FOURTH FORM BIOLOGY

THE SPRING TERM PART II

TABLE OF CONTENTS

Plant Transport

Transport Systems

Molecules may move in and out of cells by diffusion, osmosis or active transport. However, diffusion occurs at a very slow rate when the distance is large – a doubling of the distance results in a rate that is four times as slow. This is because the movement of molecules relies solely on the kinetic energy of the molecules themselves. Therefore, the rate of diffusion places severe constraints on cells and organisms.

In addition, as a cell or organism *increases* in size, the surface area to volume ratio of the cell *decreases*. If a cell is to obtain oxygen at a sufficient rate to meet its demands by diffusion, it must be small enough so that it

a. has a large surface area to volume ratio and
b. has a short distance from the cell surface membrane to the centre of the cell.

For single-celled organisms, this places a limit to how large they can grow, and is the reason why single-celled organisms are microscopic.

If an organism is to grow any larger, the only solution to this rate-of-diffusion-problem is to become multicellular. This means that any individual cell can remain small, but collectively the organism can grow larger. However, for many multicellular organisms, the problem of transporting materials *within* the organism as a whole remain: with many cell layers, the inner-most cells are a large distance from the supply of oxygen, which is often obtained via a specialised organ such as lungs or gills far away from the rest of the organism. Additionally, as organisms become larger, their overall surface area to volume decreases. Many multicellular organisms have solved this problem through the evolution of **circulatory systems**.

The principle behind all transport systems is to minimise the use of diffusion, and instead rely on a different method for transporting liquids over large distances – **mass flow** (or **bulk flow**). Mass flow is the concerted movement of groups of molecules, most often in response to a **pressure gradient**. Examples of mass flow are water moving through a garden hose and a flowing river. Note that in each case the water can transport small solid particles that are suspended in the water or dissolved solute molecules.

In the Fifth form you will study the human circulatory system, which includes the following parts: a fluid (blood, mostly water but with solid particles (blood cells) suspended in it and solutes such as glucose dissolved in it), a pump to pressurise the fluid (the heart), and a series of tubes for the fluid to flow through (arteries, veins and capillaries). Blood flows via mass flow through the blood vessels, using the heart to increase its pressure so that it moves under pressure through the blood vessels. Diffusion only occurs where the distance is very short, when oxygen/carbon dioxide move in or out of cells such as in the lungs. Mass flow is used to transport the blood quickly over large distances.

In plants the same principles apply. Almost all land plants have **vascular tissue** specialised to conduct water and dissolved substances over large distances using mass flow. Mosses and their relatives lack vascular tissue, but they are quite limited in the habitats they can inhabit and they rarely grow very large and their 'leaves' are often one cell thick.

In contrast to humans, plants have two separate systems for transporting materials – **xylem** conducts water and dissolved mineral ions from the roots to the rest of the plant, and **phloem** conducts water with dissolved sugars, amino acids or hormones from the leaves to other parts of the plant. Collectively, xylem and phloem make up the vascular tissue of a plant. Note that plants do not have systems for transporting gases such as oxygen or carbon dioxide around the plant. Instead, gases must move via diffusion into leaves and through air spaces within stems, roots and leaves.

The Structure of Leaves, Roots and Stems

The Leaf

Stems, roots and leaves are the main **organs** of a plant. Most green parts of a plant can photosynthesise, but the leaves are the plant organs which are best adapted for this function. In the leaf, the main tissue types are the upper and lower epidermis, and the two mesophyll layers (spongy mesophyll and palisade mesophyll).

An organ is a structure composed of several tissues carrying out a particular function.

A tissue is a group of cells with a similar function.

To be able to photosynthesise efficiently, leaves need to have a large surface area to absorb light, many chloroplasts containing the green pigment chlorophyll, a supply of water and carbon dioxide, and a system for carrying away the products of photosynthesis to other parts of the plant. They also need to release oxygen and water vapour from the leaf cells. Most leaves are thin, flat structures supported by a leaf stalk which can grow to allow the blade of the leaf to be angled to receive the maximum amount of sunlight.

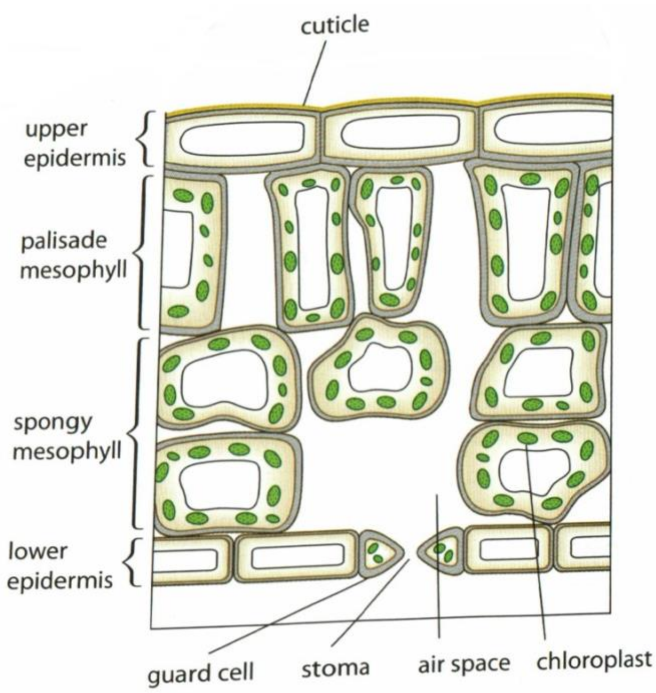
Inside the leaf are layers of cells with different functions:

The two outer layers of cells (the **upper** and **lower epidermis**) have few chloroplasts and are covered by a thin layer of a waxy material called the **cuticle**. This *reduces* water loss by evaporation, and acts as a barrier to the entry of disease-causing microorganisms such as bacteria and fungi. About 5% of the water lost via transpiration is lost through the cuticle.

The lower epidermis has many pores called **stomata** (a single pore is a **stoma**). Usually the upper epidermis contains fewer or no stomata. The stomata allow carbon dioxide to diffuse into the leaf and also allows oxygen and water vapour to diffuse out. The remaining 95% of water vapour lost in transpiration is lost via the stomata. Each stoma is formed as a gap between two highly specialised cells called **guard cells**, which can alter their shape to open or close the stoma.

In the middle of the leaf are two layers of photosynthetic cells called the **mesophyll** (mesophyll means 'middle of the leaf'). Just below the upper epidermis is the **palisade** layer. This is tissue made of elongated cells, each containing many chloroplasts, and is the main site of photosynthesis.

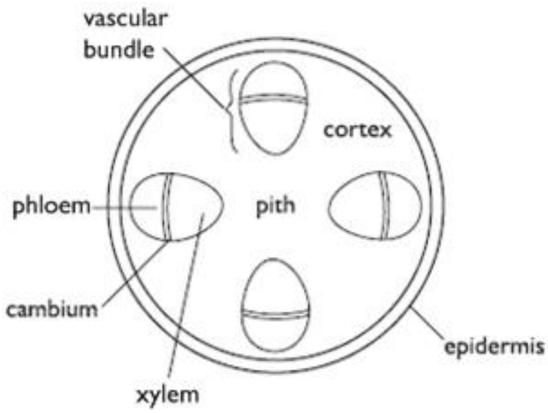
Below the palisade layer is tissue made of more rounded, loosely-packed cells, with air spaces between them, called the **spongy mesophyll**. These cells also photosynthesise, but have fewer chloroplasts then the palisade cells. The air spaces between the cells allow oxygen and carbon dioxide to diffuse in and out to reach the palisade mesophyll cells.



The Stem

The stem consists of four main tissues: the epidermis, the cortex, the pith and the vascular bundles. The epidermis forms a single layer of cells, usually containing chloroplasts, that covers the outside of the stem. This encloses the **cortex** and the **pith**. The cortex is the tissue that forms the outer part of the stem, whereas the pith makes up the central part. Neither of these tissues are photosynthetic and the cells have quite thin cell walls. Embedded within the cortex are numerous **vascular bundles** arranged in a circle around the outer part of the stem. In older, larger stems, the vascular bundles grow to form a complete ring around the stem.

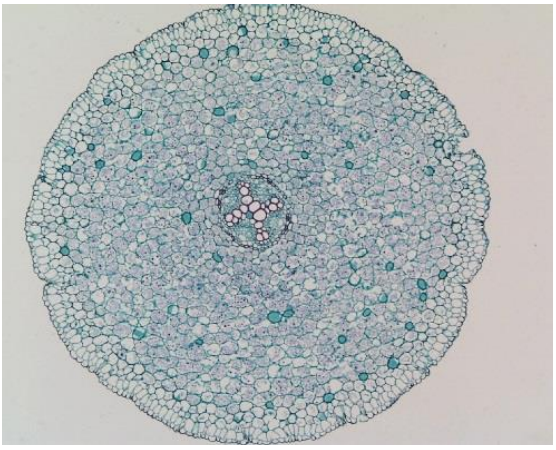
Within each vascular bundle, the xylem is found in the inner part, with the phloem on the outside. Sandwiched between the xylem and phloem is a narrow band of cells called the **cambium**; cells of the cambium are able to divide and produce new xylem and phloem as the plant grows.

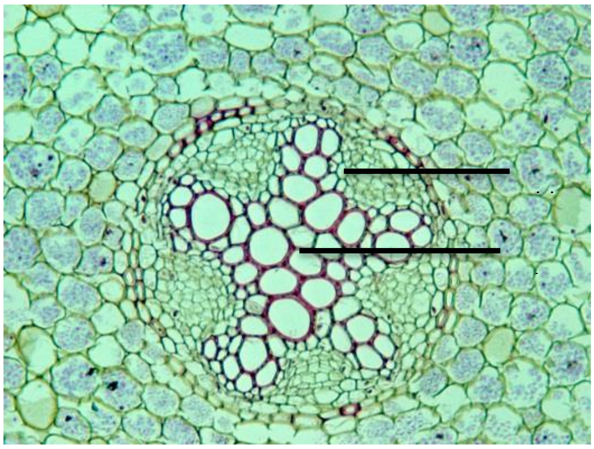


A cross-section through the stem, showing the distribution of different tissues.

The Root

Like leaves and stems, roots also have an outer layer of epidermal cells. Epidermal cells near the tip of the root produce slender outgrowths called root hairs (described in detail below). In contrast to the stem, the vascular bundle is located in the centre of the root. The xylem tissue usually appears as a cross-shaped region in the centre, with four or five 'arms'. This can be easily recognised because the cells that make up the xylem usually have a wide diameter. In between each of these arms is the phloem.





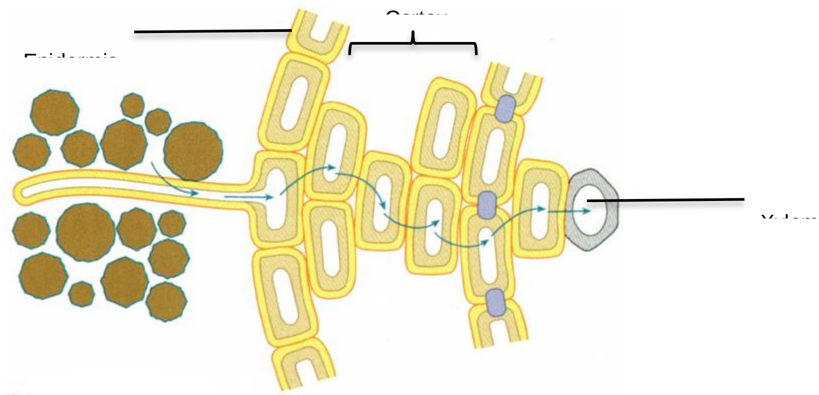
Left: A cross-section through a root, showing the vascular bundle in the centre. *Right*: A close-up of the vascular bundle, showing the cross-shaped xylem with smaller-celled phloem in between.

Root Hairs

The regions just behind the growing tips of the roots of a plant are covered in thousands of tiny root hairs. These areas are the main sites of water absorption by the roots, where the hairs greatly increase the surface area of the root epidermis.

Each hair is a single, elongated cell of the root epidermis. The long, thin outer projection of the root hair cell penetrates between the soil particles, reaching the water that lies in between soil particles. The water in the soil has solutes, such as mineral ions, dissolved in it, but their concentrations are much lower than the concentrations of solutes inside the root hair cell.

The soil water therefore has a higher water potential than the inside of the cell. This allows water to enter the root hair cell by osmosis down the water potential gradient. This water dilutes the contents of the root hair cell, increasing its water potential. The neighbouring cell now has a lower water potential than the root hair cell, and so water moves by osmosis from the root hair cell into the next cell. Thus, there is a flow of water by osmosis between cells in the root cortex into the xylem in the centre of the root.



Once water has entered the root hair cell, it moves down a water potential gradient between neighbouring cells across the root cortex and into the xylem in the centre of the root.

Uptake of Mineral Ions – Active Transport

In order for water to move into the root hair cell, the root hair cell must accumulate higher concentrations of mineral ions than the soil water. Diffusion can only occur *down* a concentration gradient, and so diffusion cannot account for a high concentration of solutes in the root hair cell. Furthermore, the cell surface membrane of the root hair cell is impermeable to solutes such as mineral ions. Thus, mineral ions have to enter the root cells by other means.

To accumulate mineral ions inside the cells, the root hairs must pump the mineral ions in, *against their concentration gradient*. The cell surface membranes of plant cells, including the root hair cell, contain molecular pumps which push the mineral ions into the cells against a concentration gradient using energy. This process is called **active transport**. Unlike diffusion, which just uses the kinetic energy of the diffusing particles, active transport uses chemical energy from respiration. Active transport is responsible for the uptake of several mineral ions into the root hair cells. Once inside the root, mineral ions pass across the cells of the root cortex and enter the xylem vessels. They are then transported around the plant in the xylem.

Transpiration

Plants continuously absorb water in their roots and lose it from their surface. Most of the water lost by the plant evaporates from the leaves – on a warm, dry, sunny day a leaf will exchange up to 100% of its water in a single hour. During the plant's lifetime, water equivalent to 100 times the weight of the plant may be lost through the leaf surfaces. Such water loss is called **transpiration**.

Transpiration is the evaporation and loss of water vapour from the aerial parts of a plant.

The loss of water from the leaves of a plant causes water to be pulled up the xylem in the stem and roots in a continuous flow known as the **transpiration stream**. The transpiration stream has more than one function:

(i) it supplies water for the leaf cells to carry out photosynthesis

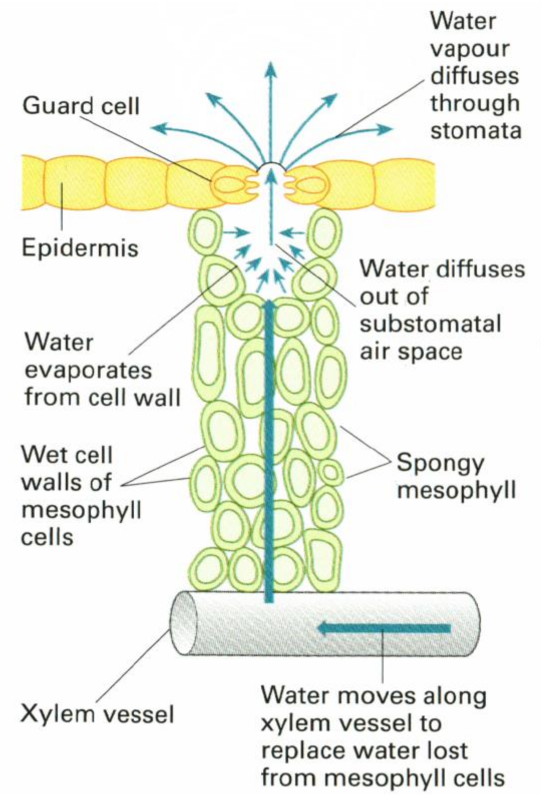
(ii) it carries mineral ions dissolved in the water to other parts of the plant where they can be used to make a range of molecules such as amino acids and proteins

(iii) it provides water to keep the plant cells turgid

(iv) it is an important means of cooling the plant; heat dissipates because the water molecules that escape into the atmosphere have higher-than-average energy, which breaks the bonds holding them in the liquid state. When these molecules escape, they leave behind molecules with lower-than-average energy and thus a cooler body of water. For a typical leaf, nearly half of the net heat input from sunlight is dissipated by transpiration.

The cell walls of plant cells have water molecules attached to them – the water molecules **adhere** (as in **adhesion** – to stick to) to the cell walls. If these water molecules gain energy by absorbing heat energy from the sun, some of them will evaporate. In the leaf, the water molecules will evaporate into the air spaces between the spongy mesophyll cells. The **water vapour** will then diffuse out through the stomatal pores.

The loss of water from the mesophyll cells sets up a water potential gradient which causes water to move by osmosis from surrounding mesophyll cells. In turn, this water is replaced with water from the xylem vessels in the leaf. The continual loss of water from the xylem in the leaf to the mesophyll cells is crucial to how water moves up the stem in xylem. Remember that there is no 'pump', such as a heart, in plants, and in trees such as the giant redwood water needs to be moved up to 100m against gravity to reach the leaves. The force of gravity is overcome by the **tension** (negative pressure) generated in the column of water in the xylem as water molecules move from the xylem to the mesophyll in the leaf. Water is therefore *pulled* up the stem by a force generated in the leaves.



A summary diagram showing the movement of water through the different tissues in a leaf, from the xylem to the air space in the spongy mesophyll layer.

Two properties of water are important for this process:

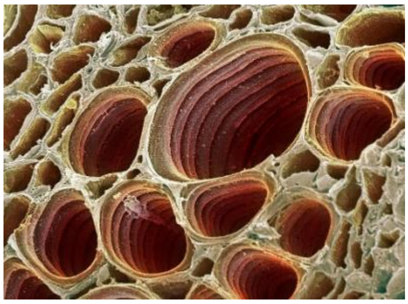
(i) Water molecules are able to stick to each other – they are **cohesive**. This means that when the column of water is pulled at the top of the xylem, the entire column of water is pulled up and does not break.

(ii) Water molecules are able to stick to the walls of the xylem vessels by **adhesion**. This prevents the water column from slipping back down the xylem vessel by gravity.

The energy for pulling the column of water up the stem ultimately comes from the sun – the heat energy from the sun causes the water molecules in the leaf to evaporate, thus setting up the gradient for water to move from the xylem.

The Structure of Xylem

Xylem is vascular tissue made up of cells working together to carry out support and transport. Mature xylem consists of dead cells called vessels that contain no cytoplasm arranged end-to-end to form a continuous vessel. The hollow central space of the xylem vessel is referred to as the **lumen**, and it is through the lumen that water is transported. The walls of the xylem vessels contain a tough, waterproof material called **lignin**; it is lignin that gives wood its strength.



The xylem vessels begin life as living cells with cytoplasm and cellulose cell walls. As they mature they become elongated and gradually the cell wall becomes impregnated with lignin. With the cell wall becoming impermeable to water, the cell dies and forms a hollow tube.

Xylem vessels thus have several adaptations to conduct water from the roots to the leaves:

(i) The lumen has a wide diameter, enabling a large volume of water to be transported.
(ii) There are no end walls between vessels, so there is a low resistance to the flow of water.
(iii) They have no cytoplasm, so there is low resistance to the flow of water.
(iv) The cell walls are thickened with cellulose and lignin which strengthens the wall to prevent it collapsing under tension.
(v) The cell walls are impregnated with lignin so they are waterproof.

Note that the fact they are dead is not an adaptation in itself, it is simply the inevitable consequence of having no cytoplasm.

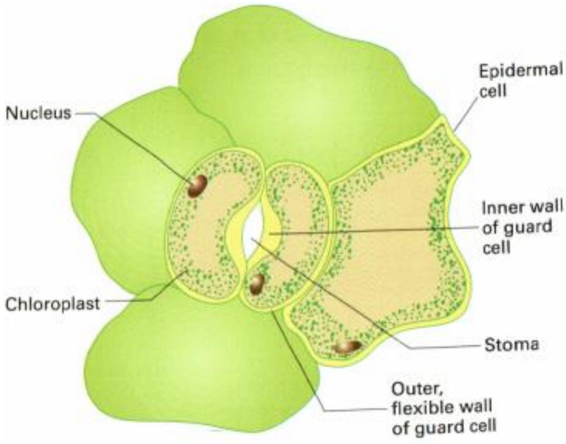
Stomata

The waxy cuticle that covers the aerial parts of a plant prevents gas exchange as well as reducing the evaporation of water from the leaf surface. Therefore, the presence of stomata on the underside of leaves allows carbon dioxide to diffuse into the leaf for photosynthesis to occur, and for oxygen, a waste product of photosynthesis, to diffuse out of the leaf. However, it also allows water vapour to diffuse out of the leaf into the air.

In most plant species there are usually more stomata on the lower surface of the leaves than the upper surface. This prevents too much water loss from the plant. If they were mainly on the upper leaf surface the stomata would be exposed to direct sunlight and the leaf would lose too much water. There is also less air movement on the underside of leaves.

Stomata can open and close in response to changing environmental conditions. The guard cells that surround each stoma have a 'banana' shape, and the part of their cell wall nearest the stoma is thickened with cellulose. In the light, water enters the guard cells by osmosis from the surrounding epidermal cells.

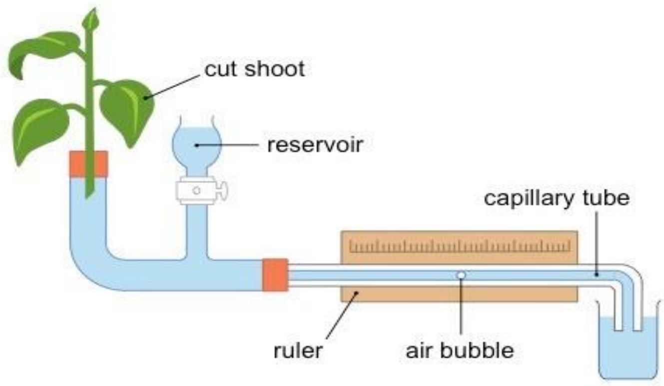
This causes the guard cells to swell up and become turgid. Their shape changes and they bend outwards, opening up the stoma. In the dark, the guard cells lose water and become flaccid, causing the stoma to close. The mechanism for the movement of water into or out of the guard cells is thought to involve actively transporting potassium into the guard cell, which causes the water potential to fall and water to move in by osmosis. In the dark, potassium is pumped out of the guard cell and the process reverses.



Plants are also able to close their stomata in response to drought. In this case, a chemical hormone is produced by the plant which triggers the stomata to close. Although gas exchange for photosynthesis is prevented, the need to conserve water is greater than the need for photosynthesis, so this would occur in the light as well as at night.

Potometers

A potometer is a piece of apparatus which measures the rate of uptake of water by a plant. To set up a potometer, the whole apparatus is placed in a sink of water and any air in the tubing removed. A healthy shoot is taken from a plant and the end of the stem cut at an angle which is done under water to prevent air entering. The apparatus is removed from the sink and Vaseline used to seal any joints and the leaves dried. The movement of the water column in the capillary tube can be timed; if the water moves more quickly, this shows a faster rate of transpiration. The plant can be exposed to different conditions to see how they affect the rate. The volume of water taken up by the shoot can be calculated by measuring the distance travelled by the column of water and multiplying it by the surface area of the capillary tube.



Factors Affecting the Rate of Transpiration

There are four main environmental factors which affect the rate of transpiration:

(i) Light intensity. The rate of transpiration increases in the light, because the stomata open to allow gas exchange for photosynthesis.
(ii) Temperature. Higher temperatures increase the rate of evaporation of water from the mesophyll cells, thus increasing the rate of transpiration.
(iii) Humidity. When the air around the plant is humid, the concentration gradient for water vapour between the air spaces in the leaf and the external air is reduced. Thus, the rate of loss of water vapour is reduced and the therefore the rate if transpiration decreases.
(iv) Wind speed. The moving air around the leaf removes water vapour from around the stomata. This increases the steepness of the concentration gradient for water vapour between the leaf and the air, and so the rate of transpiration increases.

Xerophytes

Plants that live in arid habitats and are able to endure drought conditions are referred to as **xerophytes**. They have a number of features that help to reduce transpiration and therefore conserve water:

(i) Thick waxy cuticle on the leaves; this reduces the loss of water by evaporation from the leaf surface.
(ii) Sunken stomata; the stomata are located in depressions on the leaf surface, which traps a layer of humid air next to the stomata and reduces the concentration gradient for water vapour. The length of the diffusion path between the stomata and the air also increases, further reducing the rate of diffusion.
(iii) Rolled leaves; some plants such as marram grass (*Ammophila*) have leaves that are rolled up to enclose a central space. The stomata face into the enclosed space, thus creating a humid environment away from the outside air.

(iv) Hairs on the leaf surface; the hairs trap a layer of humid air next to the leaf, thus reducing the concentration gradient for water vapour. Often the leaves are white or silver, which also helps prevent the leaf heating up in the sun.

(v) Smaller leaves; a smaller surface area with fewer stomata reduces the rate of transpiration. In cacti, the leaves are absent and the stems (which have a low surface area: volume ratio) are photosynthetic.

(vi) Reversed stomatal rhythm; in some species the stomata open at night and close during the day, when temperatures are hottest. They use a different mechanism of photosynthesis so that it is able to capture the carbon dioxide at night when there is no light.

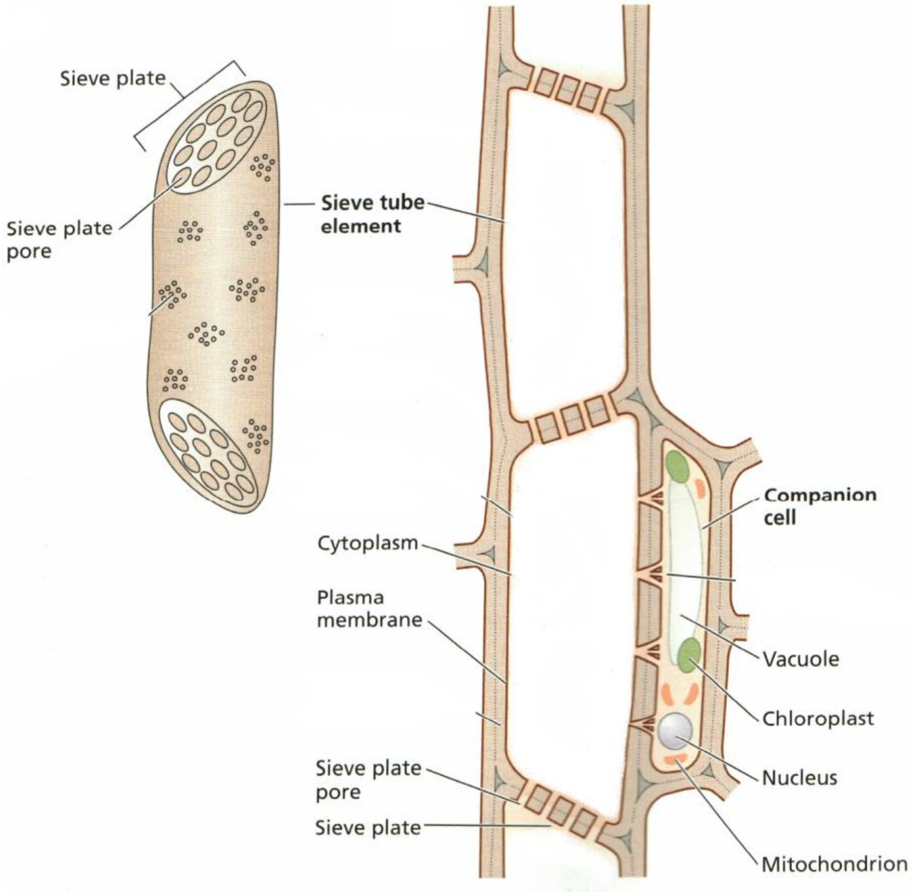
Note that not all xerophytes grow in deserts. Marram grass, for example, grows on sand dunes in Britain where there is plenty of rainfall, but the sandy soil means that the water quickly drains away. In some environments the water in the soil can be frozen for much of the year which also causes problems for plants – plants such as pine trees and holly show xerophytic adaptations as a result, such as the needle-like leaves of pine which have a reduced surface area to volume ratio and a thick waxy cuticle.

Phloem Transport

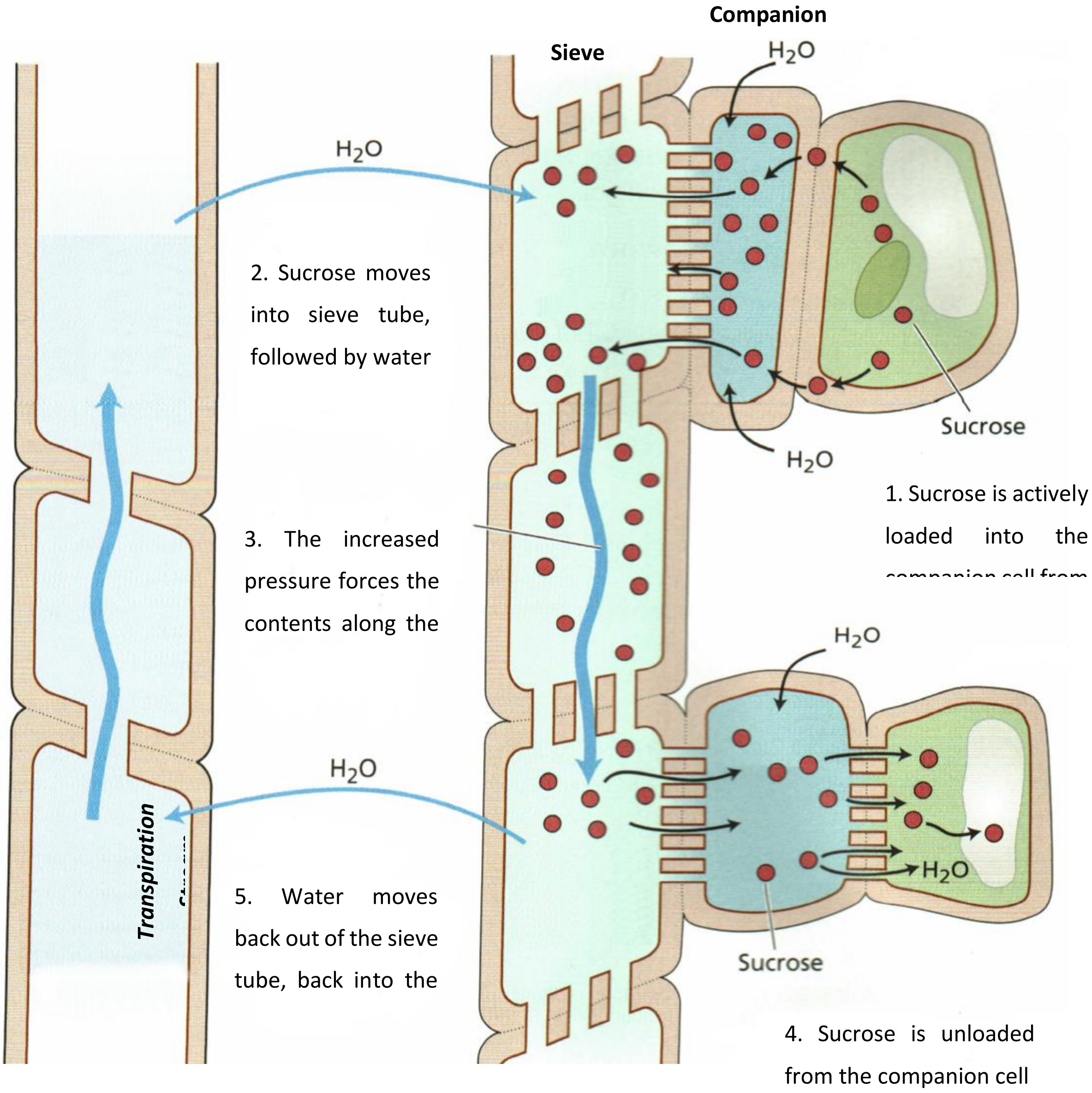
The other plant transport system, phloem, consists of living cells and its function is to transport substances that the plant has made itself – sugars, amino acids and plant hormones. In contrast to xylem transport, phloem is able to transport material up and down a plant – wherever the substances are required.

Phloem tissue is composed of two types of cells – **sieve tube elements** and **companion cells**. The sieve tube elements are arranged end to end to form **sieve tubes**. At maturity they lack nuclei but do retain their cytoplasm. They do not have lignin in the cell walls, which is just made of cellulose. The end walls have holes in them and are known as **sieve plates**. The cytoplasm extends through the holes in the sieve plates, linking each sieve tube element with the next.

Adjacent and connected to each sieve tube element is a companion cell. Companion cells contain cytoplasm and a nucleus. There are many mitochondria in companion cells. The companion cells are required for transport to occur in phloem. In contrast to xylem transport, the plant must expend energy to transport material in phloem, and if companion cells are treated with a chemical that stops respiration then phloem transport stops.



The basic mechanism is that sugars, such as sucrose, are actively transported from the mesophyll cells, where they are made, and into the companion cells. This requires energy which comes from the mitochondria in the companion cells. The sucrose is then loaded into the sieve tube element to which it is directly connected. Sucrose concentrations in sieve tubes can be as high as 30%, but only 0.5% in mesophyll cells. By accumulating high concentrations of sugars in the sieve tube element, the water potential of the cytoplasm is lowered and water moves in by osmosis from neighbouring xylem vessels. This causes the pressure in the sieve tube to increase, forcing the contents of the cytoplasm along the sieve tube via mass flow. The contents are moved to a region in another part of the plant, such as the roots, where there is a lower pressure. Sucrose is actively unloaded from the sieve tube element and companion cell, and water moves out by osmosis, reducing the pressure.


Companion
Sieve
H_2O
H_2O
2. Sucrose moves into sieve tube, followed by water
Sucrose
H_2O
1. Sucrose is actively loaded into the
3. The increased pressure forces the contents along the
H_2O
H_2O
Transpiration
5. Water moves back out of the sieve tube, back into the
H_2O
Sucrose
4. Sucrose is unloaded from the companion cell