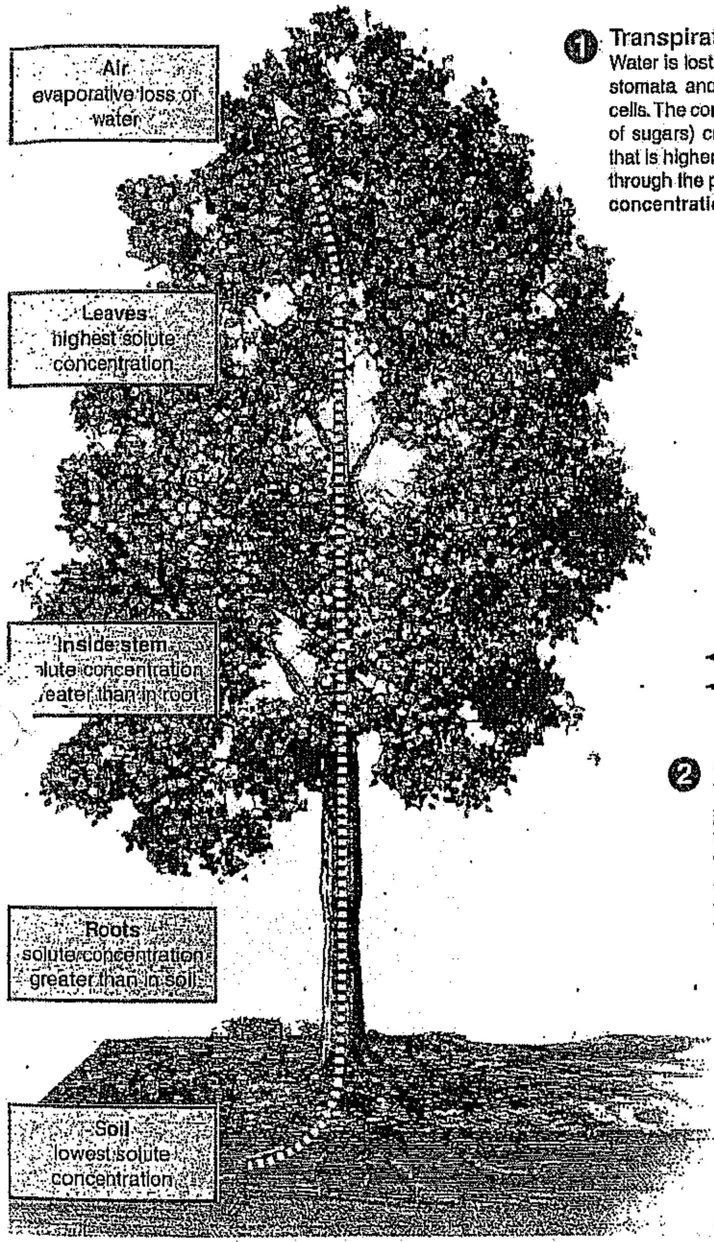
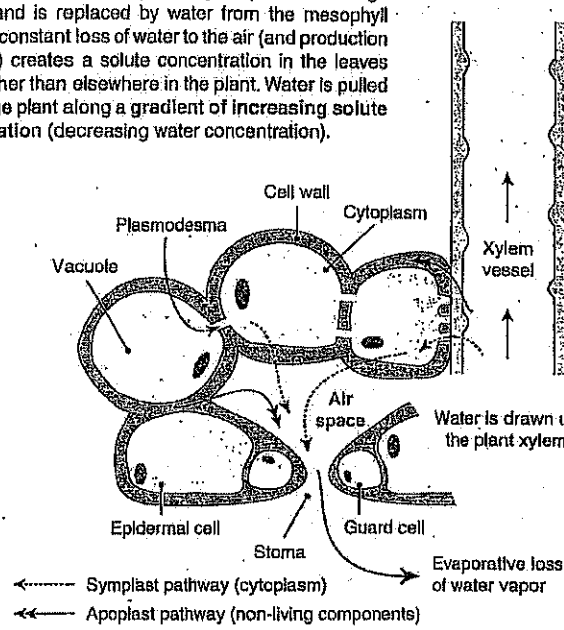
{Answer Key}

Plants lose water all the time, despite the adaptations they have to help prevent it (e.g. waxy leaf cuticle). Approximately 99% of the water a plant absorbs from the soil is lost by evaporation from the leaves and stem. This loss, mostly through stomata, is called **transpiration** and the flow of water through the plant is called the **transpiration stream**. Plants rely on a gradient in solute concentration from the roots to the air to move water through their cells. Water flows passively from soil to air along a gradient of increasing solute (decreasing water) concentration. This gradient is the driving force in the ascent of water up a plant. A number of processes contribute to water movement up the plant: transpiration pull, cohesion, and root pressure. Transpiration may seem wasteful, but it has benefits; evaporative water loss cools the plant and the transpiration stream helps the plant to maintain an adequate mineral uptake, as many essential minerals occur in low concentrations in the soil.



1 Transpiration pull
Water is lost from the air spaces by evaporation through stomata and is replaced by water from the mesophyll cells. The constant loss of water to the air (and production of sugars) creates a solute concentration in the leaves that is higher than elsewhere in the plant. Water is pulled through the plant along a gradient of **increasing solute concentration** (decreasing water concentration).



2 Cohesion-tension
The transpiration pull is assisted by the special **cohesive** properties of water. Water molecules cling together as they are pulled through the plant. They also adhere to the walls of the xylem (**adhesion**). This creates one unbroken column of water through the plant. The upward pull on the cohesive sap creates a tension (a negative pressure). This helps water uptake and movement up the plant.

3 Root pressure
Water entering the stele from the soil creates a **root pressure**; a weak 'push' effect for the water's upward movement through the plant. Root pressure can force water droplets from some small plants under certain conditions (guttation), but generally it plays a minor part in the ascent of water.

1. (a) Plants constantly lose water by transpiration. Explain how plants compensate for this: Take up water by the roots, close stomata, lose leaves.

   (b) Describe one benefit of the transpiration stream for a plant: Moves water and minerals throughout plant. Also cools the plants.

2. Briefly describe three processes that assist the transport of water from the roots of the plant upward:

   (a) Root pressure provides a weak push.

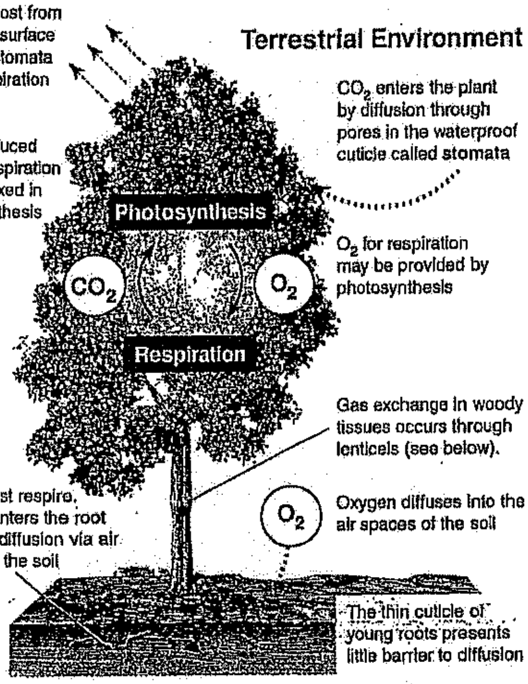
   (b) Transpiration pull: water molecules evaporate and pull on liquid water.

   (c) Cohesion: water forms sticky hydrogen bonds with other water molecules.

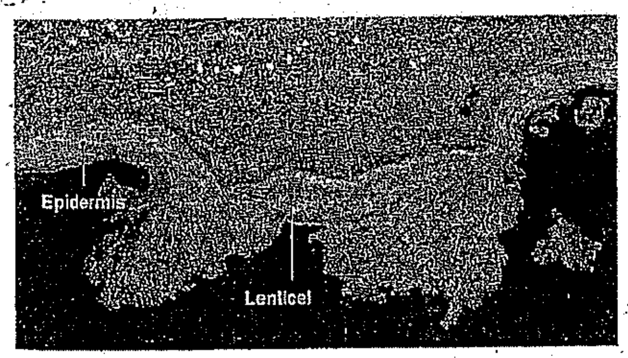
Gas Exchange in Plants

Respiring tissues require oxygen, and the photosynthetic tissues of plants also require carbon dioxide in order to produce the sugars needed for their growth and maintenance. The principal gas exchange organs in plants are the leaves, and sometimes stems. In most plants, the exchange of gases directly across the leaf surface is prevented by the waterproof, waxy cuticle layer. Instead, access to the respiring cells is by means of **stomata**, which are tiny pores in the leaf surface. The plant has to balance its need for carbon dioxide (keeping stomata open) against its need to reduce water loss (stomata closed).

Terrestrial Environment



Most gas exchange in plants occurs through the leaves, but some also occurs through the stems and the roots. The shape and structure of leaves (very thin with a high surface area) assists gas exchange by diffusion.



In woody plants, the wood prevents gas exchange. A lenticel is a small area in the bark where the loosely arranged cells allow entry and exit of gases into the stem tissue underneath.

Aquatic Environment

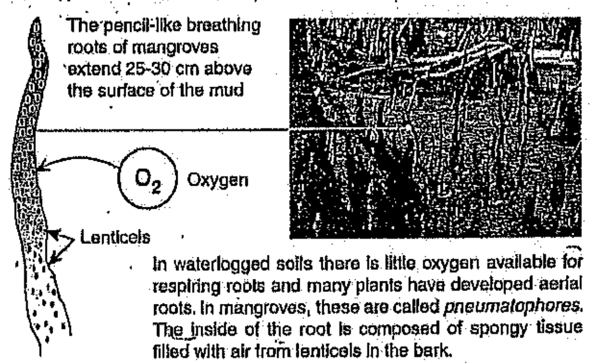
The aquatic environment presents special problems for plants. Water loss is not a problem, but CO_2 availability is often very limited because most of the dissolved CO_2 is present in the form of bicarbonate ions, which is not directly available to plants. Maximizing uptake of gaseous CO_2 by reducing barriers to diffusion is therefore important.

Algae lack stomata but achieve adequate gas exchange through simple diffusion into the cells.

Floating leaves, such as the water lilies above, generally lack stomata on their lower surface.

With the exception of liverworts, all terrestrial plants and most aquatic plants have stomata to provide for gas exchange. CO_2 uptake is aided in submerged plants because they have little or no cuticle to form a barrier to diffusion of gases. The few submerged aquatics that lack stomata altogether rely only on diffusion through the epidermis. Most aquatic plants also have air spaces in their spongy tissues (which also assist buoyancy).

Transitional Environment



In waterlogged soils there is little oxygen available for respiring roots and many plants have developed aerial roots. In mangroves, these are called *pneumatophores*. The inside of the root is composed of spongy tissue filled with air from lenticels in the bark.

1. Name the gas produced by cellular respiration that is also a raw material for photosynthesis: Carbon dioxide

2. Describe the role of lenticels in plant gas exchange: Lenticels allow some gas exchange to occur through the woody bark.

3. Identify two properties of leaves that assist gas exchange: Thin, large surface area, stomata.

4. With respect to gas exchange and water balance, describe the most important considerations for:

   (a) Terrestrial plants: Limit water evaporation loss, but still get CO_2 gas.

   (b) Aquatic plants: Water loss is not an issue, but must maximize diffusion of CO_2 into tissue. (Thin, no cuticle)

5. Describe an adaptation for gas exchange in the following plants:

   (a) A submerged aquatic angiosperm: Very thin leaves, no cuticle.

   (b) A mangrove in a salty mudflat: Aerial roots, some roots that stick up in the air to get enough oxygen.

Gas Exchange and Stomata

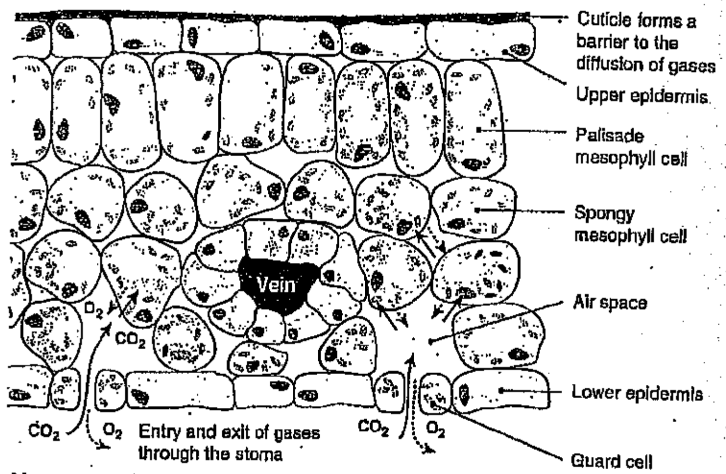
The leaf epidermis of angiosperms is covered with tiny pores, called **stomata**. Angiosperms have many air spaces between the cells of the stems, leaves, and roots. These air spaces are continuous and gases are able to move freely through them and into the plant's cells via the stomata. Each stoma is bounded by two **guard cells**, which together regulate the entry and exit of gases and water vapor. Although stomata permit gas exchange between the air and the photosynthetic cells inside the leaf, they are also the major routes for water loss through transpiration.

Gas Exchanges and the Function of Stomata

Gases enter and leave the leaf by way of stomata. Inside the leaf (as illustrated by a dicot, right), the large air spaces and loose arrangement of the spongy mesophyll facilitate the diffusion of gases and provide a large surface area for gas exchanges.

Respiring plant cells use oxygen (O_2) and produce carbon dioxide (CO_2). These gases move in and out of the plant and through the air spaces by diffusion.

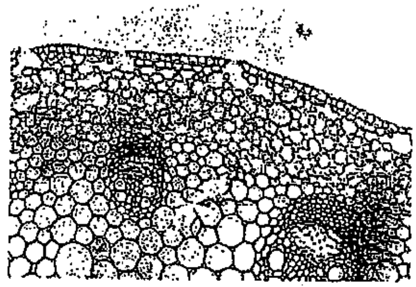
When the plant is photosynthesizing, the situation is more complex. Overall there is a net consumption of CO_2 and a net production of oxygen. The fixation of CO_2 maintains a gradient in CO_2 concentration between the inside of the leaf and the atmosphere. Oxygen is produced in excess of respiratory needs and diffuses out of the leaf. These net exchanges are indicated by the arrows on the diagram.



Net gas exchanges in a photosynthesizing dicot leaf

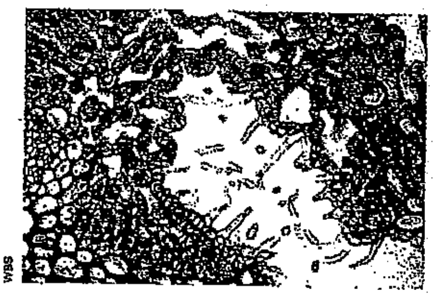
RCN

A surface view of the leaf epidermis of a dicot (above) illustrating the density and scattered arrangement of stomata. In dicots, stomata are usually present only on the lower leaf surface.



WBS

The stems of some plants (e.g. the buttercup above) are photosynthetic. Gas exchange between the stem tissues and the environment occurs through stomata in the outer epidermis.

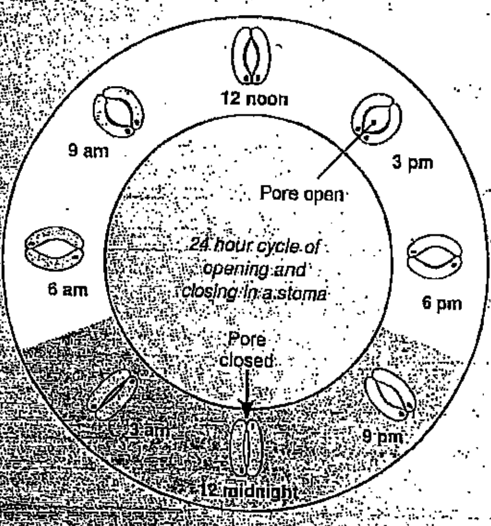


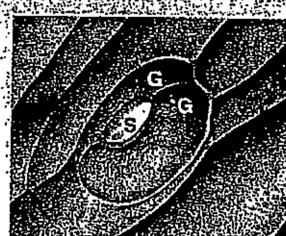
WBS

Oleander (above) is a xerophyte with many water conserving features. The stomata are in pits on the leaf underside. The pits restrict water loss to a greater extent than they reduce CO_2 uptake.

The cycle of opening and closing of stomata

The opening and closing of stomata shows a daily cycle that is largely determined by the hours of light and dark.





EII

The image left shows a scanning electron micrograph (SEM) of a single stoma from the leaf epidermis of a dicot.

Note the guard cells (G), which are swollen, tight and open the pore (S) to allow gas exchange between the leaf tissue and the environment.

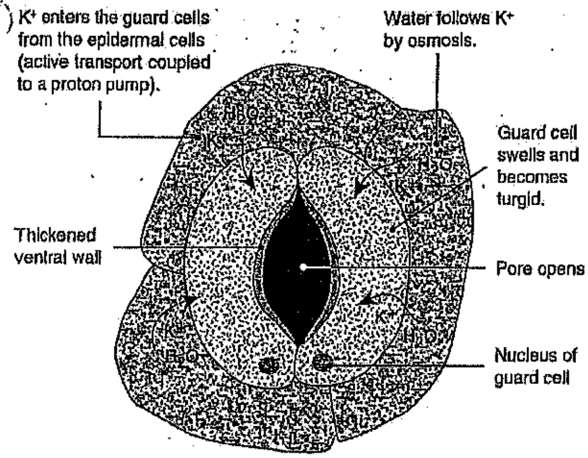
Factors influencing stomatal opening

Stomata	Guard cells	Daylight	CO_2	Soil water
Open	Turgid	Light	Low	High
Closed	Flaccid	Dark	High	Low

The opening and closing of stomata depends on environmental factors, the most important being light, carbon dioxide concentration in the leaf tissue, and water supply. Stomata tend to open during daylight in response to light, and close at night (left and above). Low CO_2 levels also promote stomatal opening. Conditions that induce water stress cause the stomata to close, regardless of light or CO_2 level.

The regulation of stomatal size by the guard cells is the primary way in which plants can balance their need for carbon dioxide against their need to limit water loss. The guard cells that lie each side of a stoma control the diameter of the pore by changing shape. When the guard cells take up water (by osmosis) they swell and become turgid, making the pore wider. When the guard cells lose water, they become flaccid, and the pore closes up. By opening and closing the stomata a plant can control the amount of gas entering, or water leaving, the plant.

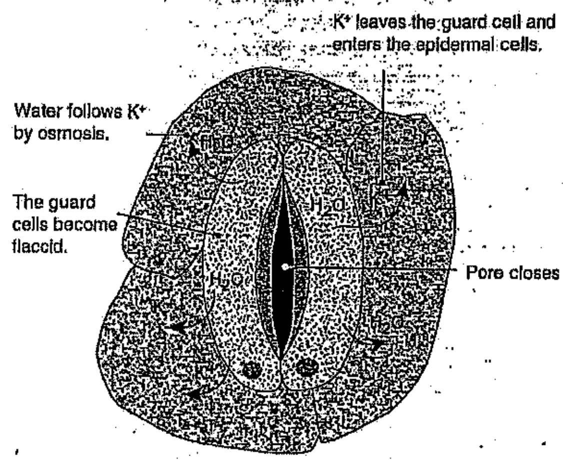
Stomatal Pore Open



Water enters the guard cells

Stomata open when the guard cells actively take up K^+ from the neighboring epidermal cells. The ion uptake results in a lower concentration of water molecules in the guard cells. As a consequence, water is taken up by the cells and they swell and become turgid. The walls of the guard cells are thickened more on the inside surface (the ventral wall) than the outside wall, so that when the cells swell they buckle outward, opening the pore.

Stomatal Pore Closed



Water leaves the guard cells

Stomata close when K^+ leaves the guard cells. The loss of these ions increases the concentration of water molecules in the guard cells relative to the epidermal cells. As a consequence, water is lost by osmosis and the guard cells sag together and close the pore. The K^+ movements in and out of the guard cells are thought to be triggered by blue-light receptors in the plasma membrane, which activate the active transport mechanisms involved.

1. With respect to a mesophytic, terrestrial flowering plant:

   (a) Describe the net gas exchanges between the air and the cells of the mesophyll in the dark (no photosynthesis):

   Oxygen is used ; CO_2 is produced

   (b) Explain how this situation changes when a plant is photosynthesizing:

   Net use of CO_2 ; net production of O_2.

2. Identify two ways in which the continuous air spaces through the plant facilitate gas exchange:

   (a) Facilitate diffusion of gases into and out of the leaf.

   (b) Provide a large surface area for gas exchange.

3. Briefly outline the role of stomata in gas exchange in an angiosperm:

   Stomata regulate the entry and exit of gases into and out of the leaf. And they regulate water loss.

4. Summarize the mechanism by which the guard cells bring about:

   (a) Stomatal opening: Active transport of K^+ into the guard cells ~~causes~~ causes water to follow osmotically. Guard cell swell, bend, and open.

   (b) Stomatal closure: Potassium ions leave the guard cells, water leaves by osmosis, guard cells "deflate" and move back together and close.

Translocation

Answer Key

Phloem transports the organic products of photosynthesis (sugars) through the plant in a process called **translocation.** In angiosperms, the sugar moves through the sieve elements, which are arranged end-to-end and perforated with sieve plates. Apart from water, phloem sap comprises mainly sucrose (up to 30%). It may also contain minerals, hormones, and amino acids, in transit around the plant. Movement of sap in the phloem is from a **source** (a plant organ ~~where sugar is made or mobilized~~) to a **sink** (a plant organ where sugar is stored or used). Loading sucrose into the phloem at a source involves energy expenditure; it is slowed or stopped by high temperatures or respiratory inhibitors. In some plants, unloading the sucrose at the sinks also requires energy, although in others, diffusion alone is sufficient to move sucrose from the phloem into the cells of the sink organ.

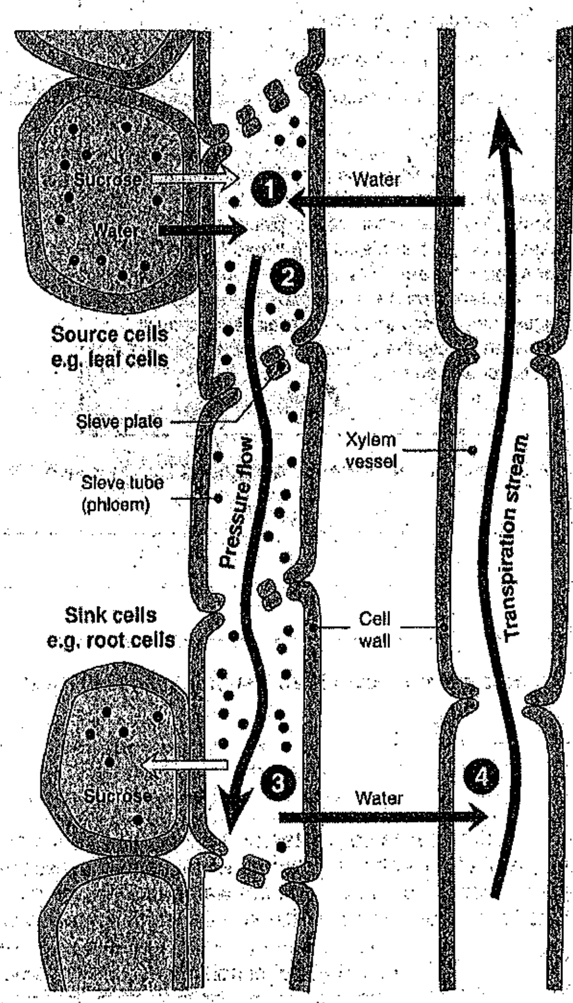
Transport in the phloem by pressure-flow

Phloem sap moves from source (region where sugar is produced or mobilized) to sink (region where sugar is used or stored) at rates as great as 100 m h⁻¹, too fast to be accounted for by cytoplasmic streaming. The most acceptable model for phloem movement is the **pressure-flow** (bulk flow) hypothesis. Phloem sap moves by bulk flow, which creates a pressure (hence the term "pressure-flow"). The key elements in this model are outlined below and in steps 1-4 right. For simplicity, the cells that lie between the source (and sink) cells and the phloem sieve tube have been omitted.

1. Loading sugar into the phloem from a source (e.g. leaf cell) increases the solute concentration inside the sieve tube cells. This causes the sieve tubes to take up water from the surrounding tissues by osmosis.
2. The water absorption creates a hydrostatic pressure that forces the sap to move along the tube (bulk flow) just as pressure pushes water through a hose.
3. The gradient of pressure in the sieve tube is reinforced by the active unloading of sugar and consequent loss of water by osmosis at the sink (e.g. root cell).
4. Xylem recycles the water from sink to source.

Measuring phloem flow

Experiments investigating flow of phloem often use aphids. Aphids feed on phloem sap (left) and act as natural **phloem probes**. When the mouthparts (stylet) of an aphid penetrate a sieve-tube cell, the pressure in the sieve-tube force-feeds the aphid. While the aphid feeds, it can be severed from its stylet, which remains in place in the phloem. The stylet serves as a tiny tap that exudes sap. Using different aphids, the rate of flow of this sap can be measured at different locations on the plant.



Modified after Campbell Biology 1993

1. (a) Explain what is meant by *source to sink* flow in phloem transport: Sugars flow from where they are produced/stored to where they are needed.

   (b) Name the usual **source** and **sink** in a growing plant:

   Source: Leaves Sink: Growing tissues, fruits, flowers, roots, etc.

   (c) Name another possible **source** region in the plant and state when it might be important: Tubers (like a potato) where sugars are stored and then used when photosynthesis is not ocurring.

   (d) Name another possible **sink** region in the plant and state when it might be important: Growing tissues, fruits, flowers, roots, nuts, seeds, etc.

2. Explain why energy is required for translocation and where it is used: Loading and Unloading of sugars into and out of the phloem usually requires active transport.

3. In your own words, describe what is meant by the following:

(a) Translocation: The transport of sugars from where they are made or stored to where they are needed throughout the plant.

(b) Pressure-flow movement of phloem: The movement of sugary phloem sap from where osmotic pressure is high at the source to where osmotic pressure is low at the sink.

4. Briefly explain why water follows the sucrose as the sucrose is loaded into the phloem sieve-tube cell:

The increase in dissolved sugars in the phloem at the source increases its solute concentration. Because of this, water moves in by osmosis. Water moves to regions of higher solute concentration.

6. Contrast the composition of phloem sap and xylem sap (see the activities on xylem and phloem if you need help):

Xylem sap is only water and dissolved minerals. Phloem is mainly a sugary sap (mainly sucrose), but also contains some minerals, hormones, and amino acids.