12.5 Transport in Vascular Plants

Lake Temagami is located in northern Ontario, northeast of Sudbury. Lake Temagami and the surrounding region are home to the largest old-growth forests in Ontario (**Figure 1**). Old-growth forests have never been logged or otherwise altered by human activity and are very rare. Some trees in the Temagami forest are between 300 and 400 years old and have reached heights of 50 m and more. Unlike animals, plants lack a pump to move internal fluids. How do these trees get water and nutrients from their roots up to the leaves at their tops? How do they transport the products of photosynthesis to the vast number of cells they contain? You may be surprised to learn that vascular plants of all sizes use the same basic mechanisms to transport materials in their bodies.

Figure 1 The tall trees in the old-growth forest of Temagami transport water and nutrients in the same way as all vascular plants on the forest floor.

CAREER **LINK**

Forester
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Overview of Transport in the Plant

Figure 2 is an overview of the processes involved in the movement of substances in the plant. The water in the environment (either in the soil or in bodies of water, such as rivers and streams) is really a solution containing dissolved substances, including nutrients. For this discussion, this water will be called "soil water." Water moves between the xylem and phloem and is critical to the delivery of soil nutrients and sugars to all the cells of the plant. Sugars are transported solely in the phloem. Nutrients in the soil water are transported in the xylem.

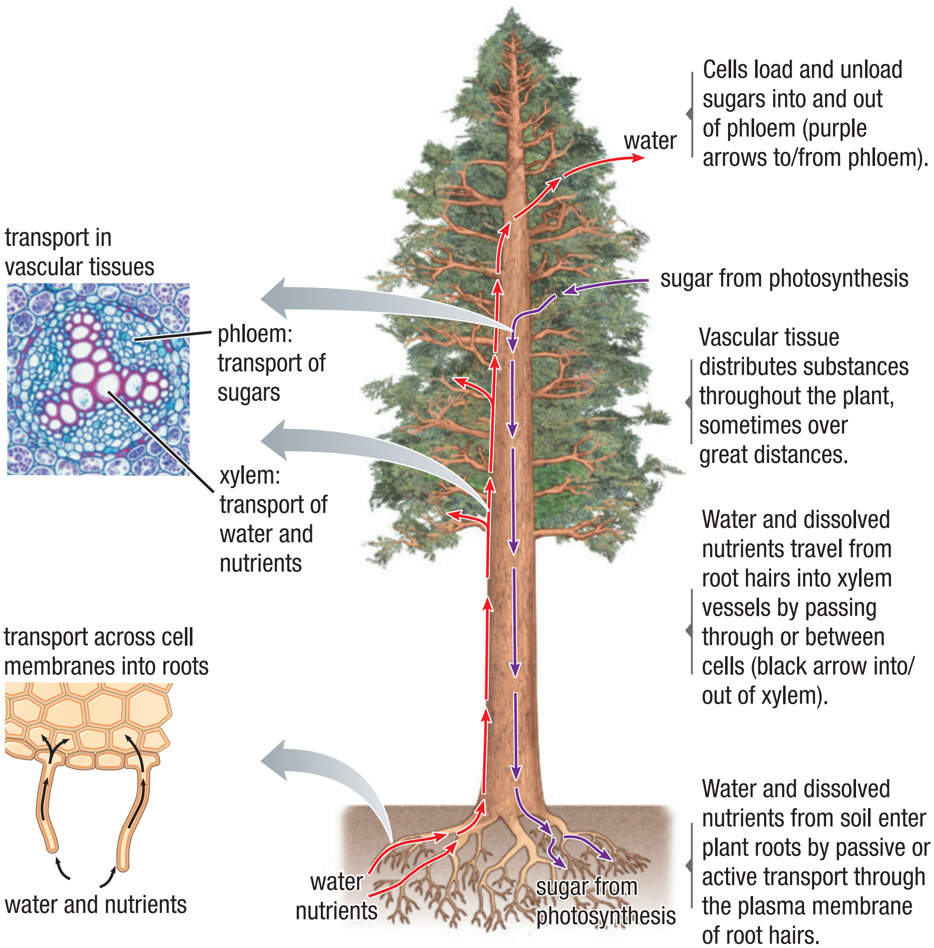

Figure 2 Overview of transport routes in plants

Transport of Water and Nutrients

Moving water and nutrients from the surface of a root hair all the way to the parenchyma cells in the leaves is a complex process. The same processes occur in plants in bodies of water. Water and nutrient transport involves three stages: (i) from the soil into the roots, (ii) from the roots to the stem, and (iii) from the stem to the leaves. Water also returns to the environment, mostly from the leaves.

Transport into the Root

Transport of water and nutrients into the root happens by two different processes: water enters the root cells by osmosis, but nutrients enter by active transport.

The cytoplasm of plant cells has a lower concentration of water molecules than the soil water, and the plant cell membrane allows water molecules to cross freely. Water molecules therefore enter cells in the plant root by osmosis. Recall that osmosis is the diffusion of water molecules across a selectively permeable membrane, from an area of higher concentration to an area of lower concentration. Water molecules can also enter the root and move through the spaces between the cells before being absorbed by osmosis (**Figure 3**). Once inside the cells, the water molecules move toward the vascular cylinder.

The concentration of nutrients in the cytoplasm of a plant cell is higher than the concentration of nutrients in the soil water. Therefore, needed nutrients will not enter the root cells by diffusion. Instead, the plant must use active transport to move nutrients from the soil water into the root cells. Once the needed substances are within the cytoplasm of the outer root cells they are moved through the cells of the cortex toward the endodermis. This movement is made easier by the fact that adjacent plant cells have interconnecting strands of cytoplasm. Once nutrients (or water) enter a root cell they will not have to cross another cell membrane until they reach the vascular cylinder.

Once water molecules and nutrients reach the endodermis, they encounter the Casparian strip. The wax-like substance that makes up the strip prevents all substances from passing through the spaces between the endodermal cells. Therefore all substances entering the vascular cylinder pass directly through the endodermal cells. The key role of the Casparian strip is to prevent substances from leaking back into the cortex. Once inside the vascular cylinder, nutrients are actively pumped across cell membranes into the xylem.

LEARNING TIP

Passive and Active Transport
Passive transport does not require energy and involves movement of substances across a membrane from an area of high concentration to an area of low concentration. Active transport, however, always requires energy. In active transport, substances are transported across a membrane from an area of low concentration to an area of high concentration.

LEARNING TIP

Envisioning the Casparian Strip
The term "Casparian strip" can be used to refer to the strip around each cell in the endodermis, or it can refer to the barrier around the vascular cylinder, which is made up of all Casparian strips of the endodermal cells.

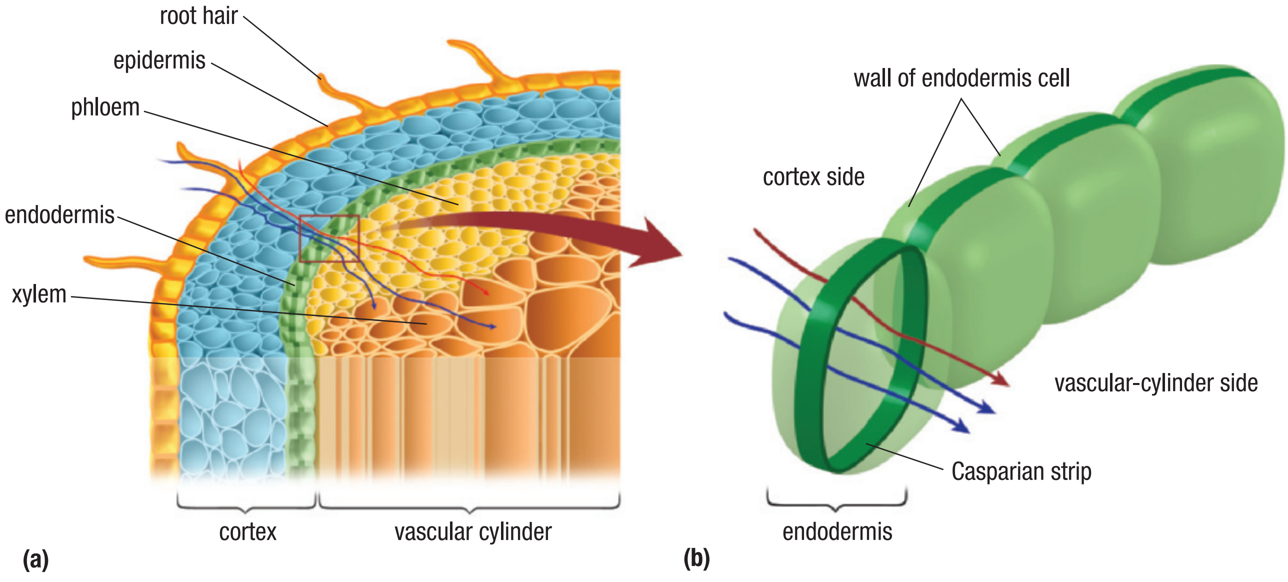

Figure 3 (a) Water moves through the cortex by two routes (blue arrows): it either flows between the cells or enters the cells by osmosis and then moves from cell to cell. Nutrients are taken in by active transport and move from cell to cell (red arrow). (b) At the endodermis, the Casparian strip prevents substances from passing between the endodermal cells and forces them to pass through the cell membrane instead. Nutrients enter the xylem by active transport.

Transport into the Stem

root pressure the osmotic force pushing xylem sap upward in root vascular tissue

capillary action the tendency of a liquid to rise or fall because of attractive forces between the liquid molecules

Once water molecules and dissolved nutrients have crossed the Casparian strip, the liquid they form is called xylem sap. Substances in the xylem sap then move up the root toward the stem. How does the liquid sap move against gravity?

As more nutrients are actively pumped into the xylem, their concentration increases and water molecules follow by osmosis. In many plants this creates **root pressure** and helps push the xylem sap upward.

Capillary action, which is the tendency of a liquid in a narrow tube to rise or fall (**Figure 4**), also contributes to the rise of the xylem sap. In capillary action, a column of liquid is held together by weak attractive forces between molecules and rises because of attractive forces between the liquid and the sides of the tube. In the xylem tubes, attractive forces occur between different water molecules and between water molecules and molecules in the cell walls. The water molecules in the xylem sap stick to each other and are also drawn up the sides of the xylem tubes. As a result, the water column moves upward. Xylem sap also moves from one xylem tube to another, through the pits in the cell walls of xylem cells. Xylem sap can also move out of the xylem through the pits into the surrounding tissue. This ensures that all cells in the plant body receive water and nutrients, not just those at the top of the xylem column.

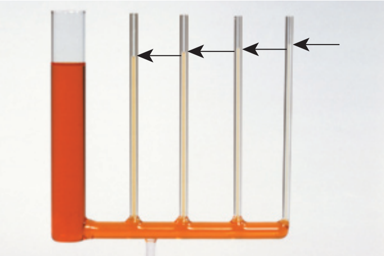

Figure 4 Capillary action increases as the diameter of the tube decreases.

Mini Investigation

Transport in Xylem Tissue

Skills: Controlling Variables, Performing, Observing, Analyzing, Communicating — SKILLS HANDBOOK A2.1

In this investigation, you will observe how water is transported in the xylem of a carnation stem.

Equipment and Materials: two 50 mL beakers; masking tape; knife; hand lens; red and blue food colouring; one long-stemmed white carnation with leaves

Always cut away from yourself and others sitting near you in case the knife slips.

1. Place two 50 mL beakers beside each other in a well-lit area. Secure them in place with masking tape.
2. Add enough water so that the beakers are three-quarters full. Add 10 to 15 drops of blue food colouring to one beaker and 10 to 15 drops of red food colouring to the other.
3. Use the knife to cut a 1 cm section from the end of the carnation. This provides a fresh end.
4. Starting at the cut end, carefully cut the stem lengthwise for 10 cm. The lower half of the stem should now be cut into two equal halves, but each should still be attached to the intact part of the stem (**Figure 5 (a)**).
5. Place one half of the split stem in the beaker of red water and the other half in the beaker of blue water. Be careful not to bend, kink, or damage the stem (**Figure 5(b)**).

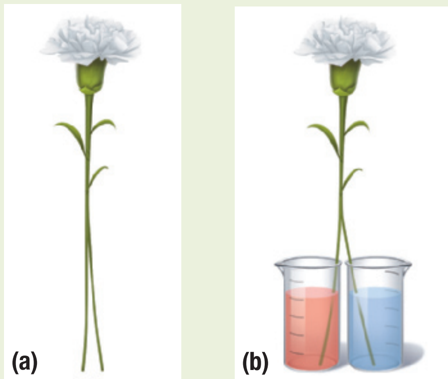

Figure 5 (a) Step 4 (b) Step 5

6. Let the carnation sit for 24 h. Then observe and record any changes in the stem or flower.
7. Remove the carnation from the beakers. Cut across the intact part of the stem, just above the lengthwise cut. Observe the cut end using a hand lens. Record your observations.

A. Describe the location(s) where you found food colouring in the carnation after 24 h. T/I

B. Was there any mixing of the two dyes? What does this tell you about the flow of liquid in the plant? T/I A

C. When you observed the cut through the stem diameter, did all cells contain dye? T/I

D. Relate your observations in B to your observations in C. T/I A

Transport to the Leaves

Capillary action and root pressure alone are not enough to get xylem sap all the way to the top of a tall tree. The main driving force of transport up the xylem actually comes from the leaves. Recall that the epidermis of leaves contains many stomata, the pores formed by guard cells. Plants release water vapour through their stomata during **transpiration**, which is evaporation of water from plant leaves. The water vapour evaporates through the stomata when they are open. Because of the attractive force between water molecules, when a water molecule moves up the xylem column, it pulls a neighbouring water molecule with it. The second molecule pulls the one behind it, and the "pull" continues down the length of the xylem. If a plant does not transpire, the water column will not move.

transpiration evaporation of water through the stomata of plant leaves

Figure 6 is an overview of how the different transport mechanisms in the root, stem, and leaf work together.

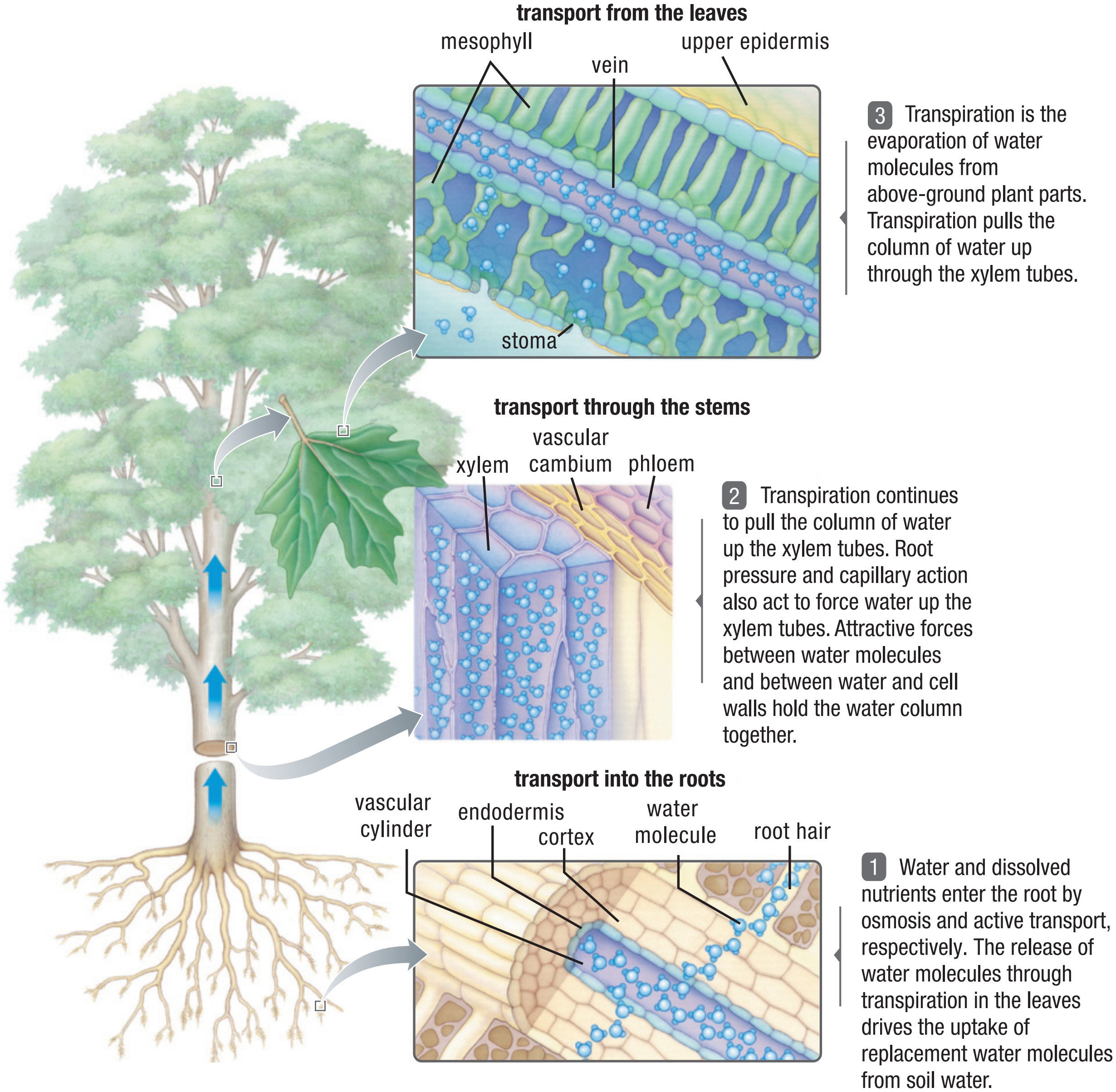

Figure 6 The transport of xylem sap from the roots to the leaves.

If a plant does not have sufficient water, it may wilt. A plant cell stores water and dissolved substances in its central vacuole. When the central vacuole is full, it exerts pressure against the cell wall; this pressure is called **turgor**. Turgor helps support the plant. When the plant is unable to take up water from the soil, water will move out of the vacuole and the plant will wilt.

turgor pressure caused by the fluid contents of the central vacuole, which pushes against the wall of a plant cell

Transport of Sugars

source a plant cell with a high concentration of sugars and other solutes, such as a leaf cell

sink a plant cell with a low concentration of sugars; sugars may be converted to starch for storage or used rapidly for energy or as building blocks of other carbohydrates

Plant cells use glucose and other sugars as a source of energy. In plants, sugars may be produced by photosynthesis or from breaking down carbohydrates in storage organs, such as tubers. A cell with a high concentration of sugars can be called a source. A photosynthesizing mesophyll cell is an example of a **source**. A **sink** is any cell that has a low concentration of sugar. A sink may convert sugars to starch for storage or use them rapidly. For example, cells that are rapidly growing are sinks, since they use up their sugar supplies quickly.

Direction of Sugar Transport

Unlike water and nutrients, which always move up the plant, sugars can move up or down the plant. The direction in which sugars are transported depends on the location of source cells relative to sink cells. In general, sugars are transported from a source to a sink, which are connected by columns of phloem cells. However, the location of sink and source cells in a plant may change. For example, the cells in storage structures may be either sources or sinks, depending on the time of year or the plant's development.

In places with four seasons, such as Canada, the location of sink and source cells in plants often changes with the seasons (**Figure 7**). In winter, many plants are dormant. A dormant plant does not grow and does not photosynthesize. In the spring, the plant initially depends on carbohydrates stored in its roots or stems, usually as starch. As it begins to grow, the plant breaks down the starch into sugars. As a result, root and stem cells are sources. The upper portions of the plant need energy to grow leaves. The sink cells therefore are mainly at the top of the plant, so that water and dissolved sugars (phloem sap) tend to move upward in the phloem. In summer, the leaves are photosynthesizing and the sugars they produce are stored in roots and stems. Therefore, the source cells are now at the top of the plant, and the phloem sap moves downward.

Figure 7 (a) In early spring, phloem sap moves mainly upward from the roots to the growing shoots. (b) In summer, phloem sap moves mainly downward from mature leaves to the stems and roots.

Cells in developing seeds and fruits are also sink cells, since they store carbohydrates for the plant embryo. This is one reason why many fruits taste sweet. When a plant produces seeds or fruits, it is still photosynthesizing (**Figure 8**). Sugars must therefore move from source cells in the shoot to sink cells that are also in the shoot.

We can divide the process of sugar transport into three general stages: (i) transport of sugars from source cells to phloem cells, (ii) transport through the phloem, and (iii) transport from phloem cells to sink cells.

Figure 8 Source and sink cells may be on the same part of the plant.

From Source to Phloem

After a sugar molecule is produced, it must be transported from the source cell to a phloem cell. The concentration of sugars in phloem cells is generally higher than the concentration in source cells, so sugar transport to the phloem involves active transport across the cell membrane.

The upper part of **Figure 9** shows the transport of sugars from a source cell (a mesophyll cell) into the phloem of an angiosperm. In angiosperms, companion cells transport sugars from source cells to the sieve tube elements. In gymnosperms, sugars are transported from source cells directly into sieve cells, since this is the only cell type in the phloem.

As transport continues, the concentration of sugars in the phloem sap increases. This causes water to be drawn from the xylem cells into the phloem cells by osmosis, which increases the turgor of the phloem cells near the source cells.

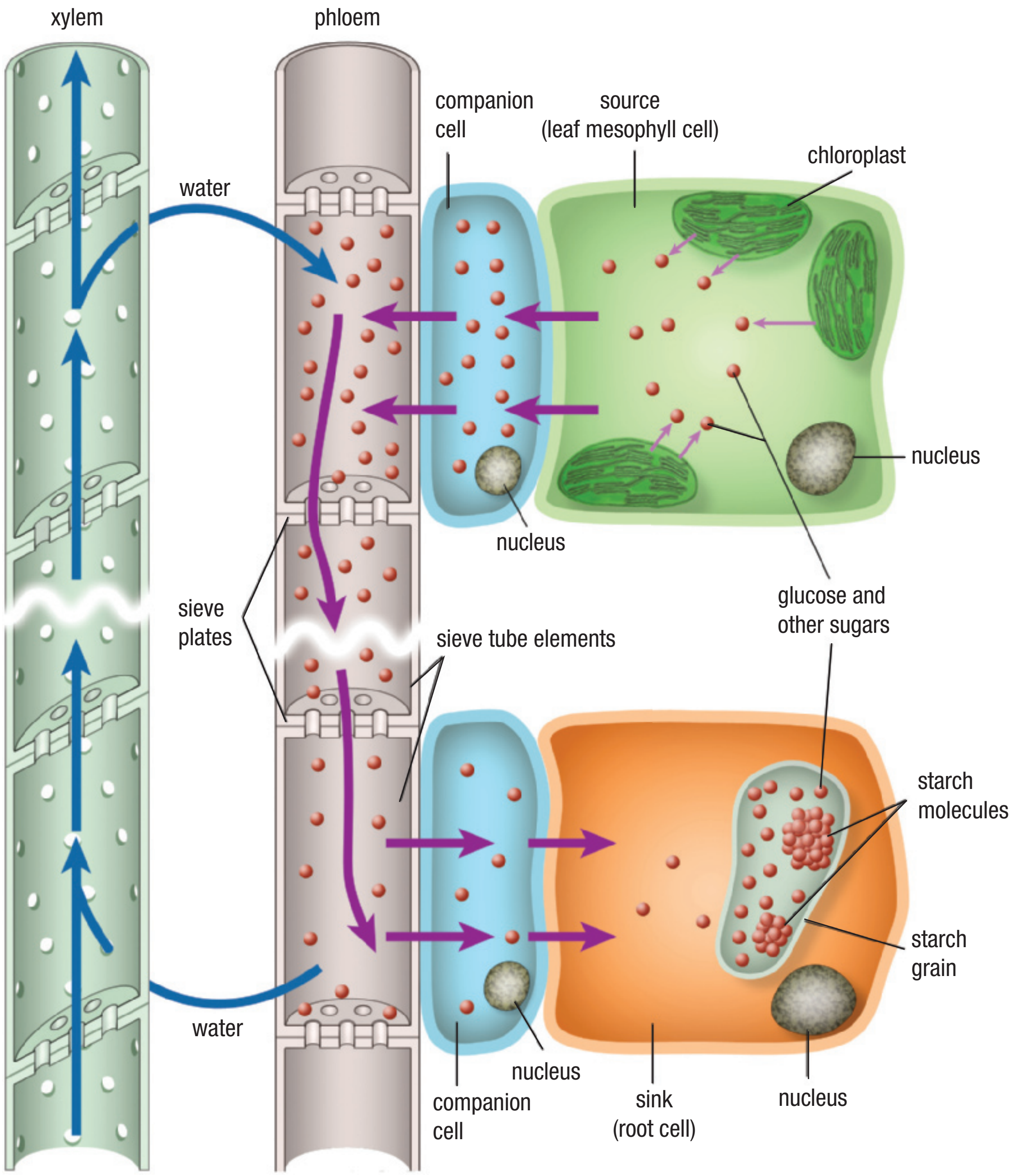

Figure 9 Transporting sugars from a source to a sink cell involves both passive and active transport.

Translocation

The transport of substances for long distances through the phloem is called **translocation**. Unlike xylem tubes, phloem tubes are not hollow, and substances in the phloem sap have to move between living cells. However, sugar molecules can travel more quickly between phloem cells than between other living cell types. Translocation therefore moves sugars quickly enough to supply energy to cells throughout the plant.

translocation long-distance transport of substances through the phloem, particularly glucose

It is not yet entirely clear how translocation is able to move sugars so quickly through the phloem. However, evidence suggests that translocation is driven by the difference in turgor between the phloem cells near source cells and the turgor of phloem cells near sink cells. This difference in turgor pushes the phloem sap in the direction of sink cells.

From Phloem to Sink

Once sugar molecules reach a sink cell, they leave the phloem. The sink cells have a lower concentration of sugars than the phloem cells. The sugars therefore move from the phloem to the sink by passive transport. In angiosperms, the sugars move from the sieve tube elements to the companion cells and then to the sink cells. In gymnosperms, the sieve cells transport sugars directly to the sink cells.

Because sieve tube elements lose sugar molecules, they have a lower concentration of sugars. Water then returns to the xylem from the phloem by osmosis. This maintains the relatively low turgor of phloem cells near the sink and also recirculates the water back into the xylem.

12.5 Summary

- Water and nutrient transport in the xylem tissue involves root pressure, capillary action, and transpiration.
- Nutrients enter root cells by active transport; water enters by osmosis.
- The Casparian strip forces water and nutrients to pass directly through the cells of the endodermis. It also prevents water and dissolved substances from moving back out.
- Water and nutrients move up the xylem tubes by root pressure, capillary action, and transpiration.
- Transpiration is the evaporation of water from the leaves; it is the force that pulls the column of water up the xylem tubes.
- Sugars are actively transported from source to sink in the phloem.
- Phloem sap moves along the phloem tubes as a result of a pressure difference between source cells and sink cells.
- Movement of fluid in the xylem is always upward (or sideways). Movement in the phloem can be upward or downward (or sideways), depending on source and sink locations.

12.5 Questions

1. What is the main driving force for the movement of water in plants? K/U
2. Why must active transport be used to move sugars and other solutes into the phloem? K/U
3. Describe the role of osmosis in movement of solutes in the phloem. K/U
4. During an experiment, a student covers all the stomata of a plant with nail polish, sealing them shut. T/I
   (a) Predict how this would affect water transport.
   (b) How would this affect transport in the phloem?
5. Maple syrup, chicle, and natural rubber all come from the "sap" of trees. Use the Internet and other sources to determine if these products are harvested from the xylem or the phloem. What are the main chemical ingredients in these substances and of what benefit were they to the plant? T/I
6. You purchase some fresh carrots that still have their green leafy tops. Your father tells you to put the carrots in the refrigerator and leave the tops on because that will keep the carrot roots nutritious and crisp. Your mother says she thinks you should cut the tops *off* for the same reason. Who is correct? Explain your reasoning. K/U