MASTER BIOLOGY

AQA Biology A-level

Module 3: Organisms exchange substances with their environment

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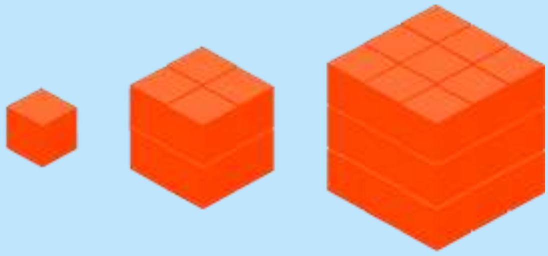
Exchange

The need for specialised exchange surfaces increases as **surface area to volume ratio** of an organism increases. In **single celled organisms**, substances can easily enter the cell due to a short distance needed to travel. In much larger **multicellular organisms**, the distance to transport substances over is longer. This is because the surface area to volume ratio is **smaller**.



Length	1cm	2cm	3cm
SA	1x1x6 =6cm^2	2x2x6 =24cm^2	3x3x6 =54cm^2
V	1x1x1 =1cm^3	2x2x2 =8cm^3	3x3x3 =27cm^3
SA:V=	6:1	3:1	2:1

This diagram shows that smaller organisms have a larger surface area to volume ratio.

A **larger surface area to volume ratio** means **more efficient gas exchange**. This is because there is more surface area for substances to diffuse across in proportion to the volume of 'body' the organism has.

Because of this, multicellular organisms that are much larger need specialised **exchange surfaces** for efficient gas exchange and exchange of other substances across the gut such as glucose and ions.

Features of an efficient exchange surface include:

- **Large surface area**, for instance the **root hair cells** in the roots of a plant or **folded membranes**, such as the **cristae** of mitochondria
- Should be **thin** to ensure a **short diffusion distance**
- **Good blood supply/ventilation** to maintain a steep concentration gradient. This is seen in the gut and the alveoli.

Ventilation and Gas Exchange

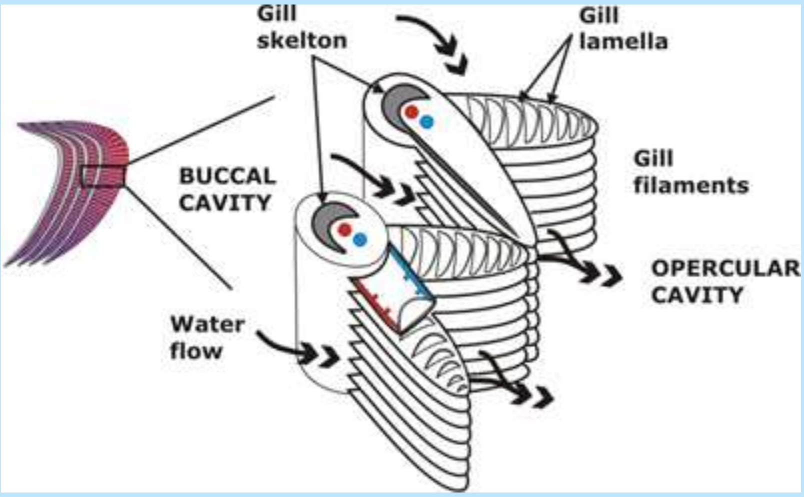
Fish

Fish require a specialised gas exchange surface to extract oxygen from the water to use for aerobic respiration. Bony fish have **four pairs of gills** and each gill is supported by an **arch**.

Along each arch there are multiple projections called **gill filaments**. Gill filaments have lamellae sticking out. This is where gas exchange occurs.

Blood and water flow across the lamellae in a **counter current** flow system. This means that water and blood flow in the opposite direction to one another. This ensures that a **steep diffusion gradient** is maintained so that the **maximum amount of oxygen** diffuses into the blood from the water, down a concentration gradient. The lamellae are **held apart** by **water flow** and collapse together when there is no water. This means, no oxygen exchange meaning fish cannot survive very long out of water.

Ventilation is required to maintain a **continuous unidirectional flow**. Ventilation begins with the fish opening its mouth which causes the floor of **buccal cavity** to lower. This enables water to flow in. Then the fish closes its mouth, causing the **buccal cavity floor to raise**. This increases the pressure in the water and it is therefore forced over the gill filaments by the **difference in pressure** between the **mouth cavity and opercular cavity (the cavity at the other end of the gill filaments to the mouth)**. The operculum acts as a **valve and pump** and lets water out.



Insects

Insects don't have a transport system such as blood vessels. This means that oxygen must diffuse directly to tissues undergoing respiration from the outside of the body. This is achieved with the help of **spiracles**, which are small holes in the side of the insect's body. These holes are the openings of tubes, which run through the body to deliver the oxygen from outside of the body to inside. These tubes start at the spiracles with the bigger **trachea**. These branch off into smaller **tracheoles**. The tracheoles deliver oxygen to the tissues deep inside the insect's body. Gases move in and out through **diffusion**. The insect helps to speed up this process by using small pumping movements of its abdomen via **muscle contraction**. At the end of the tracheoles, the surfaces are moist for oxygen gas to dissolve into, making it easier to deliver the gas to tissues.

The downside of this system is that sometimes, insects can suffer **water loss** from the spiracles. This can be negated by reducing pumping action at the hottest part of the day (water will have more kinetic energy due to the increased heat energy, increasing its escape from the spiracles) and by trapping water vapour in the opening of the spiracles, reducing the water potential gradient between the outside of the insect and the inside and thus reducing water loss.

Plants

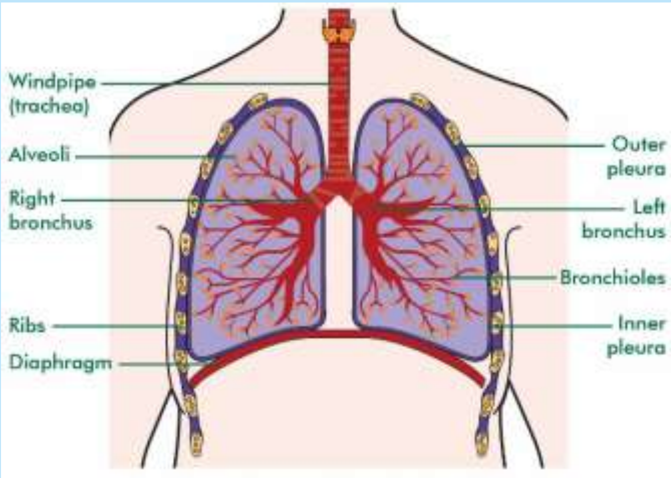
Plants are adapted to efficient gas exchange.

1. Leaves have many small holes called **stomata** on the underside of the leaf. This allows gases to enter and exit the leaves. There is a high number of these, reducing the diffusion distance for gases to enter and exit.
2. Leaves have **air spaces** which allow gases to move around the leaf. This means gases can easily reach the photosynthesising mesophyll cells in the spongy mesophyll
3.

Mammalian Gas Exchange System

The **lungs** are a pair of organs with a **large surface area** located in the **thoracic cavity** (chest). They are surrounded by the **rib cage** for protection and a lubricating substance, a liquid known as **pleural fluid** is secreted to prevent friction between the rib cage and lungs during inflation and deflation.

External and internal intercostal muscles between the ribs contract to raise and lower the ribcage respectively. A muscle called the **diaphragm** separates the lungs from abdomen area and also aids in inflation of the lungs by increasing the volume of the thoracic cavity when it contracts and flattens.



Air Flow

The air enters through the nose

1. Enters the **trachea** (windpipe)
2. Then it enters the **bronchi and then bronchioles**

3. Air then enters the **alveoli**, which are tiny sacs filled with air. This is where gas exchange with the blood takes place

Trachea

The trachea is held open with the help of a **rings of cartilage**. These rings are incomplete and C-shaped in the trachea to allow passage of food down **the oesophagus** behind the **trachea.** The oesophagus needs to be soft and flexible for this therefore cartilage down one side would impede its function.
Cartilage is a tough form of tissue which holds its shape very well. An obvious example for you to understand what cartilage is and how it holds its shape is to feel your ear – this is mainly made from cartilage with the exception of your ear lobe, which is soft and flexible.

Bronchi

The bronchi are made when the trachea splits into two. The **trachea** and **bronchi** (singular = bronchus) are similar in structure, with the exception of size as the bronchi are narrower than the trachea. They also have **c-shaped cartilage** to help them hold their shape open. The walls are made of layers, with the innermost layer being the epithelium. This **epithelium** is a thin layer of ciliated cells (ciliated epithelium) and **goblet cells**, which make mucus. This mucus helps to trap dust, bacteria and other possible pathogens to be coughed out of the airways. On the inside of the epithelium is the cartilage and then a layer of **glandular and connective tissue, elastic fibres, smooth muscle and blood vessels.** This is referred to as the '**loose tissue'**.

Bronchioles

The right and left bronchi then branch off to produce smaller branches called **bronchioles.** They are narrower than the bronchi. Bronchioles then branch off smaller and smaller from each other like the branches of a tree. Only the larger bronchiole contain **cartilage**, but this cartilage is a **full ring**, unlike the C shaped cartilage seen in the bronchi and trachea.

The walls of bronchioles are made out of **smooth muscle** and **elastic fibres**. The smallest of bronchioles have **alveoli** at the ends.

Alveoli

The alveoli are small sacs of air at the end of the bronchioles. This is where gas exchange with the blood takes place. These are adapted for transport for the following reasons:

- They are thin, with the wall of the sac being only around **one cell thick**
- They are surrounded by **capillaries** which are also only one cell thick
    - Both of these points reduce the diffusion distance for gases

- The alveoli have an **excellent blood supply** from the capillaries. This means that a **steep concentration gradient** is always maintain, maximising the rate of diffusion that takes place between the alveolus and the blood (and vice versa)
- The are a large number of alveoli **(~300 million)**, collectively giving a surface area of around **70m²**.

Structures in the Mammalian Airway

- Cartilage supports the trachea and bronchi, and ensures that they can hold their shape and stay open. This stops them collapsing and ensures clear air flow. This stop them collapsing in on themselves during the pressure drop during exhalation.

- Ciliated epithelium are present in **bronchi, bronchioles** and **trachea**. The cilia are like **small hairs** on the surface of the cell, sticking out into the airway. These hairs can **waft** mucus and any pathogens the mucus has trapped **away from the lung**. This means it can be moved upwards where it can be coughed up and swallowed and destroyed by stomach acid.

- Goblet cells are present in the trachea, bronchi and bronchioles. These cells produce mucus. Mucus traps pathogens and dust to reduce the risk of lung infection (pneumonia). Lysozymes are enzymes present in the airway which can also digest bacteria.
- Smooth muscle is present in the bronchioles. This means that smooth muscle in the bronchiole walls can contract and reduce their diameter. This means they can reduce the flow of air to and from the alveoli.

- Elastic fibres are present in the airway walls and in the **alveoli** especially. The latter is important as it allows the alveoli to stretch when we inhale and recoil when we exhale thus controlling the flow of air and improving ventilation.

Ventilation

The flow of air in and out of the **alveoli** is referred to as ventilation and is composed of two stages: **inspiration** (air moving in to the lung) and **expiration** (air moving out). This process occurs with the help of two sets of muscles, the **intercostal muscles** and **diaphragm**.

The most important thing you must remember about air movement is that **air moves from a high pressure to a low pressure**, **down a pressure gradient**.

Inspiration

1. The **external intercostal** muscles contract
2. The **internal intercostal** muscles relax
3. This causes the **ribs** raise upwards and outwards.
4. The diaphragm **contracts and flattens**
5. This causes the thoracic cavity, where the lungs are, to **increase in size.** This **lowers the pressure** inside the thoracic cavity.
6. **Air moves from high pressure to low pressure**. The difference between the pressure inside the **lungs** and atmospheric pressure creates a gradient, thus causing the air to be **forced into the lungs**

Expiration

1. During **expiration**, the **internal** intercostal muscles **contract** whereas the external muscles relax
2. The rib cage lowers and moves inwards
3. The diaphragm **relaxes** and raises **upwards**
4. This causes a decrease in the volume inside the thorax (thoracic cavity)
5. This increases the pressure in the lungs. This is above the pressure of the air outside the lungs. The pressure gradient means that the forcing the air **out of the lungs, down a pressure gradient**.

Spirometry

A **spirometer** is a device used to measure **air flow** in and out of the lungs and to measure **lung volume** ie. How much air the lungs can hold**.** A person using a spirometer breathes in and out of the **airtight chamber** which causes it to move up and down. This movement leaves a **trace on a graph** which can then be interpreted.

Key Terms

Vital capacity (VC or FVC = Forced vital capacity) – the **maximum** volume of air that can be inhaled or exhaled in a single breath when we force it. Can vary depending on gender, age, size and height. The tidal volume + inspiratory reserve volume = vital capacity
Tidal volume – the **volume of air** we breathe in and out at **each breath at rest** ie. not forced. The **tidal volume** can be exceeded, in cases such as during exercise where the **inspiratory reserve volume** is reached in an attempt to increase the amount of air breathed in.

Breathing rate/Respiratory Rate – the **number of breaths per minute**, can be calculated from the spirometer trace by counting the **number of peaks** or troughs in a minute

Residual Volume - The volume of air which is always present in the lungs, even after maximal exhalation

Expiratory reserve volume is the additional volume of air that can be exhaled **on top of the tidal volume.**

FEV1 – The volume of air that can be breathed out in the first second of **maximal effort of breathing out forcefully**

FEV1/FVC Ratio – Can be used to diagnose someone with an obstructive or a restrictive lung disease. An obstructive disease will have a reduced ratio.

Digestion and absorption

Digestion is the hydrolysis of large biological molecules into smaller molecules which can be absorbed across cell membranes in the gut and into the blood.

- Carbohydrates can be digested by many different enzymes. This process starts in the mouth with **salivary amylase.** This can be then continued in the small intestine by the **pancreatic amylase**. This breaks long polymers into smaller sugars such as disaccharides. **Maltases** in the **ileum** break down the disaccharide **maltose**, and **sucrases** and **lactases** break down the dissacharides sucrose and lactose respectively.

- Lipids are digested by **lipases** in the ileum which hydrolyse the **ester bond** between the **monoglycerides** and **fatty acid**. Before being broken down by lipases in the ileum, lipids must be **emulsified** into **micelles** by **bile salts** released by the liver and stored in the gall bladder until use. Emulsification increases the **surface area**, meaning that enzymes can work on the lipids faster.

- **Proteins** (polypeptides) are digested by enzymes called **peptidases**. These enzymes are divided into 3 main groups:

    - Endopeptidases - hydrolyse peptide bonds between specific amino acids in the middle of a polypeptide.

    - Exopeptidases - hydrolyse bonds at ends of a polypeptides

    - Dipeptidases - break dipeptides, consisting of only 2 amino acids, into individual amino acids

Absorption

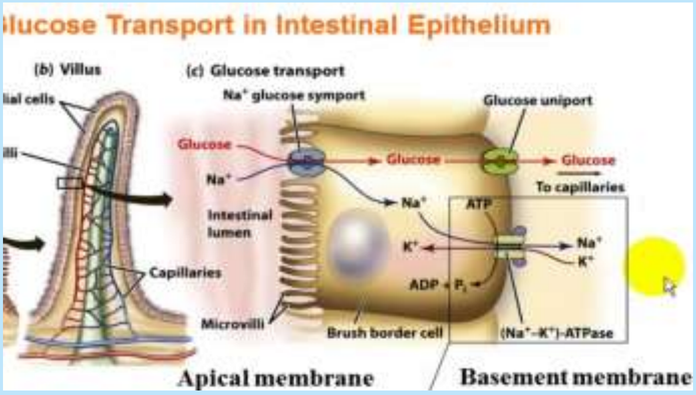
Once food has been hydrolysed and digested by each type of enzyme, the monomer products of digestion need to be **absorbed** into the bloodstream from the small intestine. This happens mainly in the **ileum**, which is a section of the small intestine. The products of digestion start in the **lumen** of the small intestine, which is the name for the hollow 'tube' of the small intestine.

Products of digestion are **absorbed** by cells lining the ileum of mammals

Carbohydrate Absorption

1. The glucose monomer reaches the gut. There is a much higher concentration of glucose inside the cell than there is in the gut. This means glucose must travel **against its concentration gradient** from the gut lumen into the cell

2. The glucose uses a **sodium-glucose symporter** to enter the cell. This transporter is a **carrier protein** which uses the concentration gradient of sodium (high concentration in the **lumen**, low concentration of sodium **inside the cell**) to transport glucose **against** its concentration gradient.
3. However, this would eventually lead to a high concentration of sodium inside the cell and therefore ruin this gradient. Therefore a **Sodium-Potassium Pump actively transports** sodium out of the cell **into the bloodstream** and potassium into the cell from the bloodstream. This sodium potassium pump is on the **other side of the** cell to the symporter, on the side we call the **basal** side. This is the side that faces the bloodstream instead of the intestinal lumen. This sodium-potassium pump **requires ATP** as it is active transport. This ensures there is still a **concentration gradient** for the sodium-glucose symporter to work.



Amino Acids

Amino acids are transported in **exactly the same way as glucose above**. Utilising a sodium-amino acid **symporter**, amino acids are taken from the lumen along with one sodium ion. This protein carrier (the symporter) utilises the concentration gradient of sodium to transport both the sodium and amino acid into the cell, down sodium's concentration gradient (from high concentration of sodium in the lumen to lower concentration inside the cell).

To ensure a **low concentration of sodium remains inside the cell**, active transport is used. This is in the form of a sodium-potassium pump in the **basal side** of the cell (the other side to the luminal side which faces the bloodstream instead of the lumen), which uses ATP to pump sodium **out of the cell** into the **bloodstream** and pump potassium **into the cell** from the bloodstream. It does this **against both of the ions' concentration gradients.**

Lipids

We need to transport our **monoglycerides** and **fatty acids** into the body from our intestinal lumen.

1. Monoglycerides and fatty acids are **polar**. This means they can easily diffuse across the **cell membrane** into the **epithelial cells** lining the epithelium.
2. Once inside the epithelial cell, they are transported to the **endoplasmic reticulum** where they are repackaged into **triglycerides** again.

3. After this they move out of the cells by **vesicles** into the lymph system NOT THE BLOODSTREAM

Adaptations of the Gut

The gut is **well adapted** to its purpose with the following adaptations:

1. Excellent blood supply – This maintains a **steep concentration gradient** for all of the nutrients and ions that need to be transported from the cells of the small intestine into the bloodstream. This means **faster**, more efficient **transport**.
2. Folds of the gut wall – the wall of the small instestine has many folds which **increases its surface area**, meaning **diffusion** and **active transport** can happen **faster**
3. Villi – The gut wall is arranged into even **smaller projections** called villi, which consist of many small intestinal epithelial cells. This makes transport of substances through diffusion and active transport **faster**.
4. Microvilli – present on the side of the cell which is facing the lumen of the gut (**luminal surface**) of every single small intestinal epithelial cell. This **increases the surface area** to improve the **speed** and efficiency of transport of substances such as glucose and ions into the bloodstream
5. Many mitochondria – the small intestinal epithelial cells have many mitochondria to make a lot of **ATP for energy**. This is important as energy is needed for the **active transport** of many ions such as sodium and potassium out of and into the small intestinal cells

Haemoglobin

Haemoglobin is a water soluble **globular** protein which consists of **two beta** polypeptide chains (proteins) and **two alpha helix** polypeptide chains (proteins). Each polypeptide chain forms a complex containing a **haem** group. A **haem** group is an iron ion (Fe^{2+}). This haem group can bind to **oxygen** and therefore it **carries oxygen** in the blood as Each molecule can carry **four oxygen molecules** as each polypeptide chain has a haem group each.

The measure of how easily and tightly oxygen binds to haemoglobin at any given time is called the **affinity for oxygen.** The affinity for oxygen of haemoglobin varies depending on the **partial pressure of oxygen.** The partial pressure of oxygen is just a measure of **oxygen concentration**.

Important Rules

- The greater the concentration of dissolved oxygen in cells the greater the partial pressure
- As partial pressure of oxygen increases, the affinity of haemoglobin for oxygen increases

Binding of oxygen to haemoglobin happens in the lungs (loading), where there is a **high partial pressure of oxygen.** Therefore, the **affinity** of haemoglobin for oxygen in the lungs is high. So, when loading occurs, **binding to haemoglobin happens tightly.**

Once one molecule of oxygen binds to haemoglobin, it increases the affinity for oxygen by making it easier for subsequent molecules to bind.

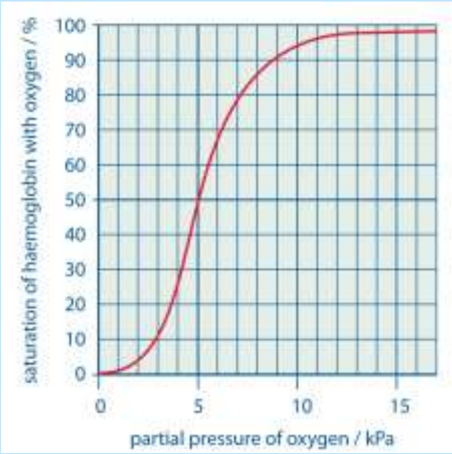
At the tissues, during aerobic respiration, oxygen is used up**.** The partial pressure of oxygen in the tissues is low. Therefore at the tissues, the affinity for oxygen is **low.** This means haemoglobin binds **much less** tightly to oxygen and it **much more easily released than before.** As a result of that, **oxygen is released** in respiring tissues where it is most needed. This is called **unloading** or **dissociation of oxygen.**

After the unloading process, the haemoglobin returns to the lungs where it binds to oxygen again.

Dissociation Curves

Dissociation curves illustrate the change in haemoglobin saturation as partial pressure changes. The saturation of haemoglobin is affected by its affinity for oxygen, therefore in the case where partial pressure is high, haemoglobin has high affinity for oxygen and is therefore highly saturated, and vice versa.

Saturation also affects affinity for oxygen. After one oxygen molecule binds, the affinity of haemoglobin for oxygen increases. This is due to a change in shape (quaternary structure) that makes it easier for the oxygen to bind.



Explanation of the Shape of the Curve

1. Initially the curve is shallow because it is hard for the first oxygen molecule to bind
2. Once it has bound though it changes the shape making it easier for oxygen molecules two and three to bind, hence the steep increase. This is called **positive co-operativity**.
3. The gradient begins to flatten out because the likelihood of the fourth oxygen finding a binding site is low.

Foetal Haemoglobin

Foetal haemoglobin (HbF) has a higher affinity for oxygen compared to adult haemoglobin (HbA). This is because it needs to be better at binding oxygen. The reason because by the time oxygen reaches the placenta, the oxygen saturation of the blood has decreased. Not only this, but the foetal haemoglobin must 'steal' oxygen that has already been bound to the adult haemoglobin of the mother's blood. Therefore, foetal haemoglobin must have a higher affinity for oxygen in order for the foetus to survive at low partial pressure.

Carbon Dioxide

The affinity of haemoglobin for oxygen is also affected by the partial pressure of **carbon dioxide.** Carbon dioxide is released by respiring cells which require oxygen for the process to occur. Therefore, in the presence of carbon dioxide, the affinity of haemoglobin for oxygen decreases. This causes oxygen to be unloaded at the tissues. This is known as the **Bohr effect.** It does this because carbon dioxide creates slightly **acidic** conditions which change the shape of the haemoglobin protein, thus making it easier for the oxygen to be released.

Circulatory System of a Mammal

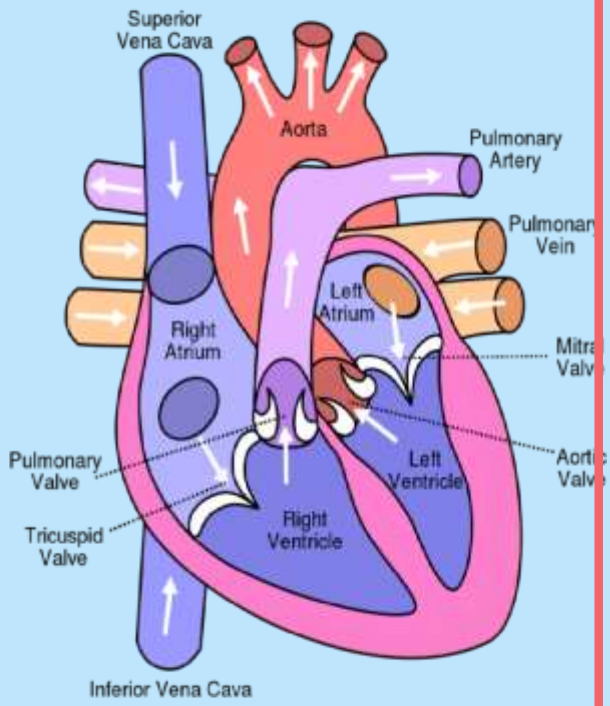
In large organisms the surface area to volume ratio is very small. Because of this, diffusion alone cannot supply substances like oxygen, glucose and other molecules to cells where they are needed. For this reason, a circulatory system is used.

There are many common features of a circulatory system:

1. **Suitable medium** - in mammals the transport medium is the blood. A major component of blood is water. This is useful as substances can easily dissolve into it.
2. **Means of moving the medium** - the heart is a pump seen in most animals. This helps to maintain pressure differences around the body.
3. **Mechanism to control flow around the body** - valves are used in veins to prevent any backflow and smooth muscle is found in the walls of arteries and arterioles to control the flow of blood and blood pressure
4. **Closed system of vessels** - the circulatory system in most animals and plants is closed and is branched to deliver substances to all parts of the body

In mammals the circulatory system is a **closed double circulatory system**. The heart at the centre has two pumps split into two sides. The right side **pumps bloods to the lungs** to be oxygenated whilst the left side is larger and stronger and **pumps the oxygenated blood around the body** to supply vital organs and tissues

Structure of the Human Heart



The heart is made up of two pumps each with two chambers. This makes four chambers in the heart total. These are:

- Atria (singular atrium) are thin walled and the walls have elastic fibres, allowing them to stretch when they fill with blood. Blood flows into the atria first, at the same time.
- Ventricles are much bigger chambers which have thick muscular walls. This is to pump blood around the body or to the lungs. The wall of the left ventricle is much more muscular and thick than the right, as this has to pump the blood much further – around the body rather than just to the lungs.

Heart Vessels

- The Aorta is the main artery carrying oxygenated blood out of the heart to be delivered to the rest of the body. It flows out of the left ventricle and is separated from the left ventricle by the semilunar valve, which stops the blood flowing backwards into the ventricle.
- The Pulmonary Artery is the blood vessel leaving the right side of the heart, carrying deoxygenated blood to the lungs from the heart, to pick up oxygen and drop off carbon dioxide. The blood leaves the right ventricle and passes through the right semilunar valve to enter the pulmonary artery.
- The Pulmonary Vein is the blood vessel that carries newly oxygenated blood from the lungs back to the heart in order to be pumped back round the body. It enters the left atrium.
- The Vena Cava is the main blood vessel (vein) carrying the deoxygenated blood back from going round the body. This is where all of the blood enters the heart at the right atrium.

Valves

Between the atria and ventricles there are a set of valves. The left **atrioventricular** valve (bicuspid valve) and the right atrioventricular valve (tricuspid valve). Between the right ventricle and the pulmonary artery, there is a right **semilunar valve**. Between the left ventricle and the aorta there is another valve with the same name (left semilunar valve).

Order of Bloodflow

Vena cava → Right atrium → (right atrioventricular valve) → right ventricle → (right semilunar valve) → pulmonary artery → lungs → pulmonary vein → left atrium → (left atrioventricular valve) → left ventricle → (left semilunar valve) → aorta

Cardiac Cycle

The heart is referred to as being **myogenic** as it can initiate its own electrical impulse to start its own contraction. This electrical impulse is initiated in the **sinoatrial node (SA Node).** This node is found in the upper right hand wall of the right atrium. The SA node is often known as the pacemaker of the heart. The SA node starts an electrical impulse which spreads gradually through the heart muscle. It reaches the atria first at roughly the same time and is slightly delayed by the **atrioventricular node** in the **septum** between both atria. This allows them to contract together at roughly the same time and push the blood through the atrioventricular valves (AV Valves) to the ventricles.

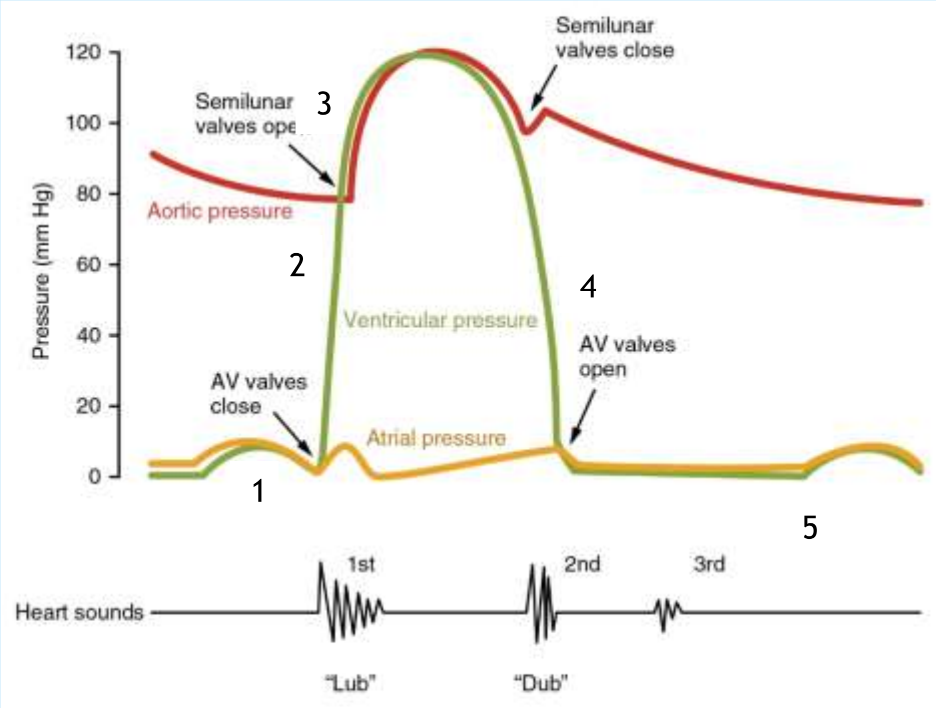
The **ventricles** do not start contracting until the **atria** have finished due to the presence of the atrioventricular node, which momentarily delays the electrical impulse before passing it on to the ventricles through the **Bundle of His**. The Bundle of His is a bunch of conducting fibres which pass the impulse down to the very bottom corner of the heart, called the **apex**. At the apex, the Bundle of His branches into two bundles of **Purkyne or Purkinje fibres** which carry the impulse sideways and upwards. This causes the ventricles to **contract** first at the **bottom (the apex)** and then upwards, thus emptying the most blood possible upwards out of the aorta and pulmonary artery.

Stages

Cardiac diastole – atria and ventricles relax with the atrioventricular valves closed and the elastic fibres in the walls of the heart chambers allow elastic recoil. This lowers the pressure inside the heart chambers. Blood to return to the right side of the heart from the **vena cava** and the left side from the pulmonary vein and fill the atria. Due to the filling with blood, pressure increases in the atria until the **atrioventricular valves open,** allowing blood to flow into the ventricles. The atrioventricular valves will open when the pressure in the atria is higher than in the ventricles. The semilunar valves are closed throughout diastole.

Atrial systole – At this point, the atria contract due to the electrical impulse from the sinoatrial node. This forces any remaining blood in the atria into the ventricles.

Ventricular systole – all the blood has now entered the ventricles. The contraction of the ventricles raises the pressure above that of the atria, causing the **atrioventricular valves to close** and the **semilunar valves to open**. This allows the **blood to leave the left** ventricle through the **aorta** and right ventricle through the **pulmonary artery.**



This is a common graph that is used in Biology exams. It is important you use the description above to understand every single wave as they happen.

1. The atria begin to fill, and then the ventricles causing a bulge in pressure in both the atria and ventricles. When the pressure in the ventricles becomes higher than the pressure in the atria, the **atrioventricular valves (AV valves)** close. This is the **first heart sound ("lub")**
2. Ventricular contraction causes the pressure in the ventricles to sky rocket. There is a slight increase in atrial pressure here (small bump) as the ventricles bulge back into the atria and raise their pressure slightly
3. Once the pressure in the ventricles rises above the pressure in the pulmonary artery and aorta, the **semilunar valves open**
4. As the blood enters the pulmonary artery and aorta, the pressure in the ventricles begins to drop again as they empty. When the pressure drops beneath the pressure in the aorta and pulmonary artery, the **semilunar valve closes** again. This is the **second heart sound ("dub")** The pressure in the ventricles drops like a stone as there is no blood left in them and they relax (**diastole**).
5. Eventually the pressure in the ventricles drops below the pressure in the atria again. This allows the AV valves to open again and the atria begin to refill with blood, then the ventricles. The cycle begins again.

Structure and Function of Blood Vessels

- Arteries are adapted to carrying blood away from the heart to the rest of the body. They have:
  - **Thick walls** to withstand **high blood pressure**

- Walls have lots of **elastic tissue** so they can stretch and recoil, smoothing blood pressure and blood flow
- Lots of **smooth muscle** which enables them to control blood flow
- They are lined with **smooth endothelium** to reduce friction and ease the flow of blood

- Arterioles are smaller versions of arteries, which branch off them. They still contain smooth muscle, albeit a much thinner layer of it. They also contain elastic tissue just like their bigger counterparts for the same reason. Their main role is to bring blood into capillaries.

- Capillaries are the smallest blood vessels and are found at the tissue. This is where the red blood cells dissociate from oxygen and unload it for diffusion and use at the tissues. It is also where carbon dioxide, the produce of respiration at the tissues, diffuses into the blood and dissolves into the water in the blood to be taken back to the lungs. The capillary is only one cell thick for fast **exchange** of substances and short diffusion distances.

- Venules are smaller versions of the veins that carry the blood from the capillary to the veins. They are larger than capillaries but smaller than veins. They have a wider lumen compared to the arterioles but do not have smooth muscle or elastic tissue in their walls.

- Veins carry blood from the body to the heart, they have:
  - **A wide lumen** to maximise the volume of blood carried to the heart
  - **Thin walls** as blood is under **low pressure**
  - **Valves** to prevent the blood flowing backwards as it doesn't have the forward force of the heart behind it.
  - Very little elastic tissue or smooth muscle as there is no need for stretching and recoiling

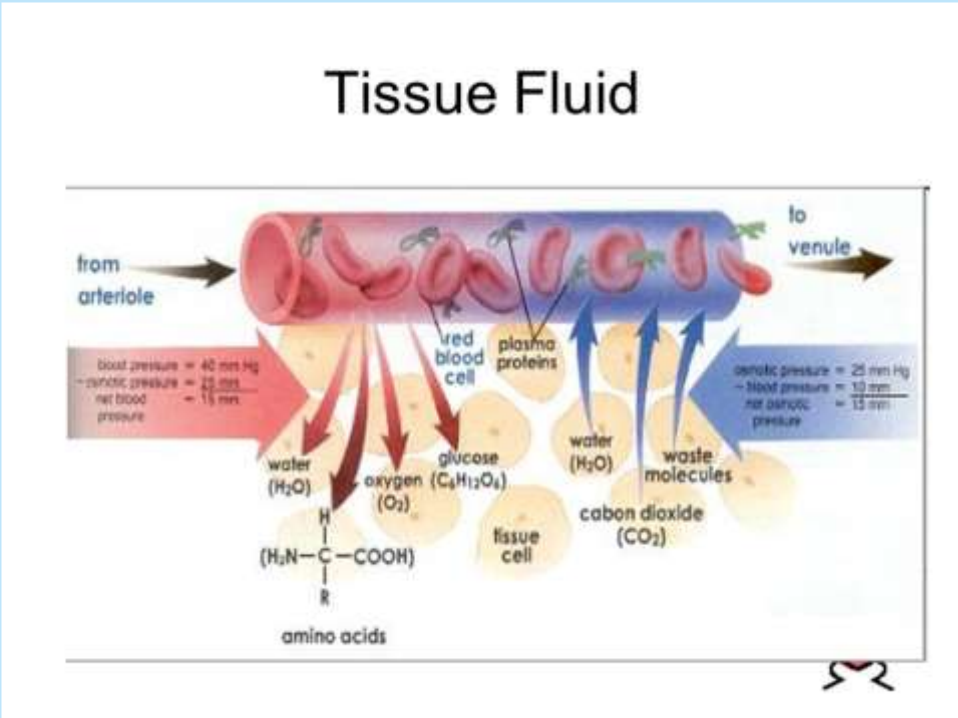
Tissue Fluid

Tissue fluid is a liquid containing dissolved **oxygen, carbon dioxide, ions** and **nutrients.** It supplies the tissues with the essential **solutes** in exchange for **waste products** such as **carbon dioxide.**

Tissue fluid is formed using hydrostatic pressure. This is an outward force exerted on the capillary walls when the blood reaches the capillaries (imagine lots of water in a hose pipe pressing outwards on the wall of hose). The force is greater at the **arteriole** end of the capillary, as there are a lot of nutrients, water and oxygen within the blood when it first arrives at the tissue. The **hydrostatic pressure** will force the some fluid out of the blood, along with substances which are small enough to escape through the gaps in the capillary walls. The fluid that escapes, plus the substances which can escape make **tissue fluid**. The tissue fluid then bathes the surrounding cells in its solutes, which include **amino acids, fatty acids, ions, glucose and oxygen.**

At the other end of the capillary, the **venule end** of the capillary, once the fluid has all been squeezed out of the capillary, the hydrostatic pressure drops down again. This allows some fluid from the tissue to re-enter the capillary to be taken back to the heart due to actually having a higher hydrostatic pressure in the tissues than in the capillary at this end. Although the **water potential** of the tissue fluid is negative, it is less negative in comparison to the blood (the blood contains more **solutes**). This causes water to move down the **water potential gradient** from the tissue fluid to the blood via **osmosis.**

The remaining tissue fluid that is not pushed back into the capillaries is carried back to the heart via the **lymphatic system.** The lymphatic system contains **lymph fluid,** similar in content to **tissue fluid**. However, lymph fluid contains less **oxygen and nutrients** compared to tissue fluid, as its main purpose is to carry **waste products** and provide transport for lymphocytes. The lymph system also contains **lymph nodes** which filter out **bacteria and foreign material** from the fluid with the help of **lymphocytes** which destroy pathogens as part of the immune system defences.



Mass transport in plants

Plants also require a **transport system** to ensure that all the cells of a plant receive a sufficient amount of **nutrients**. This is because their surface area to volume ratio is often much too small also. This is achieved through the combined action of **xylem tissue** which enables water and minerals to travel up the plant through the passive process of **transpiration**, and **phloem tissue** which enables sugars to reach all parts of the plant in the active process of **translocation.** These two systems are located in the vascular bundle, which runs from the roots to the leaves.

Vessels in Plants

The vascular bundle in the roots:

- Xylem and phloem are components of the **vascular bundle,** which enable the transport of substances and provide structural support to the plant
- The xylem vessels are arranged in an **X shape** in the **centre** of the vascular bundle. This enables the plant to withstand various **mechanical forces** such as pulling.
- The X shape arrangement of xylem vessels is surrounded by **endodermis**, which is an outer layer of cells which supply xylem vessels with water.
- An inner layer of meristem cells known as the **pericycle**

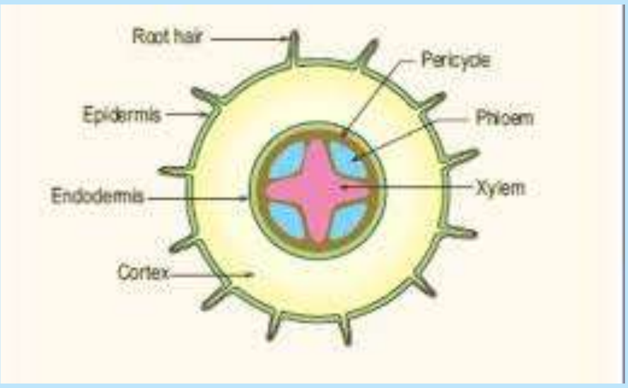


Figure 1: Vascular bundle in the root

The vascular bundle in the stem:

- The xylem is located on the inside in **non-wooded plants** to provide support and flexibility to the stem.
- Phloem is found on the outside of the vascular bundle.
- There is a layer of **cambium** in between the xylem and phloem, which are meristem cells involved in the production of new xylem and phloem tissue

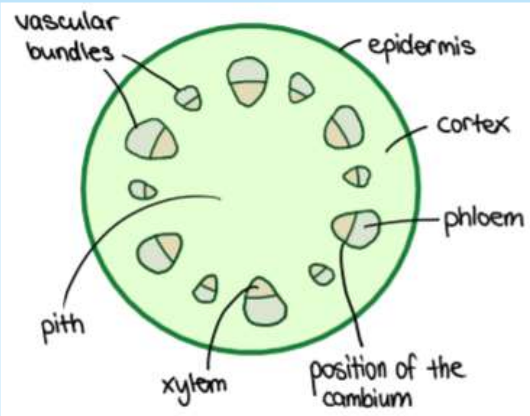
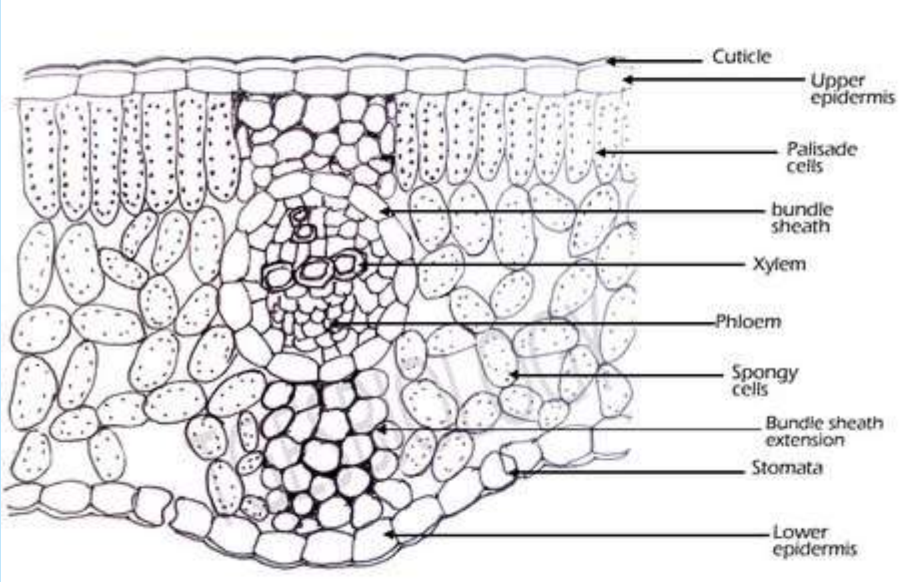


Figure 2:Vascular Bundle in the stem

The vascular bundle in the leaf:

- The vascular bundles forms the **midrib and veins** of a leaf.
- **Dicotyledonous leaves** have a network of **veins**, starting at the midrib and spreading outwards which are involved in transport and support



Transpiration

Water and minerals move through **xylem** vessels in plants. The xylem has the following features:

- They transport water and minerals, and also serve to provide structural support.
- They are long cylinders made of **dead cells** that have **open ends**. Because these dead cells are stacked end to end, they form a continuous column.
- Xylem vessels contain **pits** in the sides of the column which enable water to move sideways between the vessels.
- They are thickened with a tough substance called lignin, which is deposited in **spiral patterns** to enable the plant to remain flexible.

Transpiration is the process where plants absorb water through the roots, which then moves up through the plant and is released into the atmosphere as water vapour through pores in the leaves.

Factors which affect the rate of transpiration (rate of loss of water vapour at the leaves) include:

- Number of leaves
- Number/size or position of stomata
- Presence of waxy cuticle – this is waterproof so reduces water loss from the leaf
- Light – the stomata close in the dark, therefore reducing transpiration
- Temperature – increased **kinetic energy** of the water molecules due to more heat energy means they are more likely to escape out of the stomata as they move around more
- Humidity of the air – when the air is **humid**, it is already very full of water vapour. Water will naturally move into a more drier environment. If the air outside of the leaf is already saturated with water, water is less likely to move out of the leaf
- Air movement – wind naturally blows water vapour near the leaf away, meaning a drier environment on the outside of the leaf. As described above, this means more water loss

as water naturally moves from a more saturated area to a dry area. We call this a water vapour potential gradient.
- Water availability – if the plant has lots of water from the roots, the guard cells will be turgid and cause the stomata to be open. If the plant does not have as much water, the cells become **flaccid** and therefore the stomata close. This reduces water loss

The **transpiration stream,** which is the movement of water up the stem, enables processes such as photosynthesis, growth and elongation as it supplies all of the tissues of the plant with water which is necessary for all of these processes. Apart from this, the transpiration stream supplies the plant with the required minerals, whilst enabling it to control its temperature via evaporation of water.

Measuring Transpiration

The rate of transpiration can be investigated with the help of a **potometer** where water lost by the leaf is replaced by water in a capillary tube. Therefore, measuring the movement of the meniscus or a bubble can be used to determine the rate of transpiration.

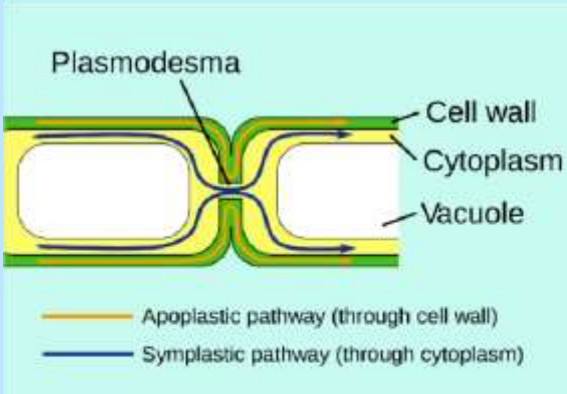
Xerophytes are plants adapted to living in **dry conditions**. They are able to survive in such conditions because of various adaptations which serve to **minimise the water loss**. Their adaptations include smaller leaves to reduce the surface area for water loss. Both densely packed mesophyll and thick waxy cuticle prevent water loss via evaporation. Moreover, xerophytes respond to low water availability by closing the stomata to prevent water loss. Apart from this, they also contain hairs and pits which serve as a means of trapping moist air, thus reducing the water vapour potential gradient. Xerophytes also roll their leaves in order to reduce the exposure of the lower epidermis to the atmosphere, thus trapping air that is moist.

Movement of water in the root

1. Minerals and ions from the soil are **actively transported** against their concentration gradient into the root hair cell. Root hair cells have a long, hair like extension on them to increase their surface area and therefore increase the efficiency of active transport.
2. This lowers the water potential inside the root hair cells
3. This causes water to enter the root hair cells via **osmosis** down a **water potential gradient**
4. The active transport of ions into the next cell and the next cell lowers the water potential of each cell in turn and the water subsequently moves through the root via osmosis towards the xylem in the centre. It can pass from cell to cell **without going through the membrane** through the **plasmodesmata**, which are gaps in the cell surface membrane of each cell. This pathway is called the **symplast pathway.**

- There is one other way in which the water taken up by root hair cells can travel through the root to the xylem. This is the **apoplast pathway:**
    - Water can also travel using the cell walls of the cells
    - There are spaces between the cellulose molecules in the cell walls. Water can occupy this space

- The water can move between these spaces without ever entering the cell, instead moving from cell wall to cell wall of each cell until it reaches the xylem
- This water can also carry dissolved ions and salts to the xylem



- When the water reaches a part of the root called the **endodermis**, it encounters a waterproof layer of **suberin** which is known as the **Casparian strip**, which cannot be penetrated by water.

- Therefore, in order for the water to cross the **endodermis**, the water that has been moving through the cell walls in the apoplast pathway must now enter the cells and only travel via the **symplast pathway**.

- Once it has moved across the endodermis, the water continues down the water potential gradient from cell to cell until it reaches a pit in the **xylem** vessel which is the entry point of water.

Water movement in the xylem up the stem

The water enters the xylem at the bottom end of the plant near the root. Now it needs to move upwards towards the leaves so it can be used for photosynthesis.

There are 3 forces that help move this water upwards:

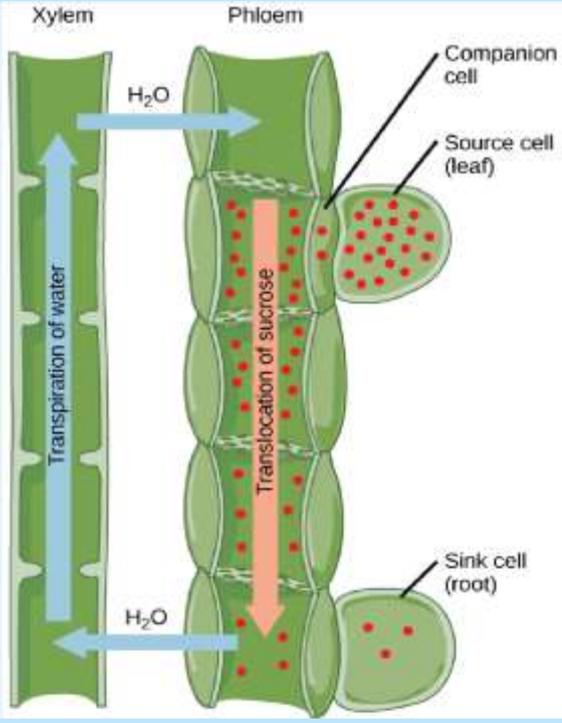
1. The push of water upwards is aided by the **root pressure** which is where the action of the endodermis moving minerals into the xylem by **active transport** drives water into the xylem by **osmosis**, thus pushing it upwards.
2. The flow of water is also maintained with the help of **surface tension** of water. Surface tension is the reason there is a meniscus when you have water in a test tube – it is the nature of the hydrogen bonds between the water that makes them stick to the side of the test tube
3. The attractive forces between water molecules known as **cohesion.** This is where the hydrogen bonding between water molecules causes them to stick together.
    a. The action of these last two forces in combination is known as the **cohesion-tension theory**. The proof of this theory is highlighted by **capillary action,** where water will slowly move up a very thin capillary tube against gravity. The same force allows the water to adhere to the walls of xylem, thus pulling water up.

The **cohesion-tension** theory allows water to be pulled up in place of water that is lost at the top of the xylem when it enters leaves. As one water molecule moves out of the xylem, a new water molecule is pulled upwards to take its place. Because of the forces allowing water molecules to stick together, there is a continuous column of water beneath this water molecule which causes the entire column of water to move upwards.

Translocation

Translocation primarily concerns the **phloem** vessels which have the following features:

- The phloem is a set of tubes made from **living cells**
- The phloem is involved in **translocation** of nutrients to storage organs and growing parts of the plant, such as leaves
- The phloem tubes consist of **sieve tube elements,** which are live cells that transport substances and **companion cells,** which help to control this transport
- Sieve tube elements form a tube to transport sugars such as sucrose, in the dissolved form of sap
- Between each sieve tube element, is a **sieve plate**, a small sieve with holes in it to allow fluid to pass through
- Companion cells are involved in **ATP production** for processes such as loading sucrose into sieve tubes, which requires active transport
- The cytoplasm of the sieve tube elements and companion cells is linked through structures known as **plasmodesmata** which are gaps between cell walls which allow communication and flow of substances such as minerals between the cells.



Translocation is an active process and therefore requires energy in the form of ATP. It helps to transports substances that the plant requires to survive, known as **assimilates.** There are many of these, but the main one which we consider at A level is **sucrose.** Sucrose is transported in the phloem between **sources** which release sucrose such as leaves and **sinks** e.g. roots and meristem which remove sucrose from the phloem.

The process of translocation occurs as follows:

1. Sucrose is made in the leaf and enters the phloem in a process known as **active loading.** Companion cells use ATP to transport **hydrogen ions** out of the companion cells into the surrounding tissue, thus creating a **diffusion gradient**
2. H+ ions to diffuse back into the companion cells through **facilitated diffusion.** The carrier protein used for this is actually a **co-transporter** which brings sucrose molecules in along with each H+
3. **Facilitated diffusion** involving co-transporter proteins allows the returning H+ ions to bring sucrose molecules **into the companion cells**, thus causing the concentration of sucrose in the companion cells to increase
4. This causes the concentration of sucrose within the companion cell to increase and creates a concentration gradient between the companion cell and the surrounding cells
5. As a result the sucrose diffuses out of the companion cells down its **concentration gradient** into the surrounding cells, eventually reaching the sieve tube elements of the phloem through links known as **plasmodesmata**
6. As sucrose enters the sieve tube elements, the **water potential** inside the tube is reduced, therefore causing water to enter via **osmosis** from the xylem, increasing the **hydrostatic pressure** of the sieve tube element. This produces **sap.**
7. The water in the sap moves down the sieve tube from an area of **high hydrostatic pressure** to an area of **low hydrostatic pressure** down a **hydrostatic pressure gradient**
8. Once it has arrived at its destination lower down the plant, the sucrose is removed from the sieve tube elements (phloem) by diffusion or active transport into the surrounding cells, thus increasing the water potential in the sieve tube.
9. This in turn means that water leaves the sieve tube by **osmosis** back into the xylem, and as a result **reduces the pressure in the phloem at the sink.**

Evidence for Mass Transport in Plants

A level papers often require you to remember the arguments for and against the mass transport hypotheses in plants. A summary can be found below:

For

- There is pressure in the sieve tube elements, as shown by sap being released when the stem of a **plant is cut**
- If an aphid which is feeding on the sap through inserting its **mouthpiece** through the bark of a tree has its body pulled off, leaving the mouthpiece in place, sap leaks out of it. This proves the sap is under **positive pressure**
- The concentration of sucrose is higher in the leaves (source) of plants than in roots (sink).
- Increases in sucrose levels in the leaves are followed by a similar increase in sucrose concentration in the phloem

- If you use radiolabelled sucrose by giving the plant **radiolabelled carbon dioxide**, radioactivity will be detected at the bottom of the plant after some time. This proves that the sucrose is transported from the top of the plant (leaves), to the bottom
- Metabolic poisons/a lack of oxygen inhibit translocation of sucrose in the phloem.
- If you remove the bark on a tree, where the phloem is, the sap causes the bottom of the tree to bulge as it can no longer be transported elsewhere

Against

- The function of the **sieve plates** is unclear as they would appear to **hinder mass flow** (some suggest though they have a structural function to help prevent bursting under pressure).
- Not all solutes move at the same speed, they should do if it is mass flow
- Sucrose is delivered at more or less the same rate to all regions, rather than going more quickly to the ones with the lowest sucrose concentration, which the mass flow theory would suggest.

Ringing Experiments

In order to investigate if the phloem is responsible for mass flow a **ringing experiment** can be used. In this the bark and phloem of a tree are removed leaving just the **xylem** in the centre. Overtime the tissues above the missing ring **swell with sucrose solution** and the **tissue below dies**. This shows that sucrose is transported in the phloem

Tracer Experiments

Tracer experiments can also be used to investigate the transport of sucrose in plants. Plants are grown in a environment that contains **radioactivity labelled carbon dioxide ($^{14}CO_2$)**. The presence of this means that they are incorporated into the sugar produced in photosynthesis.

The movement of these sugars can now be traced through the plant using **autoradiography**. Those areas that have been exposed to the radiation produced by the 14C in the sugars will appear **black**. It follows that these regions correspond to the area where the phloem is and therefore suggest that this is where the sugars are transported.