KEY CONCEPTS

21.1 Plant Cells and Tissues
Plants have specialized cells and tissue systems.

21.2 The Vascular System
The vascular system allows for the transport of water, minerals, and sugars.

21.3 Roots and Stems
Roots and stems form the support system of vascular plants.

21.4 Leaves
Leaves absorb light and carry out photosynthesis.
Fig trees (*Ficus*) have a unique way of growing. Many trees of this genus are called strangler figs because their aggressive growth actually strangles other trees. Strangler figs can also wrap around unmoving objects such as these temple walls. Their seeds germinate easily in tree branches or building cracks, and then snakelike roots grow down to the ground.

**Connecting Concepts**

**How would this tree compete with other species?**

*Competition* Besides strangling their host trees, figs can kill by outcompeting other plants for sunlight. Many tropical figs develop aerial roots that extend through the air from the branches to the ground. These roots are commonly called prop roots, and they allow the tree to spread outward for long distances. In fact, the tree canopy of a great banyan fig in Calcutta, India, covers three acres and has 1775 prop roots.
Recall from Chapter 3 that plant cells differ from animal cells in having cell walls, plastids, and a large vacuole. Just as with animals, plants are made up of many types of cells that are organized into tissues. Three basic types of plant cells, shown in FIGURE 21.1, are parenchyma cells, collenchyma cells, and sclerenchyma cells.

**Parenchyma Cells**
A parenchyma cell (puh-REHNG-kuh-muh)—the most common type of plant cell—stores starch, oils, and water for the plant. You can find parenchyma cells throughout a plant. These cells have thin walls and large water-filled vacuoles in the middle. Photosynthesis occurs in green chloroplasts within parenchyma cells in leaves. Both chloroplasts and colorless plastids in parenchyma cells within roots and stems store starch. The flesh of many fruits we eat is also made of parenchyma cells. Parenchyma cells are sometimes thought of as the least specialized of plant cells, but they have one very special trait. They have the ability to divide throughout their entire lives, so they are important in healing wounds to the plant and regenerating parts. For example, parenchyma cells let you place stem cuttings of many types of plants in water to grow into a complete, new plant.

**Collenchyma Cells**
A collenchyma cell (kuh-LEHNG-kuh-muh) has cell walls that range from thin to thick, providing support while still allowing the plant to grow. These cells are most common in the younger tissues of leaves and shoots. They often form into strands. For example, celery strings are strands of collenchyma cells.
FIGURE 21.1 Basic Plant Cell Types

<table>
<thead>
<tr>
<th>PARENCHYMA</th>
<th>COLLENCHYMA</th>
<th>SCLERENCHYMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parenchyma cells have thin and flexible cell walls that can change shape. (LM; magnification 160×)</td>
<td>Collenchyma cells have walls that range from thin to thick. (LM; magnification 250×)</td>
<td>Sclerenchyma cells have very thick and rigid walls that support the plant, even when the cells die. (LM; magnification 400×)</td>
</tr>
</tbody>
</table>

The unique feature of collenchyma cells is that they are flexible. Their cell walls don’t contain lignin, so they are stretchy and can change size. As a young leaf grows, collenchyma cells can elongate and still give the leaf structure.

**Sclerenchyma Cells**

Of the three basic plant cell types, a sclerenchyma cell (skluh-REHNG-kuh-muh) is the strongest. These cells have a second cell wall that is hardened by lignin, which makes these cells very tough and durable. But the lignin also makes these cells very rigid. Unlike collenchyma cells, they can’t grow with the plant. Therefore, sclerenchyma cells are found in parts of the plant that aren’t lengthening anymore. Many sclerenchyma cells, such as those within the vascular system, die when they reach maturity. The cytoplasm and organelles of these dead cells disintegrate, but the rigid cell walls are left behind as skeletal support for the water-conducting tissues or for the plant itself. Sclerenchyma cells form a major part of fruit pits and the hard outer shells of nuts. They are also found in stems and leaf veins and are responsible for the gritty texture of pears. Humans use sclerenchyma cell fibers to make linen and rope.

**Contrast** How are the cell walls of parenchyma, collenchyma, and sclerenchyma cells different from one another?

**MAIN IDEA**

Plant organs are made of three tissue systems.

Just as there are three basic types of plant cells, there are three groups of tissue systems in plants: dermal, ground, and vascular tissue systems. Recall from Chapter 5 that a tissue is a group of cells working together to perform a certain function. The tissue systems of plants may consist of simple tissues from the basic cell types: parenchyma, collenchyma, and sclerenchyma. They may also be made of complex tissues that have additional types of cells. Neighboring cells are often connected by plasmodesmata (PLAZ-muh-DEHZ-muh-tuh), strands of cytoplasm that pass through openings in cell walls and connect living cells. Through the plasmodesmata, cells of a plant tissue can share water, nutrients, and chemical signals.
Dermal Tissue System
Your body is covered with skin. Plants don’t have skin, but they do have a system of dermal tissue, shown in FIGURE 21.2, that covers the outside of a plant and protects it in a variety of ways. Dermal tissue called epidermis is made up of live parenchyma cells in the nonwoody parts of plants. On leaves and some stems, epidermal cells may secrete a wax-coated substance that becomes the cuticle. Dermal tissue made of dead parenchyma cells makes up the outer bark of woody plants.

Ground Tissue System
Dermal tissue surrounds the system of ground tissue, which makes up much of the inside of a plant. Ground tissue provides support and stores materials in roots and stems. In leaves, ground tissue is packed with chloroplasts, where photosynthesis makes food for the plant. The ground tissue system consists of all three of the simple tissues—parenchyma tissue, collenchyma tissue, and sclerenchyma tissue—but parenchyma is by far the most common of the ground tissues. The ground tissue of cacti has many parenchyma cells that store water. However, the spines of cacti—which are actually modified leaves—contain mostly rigid sclerenchyma cells in their ground tissue.

Vascular Tissue System
Surrounded by ground tissue, the system of vascular tissue transports water, mineral nutrients, and organic compounds to all parts of the plant. Plants can transport necessary fluids and nutrients throughout their systems. A plant’s vascular system is made up of two networks of hollow tubes somewhat like our veins and arteries. Each network consists of a different type of vascular tissue that works to move different resources throughout the plant. Xylem (ZY-luhm) is the vascular tissue that carries water and dissolved mineral nutrients up from the roots to the rest of the plant. Phloem (FLOH-eehm) is the vascular tissue that carries the products of photosynthesis through the plant. You will learn more about the vascular system in the next section.

Identify What tissue system contains the most photosynthesizing cells?
The Vascular System

**KEY CONCEPT** The vascular system allows for the transport of water, minerals, and sugars.

**MAIN IDEAS**
- Water and dissolved minerals move through xylem.
- Phloem carries sugars from photosynthesis throughout the plant.

**VOCABULARY**
- **cohesion-tension theory**, p. 643
- **transpiration**, p. 645
- **pressure-flow model**, p. 645

**Review**
- hydrogen bond, cohesion, adhesion, osmosis

**Connect** As you read this, your heart is pumping blood, which carries nutrients to your cells and removes wastes from them. In the world outside, fluids are also moving from tree roots all the way up to the highest leaves. But a tree has no heart to act as a pump. How can it move water up to a height of two, three, even ten stories?

**MAIN IDEA**

**Water and dissolved minerals move through xylem.**

Recall that xylem is one of the two types of vascular tissue. Water and dissolved minerals move up from the roots to the rest of the plant through xylem. Xylem contains other types of cells besides the basic cell types. Because it contains other types of cells, xylem tissue is called a complex tissue.

One type of specialized cell in xylem is called a tracheid (TRAY-kee-ihd). Tracheid cells, shown in **FIGURE 21.3**, are long and narrow. Water can flow from cell to cell in tracheids through openings in the thick cell walls. Some types of vascular plants, including most flowering plants, have an additional kind of xylem cell called a vessel element. Vessel elements are shorter and wider than tracheids. Both types of cells mature and die before water moves through them. When a vessel element dies, the cell wall disintegrates at both ends. The cells then connect end to end, forming long tubes.

Amazingly, plants don’t use any metabolic energy to move water through xylem. So how do they do it? The **cohesion-tension theory** proposes that the physical properties of water allow the rise of water through a plant. This well-supported theory is based on the strong attraction of water molecules to one another and to other surfaces. The tendency of hydrogen bonds to form between water molecules creates a force called cohesion. However, water molecules are also attracted to the xylem wall due to adhesion, a force made by hydrogen bonds forming between water molecules and other substances. Cohesion and adhesion create tension that moves water upward in xylem.

**FIGURE 21.3** Xylem tissue consists of tracheids and vessel elements, conducting and supporting cells that lie end-to-end throughout xylem. Tracheid cells are narrow and long, while vessel elements are wider and shorter. (colored SEM; magnification 250× © Dr. Richard Kessel & Dr. Gene Shih/Visuals Unlimited)
What process is the main force for the movement of fluids through xylem? Explain.

Forces responsible for the movement of fluids through xylem are transpiration, cohesion, adhesion, and absorption.

Transpiration is the evaporation of water through leaf stomata. It is the major force moving water through plants.

Cohesion and adhesion create tension within xylem that helps move water upward.

Water and dissolved minerals in the soil are pulled into roots through cell walls, through plasmodesmata (channels), or from cell to cell through their vacuoles.
To understand how cohesion and adhesion affect xylem flow, imagine you are inside the cylinder of a xylem vessel. In the middle, the water molecules float freely, attracted to each other. Toward the edges, though, the molecules are also drawn to the xylem wall. Where the water meets the wall, this attraction draws it upward a bit so that the actual shape of the water surface is slightly concave. You can see this shape if you fill a test tube with water. The tendency of water to rise in a hollow tube is known as capillary action. Capillary action causes water to rise above ground level in the xylem of plants.

For most plants, capillary action is not enough force to lift water to the top branches. Upward force is also provided by the evaporation of water from leaves. The loss of water vapor from plants is called transpiration. As leaves transpire, the outward flow of water lowers the pressure in the leaf xylem, creating a vacuum that pulls water upward. This force is responsible for most of the water flow in plants, including lifting water to the tops of trees. The movement of water through xylem is shown in FIGURE 21.4.

Apply How does transpiration affect water movement through a plant?

**MAIN IDEA**

**Phloem carries sugars from photosynthesis throughout the plant.**

The second tissue in a plant’s vascular system is phloem tissue, shown in FIGURE 21.5. Phloem carries plant nutrients, including minerals and sugars, throughout the plant. Phloem moves the products of photosynthesis out of the leaves to stems and roots. Minerals that travel up the xylem can also move into the phloem through specialized parenchyma transfer cells in the leaves.

Unlike xylem, phloem tissue is alive. Phloem is a complex tissue made mostly of cells called sieve tube elements. Their name comes from the small holes in the end walls of their cells. These holes let the phloem fluids, or sap, flow through the plant. As they form, sieve tube elements lose their nuclei and ribosomes. Nutrients can then move from cell to cell. Each sieve tube element is next to a companion cell, and the two cells are connected by many plasmodesmata, or small channels. Because the companion cells keep all their organelles, they perform some functions for the mature sieve tube cells. In some plants, the companion cells help load sugars into the sieve tube cells.

Recall that fluids in xylem always flow away from the roots toward the rest of the plant. In contrast, phloem sap can move in any direction, depending on the plant’s need. The *pressure-flow model* is a well-supported theory that explains how food, or sap, moves through a plant. Phloem sap moves from a sugar source to a sugar sink. A source is any part of the plant that has a high concentration of sugars. Most commonly this source is the leaves, but it can also be a place where the sugars have been stored, such as the roots. A sink is a part of the plant using or storing the sugar, such as growing shoots and stems, a fruit, or even the storage roots that will be a sugar source later in the season. The locations of sugar sources and sinks in a plant can change as the plant grows and as the seasons change.
The sugars move into the sink, such as a root or fruit, where they

The pressure changes between sugar sources and sinks, shown in FIGURE 21.6, keep nutrients moving through phloem. At a source, many plants use ATP to pump or load sugar into phloem at a high concentration. Therefore, at a source, there is a low concentration of water relative to sugars. Water then flows into the phloem through osmosis, due to the high concentration of sugars. Osmosis requires no energy on the part of the plant. This active loading of sugars and passive flow of water creates high pressure at the sugar source. At the same time, the sugar concentration of the sink end is lessened as sugar is unloaded into the sink. Unloading sugars also uses ATP from the plant. The overall result is higher pressure at the source end and lower pressure at the sink end. This difference in pressure keeps the sugary sap flowing in the direction of the sink.

Apply What are two plant parts that can be sugar sources?

The pressure-flow model explains the movement of sugars through the phloem.

1. Sugars move from their source, such as photosynthesizing leaves, into the phloem.
2. Water moves from the xylem into the phloem by osmosis, due to the higher concentration of sugars in the phloem. The water flow helps move sugars through the phloem.
3. The sugars move into the sink, such as a root or fruit, where they

Connecting CONCEPTS

Osmosis Recall from Chapter 3 that osmosis is the diffusion of water molecules across a semi-permeable membrane from an area of high concentration to an area of lower concentration.

21.2 ASSESSMENT

REVIEWING MAIN IDEAS

1. How are absorption and transpiration involved in the movement of water through the xylem of a plant?
2. Describe how nutrients are moved through the phloem according to the pressure-flow model.

CRITICAL THINKING

3. Infer Suppose that xylem were located only in the roots and stems of a plant. Would fluids in the xylem still move? Why or why not?
4. Analyze How are the specialized cells of xylem and phloem suited for their functions?

5. Cell Function Which process requires more energy from the plant, moving water up through the xylem or moving nutrients down through the phloem? Explain.

ONLINE QUIZ ClassZone.com
Density of Stomata

In this lab, you will examine the upper and lower leaf surfaces from trees and determine the density of the stomata in the leaves.

**PROBLEM** How does the density of stomata vary among leaf surfaces?

**PROCEDURE**

1. Obtain a leaf of a known species.
2. Paint both the upper and lower surfaces of an area of leaf between two veins with clear fingernail polish. Allow the fingernail polish to dry completely.
3. Place a piece of clear tape over the dried nail polish on the lower surface of the leaf. Gently but firmly press the tape to the leaf.
4. Peel the tape from the leaf and place the tape onto the microscope slide. Examine the tape, which has an impression of the leaf cells, under low power and high power of the microscope.
5. Under high power, count the number of stomata in the field of view. Then count the number of epidermal cells in the same field of view. Record your data in a table like the one shown below.
6. Repeat steps 2–5 two more times, using a new leaf of the same species each time, and find the average number of stomata and the average number of cells of your three samples.
7. Repeat steps 3–6 using the upper surface of the leaf.

<table>
<thead>
<tr>
<th>TABLE 1. STOMATA AND EPIDERMAL CELLS IN THE SURFACES OF A LEAF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field of View</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>TOTAL</td>
</tr>
</tbody>
</table>

**ANALYZE AND CONCLUDE**

1. **Calculate** Find the density of stomata for the lower and upper leaf surfaces of each leaf using the following equation:

   \[
   \text{Stomata Density} = \frac{5}{(S + E)} \times 100
   \]

   where \( S = \) the average number of stomata and \( E = \) the average number of epidermal cells in one surface of the leaf.

2. **Analyze** What is the difference between the density of stomata on the lower surface of the leaf and on the upper surface of the leaf? Form a hypothesis that might explain this difference.

3. **Predict** How might the stomata density be different for a tree in the desert? in the rain forest?
21.3 Roots and Stems

**KEY CONCEPT** Roots and stems form the support system of vascular plants.

**MAIN IDEAS**

- Roots anchor plants and absorb mineral nutrients from soil.
- Stems support plants, transport materials, and provide storage.

**VOCABULARY**

- vascular cylinder, p. 648
- root hair, p. 648
- root cap, p. 648
- meristem, p. 648
- fibrous root, p. 649
- taproot, p. 649
- primary growth, p. 651
- secondary growth, p. 651

**Connect** Humans reach a certain height and stop growing. Plants, however, can continue growing their entire lives. Woody plants in particular can keep growing in both height and width. Each part of a plant grows in the direction that allows it to reach the resources the plant needs, and each part plays a role in the plant’s survival.

**MAIN IDEA** Roots anchor plants and absorb mineral nutrients from soil.

Why are roots important? Roots may make up over half of the body of a plant. They anchor the plant to the ground, and from the soil they absorb water and minerals the plant needs.

**Parts of a Root**

Roots support the plant and absorb, transport, and store nutrients. Like other plant parts, roots contain all three tissue systems—vascular, ground, and dermal. Parts of a root are shown in FIGURE 21.7.

In the center of the root is the vascular cylinder, which is made of xylem and phloem tissues. The vascular cylinder is surrounded by ground tissue, covered by dermal tissue. A plant absorbs most of its water in the dermal tissue just above the root tips. These cells have tiny projections called root hairs, shown in FIGURE 21.8. Root hairs find their way through the spaces between soil particles, greatly adding to the surface area available to take up water. Covering the tip of the root is the root cap, a small cone of cells that protects the growing part of the root as it pushes through the soil.

Just behind the root cap is where most of the root’s growth occurs. Groups of cells that are the source of new cells form tissue called meristem. Meristem cells aren’t specialized, but when they divide, some of the new cells specialize into tissues. Areas of growth that lengthen the tips of roots and stems are called apical (AY-pik-kul) meristems. Lateral meristems, found all along woody roots and stems, increase the thickness of these plant parts.

**FIGURE 21.7** This light micrograph of a root tip cross-section shows some of the parts of a root. (LM; magnification 35×)

**FIGURE 21.8** Root hairs are located above the root tip. (colored SEM; magnification 80×)
Types of Roots
Roots take one of two basic forms, as shown in FIGURE 21.9. Fibrous root systems make fine branches in which most of the roots are the same size. These roots spread like a mat beneath the soil surface, and firmly anchor the plant to the ground. Taproot systems have a long, thick, vertical root with smaller branches. Long taproots allow plants to get water from deep in the ground. The thick taproot can also sometimes store food. Radishes, carrots, and beets are examples of taproots that we eat.

Water and Mineral Uptake
All plants require water and certain mineral nutrients for growth, development, and function. Their roots take up nutrients in a process that also results in water absorption. Mineral nutrients are usually dissolved in soil water as ions. For example, nitrogen is often taken up as NO$_3^-$ ions, and iron can be taken up as Fe$^{2+}$ ions. Plants use energy to transport nutrient ions into the roots through active transport. The increased concentration of ions within root cells also causes water to move into the root tip by osmosis.

Some minerals are needed in large amounts. Nitrogen, for example, is an essential mineral needed for nucleic acids, proteins, and chlorophyll. Other minerals serve mostly to catalyze reactions and are needed only in tiny amounts. Magnesium is a mineral involved in the production of chlorophyll. Even though only tiny amounts are needed, these minerals are also necessary for plant health.

**Explain** How do root hairs help roots absorb water?

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**DATA ANALYSIS**

**IDENTIFYING THE IMPORTANCE OF REPEATED TRIALS**
Scientists need to include repeated trials in experiments in order to draw reliable conclusions. One factor to consider when determining the number of trials in an experiment is how much variation there is among the organisms being tested.

A group of students collected data on the effect of water on the root densities of bean plants. They planted three bean seeds of the same species, each in the same size pot. They used the same type and amount of soil for each plant. Each plant received the same amount of sunlight.

- Plant A received 30 mL of water every day.
- Plant B received 30 mL of water every other day.
- Plant C received 30 mL of water once a week.

Root density, the number of roots per cm$^2$, was measured in all three plants after 30 days. The graph shows the results of the experiment. The students conclude that this species of bean plant should receive 30 mL of water every other day in order to produce the most roots.

1. **Analyze** Did the students reach a valid conclusion? Why or why not?
2. **Experimental Design** How would you change the experiment to improve the experimental design?
**Stems support plants, transport materials, and provide storage.**

You may know that stems support flowers and leaves, giving them better access to pollinators and sunlight. But stems have other functions as well, as you can see in **FIGURE 21.10**. Stems often house a majority of the vascular system and can store food or water. The green stems of cacti, for example, can both photosynthesize and store water. Although most stems grow above ground, potatoes and ginger are examples of stems that can grow underground.

Some stems are herbaceous. Herbaceous plants produce little or no wood. They are usually soft because they do not have many rigid xylem cells. Herbaceous plants may be monocots, such as corn, or dicots, such as beans, and most do not grow taller than two meters. Herbaceous stems are often green and may conduct photosynthesis.

Stems can also be woody. Most plants with woody stems are dicots, such as many broadleaf trees or gymnosperms—pines or fir trees. Tree trunks are an example of woody stems. The oldest part of the xylem, the heartwood, is in the center of a tree trunk. Heartwood no longer conducts water but still provides structure. Sapwood, which is xylem and conducts water, surrounds the heartwood. Phloem produced near the outside of the trunk forms the inner layer of bark. An outer layer of bark provides a protective covering.

**Stem Growth**

For as long as a plant survives, it is capable of growth. The continued growth of plants is possible because meristems are active throughout the life of the plant. Meristem cells divide to create more cells. Some of the divided cells remain meristem cells for future divisions, while the others become specialized and end up as part of the tissues and organs of a plant.
The pattern of plant growth depends on the location of the meristems within the plant. Growth that increases a plant’s length—makes stems grow taller or roots grow longer—is called primary growth. This type of growth takes place in apical meristems found at the ends of stems and roots. Secondary growth adds to the width in the stems and roots of woody plants. Dicot trees, such as oak and maple, produce a lot of secondary growth over their lifetimes. Secondary growth takes place in lateral meristems in the outer trunk layers.

**Tree Rings**

Secondary growth is also responsible for the formation of tree rings, shown in FIGURE 21.11. Tree rings form due to uneven growth over the seasons. In spring, if water is plentiful, new xylem cells are wide and have thin walls. These cells appear light in color. When water becomes more limited in the following months, xylem cells are smaller and have thicker walls, so they appear darker in color.

The age of a tree can be determined by counting these annual rings. One ring represents one year of growth. Each ring includes both the larger, lighter cell bands of spring growth and the smaller, darker cell bands of later season growth. Climate, too, can be inferred from the rings since the rings will be thicker if there were good growing conditions. Some trees live thousands of years and can provide climate data that are not available from any other scientific records.

**VISUAL VOCAB**

- **Primary growth** lengthens roots and stems.
- **Secondary growth** widens roots and stems.

**FIGURE 21.11** Bark is the outside protective covering of woody plants. The light-colored wood, sapwood, conducts water and grows in bands. One year of growth is represented by a light and a dark band. Heartwood is the non-functional dark-colored wood in the center.

**Summary** How are tree rings formed?

**21.3 ASSESSMENT**

**REVIEWING MAIN IDEAS**

1. Describe two major functions of roots. Explain why these functions are important to the plant.
2. How do the functions of stems differ from those of roots? How are they similar?

**CRITICAL THINKING**

3. **Analyze** Some stems, such as ginger rhizomes, grow underground. Why are they considered stems rather than roots?
4. **Apply** What effect could a cold winter with little precipitation have on the primary growth and secondary growth of a tree?

5. **Earth’s History** The principle of uniformitarianism states that processes that can be observed today can be used to explain events that occurred in the past, or “The present is the key to the past.” How does this principle relate to tree ring dating?
Leaves

**KEY CONCEPT** Leaves absorb light and carry out photosynthesis.

**MAIN IDEAS**
- Most leaves share some similar structures.
- Most leaves are specialized systems for photosynthesis.

**VOCABULARY**
- blade, p. 652
- petiole, p. 652
- mesophyll, p. 652
- guard cell, p. 653

Connect  “Leaves of three, let it be.” This is a saying of many experienced hikers who know how to avoid poison ivy. Hikers can identify poisonous plants in the same way that people can identify many plants that are safe to eat—by the shapes of their leaves. Plant species have their own unique leaf shapes, specially adapted for light gathering and retaining water in their particular environment.

**MAIN IDEA**

*Most leaves share some similar structures.*

Leaves of different species don’t all look the same, but most leaves do share some common parts. Leaves grow out from a plant’s stem, and they are made up of a few basic parts. The **blade** is usually broad and flat, and it collects the sunlight for the plant. The blade connects to the stem by a thin stalk called the **petiole** (PEHT-ee-ohl). A bud that grows between the petiole and the stem of a plant, called an axillary bud, marks where a leaf ends.

**Leaf Tissues**

Like roots and stems, leaves have an outer covering of dermal tissue and an internal system of vascular tissue surrounded by ground tissue. The dermal tissue of many leaves is covered by a waxy cuticle that forms a water resistant covering. The cuticle protects the inner tissues and limits evaporation from the plant. Between the two dermal layers of a leaf is parenchyma tissue called **mesophyll** (MEHZ-uh-fiHl). The vascular tissues of xylem and phloem make up the veins that run throughout the mesophyll.

**Stomata and Guard Cells**

In most plants, the top and undersides of leaves have different functions. The upper portion of the mesophyll has most of the chloroplasts and is where most photosynthesis takes place. The underside portion of a leaf has stomata and is the site of transpiration and gas exchange.
A pair of guard cells, shown in FIGURE 21.12, surround each stoma, and can open and close by changing shape. During the day, the stomata of most plants are open, allowing the carbon dioxide (CO₂) necessary for photosynthesis to enter. Potassium ions (K⁺) from neighboring cells accumulate in the guard cells. A high concentration of K⁺ causes water to flow into the guard cells as well. When the plant is full of water, the two guard cells plump up into a semicircle shape, opening the stoma.

When the stomata are open, water evaporates from the leaves. When the plant is losing water from transpiration faster than it is gaining water at its roots, the guard cells deflate and close the stomata. With the stomata closed, the plant may run low on CO₂ for photosynthesis. The stomata also close at night. Factors such as temperature, humidity, hormonal response, and the amount of CO₂ in the leaves signal the guard cells to open or close.

**Leaf Characteristics**

It is not always obvious what part of a plant is actually a leaf. As shown in FIGURE 21.13, leaves may be simple, with just one blade connected to the petiole, or they may be compound, with many blades on one petiole. The multiple blades are called leaflets. All of the leaflets and their petiole together are actually a single leaf because the axillary bud is at the base of the petiole. There are no buds at the bases of the leaflets. Besides leaf shape, other traits of leaves used to identify plants include the pattern of veins and the leaf edge, or margin.

**Summarize** What is the function of the guard cells of a plant?

**Infer** How might compound leaves and leaves with lobed margins be well-suited to windy environments?
**QUICK LAB**

**Chlorophyll Fluorescence**

If you remove chlorophyll molecules from their cells and then expose them to bright light, the energy absorbed from the excited electrons in the chlorophyll will be either lost as heat or released as a dull-colored light as the electrons return to their normal state. This is an example of fluorescence: the absorption of light at one wavelength, and its release at a longer—and lower-energy—wavelength.

**PROBLEM** How can fluorescence be used to study photosynthesis?

**PROCEDURE**

1. Use the mortar and pestle to crush a handful of spinach leaves, adding enough methanol to make 10 mL of extract. Use a graduated cylinder to collect and measure the extract.
2. Place the filter paper in the funnel, and hold the funnel over a beaker. A second person should pour the extract through the funnel to filter the extract.
3. Carefully transfer the extract to a test tube, and hold it in front of a lit flashlight. Observe the fluorescence that occurs at a 90-degree angle from the beam of light.

**ANALYZE AND CONCLUDE**

1. **Identify** What color does the fluorescence appear?
2. **Analyze** Why did the chlorophyll have to be extracted before the fluorescence could be observed?

**MATERIALS**

- mortar
- pestle
- handful spinach leaves
- 10 mL methanol
- graduated cylinder
- filter paper
- funnel
- beaker
- eye dropper or pipette
- test tube
- test tube rack
- flashlight

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**MAIN IDEA**

Most leaves are specialized systems for photosynthesis.

The leaves of a plant are the main sites for photosynthesis. The broad, flat shape of many leaves allows for light gathering on the upper surface and gas exchange on the underside. Since the undersides of leaves are not exposed to direct sunlight, the plant loses less water while the stomata are open.

**Photosynthetic Structures**

There are two types of mesophyll cells in leaves, shown in **FIGURE 21.14**. Mesophyll is the photosynthetic tissue of a leaf. Both types of cells in mesophyll have chloroplasts. Just under the dermal layer is a layer of tall, rectangular cells called the palisade mesophyll. These cells absorb much of the light that enters the leaf. Beneath this layer is the spongy mesophyll. Spongy mesophyll has cells that are loosely packed, creating many air spaces. These air spaces connect with the outside of the plant through the stomata, allowing carbon dioxide and oxygen to diffuse in and out of the leaf. Carbohydrates that the plant makes move from mesophyll cells into phloem vessels, which carry the products to tissues throughout the plant.
Leaf Adaptations

Not all leaves are “leafy.” Leaves are adapted for photosynthesis in the plant’s particular environment. For example, cacti leaves are actually the sharp spines that protect them from predators and help minimize water loss due to transpiration. Other desert plants, such as agave, store water in their leaves. The leaves and stems of many desert plants are protected by very thick cuticles, which minimize the loss of water from the plant.

Similar adaptations are common in coniferous trees in cold, dry climates. Pine needles, for example, are leaves with a small surface area and a thick, waxy epidermis that protects them from cold damage. Tiny sunken areas for the stomata help reduce water loss.

Water loss is not a problem for aquatic plants, however. The undersides of a water lily’s leaves are below the water surface. To accommodate gas exchange in an aquatic environment, the water lily has stomata on the upper surface of its leaves. Many aquatic plants also have flexible petioles adapted to wave action.

Many tropical plants have very large, broad leaves. In the crowded rain forest, the challenge is to get enough light and space among all the other plants. Larger leaves mean more light-gathering surface.

A few plants are actually predators. The pitcher plant, for example, has tall, tubular leaves that help lure, trap, and digest insects. These insects provide extra nitrogen for the plant, which is needed because there is little of it in the soil where the plant grows.

Infer Flower petals are also an adaptation of leaves. Their bright colors and fragrance attract animals and insects. Why is attracting other organisms important for some plants?

21.4 ASSESSMENT

REVIEWING MAIN IDEAS

1. Describe the functions of the blade and petiole in a leaf.
2. How do the palisade and spongy mesophyll layers help a leaf perform photosynthesis?

CRITICAL THINKING

3. Infer The leaves of aquatic plants that are completely underwater have few stomata. Why might this be so?
4. Apply Grass blades are leaves that are joined directly to the stem. What structure that is typical of many leaves is missing in grass?

5. Analogous Structures The tendrils that allow pea plants to climb up an object are modified leaves, whereas the tendrils of grape vines are modified stems. Explain.
Use these inquiry-based labs and online activities to deepen your understanding of plant structure and function.

**INVESTIGATION**

### Photosynthesis and Red Leaves

How do plants with yellow, purple, or red leaves year-round carry out photosynthesis to produce the food they need to live? In this lab, you will investigate whether a red-leafed plant contains the same pigments for photosynthesis as a green-leafed plant.

**SKILLS** Observing, Interpreting Data, Drawing Conclusions

**PROBLEM** What pigments are found in plants that appear red?

**PROCEDURE**

1. Make a J-shaped hook out of each paper clip. Carefully push the straight end into the bottom of the rubber stoppers. Attach the strip of chromatography paper to the other end of each wire. **Caution:** Do not force the stopper.

2. Place the green leaf on one paper strip, about 2 cm from the bottom. Roll the coin over the leaf until you see a horizontal green line across the strip. Repeat with the red leaf on the other strip of paper.

3. Add alcohol to the test tubes so that the bottom edge of the chromatography paper will be submerged. Lower the papers into the test tubes, making sure that each horizontal line of pigments is NOT submerged in the alcohol.

4. Place the tests tubes in a holder and leave them undisturbed for 15–30 minutes. Record your observations.

5. After the alcohol has traveled to the top of the paper strips, remove the papers from the test tubes. Allow the papers to dry and compare the chromatograms, or records of pigment patterns, for the two leaves. Use the table provided by your teacher to identify the separated pigments.

**ANALYZE AND CONCLUDE**

1. **Compare and Contrast** Describe the similarities and the differences between the two chromatograms.

2. **Apply** Based on your results, explain how a red-leafed plant photosynthesizes.

3. **Analyze** During the fall, some trees form a plug at the base of their leaf petioles, cutting off water to the leaf. This causes the leaf to stop photosynthesizing. Chlorophyll begins to break down, and the colors of the other pigments present in the leaf begin to show. How do you think a chromatogram of a healthy red leaf would compare with a chromatogram of a tree leaf that just turned red in autumn?
**INVESTIGATION**

**Connecting Form to Function**
In this lab, you will examine a slice of the roots, stems, and leaves of a plant and describe how their structures relate to their functions.

**SKILL** Observing

**PROBLEM** How are plant structures related to their functions?

**MATERIALS**
- plant root, stem, and leaf
- razor tool
- 3 slides
- 3 cover slips
- eyedropper
- water
- compound microscope

**PROCEDURE**
1. Draw a table with three labeled columns: name of plant part, sketch, and function. Label three rows: root, stem, and leaf.
2. Carefully use the razor tool to cut a very thin slice from the root, stem, and leaf of the plant. You must be able to see light through the sliced sections.
3. Prepare a wet mount slide of a slice of each plant organ. Examine each slide under the microscope and sketch the structures that you see. Describe the function of each structure under the third column.

**ANALYZE AND CONCLUDE**
1. **Compare** What similarities did you observe among the slides of the three plant organs? Explain why these similarities may exist.
2. **Analyze** Which organ had the most vessels? Which organ had the most chloroplasts? Which organ had the most hairs? Is this what you would predict based on the function of these organs? Explain your answer.

**VIRTUAL LAB**
**Plant Transpiration**
Is the rate of transpiration always the same? In this interactive lab, you will determine how different environmental conditions affect the rate of transpiration.

**ANIMATED BIOLOGY**
**Name That Tree**
Is that leaf from an oak or a hickory tree? Are those needles from a pine tree or spruce? Choose a mystery leaf, then identify the tree it came from with an interactive dichotomous key.

**WEBQUEST**
How have plants adapted to their surroundings? In this WebQuest, you will learn about various adaptations that plants have developed for specific environments. Then write a description of the adaptations found on a fictitious new plant.
21.1 Plant Cells and Tissues

Plants have specialized cells and tissue systems. There are three basic types of plant cells that differ in cell wall structure. Each of these cell types can make up simple tissues. These tissues, as well as complex tissues, make up tissue systems. A plant has a dermal tissue system that covers the plant, a ground tissue system that makes up most of the inside of the plant, and a vascular tissue system that transports fluids throughout the plant.

21.2 The Vascular System

The vascular system allows for the transport of water, minerals, and sugars. Xylem and phloem are the two main tissues of the vascular system. Water and dissolved minerals move through xylem from the roots of a plant up to the leaves, where it evaporates through leaf stomata. This process is called transpiration. The pressure-flow model is a hypothesis of how sugars from photosynthesis move through the plant within the phloem.

21.3 Roots and Stems

Roots and stems form the support system of vascular plants. Roots anchor plants in the soil and absorb water and mineral nutrients for the plant to use. There are two main types of roots: fibrous roots and taproots. Stems provide support for the plant, and house the vascular systems of the plant. They also give leaves and flowers better access to sunlight and to pollinators. Some stems can store food, while other stems are adapted to store water.

21.4 Leaves

Leaves absorb light and carry out photosynthesis. Most leaves are specialized for photosynthesis, with a broad shape, many chloroplasts, and stomata that allow carbon dioxide and oxygen to move into and out of the plant. Certain leaf characteristics, such as the vein pattern and the shape of the leaf, can be used to help identify plants. There are many adaptations of leaves, such as cactus spines, pine needles, and the tubular leaves of a pitcher plant that are used to lure and trap insects for food.

Supporting Main Ideas
Use a main idea diagram to outline the tissue systems in plants.

Three-Column Chart
Make a three-column chart to summarize the forces involved in the movement of fluids within xylem.

<table>
<thead>
<tr>
<th>Force</th>
<th>Description</th>
<th>Where in Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transpiration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cohesion and adhesion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorption</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 21: Plant Structure and Function

Chapter Assessment

Chapter Vocabulary

21.1 parenchyma cell, p. 640
collenchyma cell, p. 640
sclerenchyma cell, p. 641
dermal tissue, p. 642
ground tissue, p. 642
vascular tissue, p. 642
xylem, p. 642
phloem, p. 642

21.2 cohesion-tension theory, p. 643
transpiration, p. 645
pressure-flow model, p. 645

21.3 vascular cylinder, p. 648
root hair, p. 648
root cap, p. 648
meristem, p. 648

21.4 blade, p. 652
petiole, p. 652
mesophyll, p. 652
guard cell, p. 653

fibrous root, p. 649
taproot, p. 649
primary growth, p. 651
secondary growth, p. 651

Reviewing Vocabulary

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

1. parenchyma cell, sclerenchyma cell
2. ground tissue, vascular tissue
3. xylem, phloem
4. fibrous root, taproot
5. primary growth, secondary growth

Labeling Diagrams
In your notebook, write the vocabulary term that matches each numbered item below.

Reviewing MAIN IDEAS

14. Name two roles of parenchyma cells, and briefly explain how these cells are specialized for these roles.

15. Both collenchyma and sclerenchyma cells provide support to a plant. But only one of these cell types can exist in plant parts that are still growing. Identify the cell type and explain the traits that make this so.

16. Describe one similarity and one difference between the dermal tissues in nonwoody and woody parts of a plant.

17. Some ground tissue contains many chloroplasts. Where is this tissue located and why does it contain so many chloroplasts?

18. How is the structure of vascular tissue related to its ability to transport materials in the plant?

19. What must happen to tracheids and vessel elements before they can function in xylem?

20. What processes are responsible for water flowing through xylem from the roots to the tips of leaves?

21. Name three substances that are transported by phloem.

22. What can taproots do that fibrous roots cannot do?

23. Describe similarities between herbaceous stems and woody stems.

24. How do the xylem and phloem in leaves help identify a plant species?

25. Photosynthesis requires carbon dioxide and produces oxygen. How does spongy mesophyll play a role in the diffusion of these gases into and out of the leaves?
26. **Compare** In animals, the term *stem cells* refers to unspecialized or undifferentiated cells that give rise to specialized cells, such as a blood cell. How are meristem cells in plants similar to animal stem cells?

27. **Analyze** A sugar beet plant develops a large root in the first year of growth and stores sugar in it until the second growing season. But, besides sugar, as much as three-fourths of the root’s weight can be water. Why is there so much water in the root?

28. **Apply** In 1894, naturalist John Muir wrote about white bark pines he saw at Yosemite National Park in California. At high elevations, where there was snow on the ground for six months each year, he studied a tree only three feet tall and six inches in diameter and determined it was 426 years old. How did he know how old the tree was? Why might it be so small when trees of the same species were much larger down the mountain?

29. **Infer** Many rain forest plants have leaves that taper to tips on the ends. Water from heavy rains drips off the tips of the leaves so that water doesn’t collect on the leaves. Why might this be an adaptive advantage for the plant?

30. **Synthesize** Use what you know about cohesion and adhesion to explain why almost an entire sheet of paper towel can become wet even if only a corner of it is placed in water.

### Interpreting Visuals

Use the photograph to answer the next three questions.

31. **Apply** About how many years old was this tree when it was cut down?

32. **Infer** What does the pattern of growth rings indicate about the climate and the rate of growth of this tree over the years?

33. **Predict** Imagine this tree were still growing. If the next year had a spring with much less rain than previous springs and then a summer with a lot of sunshine, what would the next growth ring look like? Explain.

### Analyzing Data

An experiment was designed to test the effect of various environmental factors on the successful germination of grass seed. The control group of seeds was planted according to the directions on the seed packet. Each of three additional groups tested one variable. The experimental design and results are shown in the chart below. Use the chart to answer the next three questions.

<table>
<thead>
<tr>
<th>ENVIRONMENTAL FACTORS THAT AFFECT GRASS SEED GERMINATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environmental Factor</strong></td>
</tr>
<tr>
<td>Hours daylight</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>Seeds planted/seeds germinated</td>
</tr>
</tbody>
</table>

34. **Infer** What does the data suggest about the conditions under which grass seeds will or will not germinate?

35. **Evaluate** Do the results seem logical? Explain.

36. **Analyze** If you could change anything in this experimental design, what would it be? Give at least two reasons to support your response.

### Connecting CONCEPTS

37. **Write an Instruction Manual** Imagine that you want to sell plant dissection kits. The kits will include instructions on where to find all of the structures of a plant, such as the different type of cells and tissues, roots, leaves, stomata, stems, phloem, and xylem. You need to write an instruction manual to help people dissect the plant. Write instructions to dissect the plant from the bottom up. Decide whether it is a woody or nonwoody plant.

38. **Analyze** Strangler figs were transplanted from the tropics to states such as Florida and California because of their unusual growth forms. Considering how they got their common name, why was this perhaps not a good idea?
1. Tree Ring Growth from 1955 to 2005

Suppose a tree farmer has collected data about tree ring growth for many years. During that time, only one major drought has occurred. Based on the graph, between which years did the drought most likely occur?
A 1955–1960
B 1965–1970
C 1975–1980
D 1990–1995

THINK THROUGH THE QUESTION
First, eliminate answer choices that list the years where there is no remarkable change in the graph. Then consider the remaining choices. Would drought have a negative or a positive effect on the width of a tree ring?

2. Plant tissues are made of three basic types of cells: parenchyma, collenchyma, and sclerenchyma. Which of the following statements is true about all plant cells?
A They do not have a nucleus.
B They do not have a cell membrane.
C They have a cell wall.
D They have the same function.

3. Plants capture radiant energy from sunlight and convert it into usable energy in the form of
A carbon dioxide.
B protein.
C oxygen.
D sugar.

4. What two structures do plant cells have that animal cells do not have?
A ribosomes and mitochondria
B mitochondria and cell walls
C chloroplasts and cell walls
D chloroplasts and ribosomes

5. Which of the following characteristics is shared by both plant cells and photosynthetic bacteria?
A cell wall of lignin
B chlorophyll
C DNA enclosed in a nucleus
D vacuole for starch storage

6. Effect of Nitrogen on Bean Plant Growth

<table>
<thead>
<tr>
<th>Trial</th>
<th>0% N</th>
<th>5% N</th>
<th>10% N</th>
<th>15% N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4 cm</td>
<td>2.2 cm</td>
<td>2.2 cm</td>
<td>3.6 cm</td>
</tr>
<tr>
<td>2</td>
<td>0.5 cm</td>
<td>2.6 cm</td>
<td>2.6 cm</td>
<td>2.6 cm</td>
</tr>
<tr>
<td>3</td>
<td>1.0 cm</td>
<td>3.6 cm</td>
<td>2.9 cm</td>
<td>3.5 cm</td>
</tr>
</tbody>
</table>

Students recorded data on the effect of different percentages of nitrogen (N) in fertilizer on the growth of bean plants in centimeters. Fertilizer with no nitrogen was included in this experiment because it served as the
A model for the experiment.
B control for the experiment.
C independent variable for the experiment.
D dependent variable for the experiment.