Vertebrates are a diverse group of land-based and aquatic animals that share certain characteristics.

25.1 Vertebrate Origins  TEKS 7A, 8B, 8C
25.2 Fish Diversity  TEKS 8B, 10A
25.3 A Closer Look at Bony Fish  TEKS 7B, 7E

Data Analysis
CONSTRUCTING SCATTERPLOTS  TEKS 2G

25.4 Amphibians  TEKS 7A, 7D, 7E, 8B, 8C
25.5 Vertebrates on Land  TEKS 7A, 7B

ONLINE BIODIVERSITY

ONLINE Labs
- Fish Reproduction
- QuickLab  Frog Development
- Anatomy of a Bony Fish
- Vanishing Amphibian—an Indicator Species
- Homologies in Vertebrate Skeletons
- Examining Zebrafish Development

Video Lab  Live Frog Observation
Comparisons
Comparing is a way of looking for similarities among different things. Contrasting is a way of looking for the differences. Comparison words include like, similar to, and also. Contrast words include unlike, however, and although.

YOUR TURN
In the following sentences, identify the things that are being compared or contrasted.
1. Like oranges, bananas have a thick peel. However, the seeds of bananas can be eaten easily.
2. Like fish, frogs lay eggs in water. Unlike fish, frogs do not have scales.

Why is this frog see-through?
The Fleischmann’s glass frog is one of several members of the family Centrolenidae. Glass frogs lack pigment on their undersides, making their skin transparent. The skin on the top portion of their body has a pigment that reflects the same wavelength of light as plants, helping them to blend in with the green leaves on which they live.
Vertebrate Origins

**KEY CONCEPT** All vertebrates share common characteristics.

**MAIN IDEAS**
- The phylum Chordata contains all vertebrates and some invertebrates.
- All vertebrates share common features.
- Fossil evidence sheds light on the origins of vertebrates.

**VOCABULARY**
- chordate
- notochord
- endoskeleton

**Connect to Your World**

Just like the glass frog, you too are a vertebrate. So are birds, tigers, lizards, and squirrels. While the vertebrates you most often see are those that live on land like us, the group first evolved in the ocean. The first vertebrates were fish, and even today the vast majority of vertebrates are still fish.

**MAIN IDEA**

The phylum Chordata contains all vertebrates and some invertebrates.

The phylum Chordata is made up of three groups. One group includes all vertebrates. Vertebrates are large, active animals that have a well-developed brain encased in a hard skull. The other two groups are the tunicates and lancelets, which are both invertebrates. Tunicates, or the urochordates, include both free-swimming and sessile animals such as sea squirts. Lancelets, or the cephalochordates (sehf-uh-luh-KAWR-dayts), are small eel-like animals that are commonly found in shallow, tropical oceans. Although lancelets can swim, they spend most of their lives buried in sand, filtering water for food particles.

Despite their enormous differences in body plans and ways of life, all chordates share the four features illustrated in **Figure 1.1** at some stage of their development.

- **Notochord** A notochord is a flexible skeletal support rod embedded in the animal’s back.
- **Hollow nerve cord** A hollow nerve cord runs along the animal’s back. The nerve cord forms from a section of the ectoderm that rolls up during development.
- **Pharyngeal slits** Pharyngeal (fuh-RIHN-je-uhl) slits are slits through the body wall in the pharynx, the part of the gut immediately beyond the mouth. Water can enter the mouth and leave the animal through these slits without passing through the entire digestive system.
- **Tail** A tail extends beyond the anal opening. The tail, as well as the rest of the animal, contains segments of muscle tissue used for movement.
Most chordate groups lose some or all of these characteristics in adulthood, but they are present in their larvae and embryos. For example, the larval form of sea squirts have all four chordate characteristics. However, an adult sea squirt, shown in Figure 1.2, retains only one chordate characteristic, the pharyngeal slits. Adult sea squirts use the pharyngeal slits for filter feeding. Similarly, vertebrate embryos have a notochord that is for the most part replaced by the vertebrae during later development. The fluid-filled disks between adjacent vertebrae are remnants of the notochord.

**Compare and Contrast** How are humans similar to sea squirts? How are they different? TEKS 8C

- **MAIN IDEA** TEKS 8B, 8C

All vertebrates share common features.

Vertebrates tend to be large, active animals. Even the smallest living vertebrate, an Indonesian carp smaller than a fingernail, is larger than most invertebrates.

**Vertebrate Endoskeleton**

One characteristic that allows vertebrates to grow to large sizes is the endoskeleton. An endoskeleton is an internal skeleton built of bone or cartilage. Bone and cartilage are both dense connective tissues. Each tissue is made of collagen fibers that are embedded in a matrix, or combination, of harder materials.

Vertebrate endoskeletons can be divided into distinct parts. Some of these parts are shown on the ape skeleton in Figure 1.3.

- **Braincase** A braincase or cranium protects the brain.
- **Vertebrae** A series of short, stiff vertebrae are separated by joints. This internal backbone protects the spinal cord. It also replaces the notochord with harder material that can resist forces produced by large muscles. Joints between the vertebrae let the backbone bend as the animal moves.
- **Connected bone structure** Bones support and protect the body’s soft tissues and provide points for muscle attachment.

The endoskeleton forms a framework that supports muscles and protects internal organs. It contains cells that can actively break down skeletal material and rebuild it. This characteristic means a vertebrate endoskeleton can slowly change size and shape. It can grow as a vertebrate changes size, unlike arthropod exoskeletons, which must be shed as the animal grows. It can also change shape in response to forces on a vertebrate's body. For example, bones subjected to large forces get thicker.
Vertebrate Classes
The phylogenetic tree shown in FIGURE 1.5 shows the probable evolutionary relationships among the seven classes of vertebrates.

Agnatha The Agnatha are the oldest class of vertebrates. These jawless animals include lampreys, a type of fish.

Chondrichthyes The Chondrichthyes, or cartilaginous fish, have skeletons made of cartilage. These animals include sharks, rays, and chimeras.

Osteichthyes The Osteichthyes, or bony fish, have skeletons made of bone. Ray-finned fish, a type of bony fish, are the most diverse group of vertebrates.

Amphibia The Amphibia were the first vertebrates adapted to live both in water and on land, although they reproduce in water or on moist land. These animals include salamanders, frogs (including toads), and caecilians.

Reptilia The Reptilia are able to retain moisture, which lets them live exclusively on land. Reptiles produce eggs that do not have to develop in water. Reptiles include snakes, lizards, crocodiles, alligators, and turtles.

Aves The Aves are birds. Aves are distinguished by the presence of feathers, along with other features.

Mammalia The Mammalia are animals that have hair, mammary glands, and three middle ear bones.

Contrast How does growth differ between an animal with an endoskeleton and an animal with an exoskeleton?

Fossil evidence sheds light on the origins of vertebrates.
Much of what we know about early vertebrates comes from fossil evidence found in the Burgess Shale located in the Canadian Rocky Mountains. This fossil site, discovered in the early 1900s, was not fully explored until the late 1960s. Fossils found within the Burgess Shale date from the Cambrian explosion and include preserved exoskeletons, limbs, and in some cases, gut contents and muscles. Fossils of sponges, worms, and arthropods are among the invertebrate remains found at the quarry site. Other fossils with traces of notochords provide evidence of the earliest chordates.

Closest Relatives of Vertebrates
In the past, scientists thought that lancelets were more closely related to vertebrates than tunicates were. They based this on fossil evidence, along with anatomical comparisons and molecular evidence. However, recent research indicates that tunicates may actually be the closest relatives of vertebrates. All vertebrate embryos have strips of cells called the neural crest, which develops into parts of the nervous system, head, bone, and teeth. Scientists have found that tunicates have cells that resemble the neural crest, but lancelets do not have such cells. This evidence could indicate that either lancelets secondarily lost these cells, or tunicates are indeed the closest relatives to vertebrates.
Each vertebrate class has unique characteristics that separate one class from another.

- **Vertebrates have a segmented backbone.**

- **Jaws**
  - Jaws help vertebrates to become successful predators.

- **Feathers**
  - Feathers insulate birds from the cold and allow for flight.

- **Hair**
  - Hair helps mammals to maintain constant body temperatures by providing insulation from the cold.

- **Amnion**
  - An amniotic egg encloses an embryo during development, letting animals reproduce on land.

- **Four Limbs**
  - Four limbs let animals move from the water to life on land.

**What characteristic is common among reptiles, birds, and mammals?**

- **Agnatha**
  - lamprey

- **Chondrichthyes**
  - sharks and rays

- **Osteichthyes**
  - bony fish

- **Amphibia**
  - frogs and salamanders

- **Reptilia**
  - reptiles

- **Aves**
  - birds

- **Mammalia**
  - mammals

**Figure 1.5 Vertebrate Phylogenetic Tree**

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Early Vertebrates

The first recognizable vertebrates were fish. The oldest fossil fish are found in 530-million-year-old rocks from China. Early fish were small, jawless bottom-feeders that sucked soft-bodied prey and detritus off the ocean floor. Jawless fish radiated into many different forms during the Paleozoic era. Some had bony head shields. Others were covered with bony plates and scales. Their heavy armor may have been a defense against predators such as giant sea scorpions. Most jawless fish were extinct by 360 million years ago. Today, two groups of jawless fish remain: the lampreys and the hagfish.

Lampreys

There are more than 35 species of lampreys. Most of these species are highly specialized fish parasites. Their physical characteristics include

- long and slender body plans that lack paired fins
- mouths surrounded by a large sucker
- tongues covered by horny toothlike projections

Lampreys hold on to fish with their suckers, then use their tongues to scrape holes in their prey. Substances in their saliva keep blood flowing by preventing clotting as they feed. The accidental introduction of sea lampreys into the Great Lakes in the early 1900s had a devastating impact on the fishing industry. Ongoing control programs have helped to restore the fisheries by reducing the sea lamprey population by 90 percent.

Hagfish

A hagfish, shown in Figure 1.6, is a jawless eel-like animal with a partial skull but no vertebrae. It uses a notochord for support. Although both hagfish and lampreys have primitive characteristics, none of the living species are ancient. They are recent animals that happen to be the living remnants of very ancient, mostly extinct groups.

Summarize

How have scientists’ views on the origins of vertebrates changed?

CONNECT TO
DEFENSE MECHANISMS
Hagfish secrete massive amounts of slime when disturbed by potential predators. Hagfish rid themselves of their slime cocoon by tying their body into a knot and sliding off the slime. You will learn more about defensive behaviors in Animal Behavior.

25.1 Formative Assessment

REVIEWING MAIN IDEAS

1. What features are shared by all members of the phylum Chordata? [TEKS] 8B
2. How is an endoskeleton involved in an animal’s movement?
3. What evidence places fish as the first vertebrates? [TEKS] 7A

CRITICAL THINKING

4. Compare and Contrast What are the advantages of having an endoskeleton instead of an exoskeleton? Are there any disadvantages? Why?
5. Summarize Draw a phylogenetic tree that shows the relationships between hagfish, lampreys, and all other fish. [TEKS] 8B

ADAPTATIONS

6. How is the structure of a lamprey’s body related to the lamprey’s function as a parasite?
25.2 Fish Diversity

KEY CONCEPT  The dominant aquatic vertebrates are fish.

MAIN IDEAS
- Fish are vertebrates with gills and paired fins.
- Jaws evolved from gill supports.
- Only two groups of jawed fish still exist.

Connect to Your World

In order to move in a swimming pool, you need to push your body through a thick, heavy blanket of water. Swimming for a long time is tiring. Long-distance swimming requires endurance and a lot of energy. Fish spend their entire lives moving through water, but adaptations to an aquatic environment make their movements through water much more energy-efficient than yours.

Fish are vertebrates with gills and paired fins.

You get the oxygen you need by breathing in the air that surrounds you. Because fish live underwater, the way that they get oxygen is completely different from the way you breathe. Fish use specialized organs called gills to take in the oxygen dissolved in water. Gills are large sheets of thin frilly tissue filled with capillaries that take in dissolved oxygen from the water and release carbon dioxide. As shown in FIGURE 2.1, gills have a very large surface area, which increases the amount of gases they can exchange with the water. Muscles in the body wall expand and contract, creating a current of water that brings a steady supply of oxygen to the blood.

Just like you, fish have body systems that provide their cells with oxygen and nutrients and also remove waste products. Fish circulatory systems pump blood in a single circulatory loop through a heart with two main chambers. An atrium collects blood returning from the body and moves it into the ventricle. The ventricle pumps blood through the gills, where carbon dioxide is released and oxygen is picked up by the blood. The blood then carries the oxygen directly to the tissues and picks up more carbon dioxide. The blood returns to the heart, and the process begins again.

FIGURE 2.1  Fish use the large surface area of their gills to exchange carbon dioxide and oxygen with the water in which they live.
**Countercurrent Flow**

Arteries in the gills carry blood to the exchange surfaces. The arteries are arranged so that blood flows in the opposite direction of the current of water entering the gills. **Countercurrent flow** is the opposite movement of water against the flow of blood in the fish's gills. Because oxygen dissolved in the water is at a greater concentration than the oxygen in the fish's blood, countercurrent flow maximizes the amount of oxygen the fish can pull from the water by diffusion. In countercurrent flow, blood is always passing by water that contains more oxygen than it does. Both well-aerated water entering the gills and depleted water leaving the gills pass by blood with an even lower oxygen load. Oxygen diffuses into the blood along the entire length of the gill.

**Swimming and Maneuvering**

Most fish swim by contracting large segmented muscles on either side of their vertebral column from the head to the tail. These muscle segments power the contractions that produce a series of S-shaped waves that move down the fish's body and push it through the water. These waves also tend to nudge the fish from side to side. Such horizontal movements waste energy, so fish counteract them with their fins.

As you can see in **Figure 2.2**, fins are surfaces that project from a fish's body. Most fish have dorsal fins on their backs and anal fins on their bellies. Most fish also have two sets of lateral paired fins. One set, the pectoral fins, are found just behind the head. The other set, the pelvic fins, are often found near the middle of the belly. The caudal fin is another name for the tail fin. Fin tissue is supported by part of the endoskeleton, and its associated muscles let fish actively move their fins as they swim.

Fins keep fish stable. Their movements redirect water around the fish as it swims, producing forces that keep it from rolling, pitching up and down, and moving from side to side. The dorsal and anal fins keep the fish from rolling over. The caudal fin moves the fish in a forward direction. The pectoral and pelvic paired fins help the fish to maneuver, stop, and hover in the water.

**Infer** What is the connection between countercurrent flow and a fish's movement in the water? [TEKS 10A]
Jaws evolved from gill supports.

The jaws of fish evolved from gill arches, also known as pharyngeal arches. Located on both sides of the pharynx, gill arches are structures made of bone or cartilage that function as a support for a fish’s gills. As shown in Figure 2.3, jaws developed from gill arches near the mouth, which fused to the cranium. The upper section of the third gill arch attached to the cranium, forming the upper jaw. Because the gill arches are jointed, the bottom part of the gill arch could bend to open and close the mouth, forming the lower jaw.

In most fish, the fourth set of gill arches are also fused to the cranium. In these animals, the upper part of the gill arch reinforces the jaws. The gill arch’s lower part supports the tissue inside the floor of the mouth. Most jawed vertebrates have teeth on their upper and lower jaws. Teeth are used to capture and process food. They evolved from the armored scales that covered early jawless fish.

As a result of natural selection, jaws gave vertebrates a huge advantage as predators and quickly pushed them to the top of the food chain. But the original function of jaws may not have been to help fish capture food. Evidence suggests that the earliest jaws prevented backflow as a fish pumped water over its gills. Clamping the front pair of arches together prevented oxygen-rich water from escaping through the mouth, ensuring that it all flowed over the gills. The fact that they also kept prey from escaping was a happy accident.

Compare What advantages are provided to an animal that has jaws, compared with an animal that does not have jaws?

Only two groups of jawed fish still exist.

Jawed fish diversified very quickly after their first appearance about 440 million years ago. Four groups of fish appeared at this time.

- **Acanthodians** Acanthodians were fish covered with spines. They became extinct about 250 million years ago.
- **Placoderms** Placoderms were heavily armored with huge bony plates. They became extinct about 350 million years ago.
- **Cartilaginous fish** Cartilaginous fish are one of the two groups of fish that survive today. The cartilaginous fish include sharks, rays, and chimeras.
- **Bony fish** Bony fish are the group that includes all other living fish and is the other group of fish still in existence.
Cartilaginous Fish

Members of the class Chondrichthyes, or cartilaginous fish, have skeletons made of cartilage, while their ancestors had skeletons made of bone. This characteristic means that their cartilaginous skeleton is not a primitive trait. These fish have lost the ability to make bone. In fact, the type of cartilage found in their skeletons is unique. It contains calcium deposits that make it stiffer than the squishy stuff found in human joints. Even though they have relatively flexible skeletons, cartilaginous fish have a strong bite, and they are major predators in every ocean. There are two groups within the Chondrichthyes—Holocephali and Elasmobranchs.

The Holocephali include chimeras, or ratfish. Chimeras are a small group of deep-sea fish with platelike grinding teeth. They feed on crustaceans and other invertebrates.

The Elasmobranchs include sharks, rays, and skates. There are more than 300 species of sharks and nearly 400 species of rays and skates. Most sharks, such as the grey reef shark shown in Figure 2.4, hunt other fish, although some species eat seals and sea lions. The biggest sharks, the whale sharks and basking sharks, are filter feeders that eat plankton.

Rays and skates have flattened bodies and large pectoral fins that they use to “fly” through the water. Most rays, such as the blue-spotted ray shown in Figure 2.5, crush invertebrates such as crustaceans for food. Others, such as the huge manta rays, are planktonic filter feeders. Most rays have poisonous venom in their barbed tails, which they use to defend themselves against predators. Skates do not have poisonous venom, but instead use thorny projections on their backs to fight off attackers.

While the cartilaginous fish as a group may be ancient, they have many advanced features. They have internal fertilization, and many species give birth to live young. They are actually denser than water, but oil stored in their livers provides buoyancy that keeps them from sinking.

Cartilaginous fish are incredibly efficient hunters. They are powerful swimmers with good eyesight and an excellent sense of smell. They can also sense their prey’s movements at a distance with a sensory system called the lateral line.
All fish have a **lateral line** system, which is a series of shallow canals on the sides of the fish made up of cells that are sensitive to small changes in water movement. The lateral line gives fish a sense of “distant touch,” letting them feel the movements in the water currents created by more distant animals as they swim.

Many fish also have sensory organs that detect the electrical currents made by muscular contractions in other animals. These sensory organs are called electroreceptive cells because they receive electric signals. In cartilaginous fish, the electroreceptive cells are clustered on the snout, and they are extremely sensitive. In experiments in which all other senses are blocked, a shark can still detect the electric currents generated by the heartbeat of a hiding animal.

**Bony Fish**

All other living fish have skeletons made of bone. These bony fish are called the Osteichthyes (the prefix oste- comes from a Greek word meaning “bone”). There are more than 20,000 species of bony fish living in nearly every aquatic environment on Earth, including tropical freshwater streams, Antarctic oceans, and deep-sea trenches. Some have become parasites of other fish. One group of bony fish can even spend short periods of time on land.

The gills of all bony fish are in a chamber covered by a protective plate called the **operculum** (oh-PUR-kyuh-luhm), shown in **Figure 2.6**. Movements of the operculum help bony fish move water over their gills by creating a low-pressure area just outside the gills. Water flows from the high-pressure area in the mouth through the gills toward the low-pressure area by the operculum.

Some of these characteristics have been modified or lost in some species of bony fish. In Section 3, Osteichthyes will be examined in more detail.

**Contrast** What is the difference between cartilaginous and bony fish?

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**25.2 Formative Assessment**

**REVIEWING MAIN IDEAS**

1. What is the function of **countercurrent flow** in a fish’s **gills**?
2. What key changes took place in the evolution of fish jaws?
3. Name the four groups of jawed fish that evolved during the Paleozoic era. Which groups are still alive today? **TEKS 8B**

**CRITICAL THINKING**

4. **Infer** How might fin shape differ in a fish with a torpedo-shaped cylindrical body and a fish with a flattened body?
5. **Analyze** How would you expect the **lateral line** system to differ in fish that live in rivers with strong currents?

**GO ONLINE**

[Self-Check Online](http://HMDScience.com)

**FIGURE 2.6** The operculum is a protective plate that covers a fish’s gills, as shown on this white margate, a bony fish.

**CONNECT TO EVOLUTION**

6. A shark’s jaw is lined with several rows of teeth. How is this adaptation related to a shark’s effectiveness as a predator? **TEKS 7D**
A Closer Look at Bony Fish

**KEY CONCEPT** Bony fish include ray-finned and lobe-finned fish.

**MAIN IDEAS**
- Ray-finned fish have a fan of bones in their fins.
- Lobe-finned fish have paired rounded fins supported by a single bone.

**VOCABULARY**
- ray-fin
- swim bladder
- lobe-fin

**Connect to Your World**
Most of the fish you are familiar with are bony fish. Perhaps you won a goldfish at a carnival or ate a tuna fish sandwich for lunch. Or maybe you fish at a local lake for trout or bass. All of these fishes are examples of bony fish.

**MAIN IDEA**
Ray-finned fish have a fan of bones in their fins.

All ray-finned fish, such as goldfish and tuna, have fins supported by a fan-shaped array of bones called a ray-fin. Ray-fins are embedded in a thin layer of skin and connective tissue. The muscles that move the bones are found in the fish’s body wall. This arrangement of bones and muscles makes the fin light, collapsable, and easy to move. Ray-finned fish can quickly change a fin’s shape, making the fish more maneuverable in the water. But the fins’ maneuverability also means that they are thin and too weak to provide support out of water. They would buckle under the fish’s weight. It would be like trying to stand on a few soda straws. Some ray-finned fish, such as mudskippers, have thickened ray-fins that let them shuffle around slowly on land.

**Diversity of Body Plans**
The ray-finned fish are the most diverse group of living vertebrates, making up nearly half of all vertebrate species. Most familiar species, such as tuna, have streamlined torpedo-shaped bodies that make it easier to swim through the water. But others can look quite different. As a result of natural selection, the bodies of bony fish are specialized for specific swimming and feeding strategies.

- Long, torpedo-shaped fish, such as the barracuda shown in **FIGURE 3.1**, are ambush predators that can accelerate quickly and surprise their prey.
- Fish that are flattened from side to side, such as butterfly fish, cannot swim quickly but are very maneuverable. They are usually found on coral reefs, in dense algae beds, or in large schools of their own species.
- Fish that feed on the surface of the water, such as some killifish, have flattened heads and mouths that point up. This body plan allows them to slurp up invertebrates from the surface while avoiding being seen by predators lurking above the surface.
• Flatfish, such as the plaice shown in **Figure 3.2**, are flat-shaped and lie on the sea floor waiting for their prey to swim by. During development into its adult form, one eye migrates to the top of its head as its body flattens out.

• Some slow-swimming fish use camouflage to hide from predators or prey. For example, a leafy sea dragon has dozens of fleshy flaps on its body that make it look like the seaweed it lives in.

**Staying Afloat**

Most ray-finned fish have lungs modified into a buoyancy organ called a **swim bladder**. The swim bladder, shown in **Figure 3.3**, helps a fish float higher or lower in the water. The swim bladder lets the fish save energy because a neutrally buoyant fish does not have to swim to keep from sinking or floating toward the surface. But if the fish changes depth, it must either add or remove air from the swim bladder to maintain neutral buoyancy. Adding oxygen from the bloodstream increases buoyancy the same way inflating a life vest makes you more buoyant. Reabsorbing oxygen into the bloodstream reduces buoyancy. Some species’ swim bladders are adapted for use as an amplifier, picking up sound waves and transmitting them to the inner ear through a series of bones. A few fish even use the swim bladder to make sounds by vibrating it like a loudspeaker.

Some ray-finned fish still have lungs. One example is the bichir, which lives in stagnant streams in West Africa. These fish have gills, but can also breathe air and survive out of water for several hours at a time.

**FIGURE 3.2** A plaice’s flat-shaped body helps it to blend in with the sea floor, where it lies and waits for prey to swim by.

**FIGURE 3.3** Bony Fish Anatomy

The unique features of the anatomy of a bony fish include a swim bladder that maintains buoyancy and gills used to breathe.

---

**Explain** What is a swim bladder, and how does it work?
DATA ANALYSIS

MAI D E

Lobe-finned fish have paired rounded fins supported by a single bone.

The lobe-finned fish include the ancestors of all terrestrial vertebrates. But most species of lobe-finned fish are extinct. Only seven species remain today. These fish first appeared about 400 million years ago in the Devonian period. Despite their early presence in the fossil record, the lobe-finned fish have never been as diverse as the ray-finned fish, which first appeared in the Devonian period as well.

Lobe-fins are paired pectoral and pelvic fins that are round in shape. These fins are arranged around a branching series of bony struts, like the limb of a land vertebrate. There is always one bone at the base of the fin. It is attached to a pair of bones, which are attached to a fan of smaller bones. Muscles extend into the fin and stretch across the bones, making the fin thick and fleshy. Lobe-fins cannot change shape as quickly as ray-fins can, and they provide less maneuverability in the water. But they are excellent at supporting weight, a feature that eventually let some of these fish walk out of the water onto land.

CONSTRUCTING SCATTERPLOTS

In order to analyze the relationship between two variables, scientists graph their data. The table below contains data about the length and age of largemouth bass in two lakes in Washington state.

1. **Graph** Construct a graph of the data in the table. Remember, for scatterplots you do not connect the data points.

2. **Analyze** What is the relationship between length and age in largemouth bass?

3. **Infer** An additional fish is measured with a length of 250 millimeters (mm). What might be the age of this fish? Explain your answer.

<table>
<thead>
<tr>
<th>TABLE 1. LARGEMOUTH BASS LENGTH AND AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
</tr>
<tr>
<td>Age (years)</td>
</tr>
</tbody>
</table>

Source: Washington State Department of Ecology

An animated biology module can be accessed online to explore fish features and characteristics.
Coelacanths
Coelacanths (SEE-luh-kahnths) are distinctive-looking fish with thick, fleshy fins and a tail with three lobes. They breathe with gills. Their swim bladders are filled with fat and provide buoyancy. There are two species of coelacanth. Both live in deep water in the Indian Ocean.

Coelacanths were first known from fossils. They are found in freshwater and shallow marine deposits from the Devonian until the late Cretaceous periods (410 to 65 million years ago), and then completely disappear from the fossil record. Before 1938, scientists assumed that they had gone extinct at the same time as the dinosaurs. In 1938, a modern coelacanth was caught off the coast of South Africa. Another was discovered near Indonesia in 1997.

Lungfish
Lungfish, such as the one shown in Figure 3.4, live in streams and swamps in Australia, South America, and Africa. They can breathe with either gills or lungs. This characteristic means that they can live in stagnant, oxygen-poor water that other fish cannot tolerate. Lungs even keep some species alive when their ponds dry up. They make burrows in the mud, which hardens as the water dries up. Then they breathe air until the next rain refills their pond.

The relationships between lungfish, coelacanths, and the terrestrial vertebrates are controversial. Recent studies of mitochondrial DNA suggest that lungfish are the closest living relatives of terrestrial vertebrates. Anatomical evidence also supports this idea. For example, lungfish and terrestrial vertebrates are the only animals with separate blood circuits for the lungs and the rest of the body. However, this characteristic does not mean that modern lungfish are the direct ancestors of terrestrial vertebrates. Both groups are descended from ancient lungfish, and they have changed in different ways over time.

Identify What are two examples of living lobe-finned fish?

25.3 Formative Assessment

REVIEWING MAIN IDEAS
1. How are the bones arranged in a ray-fin? How is the arrangement related to the fin’s function?
2. How are lobe-finned fish different from ray-finned fish?
3. How are lobe-fins related to vertebrate evolution? (TEKS 7E)

CRITICAL THINKING
4. Infer You are looking at a long, torpedo-shaped fish with a flat head and a mouth that points upward. What do you predict about the hunting style of this fish?
5. Predict Any animal that is underwater is under pressure. Diving exposes animals to higher pressures. How would this affect a fish’s swim bladder?

6. Early coelacanth fossils have single dorsal and anal fins. Second sets of dorsal and anal fins appear suddenly in the fossil record and persist in modern species. Explain how Hox genes could be responsible for the sudden appearance of this novel feature. (TEKS 7B)
Fisheries on the Brink
Worldwide, many marine fisheries have been fished to their sustainable limits or overfished, while more people are depending on fish for food. Explore the problems facing the marine fisheries and what we can do to save them.

What Type of Fish Is It?
Can you tell a ray-finned fish from a cartilaginous fish? Use physical characteristics to categorize a set of jawed fish.
Amphibians

**VOCABULARY**
tetrapod  
amphibian  
tadpole

**KEY CONCEPT**  Amphibians evolved from lobe-finned fish.

**MAIN IDEAS**
- Amphibians were the first animals with four limbs.
- Amphibians return to the water to reproduce.
- Modern amphibians can be divided into three groups.

**Connect to Your World**

What would it really be like to be a “fish out of water”? On shore, the air does not support your body. Gravity pulls on you and makes it hard to move. Your lateral line does not work. You are deaf because your body absorbs sound waves before they reach your ear. The air is too thin to let you suck food into your mouth, and it is so dry that you start losing water through your skin. These are just a few of the conditions animals faced when they first moved onto land.

**Main Idea**  
Amphibians were the first animals with four limbs.

One of the oldest known fossils of a four-limbed vertebrate was found in 360-million-year-old rocks from Greenland. We know that *Acanthostega* had lungs and eight-toed legs. But it also had gills and a lateral line system, neither of which work in air. These features suggest that the earliest animals with four limbs were aquatic and used their limbs to paddle underwater.

All of the vertebrates that live on land, as well as their descendants that have returned to aquatic environments, are tetrapods. A **tetrapod** is a vertebrate that has four limbs. Each limb evolved from a lobe-fin. Tetrapod legs contain bones arranged in the same branching pattern as lobe-fins, except that the fan of bones at the end of the fin is replaced by a set of jointed fingers, wings, or toes. Animals such as snakes, which do not have four limbs, are still considered to be tetrapods because they evolved from limbed ancestors.

Limbs and lungs were features that made these animals successful in an oxygen-poor, debris-filled underwater environment. But, over time, these adaptations let tetrapods climb out of the water to search for food or escape predators. These animals gave rise to the first amphibians. **Amphibians** are animals that can live both on land and in water. In the word *amphibian*, the root *amphi* comes from a Greek word meaning “on both sides,” while the suffix -*bian* comes from a Greek word meaning “life.”

A number of adaptations help amphibians to live on land. Large shoulder and hip bones help support more weight, while interlocking projections on the vertebrae help keep the backbone from twisting and sagging. A mobile, muscular tongue allows amphibians to capture and manipulate food. Development of a middle ear helps some amphibians to hear out of the water.
Some amphibians can hear sound due to the development of a tympanic membrane attached to a bone called the stapes. The stapes evolved from the top part of the second gill arch. Sound waves moving through the air vibrate the tympanic membrane, or eardrum, which transfers the sound waves further into the ear cavity to the middle and inner ear.

Depending on the species, amphibians breathe through their skin or with the use of gills or lungs. The balloonlike lungs of an amphibian are simple in structure. An amphibian uses its lungs to breathe by changing the amount and pressure of air in its mouth. Unlike fish, which have a two-chambered heart, amphibians have a three-chambered heart. An amphibian heart is made up of two atria and one ventricle. Oxygenated and deoxygenated blood are partially separated by the two atria. Blood is pumped through the heart on a double circuit. Blood pumped through the pulmonary circuit goes to the skin and lungs. Blood pumped through the systemic circuit brings oxygen-rich blood to the organs and returns oxygen-poor blood to the heart.

Over time, amphibian species evolved with adaptations that allowed them to live on land. But they did not evolve ways to keep themselves or their eggs from drying out in the air.

**Analyze** What adaptations helped amphibians move from water to live on land?

**Main Idea**

**TEKS 7D**

**Amphibians return to the water to reproduce.**

An amphibian’s skin is thin and wet. Water constantly evaporates from it, and amphibians risk drying out if they move too far from a source of water. This need for moisture is why you rarely find an amphibian in arid habitats. A few species live in deserts, where they burrow underground, emerging only during the brief rainy season. Desert-living species can absorb large amounts of water through their skin when it is available and store it for the dry season.

**Reproduction Strategies**

Amphibians need a source of water to reproduce. Their eggs do not have a shell, and the embryos will dry out and die without a source of moisture. Amphibians use many strategies to keep their eggs wet, including

- laying eggs directly in water
- laying eggs on moist ground
- wrapping eggs in leaves
- brooding eggs in pockets on the female’s back, as shown in **Figure 4.1**

Some frogs start their lives as tadpoles. **Tadpoles** are aquatic larvae of frogs. Tadpoles have gills and a broad-finned tail, and they swim by wiggling their limbless bodies like fish. They typically eat algae, but some may eat small invertebrates or even other tadpoles.
Amphibian Metamorphosis

To grow into terrestrial adults, tadpoles must undergo metamorphosis. Recall that metamorphosis is the change in form and habits of an animal. Similar to the metamorphosis of a butterfly, the metamorphosis of a tadpole into an adult frog affects nearly every organ in the tadpole’s body. It produces enormous changes in the animal’s body form, physiology, and behavior. The stages of amphibian metamorphosis, in which a tadpole transforms into its adult form, are shown in Figure 4.2.

During metamorphosis, the tadpole undergoes many changes. The gills are reabsorbed and lungs develop, shifting the frog from a water-breathing to an air-breathing mode of life. The circulatory system is reorganized to send blood to the lungs. The tail fin (if not the entire tail) is reabsorbed. The body grows limbs and completely reorganizes its skeleton, muscles, and parts of the nervous system. The digestive system is rebuilt to handle a carnivorous diet. In the adult amphibian, digestion occurs in the animal’s stomach, and wastes are expelled through the cloaca. The cloaca is also a part of the reproductive system.

Many amphibians do not undergo metamorphosis. Adult females lay eggs on the ground or keep them in their bodies, and the young develop directly into their terrestrial forms.

**Infer** Describe the stages of amphibian metamorphosis.
Modern amphibians can be divided into three groups.

The three groups of modern amphibians are salamanders, frogs, and caecilians (suH-SIHL-yuhnz). The body plans of these amphibians are adapted to the feeding habits and requirements of the habitats in which they live.

Salamanders
There are more than 300 species of salamanders. As shown in Figure 4.3, salamanders have a long body, four walking limbs, and a tail. They walk with a side-to-side movement biologists think is similar to the way ancient tetrapods probably walked. But appearances can be deceiving. Salamanders have a number of adaptations specific to their way of life. Some salamander species, such as the axolotl (AK-suHL-LAUT-uhl), retain some juvenile features as they mature, growing into aquatic adults that look like giant tadpoles with legs. Members of the largest family of salamanders do not have lungs and exchange gases through the lining of their skin and mouth.

Salamander larvae and adults are carnivorous. They eat invertebrates such as insects, worms, and snails. Large species eat smaller vertebrates such as fish and frogs. Salamander larvae and some aquatic adults suck food into their mouths as fish do. On land, a salamander hunts by flinging its sticky tongue at its prey and pulling it back into its mouth.
Frogs
Frogs make up the largest group of living amphibians, with more than 3000 species. Adult frogs are physically distinctive, with tailless bodies, long muscular hind limbs, webbed feet, exposed eardrums, and bulging eyes. Their bodies are adapted for jumping. Elongated bones in their hips, legs, and feet increase their speed and power. Their hind legs have fused bones that absorb the shock of landing.

Toads are actually one family of frogs. They have rougher and bumpier skin than do other frogs, as well as relatively shorter legs that make them poor jumpers. Glands in the bumpy skin of toads and the smooth skin of tropical frogs make toxins that protect the animals from predators. Many species of these poisonous frogs and toads have bright coloration that warns predators that they are deadly.

Frogs live in every environment on Earth except at the poles and in the driest deserts. Although most tadpoles eat algae, adult frogs are predators and will eat any animal they can catch.

Caecilians
Caecilians (suH-SIHL-yuhn), such as the one shown in Figure 4.5, are legless, burrowing amphibians that live in the tropics. There are 160 species, ranging in length from about 10 centimeters (4 in.) to 1.5 meters (5 ft). Caecilians have banded bodies that make them look like giant earthworms, and they are specialized for a life burrowing through the soil.

Like other amphibians, caecilians are predators. They burrow through the soil searching for earthworms and grubs. Because they have no legs, they cannot dig through the soil the way a mole would. Instead, like an earthworm, a caecilian uses a hydrostatic skeleton to stiffen its body and drive its head forward like a battering ram.

Contrast How are caecilians different from other amphibians? TEKS 8B

25.4 Formative Assessment

REVIEWING MAIN IDEAS
1. What evidence suggests that the first tetrapods were amphibians? TEKS 7A
2. How have amphibians adapted to living in desert environments? TEKS 7D

CRITICAL THINKING
3. Connect Poison dart frogs and monarch butterflies are brightly colored. What might be the adaptive advantage of bright coloration?
4. Apply Amphibians are very sensitive to changes in their environment. Why might this be?

CONNECT TO EVOLUTION
5. Caecilians, snakes, and whales have no legs. Why, then, do we call them all tetrapods? (Hint: consider their evolutionary histories.) TEKS 7A
Vertebrates on Land

KEY CONCEPT  Reptiles, birds, and mammals are adapted for life on land.

MAIN IDEAS
- Amniotes can retain moisture.
- Amniotes do not need to return to water to reproduce.

Connect to Your World

Around 350 million years ago, one group of ancient amphibians evolved traits that let them walk away from the water forever. Over time, they diversified into the types of vertebrates you are most familiar with, including reptiles, birds, and mammals—the class that includes you.

Amniotes can retain moisture.

An amniote is a vertebrate that has a thin, tough, membranous sac that encloses the embryo or fetus. Amniotes first appeared as small, lizardlike creatures in the late Carboniferous period. Since that time, amniotes have evolved into thousands of different forms and have invaded nearly every ecosystem on Earth. They have become predators in the tropics, the most arid deserts, the Arctic, and in any number of freshwater and marine environments. They have become burrowers, sprinters, sit-and-wait predators, and slow trackers. Some species never leave the trees. Some specialize in eating plants and have evolved symbiotic relationships with bacteria that can break down cellulose. Some have also developed powered flight.

When you look at the phylogenetic tree of amniotes, it is clear that many of the species we see today are survivors of larger radiations that have gone extinct. Mammals are survivors of a huge line of animals that went extinct about 245 million years ago. Birds are survivors of the dinosaur radiation and extinction.

All amniotes share a set of characteristics that prevent water loss. Skin cells are waterproofed with keratin. Keratin is a protein that binds to lipids inside the cell, forming a hydrophobic—or water repellent—layer that keeps the water inside the animal from reaching the skin. The presence of this hydrophobic layer means that amniotes lose less water to evaporation than amphibians do. Waterproofing also means that amniotes cannot exchange gases across their skin. They rely on their lungs for respiration.

Kidneys and large intestines are bigger in amniotes than in amphibians. These organs contain tissues that reabsorb water. The increased surface area of these tissues enables amniotes to absorb more water internally, so they lose less to excretion than do amphibians.

Connect  What makes your skin cells waterproof? Why is this important?
MAIN IDEA
Amniotes do not need to return to water to reproduce.

With adaptations that limit water loss, amniote adults could move into drier environments on land. But it was the evolution of the amniotic egg that let them stay there. The amniotic egg is an almost completely waterproof container that keeps the embryo from drying out as it develops. After it evolved, amniotes did not have to return to a wet environment to reproduce.

An amniotic egg, shown in Figure 5.1, is essentially a private pool that the mother builds for her embryo. Like any swimming pool, the egg is expensive. In egg-laying amniotes, the mother must make enough yolk and white to feed the embryo until it hatches, then build the shell around the fertilized egg. Each egg represents a large investment of energy. For example, a bird may lose 5 to 30% of its body weight as it makes an egg.

Other amniotes, such as rattlesnakes and garter snakes, make eggs but do not lay them. Instead, they keep their eggs in their oviduct until they hatch. Retaining eggs protects them from predators. Some amniotes have evolved the ability to give birth to living, well-developed young.

Most mammal embryos develop inside of the mother's reproductive tract. Their eggs have no shells, but their embryos make the same series of membranes found in a typical amniotic egg. The placenta is a membranous organ that develops in female mammals during pregnancy. It lines the uterine wall and partially envelops the fetus. The placenta carries nutrients from the mother to the embryo and also removes metabolic wastes from the embryo.

Summarize How is an amniotic egg protected from water loss?

25.5 Formative Assessment

REVIEWING MAIN IDEAS
1. What anatomical characteristics help an amniote retain moisture?
2. Why don’t amniotes need to return to water to reproduce?

CRITICAL THINKING
3. Infer If eggshells were thicker, the egg would lose even less water to the environment. Why are eggshells thin?
4. Infer What is an advantage of giving birth to live young, rather than having young that hatch from eggs?

CONNECT TO EVOLUTION
5. Most mammals, and at least some lizards and snakes, have evolved live birth by keeping the eggs inside the mother until they hatch. However, no bird species has ever retained its eggs. Suggest a possible explanation for this fact.
25 Summary

KEY CONCEPTS

25.1 Vertebrate Origins
All vertebrates share common characteristics. At some point during development, all chordates have a notochord, a hollow nerve cord, pharyngeal slits, and a tail. All vertebrates have an endoskeleton made of bone or cartilage. The first recognizable vertebrates were fish. Lampreys and hagfish are two primitive, jawless fish still in existence today.

25.2 Fish Diversity
The dominant aquatic vertebrates are fish. Fish use the large surface area of their gills to exchange carbon dioxide and oxygen with the water in which they live. Countercurrent flow maximizes the amount of oxygen a fish can pull from the water. Fish use their fins to move around in the water. Cartilaginous fish include sharks, rays, and chimeras. All other living fish are categorized as bony fish.

25.3 A Closer Look at Bony Fish
Bony fish include ray-finned and lobe-finned fish. Ray-finned fish have a fan of bones in their fins. Most ray-finned fish use an organ called a swim bladder to stay neutrally buoyant, which means they neither sink nor float in the water. Lobe-finned fish have a series of bones in their fins. Lobe-finned fish include the ancestors of all land vertebrates. Coelacanths and lungfish are two types of lobe-finned fish.

25.4 Amphibians
Amphibians evolved from lobe-finned fish. Amphibians were the first vertebrates with four limbs. Amphibians can live both on land and in water. However, they must live in moist environments, as they need a source of water to reproduce. Modern amphibian groups include salamanders, frogs, and caecilians.

25.5 Vertebrates on Land
Reptiles, birds, and mammals are adapted for life on land. During embryonic or fetal development, an amniote is enclosed within a thin, tough, membranous sac. This waterproof container allows amniotes to reproduce outside of water. Some amniotes give birth to live young, while others lay hard-shelled eggs.

BIG IDEA
Vertebrates are a diverse group of land-based and aquatic animals that share certain characteristics.
Reviewing Vocabulary

Compare and Contrast
Describe one similarity and one difference between the two terms in each of the following pairs.

1. invertebrate, vertebrate
2. endoskeleton, exoskeleton
3. gill, lung
4. ray-fin, lobe-fin
5. tetrapod, amphibian
6. amniotic egg, placenta

Reviewing MAIN IDEAS

14. Sea squirts and dogs are both chordates, but they are very different kinds of animals. What four features do these animals share at some point in their development?  

15. All vertebrates have an endoskeleton. What are the main parts of an endoskeleton?

16. Name the seven classes of living vertebrates. TEKS 7B

17. How does countercurrent flow contribute to the function of a fish’s gills?

18. What evidence indicates that the jaws of fish were once gill arches? TEKS 7A

19. Barracuda and flatfish have very different body shapes and methods of finding food, yet both have ray-fins. How does the structure of their fins help them to survive? TEKS 7E

20. What is the function of the swim bladder in a ray-finned fish?

21. What feature of a lobe-fin fish makes it the closest relative to terrestrial vertebrates?

22. List two adaptations of amphibians, and briefly describe why each is important for life on land. TEKS 7A

23. Why does amphibian reproduction require a moist environment?

24. What are the three types of modern amphibians?

25. How does the presence of keratin in skin cells affect where an amniote can live?

26. Mammals and birds have very different methods of reproduction, but both are able to reproduce on land. Explain why amniotes do not need to return to water to reproduce. TEKS 7D
Critical Thinking

27. **Analyze** Describe the structure and function of the notochord and the internal backbone of an endoskeleton.

28. **Analyze** Gas exchange in fish occurs in the gills using a countercurrent flow. Imagine that there are five stations in a gill at which gas exchange takes place. Describe what happens and why as the water and blood pass each other at each station.

29. **Apply** Submarines rise and sink using a mechanical system that works much like a swim bladder. Use your knowledge of how a swim bladder works to explain how submarines use these systems to rise and descend in the water.

30. **Infer** Frogs have bodies that are specialized for jumping, yet they have webbed feet. How are webbed feet beneficial for frogs?

31. **Connect** Why would your kidneys help you survive for a couple of days without water better than the type of kidneys that frogs have?

Interpreting Visuals

Use the image below to answer the next three questions.

32. **Classify** This mudskipper has climbed out of the water and is resting on a rock. Based on the physical characteristics of the mudskipper’s fin shape, to which group of fish does the mudskipper belong? Explain your reasoning.

33. **Analyze** When it is out of the water, how might the lungless mudskipper breathe?

34. **Apply** If mudskippers were to evolve into a terrestrial animal, what body part might function as a limb?

Analyzing Data **Construct a Scatterplot**

Use the data below to answer the next three questions. The calling activity, body size, and body temperature were recorded for a population of Fowler’s toads. Below is a scatterplot that shows the relationship between a male toad’s body temperature and calling effort, measured as the number of seconds the male called per minute of time.

**BODY TEMPERATURE AND CALLING EFFORT**

35. **Analyze** What is the relationship between the body temperature of the Fowler’s toad and calling efforts?

36. **Analyze** Is this data an example of positive correlation, negative correlation, or no relationship?

37. **Predict** Would you expect a toad with a body temperature of 15° Celsius to have a higher or lower calling effort than a toad with a body temperature of 21° Celsius? Explain.

Making Connections

38. **Write a Letter** Imagine you are a green frog, adapted to life both in water and on land, and one of your best friends is a fish that lives in a nearby lake. Write a letter to the fish, explaining what adaptations he would need to survive outside of the water on land. In the letter, be sure to compare any similar characteristics and contrast differing characteristics.

39. **Connect** Take another look at the glass frog on the chapter opener. Its translucent skin helps it to blend in with the green leaves on which it lives. How could natural selection have played a role in the development of this trait common among all glass frogs?
**MUTLIPLE CHOICE**

1. A scientist discovers a new type of organism in the deep ocean. Because this organism was found in the water, the scientist suspects it may be related to fish. This idea most closely resembles a scientific —
   A theory  
   B hypothesis  
   C suggestion  
   D experiment

2. Fossils found in New Zealand suggest that as many as 2,000 frog species lived there in the past. Today, there are fewer than 300 frog species. What conclusion can be drawn from this information?
   A The climate conditions in New Zealand have changed over time.  
   B The species alive today are more specialized to a particular niche than the species of the past.  
   C Biological diversity of frogs in New Zealand has decreased.  
   D There are fewer frog species today because a mass extinction occurred.

3. After studying fossils of prehistoric fish in one region, scientists developed this family tree to describe how the various species they found are related. Which of the following is true with regard to the diagram above?
   A The Ancestor species has gone extinct.  
   B Species A and Species C are not related.  
   C Species D evolved before Species A, B, and C.  
   D Species C evolved before Species A and B.

4. According to the cladogram above, which of the following statements is true?
   A Fish are more closely related to humans than reptiles.  
   B Reptiles are more closely related to marsupials than fish.  
   C Marsupials and fish do not share a common ancestor.  
   D Marsupials and humans share a common ancestor.

5. Countercurrent flow in a fish's gills allows blood to efficiently release carbon dioxide into the water and absorb oxygen from the water. Which of the following best describes why this process is referred to as “countercurrent flow”?
   A Oxygen and carbon dioxide flow in opposite directions.  
   B Fish need to swim backwards in order for gas exchange to take place.  
   C The movement of the water flows in the opposite direction as the blood.  
   D Fish need to swim against the current in order for gas exchange to take place.

6. About 245 million years ago, at the boundary of the Permian and Triassic periods, 95 percent of all species died out. This event is referred to as a(n) —
   A episode of speciation  
   B population explosion  
   C mass extinction  
   D intense adaptation