Within individual cells, water is transported mainly by osmosis. In an entire multicellular organism, water must often be transported over much longer distances than across a single cell. Some trees, such as the one in Figure 9.10, transport water as far as 100 m or more from the root tips to the highest leaves. In this section, you will investigate the transport of water and nutrients in the plant vascular system. You will also identify the cells, tissues, and organs that make up this system.

**Xylem Vessels and Phloem Vessels**

Vascular plants have a system of vessels that transport water, minerals, and sugars throughout the plant. Like the circulatory system that carries blood throughout your body, the plant vascular system is made up of a series of interconnected tubes that extend throughout the plant. Xylem and phloem are the specialized tissues that make up this system of transport. You have seen xylem and phloem in leaves. These tissues are also found in the roots and stems of many plants.

The xylem tissue transports water and dissolved minerals from the soil to the leaves. In a mature plant, most xylem cells are dead. They form hollow tubes consisting of only the cell walls. The cells are linked end to end, forming long continuous tubes called **xylem vessels**. Xylem vessels extend from near the tips of the roots up into the rest of the plant. Without the water transported by the xylem vessels, the plant would die, since water is used in photosynthesis. In some non-woody plants, the water transported by the xylem vessels also prevents wilting.

Some of the sugars produced during photosynthesis are transported throughout the plant by cells of phloem tissue. As with xylem, phloem is composed of cylindrical cells joined end to end to form **phloem vessels**. Unlike xylem, however, phloem cells are living cells. Their cell walls are porous, allowing them to exchange materials with neighbouring cells. Sugary sap flows down the phloem vessels by passing through these pores. Figure 9.11 illustrates how xylem vessels and phloem vessels are grouped together in bundles in roots and stems of plants.

**Figure 9.11** Cross sections through A the root of a plant and B the stem of a plant show that strands of xylem and phloem are grouped together in bundles.
Figure 9.12 gives a more detailed look at the parts of xylem and phloem tissue. The long hollow cells within xylem vessels are called **tracheids** or **vessel elements**. Some types of plants have only tracheids, while others have both tracheids and vessel elements. Both of these structures begin as living cells, which grow end-to-end in a young plant. When these cells mature, the content of their cells die, leaving only the cell walls. Fluids pass from one tracheid or vessel element to the next within the xylem, to move water through the plant. Small pits, thin areas in the end walls, connect the tracheids. Perforations in the end walls connect vessel elements. Phloem cells consist of **sieve tubes** and **companion cells** arranged end-to-end. These cells connect in long tubes, separated by **sieve plates**, to make the phloem vessels.

**Water Uptake in Roots**

Water and minerals enter a plant from the roots. At the core of the root are the xylem and phloem, encircled by several other layers of cells. Epidermal tissue covers the root. At its tip, the epidermal cells are permeable to water, and this location is where most water uptake occurs. Water enters the cells of the root epidermis by osmosis. The surface area for absorbing water and dissolved minerals from the soil is increased by hundreds of **root hairs** (see Figure 9.13). Each tiny root hair is an outgrowth of a single epidermal cell. Water continues diffusing through the root tissue until it reaches the xylem vessels.
Although water readily diffuses across the cell membranes, minerals do not. Root cells use facilitated diffusion or, if working against a concentration gradient, active transport to move minerals across their membranes.

The solution of water and minerals that accumulates in the root xylem is called xylem sap. Xylem vessels carry the xylem sap upward from the roots, through the stem, and into the leaves. As the xylem tissue enters the leaves, the vessels branch into the many veins often visible on the leaf surface. At the end of each xylem vessel, water and minerals are absorbed by the cells for the leaf. In the next Find Out Activity you will investigate the properties that allow fluid in the xylem to flow against gravity.

### Modelling Water Transport: Pushing and Pulling

You have learned how root cells transport water and minerals from cell to cell using diffusion and active transport. Once xylem sap enters the xylem vessels, how does the fluid flow upward against gravity?

#### Safety Precautions

- Never eat or drink anything in the laboratory.
- Handle the glass microcapillary tubes carefully. They break easily and, if broken, could injure you or a classmate.
- Follow your teacher’s instructions for disposing of the glass microcapillary tubes.

#### Materials

- 100 mL beaker
- Tap water
- Food colouring
- Plastic syringe
- 20 cm clear plastic tubing
- Scissors
- Glass microcapillary tube

#### Procedure

1. With your lab partner, set up the model system. Fill a beaker with water and add 2–3 drops of food colouring.

2. Using a syringe and a piece of plastic tubing, experiment with different ways of moving the water against gravity. Try methods that push the water from below as well as methods that pull the water from above.

3. While you are pulling the water column up from above, have your lab partner use scissors to snip a small hole in the side of the plastic tubing. Continue pulling the water up. Note what happens to the water column.

4. Touch the tip of a microcapillary tube to the surface of the water. What happens?

#### What Did You Find Out?

1. Which method of water transport moved the water column the highest?

2. What limited how high the water column could go?

3. How did cutting a hole in the plastic tubing affect your ability to move the water upward? Explain your observations.

4. Cohesion is the property of water that caused it to rise in a continuous column when you pulled it from above. Based on your observations, write your own definition for cohesion.

5. Adhesion is the property of water that caused it to rise in the microcapillary tube. Based on your observations, write your own definition for adhesion in your science notebook.
Properties of Water

How can xylem sap rise in such a long, continuous column? The force holding the column together is the same force that allows you to pull water upward with a syringe or drink through a straw. The shape of water molecules, and the weak electrical forces between them, cause water molecules to be attracted to each other. **Cohesion**, the tendency of water molecules to stick to other water molecules, transmits the upward pull from the tip of the leaves to the tip of the roots.

What would happen if the column of water within a xylem vessel were to break? The effect would be similar to removing a link from a chain. If you pulled the chain up from one end, only the chain links above the point of the break could be lifted. In a xylem vessel, a break in the water column, such as a bubble, blocks the rising xylem sap. Bubbles can form in the xylem sap as a result of freezing in winter. Only the water molecules above the point of the break can be pulled upward. (You may have witnessed the same phenomenon in the previous Find Out Activity, when you cut a hole in the plastic tubing.)

Another property of water, **adhesion**, helps water fight the force of gravity. **Adhesion** is the tendency of water molecules to stick, or adhere, to certain surfaces. Just as water molecules are attracted to each other, they are also attracted to the molecules of other substances, such as the glass of a microcapillary tube, or the cellulose wall of a xylem vessel. The clinging of xylem sap to the xylem walls helps to prevent the sap from falling back down to the roots.

Root Pressure Pushes

If you did the previous Find Out Activity, you saw that water can move upward over long distances by two main mechanisms: pushing and pulling. In the roots, one force that pushes fluid upward is turgor pressure inside the root xylem.

This is called **root pressure**. As root cells bring minerals into the xylem through active transport, the mineral concentration in the xylem sap increases. This increases the tendency of water to diffuse into the root xylem by osmosis. Water flows in, building root pressure in the xylem vessels. This pressure forces fluid up the xylem. Adhesion of the xylem sap to the xylem vessel walls helps the fluid climb upward. Figure 9.14 shows xylem sap oozing from a plant's cut stem. In the next Find Out Activity you can set up a model system to study root pressure.

**Figure 9.14** This tomato plant has been severed near the bottom of its stem. Xylem sap is oozing from the cut. What effect does this injury have on the transport of substances through the xylem?
Up with Root Pressure

Can root pressure really provide enough force to push a column of water upward against gravity? In this activity, you will answer this question by using a dialysis bag to model a root xylem vessel.

Safety Precautions

- Handle the glass tubing gently. If the tubing breaks, you could easily cut your hands.
- Dispose of any broken tubing according to your teacher's directions.

Materials

- string
- 10 cm dialysis tubing
- concentrated sugar solution
- 5 cm glass tubing (5 mm diameter)
- 250 mL beaker
- tap water
- metal stand with a small clamp

Procedure

1. Work together with a lab partner to use string to tie closed (tightly) one end of the dialysis tubing. Fill the tubing with concentrated sugar solution.
2. Place a piece of glass tubing in the open end of the fluid-filled dialysis bag. Use string to tie the open end of the bag around the glass tube. Tie it tightly to prevent leaks.
3. Immerse the bag in a beaker filled with tap water. Use the metal stand to support the glass tube so that it is held upright.
4. Observe the fluid level in the glass tubing over several minutes.

What Did You Find Out?

1. What happened to the fluid inside the bag? Why?
2. By what process did water flow across the dialysis membrane?
3. How successful was root pressure in your model system in moving water against gravity?
4. Compare the fluid movement you observed in this activity with the flow of xylem sap.

Transpiration Pulls

Root pressure can move water upward a few metres at most. Therefore, root pressure can account for the flow of xylem sap only in some small plants. For the roots of a tall tree to raise a column of water 100 m, the root pressure would have to be more than 10 times greater than atmospheric pressure. Such root pressures have never been demonstrated. Indeed, many tall trees show no measurable root pressure at all. How, then, does xylem sap make the rest of the journey upward to the leaves?

Xylem sap can flow upward faster than 15 m/h. At this rate, how long would it take for water to travel from the roots to the leaves in a tree 80 m tall with roots 20 m deep?
The remaining work of water transport is accomplished by pulling from above. Transpiration from the leaves generates this pulling force, or tension. Therefore, although too much water loss through stomata can put a plant at risk of drying out, transpiration is very beneficial to plants.

As water vapour exits the leaf tissue, the air within the leaf becomes slightly drier. This causes water to diffuse out of the leaf cells and into the fluid between the cells, where solutes are more concentrated. As a result, more water evaporates from the surface of the cells. Cohesive forces between the water molecules cause more water to be pulled up the xylem vessels in the leaf, replacing the water that has evaporated. In turn, more water travels along the xylem vessels toward the leaf cells. Ultimately, this transpirational pull is exerted throughout the xylem vessels and to the plant’s water source — the soil. Like an unbroken chain, the entire column of fluid is pulled upward. Figure 9.15 demonstrates the roles of transpiration, cohesion, and adhesion in this pulling-upward process.

The Sun causes water to evaporate. The energy for xylem transport comes from the Sun. Transpiration (evaporation) of water from leaves creates tension that pulls the water column in xylem from the roots. Water column is held together by cohesion; adhesion keeps water column in place. Water from soil enters xylem in root; tension in water column extends from leaves to root.

**Figure 9.15** Tension created by transpiration at the leaves creates a force that pulls the water in the xylem in the roots and stems upward to the leaves. Leaves absorb the energy in sunlight, which causes water evaporation through stomata.
Transpiration in Different Plant Types

In this investigation, you will design your own experiment to compare the amount of transpiration in different types of plants.

Question
Is there a difference in the amount of transpiration from different plant types?

Hypothesis
Choose four to six different types of plants to use in your experiment. With your group members, formulate a hypothesis about how the type of plant affects the amount of transpiration in plants.

Safety Precautions
- Never eat or drink anything in the laboratory.
- Wash your hands with soap and water after you have completed the investigation.

Materials
small potted plants
water
clear plastic bags (large enough to fit over plants)

Procedure
1. With your group, decide how you will test your hypothesis. Identify the manipulated variable and the responding variable. Be sure to include a control in your experimental design.
2. Based on your hypothesis, predict what the outcome of your experiment will be.
3. Write a step-by-step outline for your experimental procedure. Describe exactly how you will use the materials listed.
4. Prepare a data sheet for recording your data and notes.
5. Perform your experiment.

Analyze
1. Summarize the results of your experiment in a table. Are your results qualitative or quantitative?
2. Discuss the data with the other group members. Were the results similar to your predictions?
3. What can you infer about the difference in the amount of transpiration by different plant types?
4. Do your data support your hypothesis? Explain why or why not.
5. Suggest one or two ways that your experiment could have been improved. If you were to do the experiment again, what changes would you make?
6. How valuable was working in a group in developing your experiment and carrying out your investigation?

Conclude and Apply
7. How did the structure of the different plants affect the amount they transpired?
8. Based on the results of your experiment, what is your advice to home gardeners about the water requirements of different houseplants?

Extend Your Knowledge
9. Some plants must be able to survive in challenging environmental conditions. Research a region on Earth where one environmental variable is particularly extreme. What kinds of plants are native to the region? Do these plants have special adaptations that make them well suited to their surroundings?
Sugar Transport in Phloem

After water and minerals have been delivered to the leaves, the plant is ready to carry out photosynthesis. The sugars produced by the palisade tissue cells and spongy tissue cells provide energy for the whole plant. Before the sugars can be used by cells in other parts of the plant, they must make the trek from the leaves to the stem, roots, and growing shoots and fruits.

The phloem vessels transport the sugars and other substances throughout the plant. Sugar, minerals, and other nutrients are pumped into the leaf phloem by active transport. As the sugar concentration increases within the phloem cells, water follows the sugar by osmosis. The cells swell with the increase in turgor pressure. The sugar, nutrient, and water mixture, called phloem sap, flows down the concentration gradient. The fluid pressure forces the phloem sap through the pores in the phloem cell walls and into neighbouring cells, where pressure is lower.

As the phloem sap travels down to the roots, some of it leaves the phloem and nourishes the surrounding tissue. The nutrients are taken up by growing shoots and roots, as well as by fruits and other organs that store energy. Thus, in these tissues, the pressure within the phloem remains low. Because the pressure in the roots is almost always lower than in the leaves, phloem usually flows downward. Figure 9.16 illustrates the transport of sugar throughout a plant from leaf to root.
Think About It

What happens to a plant if the flow in vascular tissue is interrupted? In 1686, an Italian scientist named Marcello Malpighi (1628–1694) asked this question. He investigated it by removing a ring of phloem tissue from a tree.

What to Do

Read the following account of Malpighi’s experiment. Then answer the Analyze questions below.

In trees, phloem forms the layer of living tissue just beneath the bark. Xylem lies beneath the phloem. In his experiment, Malpighi peeled away a ring of bark and the outer layer of living tissue from a tree.

Shortly after this treatment, a swelling appeared in the bark of the tree immediately above the stripped ring. Sweet-tasting fluid oozed out from this swelling.

Although it appeared at first that Malpighi’s manipulations had not seriously damaged the tree, the tree died a few weeks later.

Analyze

1. What do the results of Malpighi’s experiment tell you about the function of phloem?

2. Why did the tree die?

3. What would the results of Malpighi’s experiment have been had he blocked transport in the xylem instead of the phloem?

4. The removal of a ring of tree bark and phloem is called girdling. Farmers sometimes girdle trees to produce sweeter fruit.
   (a) Why would this practice increase sugar transport to the fruit?
   (b) How would it affect the health of the tree?
Dr. Malcolm King comes from a long line of people whose life’s work involved healing. His grandfather was a traditional Aboriginal healer who learned about medicines from his own mother. Dr. King is carrying on the tradition. Much of his work involves exploring herbal medicine, specifically the use of traditional Aboriginal peoples’ remedies to treat respiratory illnesses, his area of specialization. Dr. King researches diseases such as asthma, bronchitis, and cystic fibrosis, and his work has led him to patent two therapies for chronic respiratory disease.

A winner of many awards for his scientific research and work with Aboriginal students, Dr. King is currently a professor of the pulmonary division in the department of medicine at the University of Alberta.

Dr. King and his students have been using extracts from rat root and varieties of licorice root in experiments to find out what works best in assisting the lungs to clear themselves of mucus and infection. In his model system, licorice root worked especially well in helping to clear mucus; Dr. King believes this is due to the complex sugars that give licorice its distinctive sweetness.

Section 9.3 Summary

Long continuous tubes, xylem vessels and phloem vessels, transport fluids throughout the plant. Xylem tissue transports water and dissolved minerals from the soil to the leaves. Xylem vessels are made of long, hollow, dead cells called tracheids or vessel elements. Phloem vessels transport sugars produced during photosynthesis throughout the plant. Phloem cells are living cells.

Water first enters plant roots by osmosis. Hundreds of root hairs increase the surface area over which osmosis occurs. Minerals are moved into the root by facilitated diffusion or active transport. Fluid can flow through the xylem against gravity, because of the water properties of cohesion and adhesion. Upward fluid movement through plants is also facilitated by the pushing pressure created by turgor pressure in the root xylem and the pulling force of transpiration through the leaves.

Check Your Understanding

1. Describe the structure of the cells that make up phloem tissue.

2. Will a daisy plant transpire more in a humid environment or in a dry environment? Explain your reasoning.

3. Explain why root pressure alone cannot transport water from the roots to the leaves of most stems.

4. Apply If the stem of a plant is bent or snapped, the part of the plant above the bend will usually die, even if it is propped up with a support. Explain why.

5. Is transpiration part of the gas exchange system in plants, the water exchange system in plants, or both? Explain your answer.

6. Thinking Critically Maple syrup is a sweet treat harvested from maple trees. Which part of the tree produces the syrup and from which part of the tree is the sap tapped? Explain your reasoning.

7. Thinking Critically Root cells actively transport minerals from the soil. In doing so, they promote water transport in the xylem. Explain why mineral transport influences water transport.