OCR (B) Biology A-level

2.2 Transport and gas exchange systems

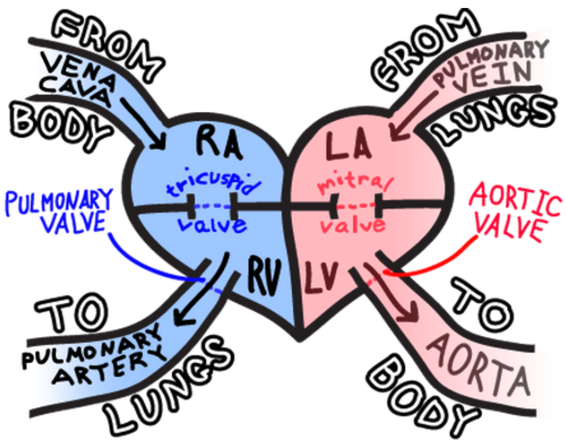
Notes

2.2.1 The heart and monitoring heart function

Structure of the heart

The **heart** is an important organ which is the control for the circulatory system. It pumps blood around the body. It is organised as a 'double circulatory system' – i.e. the heart must pump blood to the lungs and to the rest of the body, simultaneously.

- The heart is a **muscle**. The cells which compose the heart contract and relax throughout the life of an individual. Each cell is described as **'myogenic'** – this means it has its own rhythm.
- The heart is composed of four chambers – right and left atria which lie above the right and left ventricles.
- The atria are thin walled structures, whereas the ventricles are thick walled as they must withstand higher pressures.
- The atria and ventricles are separated by structures called **valves**. The right atria and ventricle are separated by the **tricuspid valve;** the left atria and ventricle are separated by **mitral valves.** Together, these are known as the **atrioventricular valves.** These valves ensure that blood flows in one direction and prevent backflow.
- The ventricles are separated from the aorta and pulmonary artery by **semilunar valves** – **aortic and pulmonic valves.**
- The vessels attached to the heart include the vena cava, pulmonary artery, pulmonary vein and the aorta.



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Function of the heart

Deoxygenated blood from the body, flows into the right atrium then to the right ventricle through the tricuspid valve. This exits the heart via the pulmonary artery (carrying deoxygenated blood) to the lungs. Here it becomes **oxygenated before** returning to the left atrium via the pulmonary vein. This flows through the **left atrium** into the **left ventricle**, and then gets **pumped** to the **body** via the **aorta**. It finally **returns** to the **heart** through the **vena cava**. This is an ongoing process.

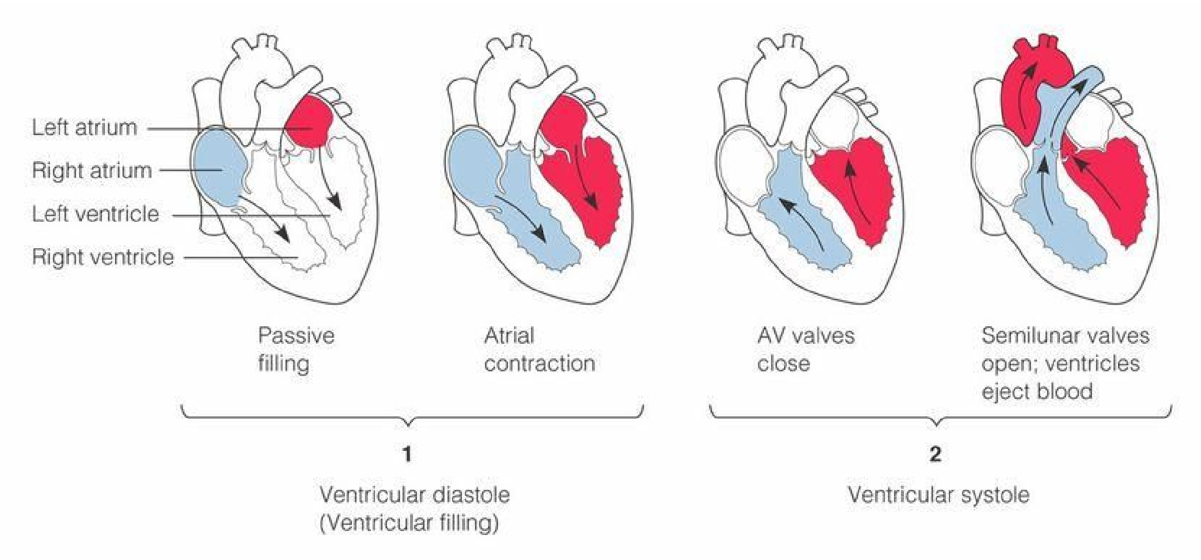
The left side of the heart provides blood to the body (systemic circulation), whereas the right side of the heart is responsible for pumping blood to the lungs (pulmonary circulation).

The cardiac cycle

To enable blood to flow around the body, the heart acts as a pump. It achieves this by cycling through phases of contraction (systole) and relaxation (diastole).

The sequence is as follows:

1) **Diastole (0.4 secs)**
   a. Heart is in the phase of relaxation; this allows blood to fill. Blood flows from the vena cava and pulmonary vein into the atria and then into the ventricles.
   b. The valves that separate these structures are open, allowing blood to flow. The pressures in the atria are greater than the ventricles. However, the pressures in the ventricles is lower than the vessels ensuring the semilunar valves are closed.
2) **Atrial systole (0.1 secs)**
   a. The atria contract which allows more blood to enter the ventricles.
3) **Ventricular systole (0.3 secs)**
   a. When a certain amount of blood is stored in the ventricles, they contract – this increases the ventricular pressures. As the pressure increases, the valves close – forming the 'lub' sound.
   b. As the ventricular pressure increases, the semilunar valves open allowing blood to flow out of the heart to the lungs and the body. As the blood flows out, the pressure decreases and hence causes closure of the semilunar valves – forming the 'dub' sound.
4) The atrioventricular valves now open and the cycle restarts
5) The total cycle lasts around 0.8 seconds



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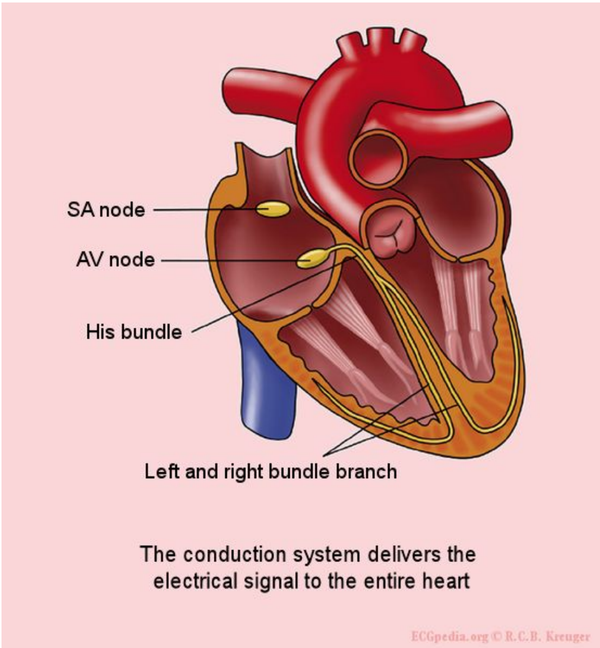
Co-ordination of the heart

The heart has its own rhythm. The heartbeat begins at a structure called the sinoatrial node (SAN). This is located in the upper part of the atrium. This generates electrical pulses which are spread throughout the heart.

- The electrical activity is responsible for ensuring atrial contraction.
- The path to the ventricles is via the atrioventricular nodes (AVN). Here, the electrical stimulation is delayed enabling the ventricles to fill with sufficient blood and enable the atria to fully contract.
- The impulse then travels through fibres within the wall separating the ventricles, towards the apex before travelling up the wall of the ventricle. This is responsible for ventricular contraction or systole.
- The fibres are known as Purkinje fibres. All of the fibres together are known as the Bundle of His.



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Calculating cardiac output

Cardiac output – amount of blood ejected from the heart in one minute
Heart rate – number of contractions (number of heart beats) per minute
Stroke volume – the amount of blood ejected from the heart with each contraction

Cardiac output (CO) = Heart rate (HR) x Stroke volume (SV)

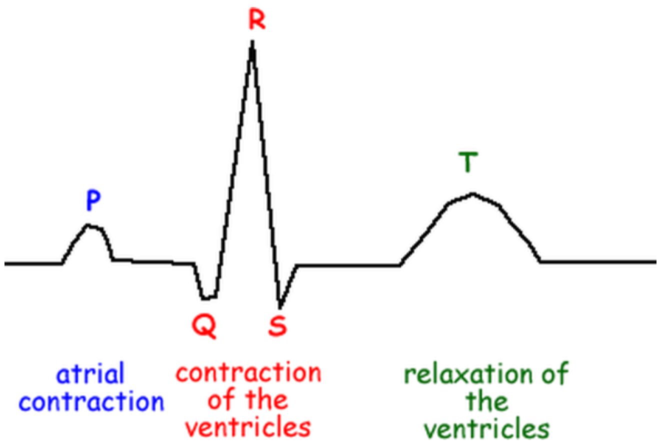
Electrocardiogram (ECG)

Device which is used to visualise the electrical activity within the heart. Electrodes are attached to sticky labels on the skin at various locations around the heart. The electrodes sense and record the electrical signals which spread through the heart.

The final recording is a series of waveforms which can then be interpreted.

Some features we can appreciate from an ECG include:

- Heart rate – i.e. slow (bradycardia <60 beats per minute), fast (tachycardia >100 beats per minute)
- Rhythm – i.e. regular heartbeat, irregular heartbeat
- Length of the phases of the cardiac cycles
- Onset of a heart attack



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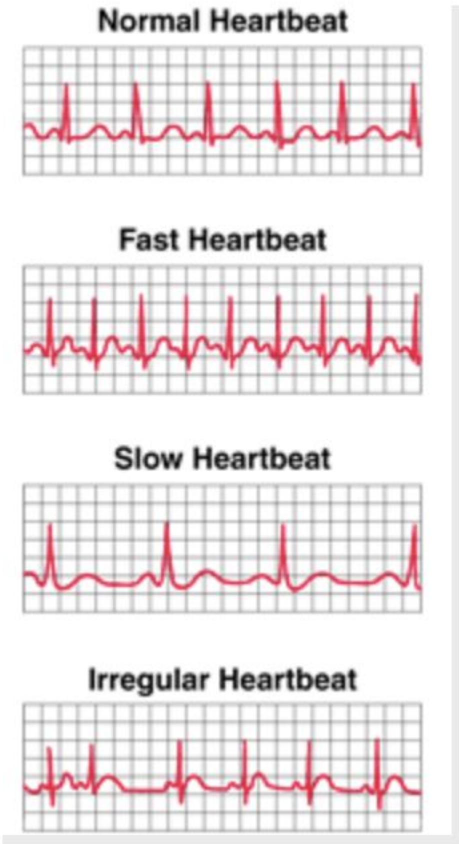
Classical ECG examples:



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2.2.2 Transport systems in mammals

Circulatory systems can either be **open**, for instance in insects, or **closed**, like in fish and mammals where the blood is confined to blood vessels only. Closed circulatory systems come in two forms, either a **single** form which consists of a heart with **two chambers** meaning the blood passes through the heart **once for every circuit** of the body, or **double**, where the heart has **four chambers** and blood passes through the heart **twice for every circuit** of the body.

Important structures and their functions

- **Arteries** – adapted to carrying blood away from the heart to the rest of the body, thick walled to withstand high blood pressure, contain elastic tissue which allows them to stretch and recoil thus smoothing blood flow, contain smooth muscle which enables them to vary blood flow, lined with smooth endothelium to reduce friction and ease flow of blood

- **Arterioles** – branch off arteries, have thinner and less muscular walls, their role is to feed blood into capillaries

- **Capillaries** – smallest blood vessels, site of metabolic exchange, only one cell thick for fast exchange of substances. They are adapted for efficient diffusion by having a narrow lumen, a large surface area, and a slow blood flow to allow more time for exchange.

- **Venules** – larger than capillaries but smaller than veins

- **Veins** – carry blood from the body to the heart, contain a wide lumen to maximum volume of blood carried to the heart, thin walled as blood is under low pressure, contain **valves** to prevent backflow of blood, no pulse of blood meaning there's 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 and nutrients** which serves as a means of supplying the tissues with the essential solutes in exchange for waste products such as carbon dioxide. Therefore, it enables **exchange of substances** between blood and cells.

Hydrostatic pressure is created when blood is pumped along the arteries, into arterioles and then capillaries. This pressure forces blood fluid out of the capillaries to form tissue fluid. Only substances which are small enough to escape through the gap in capillary are components of the tissue fluid – this includes **dissolved nutrients and oxygen**.

The fluid is also acted on by **hydrostatic pressure** which pushes some of the fluid back into the capillaries. As both the tissue fluid and blood contain solutes, they have a **negative water potential**. However, the potential of tissue fluid is less negative therefore meaning that water moves down the water potential gradient from the tissue fluid to the blood by **osmosis.**

The remaining tissue fluid which is not pushed back into the capillaries is carried back 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.** The lymph system also contains **lymph nodes** which filter out **bacteria and foreign material** from the fluid with the help of **lymphocytes** which destroy the invaders as part of the **immune system defences.**

Blood pressure

It is important to have sufficient blood pressure to enable blood to travel and supply oxygen and nutrients to all parts of the body.

Some factors which may affect blood pressure include:
- Age
- Diet
- Smoking
- Dehydration
- Exercise
- Stress
- Medication
- Disease e.g. of the heart; kidneys

Measuring blood pressure (BP)

- **Manual:**
  - Equipment: stethoscope, sphygmomanometer (BP machine)

- Tie a blood pressure cuff around the upper arm (ensure it is not too tight or too loose, select the correct cuff type)
- Listen over the brachial artery with stethoscope
- Inflate cuff to around 160-200mmHg
- Slowly deflate:
    - First occurrence of rhythmic sounds [systolic reading]– blood flows through the artery
    - Continue to listen – record the pressure at which the sounds stop [diastolic reading]

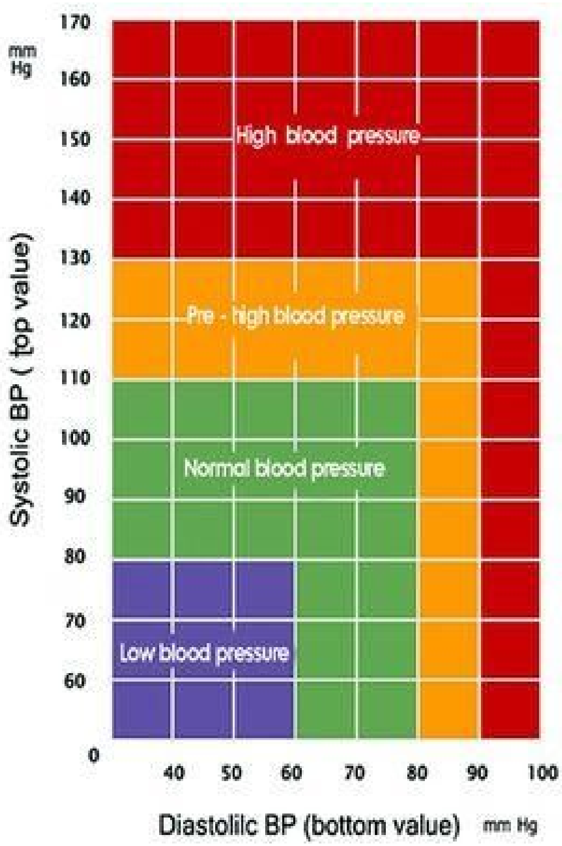
You should repeat this 3 times, and take an average of the 3 readings.

- **Automatic:**
    - Press 'start'/'on'
    - Machine calculates blood pressure automatically

- **Result**

When measuring blood pressure – two values are calculated:

- **systolic pressure** - the higher measurement when the heart beats, pushing blood through the arteries, and
- **diastolic pressure** - the lower measurement when the heart rests between beats



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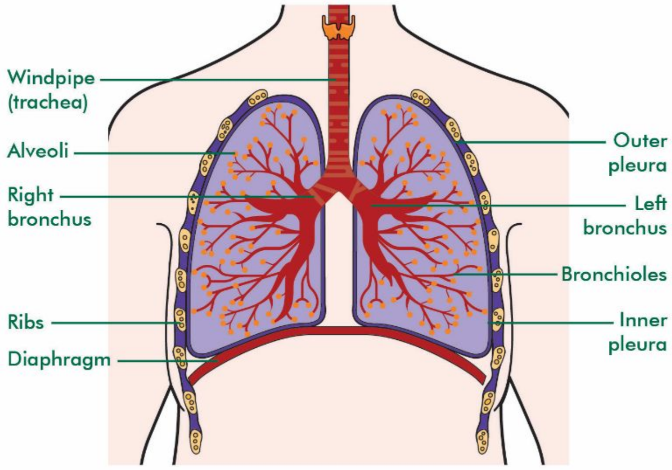
2.2.3 Gas exchange in mammals and plants



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The need for specialised exchange surfaces arises as the size of the organism, and its **surface area to volume ratio** increases. In the case of **single celled organisms**, the substances can easily enter the cell as the distance that needs to be crossed over is short. However, in **multicellular organisms** that distance is much larger due to a higher surface area to volume ratio. As a result of that, multicellular organisms require specialised exchange surfaces for efficient gas exchange of **carbon dioxide and oxygen**.

Features of an efficient exchange surface include **large surface area**, for instance the **root hair cells** or **folded membranes**, such as those of the mitochondria. An efficient exchange surface should also be **thin** to ensure that the distance that needs to be crossed by the substance is short. The exchange surface also requires a **good blood supply/ventilation** to maintain a steep gradient, for example that of the alveoli.

Mammalian gaseous exchange system

The **lungs** are a pair of structures with a **large surface area** located in the **chest cavity** with the ability to **inflate**. The lungs are surrounded by the **rib cage** which serves to protect them. A lubricating substance is secreted to prevent the friction between rib cage and lungs during inflation and deflation. **External and internal intercostal muscles** between the ribs which contract to raise and lower the ribcage respectively. A structure called the **diaphragm** separates the lungs from the abdomen area.

The air enters through the nose, along the **trachea, bronchi and bronchioles** which are structures well adapted to their role in enabling passage of air into the lungs. The gaseous exchange takes plans in the walls of the alveoli, which are tiny sacs filled with air.

The trachea, **bronchi and bronchioles** which enable the flow of air into and out of the lungs. The airways are held open with the help of **rings of cartilage**, incomplete in the trachea to allow passage of food down **the oesophagus** behind the **trachea.**

Trachea and bronchi are similar in structure, with the exception of size – bronchi are narrower. They are composed of **several layers** which together make up a thick wall. The wall is mostly composed of cartilage, in the form of incomplete C rings. Inside surface of the cartilage is a layer of g**landular and connective tissue, elastic fibres, smooth muscle and blood vessels.** This is referred to as the '**loose tissue'**. The inner lining is an epithelial layers composed of **ciliated epithelium and goblet cells.**

The **bronchioles** are narrower than the bronchi. Only the larger bronchioles contain cartilage. Their wall is made out of smooth muscle and elastic fibres. The smallest of bronchioles have alveoli clusters at the ends.

Structures and functions of mammalian gaseous exchange system include:

- **Cartilage**- involved in supporting the trachea and bronchi, plays an important role in preventing the lungs from collapsing in the event of pressure drop during exhalation
- **Ciliated epithelium** – present in bronchi, bronchioles and trachea, involved in moving mucus along to prevent lung infection by moving it towards the throat
- **Goblet cells** – cells present in the trachea, bronchi and bronchioles involved in mucus secretion to trap bacteria and dust to reduce the risk of infection with the help of lysozyme which digests bacteria
- **Smooth muscle** – their ability to contract enables them to play a role in constricting the airway, thus controlling its diameter as a result and thus controlling the flow of air to and from alveoli
- **Elastic fibres** – stretch when we exhale and recoil when we inhale thus controlling the flow of air

Ventilation

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

During **inspiration**, the **external intercostal** muscles contract whereas the internal ones relax, as a result causing the **ribs** to raise upwards. The diaphragm **contracts and flattens**. In combination, the intercostal muscles and diaphragm cause the volume inside the **thorax** to increase, thus lowering the pressure. The difference between the pressure inside the **lungs** and atmospheric pressure creates a gradient, thus causing the air to **enter the lungs**

During **expiration**, the **internal** intercostal muscles **contract** whereas the external ones relax therefore **lowering** the rig cage. The diaphragm **relaxes** and raises **up**wards. These actions in combination decrease the volume inside the thorax, therefore increasing the pressure, forcing the air **out of the lungs**.

Spirometer

A **spirometer** is a device used to measure **lung volume**. A person using a spirometer breathes in and out of the **airtight chamber**, thus causing it to move up and down, leaving a **trace on a graph** which can then be interpreted.

Vital capacity – the **maximum volume of air** that can be inhaled or exhaled in a single breath. Varies depending on **gender, age, size as well as height**

Tidal volume – the v**olume of air** we breathe in and out at **each breath at rest**

Breathing 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

The volume of air which is always present in the lungs is known as the **residual volume**. The **tidal volume** can be exceeded, in cases such as during exercise where the inspiratory reserve volume is reached in an attempt to amount of air breathed in. Similarly, the **expiratory reserve volume** is the additional volume of air that can be exhaled **on top of the tidal volume**.

2.2.4 Transport systems in plants

Mass transport in plants

Plants require a **transport system** to ensure that all the cells of a plant receive a sufficient amount of **nutrients**. This is achieved through the combined action of **xylem tissue** which enables water as well as dissolved minerals to travel up the plant in the passive process of transpiration, and **phloem tissue** which enables sugars to reach all parts of the plant in active the process of **translocation.**

The vascular bundle

The vascular bundle in the roots:

- Xylem and phloem are components of the **vascular bundle**, which serves to enable transport of substances as well as for structural support.
- 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**

The vascular bundle in the stem:

- 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 xylem and phloem, that is meristem cells which are involved in the production of new xylem and phloem tissue

The vascular bundle in the leaf:

- The vascular bundles form 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

Xylem and phloem

Xylem vessels have the following features:

- They transport water and minerals, and also serve to provide structural support
- They are long cylinders made of **dead tissue** with **open ends**, therefore they can form a continuous column.
- Xylem vessels also contain pits which enable water to more 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

The features of phloem vessels include:

- They're tubes made of **living cells**
- Involved in **translocation** which is the movement of nutrients to storage organs and growing parts of the plant
- Consist of **sieve tube elements** and **companion cells**
- Sieve tube elements form a tube to transport sugars such as sucrose, in the dissolved form of sap
- Companion cells are involved in **ATP production** for active processes such as loading sucrose into sieve tubes

- Cytoplasm of 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

Transpiration

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. Carbon dioxide enters, while water and oxygen exit through the leaf stomata.

The **transpiration stream,** which is the movement of water up the stem enables processes such as photosynthesis, growth and elongation as it supplies the plant with water which is necessary for all 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.

Transpiration involves **osmosis**, where water moves from the xylem to the **mesophyll cells**. Transpiration also involves **evaporation** from the surface of mesophyll cells into intercellular spaces and diffusion of water vapour down a water vapour potential gradient out of the stomata.

The rate of transpiration can be investigated with the help of a **potometer** where water lost by the leaf is replaced by water in the capillary tube. Therefore, measuring the movement of the meniscus can be used to determine the rate of transpiration. Factors which affect the rate of transpiration include **number of leaves, number/size or position of stomata, presence of waxy cuticle, the amount of light present, the temperature, humidity, air movement and water availability.**

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**. The adaptations include smaller leaves which reduce the surface area for water loss. Both the densely packed mesophyll and the 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 contain hairs and pits which serve as a means of trapping moist air, thus reducing the water vapour potential. Xerophytes also roll the leaves to reduce the exposure of lower epidermis to the atmosphere, thus trapping air.

Movement of water in the root

Water enters through the root **hair cells** and moves into the xylem tissue located in the centre of the root. This movement occurs as a result of a **water potential gradient**, as the water potential is higher inside the soil than inside the root hair cells, due to the dissolved substances in the **cell sap.**

Therefore, the purpose of **root hair cells** it to provide a large surface area for the movement of water to occur.

Minerals are also absorbed through the root hair cells by **active transport**, as they need to be pumped against the concentration gradient.

There are two ways the water taken up by the root hair cells can move across the cortex of the root into xylem:

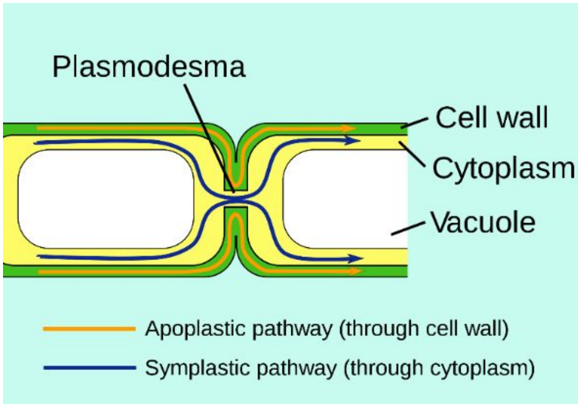
- It can either occur via the **symplast pathway** where water enters the cytoplasm through the plasma membrane and passes from one cell to the next through plasmodesma**ta**, the channels which connect the cytoplasm of one cell to the next.

- The other pathway is the **apoplast pathway** where the water moves through the water filled spaces between cellulose molecules in the cell walls. In this pathway, water doesn't pass through any plasma membranes therefore it can carry dissolved mineral ions and salts.

- When the water reaches a part of the root called the endodermis, it encounters a 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 must now enter 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.



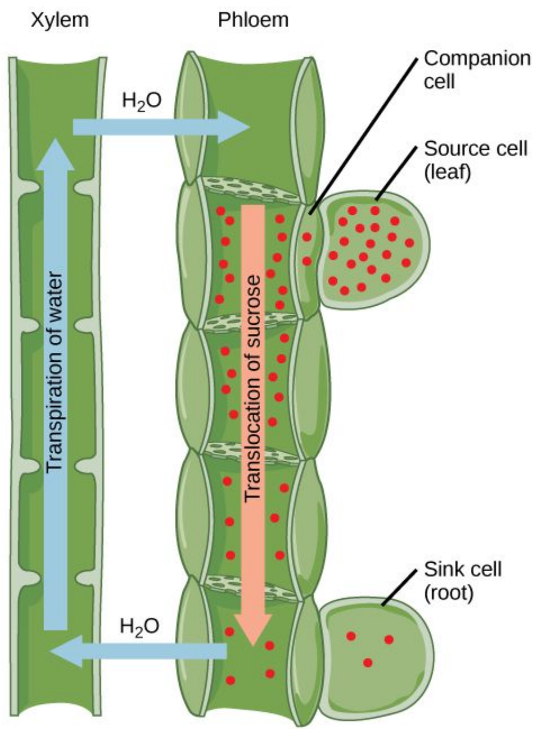
Water moving in the xylem up the stem

The water is removed from the top of the xylem vessels into the mesophyll cells down the **water potential gradient.** 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 osmo**sis**, thus pushing it upwards.

The flow of water is also maintained with the help of **surface tension** of water and the attractive forces between water molecules known as **cohesion.** The action of these two forces in combination is known as the **tension-cohesion theory**, which is further supported by **capillary action** where the forces involved in cohesion cause the water molecule to adhere to the walls of xylem, thus pulling water up.

<u>Translocation</u>

Translocation is an energy requiring process which serves as a means of transporting assimilates such as sucrose in the phloem between sources which release sucrose such as leaves and sinks e.g. roots and meristem which remove sucrose from the phloem.



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Sucrose enters the phloem in a process known as **active loading** where companion cells use ATP to transport hydrogen ions into the surrounding tissue, thus creating a **diffusion gradient,** which causes the H+ ions to diffuse back into the companion cells. It is a form of **facilitated diffusion** involving cotransporter proteins which 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. As a result of that, the sucrose diffuses out of the companion cells down the **concentration gradient** into the sieve tube elements through links known as **plasmodesmata.**

As sucrose enters the sieve tube elements, the **water potential** inside the tube is reduced, therefore causing water to enter via **osmosis**, as a result increasing the **hydrostatic pressure** of the sieve tube. Therefore, water moves down the sieve tube from an area of higher pressure to an area of lower pressure. Eventually, sucrose is removed from the sieve tube elements by diffusion or active transport into the surrounding cells, thus increasing the water potential in the sieve tube. This in turn means that water leaves the sieve tube by osmosis, as a result **reducing the pressure in the phloem at the sink.**

Therefore, in summary the mass flow of water from the source to the sink down the **hydrostatic pressure gradient** is a means of supplying assimilates such as sucrose to where they are needed.