the result of changes in the dominant alleles in the population and that may reduce fitness in the current environment will decrease in frequency in the population by natural selection. For example, the length and shape of dragonfly wings are adaptations for flight and, thus, for survival, since dragonflies prey on other insects in flight. Wing length within a population will vary slightly, but there is an optimal wing length that best suits the current environment in which the population lives. If a dragonfly has wings that are too short, it may not be able to generate enough lift to stay off the ground. If its wings are too long, they may become too heavy. So, there is a certain length of wing that results in the greatest fitness for dragonflies. Variations — such as the length of dragonfly wings, or the sharpness of eagle talons — that aid in survival and increase fitness will be preserved in a population by natural selection. If a variation is favourable for an individual, the chances are greater that the individual will survive to pass on its genes to its offspring. Over time, all surviving members of a population will have inherited that variation, at which point the original variation becomes an adaptation. In other words, the adaptation has become a general characteristic of the entire population, like a dragonfly's wing length or the sharpness of eagle talons. *In summary, while adaptations are products of natural selection, variations within a species are the raw material upon which natural selection acts.*

Evolution of Complex Adaptations

When you imagine the human eye, it seems impossible that all of its intricate parts (the lens, pupil, retina, muscles, vitreous humour, blood, nerves, and pigment), which work together to focus light into images, could have combined randomly to make such a complex organ. Adaptations, particularly ones such as the change from a simple to a complex eye, do not arise all at once. Rather, adaptations evolve over time as a result of a series of small adaptive changes. Each change is a slight modification of the traits of the previous generation.

The adaptations in the organisms living today are the result of natural selection acting on chance variations that arose at particular times in the evolutionary history of these organisms. For example, the eye has evolved in a series of steps, with each step providing organisms with vision that was slightly better for its given environmental conditions. Many marine invertebrates, such as the scallop in Figure 12.2, have ocelli — clusters of light-sensitive cells that allow the organisms to detect movement and luminosity (light level). Their eyes do not form an image. On the other hand, insects such as the fly in Figure 12.3 have compound eyes, which are excellent for detecting movement and which also form an image.

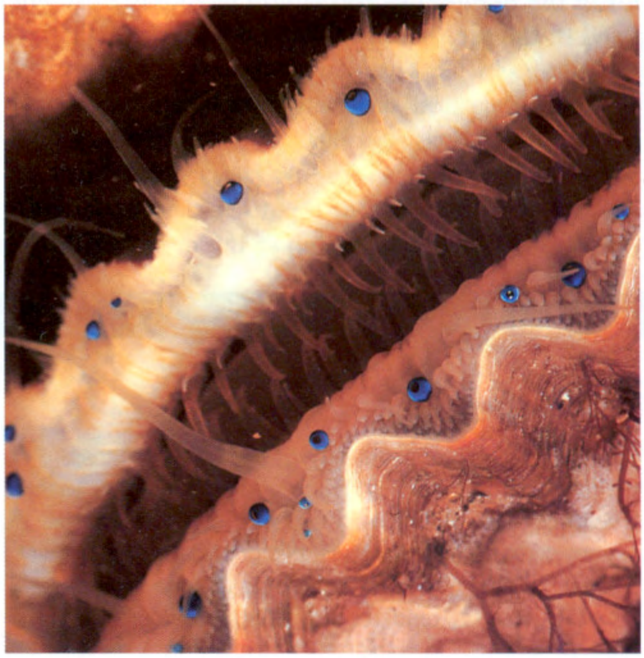


Figure 12.2 Scallops have simple eyes that are able to detect changes in light and movement, but they cannot form an image.

Figure 12.3 A compound eye enables a fly to see images.

Primitive eyes were simply a cluster of light-sensitive cells. These rudimentary "eyes" probably gave the ancient organisms an ability to see movement and to distinguish between light and dark. This gave them a selective advantage in their environment as they could detect movement of a potential predator. Over time, new variations of eyes arose in populations. For example, natural selection resulted in the formation of a simple lens that provided a blurry image. Since seeing even a blurred image is generally an advantage over seeing no image at all, this characteristic would be selected for in the population and would eventually become fixed in the population. Subsequent changes in some animals led to a sharpening of focus and, eventually, permitted colour vision. In other animals, there was no selective pressure for an advanced type of eye. In these cases, the genes for a simple lens would continue to be passed on to future generations. Each step in the evolution of eyes was due to random variations that arose in populations, and to the perpetuation of these variations within the population where the traits provided a selective advantage in a particular habitat. As a structure such as an eye becomes more adaptive for some animals and improves an animal's chances of survival, the chances of these genes being passed to offspring are increased.

WEB LINK

www.mcgrawhill.ca/links/biology12

While the eyespots of flatworms are not nearly as complex as the human eye, they still provide the flatworm with an advantage in its environment. To learn more about the evolution of a fish eye, and how long biologists think this might have taken, go to the web site above, and click on **Web Links**. Make a time line showing the changes that might have led from an eyespot to a fish eye.

MINI LAB

Small Changes, Large Gains

The adaptations that enable species to live within their environment are often difficult, or impossible, to see. Many adaptations are internal, such as changes in biochemical pathways responsible for metabolic processes. Other adaptations happen in very small steps. In the population of finches that you read about in Chapter 10 (on page 347), researchers found than even a millimetre in beak length could mean the difference between life and death in some situations. In this MiniLab, you will learn how small advantages can result in large gains for particularly well-adapted individuals.

You will need a number of different sizes, lengths, and styles of forceps and/or household tweezers. You will also need three types of small- to medium-sized seeds, such as sesame seeds, lentils, and rice. (These seeds are referred to as seeds A, B, and C here.) Mix about 30 to 40 of each of the three types of seeds together in one tray, making sure that there are an equal number of each type of seed at the beginning of the lab. Choose one style of forceps and attempt to gather seeds (any type) for 20 s. Record the number of seeds gathered by type, and record the particular characteristics of the forceps used to gather each seed. Repeat this trial three times and determine the average number of seeds gathered. Repeat this procedure using two other styles of forceps.

Now assume that there has been an environmental event (such as a drought or flood) that has reduced the availability of seed A. To simulate this, leave only 10 percent of seed A in the tray. Repeat the trials and compare the results.

Finally, assume there is an environmental event that has reduced the number of seeds B and C and doubled the number of seed A. Leave only 10 percent of seeds B and C in the tray and double the number of seed A. Repeat the trials and compare the results.

Analyze

1. Graph your results from these trials.
2. Describe any correlation between the characteristics of the forceps and their ability to pick up particular types of seeds.
3. Describe what happened after the first environmental event when the number of seed A available was reduced. How might this have affected the subsequent generations if the tweezers were actually a type of bird beak?
4. Describe what happened after the third trial. Were any of the effects of the first trial reversed? Explain how this might happen in natural situations.
5. Natural populations can have good years when the populations boom and poor years when the populations decline. Did your experiment demonstrate this phenomenon? How could you have adjusted your experiment to make it more realistic?

The Changing Function of Adaptations

Sometimes an adaptation that evolved for one function can be co-opted for another use. Originally this was called pre-adaptation, but since this term implies that there is a level of conscious planning in advance (which is not the case in evolution), a new term was coined — **exaptation**. As an example, the invertebrate ancestors of vertebrates may have stored phosphate in their skin to help them survive lean times. It turns out that the best way to store phosphate was in a matrix of calcium, which created a hard tissue. This hard tissue (for example, the shell in Figure 12.4) could also protect an animal from predators. Therefore, what originally evolved as an adaptation for metabolic processes was exapted and used for protection. Later, a calcium matrix of bone was used for muscle attachment and became the framework, or skeleton, of vertebrates.

The limbs and digits of terrestrial vertebrates did not evolve in response to a demand for walking on land. Instead, they evolved in fully aquatic tetrapods (four-legged creatures) such as *Acanthostega* that used legs and toes to move in coastal wetlands. (You were introduced to *Acanthostega* in section 10.3 on page 354.) These organisms used these limbs to crawl over logs, grip onto rocks, and clamber through marshy areas. When some of these tetrapods ventured onto land, the limbs proved useful. A living example is the lungfish of Africa, that uses its fleshy fins to move from pond to pond and to bury itself in the mud during dry periods. Paleontologists have discovered approximately 12 species of early tetrapods and all appear to have been aquatic. Thus, what evolved as an adaptation for an aquatic existence eventually became useful for a life on land. It is as though evolution borrowed something adapted for one function to perform a new function.

Types of Adaptations

Adaptations can be broadly classified as structural (or anatomical), physiological, or behavioural. The different arrangement of teeth in carnivores, herbivores, and omnivores; the tissues in vascular plants that allow transport of water and food; and the shape of fins or beaks are all **structural adaptations**. These adaptations can be anatomical (that is, dealing with the shape or arrangement of particular features), but structural adaptations can also include **mimicry** and **cryptic coloration**.

Mimicry enables one species to resemble another species or part of another species. Often, a harmless species will mimic a harmful species; the result is that predators that avoid the harmful species will also avoid the mimic. For example, the fly in Figure 12.5 is a harmless mimic of a yellow-jacket wasp. This fly, as well as other insects including some beetles, capitalizes on the fact that many predators will avoid anything with black and yellow patterning after being stung a few times by bees or wasps.

Figure 12.4 Shells are made of calcium carbonate. Calcium was originally stored by invertebrates as a way to stockpile phosphates, an energy source.

Figure 12.5 Mimics, such as this syrphid fly, copy the coloration or patterns of harmful species as a defence against predators.

Cryptic coloration makes potential prey difficult to spot. For example, animals may have colouring that blends well with their surroundings. Other animals can be camouflaged by shape and colouring, such as the bizarre sea horse (called a sea dragon) that lives among a particular type of seaweed. Figure 12.6 shows how a sea dragon can look like the algae in which it lives. Potential prey do not distinguish the sea dragon from its seaweed surroundings, and can be lured into the relative safety of the seaweed only to be consumed by the sea dragon.

Many structural adaptations are internal rather than external. For example, the strong muscle walls of the human heart are an adaptation than enables the heart to pump blood throughout the body. As another example, the digestive tracts of herbivores and omnivores are much longer relative to body size than the digestive tracts of carnivores. Vegetation is more difficult to digest than meat because of its tough cellular walls. A longer digestive tract permits more time for digestion and a greater surface area for the absorption of nutrients.

Physiological adaptations are those adaptations associated with functions in organisms. The enzymes needed for blood clotting, the proteins used in spiders' silk, the chemical defences of plants, and the ability of certain bacteria to withstand extreme heat are all examples of physiological adaptations.

Organisms are also adapted in how they respond to the environment. These **behavioural adaptations** include migration, courtship displays, foraging behaviour, and the response of plants toward light and gravity. Animals have found different ways to avoid severe environmental conditions with adaptations such as the migration of monarch butterflies, hummingbirds, caribou, and wildebeests; the winter sleep of bears and skunks; and the hibernation of jumping mice, some turtles, and garter snakes. No doubt, some of these adaptations evolved in response to changes in environmental conditions as the continents formed and moved. All these behavioural changes are the result of natural selection — those individuals that survived passed on their genes to the next generation. For example, the monarch butterflies that moved to warmer climates survived and passed on the behavioural traits for migration.

In natural situations, it is unrealistic to isolate and classify adaptations in rigid categories because adaptations often depend upon one another. For example, bird migration is considered a behavioural adaptation. But migration would not be possible without a complex set of structural adaptations such as feathers, light bones, and strong wing muscles. As well, a variety of physiological adaptations, from nerve impulses to the release of hormones, enable flight and migration to happen.

Figure 12.6 The coloration and leafy appearance of the sea dragon's (*Phycodurus sp.*) fanlike fins keep it well hidden among the seaweed in which it usually lives.

BIO FACT

The feathers and lightweight, honeycombed bones of birds are examples of exaptation. The fossil record shows that light bones actually predated flight. This means that lightweight bones must have had some use on land. It is thought that the agile, bipedal (two-legged) dinosaurs that were the probable ancestors of birds benefited from a lightweight frame. The wing-like forelimbs and the feathers (which originally had other uses, perhaps in courtship displays or in providing warmth) were also co-opted for flight. The first flights may have been hops when pursuing prey or escaping predators. As this behaviour became advantageous in the environment, the structural adaptations that allowed it to happen were passed on.

ELECTRONIC LEARNING PARTNER

Refer to your Electronic Learning Partner for more information on mimicry.

Is Evolution Perfection?

It is sometimes assumed that the result of adaptation and natural selection is perfection in organisms. This is not the case, however, for a variety of reasons. As mentioned earlier in this section, selection can only edit variations that already exist in a population; evolution essentially has to "make do" with what is presented. As a result, designs are often awkward or less than optimal. An example is the human eye, since the neurons in our retina point backward. Although our eye works well, in many ways it is quite inefficient. In general, organisms are locked into the constraints of their evolutionary history; therefore perfection is not easily achieved. Since species have descended from a long line of ancestors, they are tied to their existing anatomy. It is not the case that old structures are scrapped and new structures are created with each step in evolution. Rather, existing structures are co-opted and adapted for the new environment. The result is designs that are sometimes less than perfect. The chronic back pain experienced by many humans is thought to result from the musculature and skeleton that have been modified from our four-legged ancestors, who were not adapted specifically for an upright posture.

Another reason that adaptations and natural selection do not achieve perfection is that adaptations are often compromises. A sea lion must swim, but it must also move about on land. In their present structure, sea lions can swim well but they are far less efficient at walking.

Finally, not all evolution is necessarily adaptive. Chance events such as tropical storms or volcanoes can also affect the composition of the gene pool. Some individuals survive this type of event randomly, and it is these individuals that remain to supply the variation upon which natural selection acts as future generations emerge.

The individuals that survive and reproduce will pass on their genes to their offspring. Over time, the populations of individuals change. In the next section, you will find out how new species can be formed from changing populations.

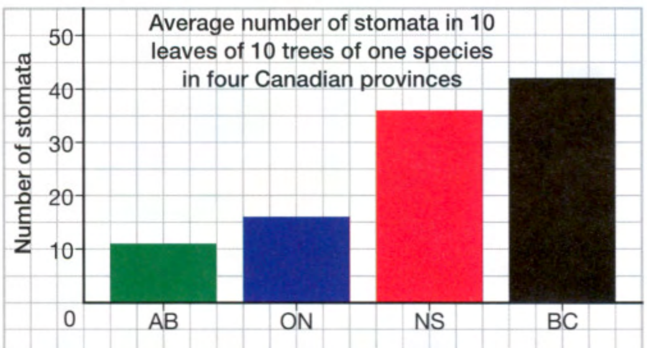
BIO FACT

Examples of ineffective adaptations include thumbs in pandas (which require the redirection of muscles from the hand to operate), hollow bones in flightless birds such as penguins (which do not need light bones since they do not fly anyway), as well as teeth in fetal baleen whales and tails in humans (both of which are re-absorbed before birth, and thus never used).

SECTION REVIEW

1. K/U Describe two mammal adaptations. Explain how each trait is adaptive.

2. I Stomata are openings on the surface of leaves that allow plants to release water. Analyze the following data showing the number of stomata on the leaves of one tree species. What might these data tell you about the rainfall in the areas where the data were collected? What is the relationship between rainfall and number of stomata?



3. C Describe, with the aid of a sketch, a plausible pathway for the evolution of a complex adaptation such as the vertebrate eye.

4. K/U Was a primitive eye that was 95 percent less effective than a modern eye useless? Explain your answer.

5. K/U Are the following adaptations behavioural, structural, or physiological? Give reasons for your answers.
   (a) plant stems grow toward light
   (b) woodpeckers' bills are pointed and sharp
   (c) cacti have spines
   (d) spiders use proteins in their webs
   (e) flowers produce scent

6. K/U Describe the relationships among variations, adaptations, and natural selection.

7. K/U Give two examples of behavioural adaptations and explain how they may have evolved.

8. K/U Explain why adaptation and natural selection do not result in perfection.

9. K/U Evolutionary biologist Karel Liem said that "Evolution is like modifying a machine while it's still running." Explain what this statement means.