**Transport Systems in Plants**

Plants don’t have a circulatory system like animals, but they do have a sophisticated transport system for carrying water and dissolved solutes to different parts of the plant, often over large distances.

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| Stem Structure     * Epidermis. One cell thick. In young plants the epidermis cells may secrete a waterproof cuticle, and in older plants the epidermis may be absent, replaced by bark. * Cortex. Composed of various “packing” cells, to give young plants strength and flexibility, and are the source of plant fibres such as sisal and hemp. * Vascular Tissue. This contains the phloem and xylem tissue, which grow out from the cambium. In dicot plants (the broad-leafed plants), the vascular tissue is arranged in vascular bundles, with phloem on the outside and xylem on the inside. In older plants the xylem bundles fuse together to form the bulk of the stem. * Pith. The central region of a stem, used for food storage in young plants. It may be absent in older plants (i.e. they’re hollow). | Root Structure     * Epidermis. A single layer of cells often with long extensions called root hairs, which increase the surface area enormously. A single plant may have 1010 root hairs. * Cortex. A thick layer of packing cells often containing stored starch. * Endodermis. A single layer of tightly-packed cells containing a waterproof layer called the casparian strip. This prevents the movement of water between the cells.      * Pericycle. A layer of undifferentiated meristematic (growing) cells. * Vascular Tissue. This contains xylem and phloem cells, which are continuous with the stem vascular bundles. The arrangement is different, and the xylem usually forms a star shape with 2-6 arms. |

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| **Xylem Tissue**  Xylem tissue is composed of dead cells joined together to form long empty tubes. Different kinds of cells form wide and narrow tubes, and the end cells walls are either full of holes, or are absent completely. Before death the cells form thick cell walls containing lignin, which is often laid down in rings or helices, giving these cells a very characteristic appearance under the microscope. Lignin makes the xylem vessels very strong, so that they don’t collapse under pressure, and they also make woody stems strong. |  | |
|  | | **Phloem Tissue**  Phloem tissue is composed of sieve tube cells, which form long columns with holes in their end walls called sieve plates. These cells are alive, but they lose their nuclei and other organelles, and their cytoplasm is reduced to strands around the edge of the cells. These cytoplasmic strands pass through the holes in the sieve plates, so forming continuous filaments. The centre of these tubes is empty. Each sieve tube cell is associated with one or more companion cells, normal cells with nuclei and organelles. These companion cells are connected to the sieve tube cells by plasmodesmata, and provide them with proteins, ATP and other nutrients. |

## **Water Transport in Plants**

Vast amounts of water pass through plants. A large tree can use water at a rate of 1 dm³ min-1. Only 1% of this water is used by the plant cells for photosynthesis and turgor, and the remaining 99% evaporates from the leaves and is lost to the atmosphere. This evaporation from leaves is called transpiration.

The movement of water through a plant can be split into three sections: through the roots, stem and leaves:

1. **Movement through the Roots**



Water moves through the root by two paths:

* The Symplast pathway consist of the living cytoplasms of the cells in the root (10%). Water is absorbed into the root hair cells by osmosis, since the cells have a lower water potential that the water in the soil. Water then diffuses from the epidermis through the root to the xylem down a water potential gradient. The cytoplasms of all the cells in the root are connected by plasmodesmata through holes in the cell walls, so there are no further membranes to cross until the water reaches the xylem, and so no further osmosis.
* The Apoplast pathway consists of the cell walls between cells (90%). The cell walls are quite thick and very open, so water can easily diffuse through cell walls without having to cross any cell membranes by osmosis. However the apoplast pathway stops at the endodermis because of the waterproof casparian strip, which seals the cell walls. At this point water has to cross the cell membrane by osmosis and enter the symplast. This allows the plant to have some control over the uptake of water into the xylem.

The uptake of water by osmosis actually produces a force that pushes water up the xylem. This force is called root pressure, which can be measured by placing a manometer over a cut stem, and is of the order of 100 kPa (about 1 atmosphere). This helps to push the water a few centimetres up short and young stems, but is nowhere near enough pressure to force water up a long stem or a tree. Root pressure is the cause of guttation, sometimes seen on wet mornings, when drops of water are forced out of the ends of leaves.

1. **Movement through the Stem**

The xylem vessels form continuous pipes from the roots to the leaves. Water can move up through these pipes at a rate of 8m h-1, and can reach a height of over 100m. Since the xylem vessels are dead, open tubes, no osmosis can occur within them. The driving force for the movement is transpiration in the leaves. This causes low pressure in the leaves, so water is sucked up the stem to replace the lost water. The column of water in the xylem vessels is therefore under tension (a stretching force). Fortunately water has a high tensile strength due to the tendency of water molecules to stick together by hydrogen bonding (cohesion), so the water column does not break under the tension force. This mechanism of pulling water up a stem is sometimes called the cohesion-tension mechanism.

The very strong lignin walls of the xylem vessels stops them collapsing under the suction pressure, but in fact the xylem vessels (and even whole stems and trunks) do shrink slightly during the day when transpiration is maximum.

1. **Movement through the Leaves**



The xylem vessels ramify in the leaves to form a branching system of fine vessels called leaf veins. Water diffuses from the xylem vessels in the veins through the adjacent cells down its water potential gradient. As in the roots, it uses the symplast pathway through the living cytoplasm and the apoplast pathway through the non-living cell walls. Water evaporates from the spongy cells into the sub-stomatal air space, and diffuses out through the stomata.

Evaporation is endothermic and is driven by solar energy, which is therefore the ultimate source of energy for all the water movements in plants:



#### **Factors affecting Transpiration**

The rate of transpiration can be measured in the lab using a potometer (“drinking meter”):



A potometer actually measures the rate of water uptake by the cut stem, not the rate of transpiration; and these two are not always the same. During the day plants often transpire more water than they take up (i.e. they lose water and may wilt), and during the night plants may take up more water than they transpire (i.e. they store water and become turgid). The difference can be important for a large tree, but for a small shoot in a potometer the difference is usually trivial and can be ignored.

The potometer can be used to investigate how various environmental factors affect the rate of transpiration.

* Light. Light stimulates the stomata to open allowing gas exchange for photosynthesis, and as a side effect this also increases transpiration. This is a problem for some plants as they may lose water during the day and wilt.
* Temperature. High temperature increases the rate of evaporation of water from the spongy cells, and reduces air humidity, so transpiration increases.
* Humidity. High humidity means a higher water potential in the air, so a lower water potential gradient between the leaf and the air, so less evaporation.
* Air movements. Wind blows away saturated air from around stomata, replacing it with drier air, so increasing the water potential gradient and increasing transpiration.

Many plants are able to control their stomata, and if they are losing too much water and their cells are wilting, they can close their stomata, reducing transpiration and water loss. So long periods of light, heat, or dry air could result in a decrease in transpiration when the stomata close.

**Adaptations to dry habitats**

Plants in different habitats are adapted to cope with different problems of water availability.

Mesophytes plants adapted to a habitat with adequate water

Xerophytes plants adapted to a dry habitat

Halophytes plants adapted to a salty habitat

Hydrophytes plants adapted to a freshwater habitat

Some adaptations of xerophytes are:

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| **Adaptation** | **How it works** | **Example** |
| thick cuticle | stops uncontrolled evaporation through leaf cells | most dicots |
| small leaf surface area | less area for evaporation | conifer needles, cactus spines |
| low stomata density | fewer gaps in leaves |  |
| stomata on lower surface of leaf only | more humid air on lower surface, so less evaporation | most dicots |
| shedding leaves in dry/cold season | reduce water loss at certain times of year | deciduous plants |
| sunken stomata | maintains humid air around stomata | marram grass, pine |
| stomatal hairs | maintains humid air around stomata | marram grass, couch grass |
| folded leaves | maintains humid air around stomata | marram grass, |
| succulent leaves and stem | stores water | cacti |
| extensive roots | maximise water uptake | cacti |

##### Mineral Ion transport in Plants

Ions are absorbed from the soil by both passive and active transport. Specific ion pumps in the membranes of root hair cells pump ions from the soil into the cytoplasms of the epidermis cells. Two lines of evidence indicate that active transport is being used:

* The concentrations of ions inside root cells are up to 100 time greater than in the soil, so they are being transported up their concentration gradient.
* If respiratory inhibitors such as cyanide are applied to living roots, ion uptake is greatly reduced, since there is no ATP being made to drive the membrane pumps. Any remaining uptake must be passive.

The active uptake of ions is partly responsible for the water potential gradient in roots, and therefore for the uptake of water by osmosis.

Ions diffuse down their concentration gradient from the epidermis to the xylem. They travel up the xylem by mass flow as the water is pulled up the stem (in other words they are simply carried up in the flow of the xylem solution). In the leaves they are selectively absorbed into the surrounding cells by membrane pumps.

**Solute Transport in Plants**

The phloem contains a very concentrated solution of dissolved solutes, mainly sucrose, but also other sugars, amino acids, and other metabolites. This solution is called the sap, and the transport of solutes in the phloem is called translocation.

Unlike the water in the xylem, the contents of the phloem can move both up or down a plant stem, often simultaneously. It helps to identify where the sugar is being transported from (the source), and where to (the sink).

* During the summer sugar is mostly transported from the leaves, where it is made by photosynthesis (the source) to the roots, where it is stored (the sink).
* During the spring, sugar is often transported from the underground root store (the source) to the growing leaf buds (the sink).
* Flowers and young buds are not photosynthetic, so sugars can also be transported from leaves or roots (the source) to flowers or buds (sinks).

Surprisingly, the exact mechanism of sugar transport in the phloem is not known, but it is certainly far too fast to be simple diffusion. The main mechanism is thought to be the mass flow of fluid up the xylem and down the phloem, carrying dissolved solutes with it. Plants don’t have hearts, so the mass flow is driven by a combination of active transport (energy from ATP) and evaporation (energy from the sun). This is called the mass flow theory, and it works like this:



1. Sucrose produced by photosynthesis is actively pumped into the phloem vessels by the companion cells.
2. This decreases the water potential in the leaf phloem, so water diffuses from the neighbouring xylem vessels by osmosis.
3. This is increases the hydrostatic pressure in the phloem, so water and dissolved solutes are forced downwards to relieve the pressure. This is mass flow: the flow of water together with its dissolved solutes due to a force.
4. In the roots the solutes are removed from the phloem by active transport into the cells of the root.
5. At the same time, ions are being pumped into the xylem from the soil by active transport, reducing the water potential in the xylem.
6. The xylem now has a lower water potential than the phloem, so water diffuses by osmosis from the phloem to the xylem.
7. Water and its dissolved ions are pulled up the xylem by tension from the leaves. This is also mass flow.

This mass-flow certainly occurs, and it explains the fast speed of solute translocation. However there must be additional processes, since mass flow does not explain how different solutes can move at different speeds or even in different directions in the phloem. One significant process is cytoplasmic streaming: the active transport of molecules and small organelles around cells on the cytoskeleton.

###### **Translocation Experiments**

1. **Puncture Experiments**

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| If the phloem is punctured with a hollow tube then the sap oozes out, showing that there is high pressure (compression) inside the phloem (this is how maple syrup is tapped). If the xylem is punctured then air is sucked in, showing that there is low pressure (tension) inside the xylem. This illustrates the main difference between transport in xylem and phloem: Water is pulled up in the xylem, sap is pushed down in the phloem. |  |

1. **Ringing Experiments**

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| Since the phloem vessels are outside the xylem vessels, they can be selectively removed by cutting a ring in a stem just deep enough to cut the phloem but not the xylem. After a week there is a swelling above the ring, reduced growth below the ring and the leaves are unaffected. This was early evidence that sugars were transported downwards in the phloem. |  |

1. **Radioactive Tracer Experiments**

Radioactive isotopes can be used trace precisely where different compounds are being transported from and to, as well as measuring the rate of transport. The radioactivity can be traced using photographic film (an autoradiograph) or a GM tube. This techniques can be used to trace sugars, ions or even water.

In a typical experiment a plant is grown in the lab and one leaf is exposed for a short time to carbon dioxide containing the radioactive isotope 14C. This 14CO2 will be taken up by photosynthesis and the 14C incorporated into glucose and then sucrose. The plant is then frozen in liquid nitrogen to kill and fix it quickly, and placed onto photographic film in the dark. The resulting autoradiograph shows the location of compounds containing 14C.



This experiment shows that organic compounds (presumably sugars) are transported downwards from the leaf to the roots. More sophisticated experiments using fluorescently labelled compounds can locate the compound specifically to the phloem cells.

1. **Aphid Stylet Experiments**

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| Aphids, such as greenfly, have specialised mouthparts called stylets, which they use to penetrate phloem tubes and sup of the sugary sap therein. If the aphids are anaesthetised with carbon dioxide and cut off, the stylet remains in the phloem so pure phloem sap can be collected through the stylet for analysis. This surprising technique is more accurate than a human with a syringe and the aphid’s enzymes ensure that the stylet doesn’t get blocked. |  |