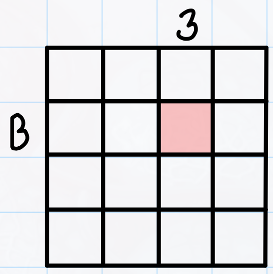
B3 .1 Gas Exchange

Guiding Questions
How are multicellular organisms adapted to carry out gas exchange?
What are the similarities and differences in gas exchange between a flowering plant and a mammal?

Linking Questions
How do multicellular organisms solve the problem of access to materials for all their cells?
What is the relationship between gas exchange and metabolic processes in cells?



Theme: Form and Function

Level of Organization: Organisms

Written and drawn by:

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NOTEWORTHY SCIENCE MARIER

SL LEARNING OUTCOMES

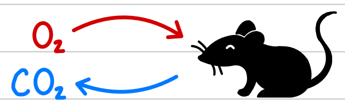
B3.1.1	Gas exchange as a vital function in all organisms	Students should appreciate that the challenges become greater as organisms increase in size because surface area-to-volume ratio decreases with increasing size, and the distance from the centre of an organism to its exterior increases.
B3.1.2	Properties of gas-exchange surfaces	Include permeability, thin tissue layer, moisture and large surface area.
B3.1.3	Maintenance of concentration gradients at exchange surfaces in animals	Include dense networks of blood vessels, continuous blood flow, and ventilation with air for lungs and with water for gills.
B3.1.4	Adaptations of mammalian lungs for gas exchange	Limit to the alveolar lungs of a mammal. Adaptations should include the presence of surfactant, a branched network of bronchioles, extensive capillary beds and a high surface area.
B3.1.5	Ventilation of the lungs	Students should understand the role of the diaphragm, intercostal muscles, abdominal muscles and ribs.
B3.1.6	Measurement of lung volumes	**Application of skills**: Students should make measurements to determine tidal volume, vital capacity, and inspiratory and expiratory reserves.
B3.1.7	Adaptations for gas exchange in leaves	Leaf structure adaptations should include the waxy cuticle, epidermis, air spaces, spongy mesophyll, stomatal guard cells and veins.
B3.1.8	Distribution of tissues in a leaf	Students should be able to draw and label a plan diagram to show the distribution of tissues in a transverse section of a dicotyledonous leaf.
B3.1.9	Transpiration as a consequence of gas exchange in a leaf	Students should be aware of the factors affecting the rate of transpiration.
B3.1.10	Stomatal density	**Application of skills**: Students should use micrographs or perform leaf casts to determine stomatal density. **NOS**: Reliability of quantitative data is increased by repeating measurements. In this case, repeated counts of the number of stomata visible in the field of view at high power illustrate the variability of biological material and the need for replicate trials.

HL LEARNING OUTCOMES

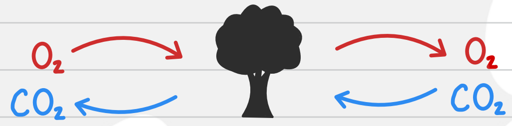
B3.1.11	Adaptations of foetal and adult haemoglobin for the transport of oxygen	Include cooperative binding of oxygen to haem groups and allosteric binding of carbon dioxide.
B3.1.12	Bohr shift	Students should understand how an increase in carbon dioxide causes increased dissociation of oxygen and the benefits of this for actively respiring tissues.
B3.1.13	Oxygen dissociation curves as a means of representing the affinity of haemoglobin for oxygen at different oxygen concentrations	Explain the S-shaped form of the curve in terms of cooperative binding.

Gas exchange: the exchange of gases (O_2 and CO_2) between an organism and its surroundings (i.e bringing one in and removing another). ※ this is a vital function in all organisms

cell respiration C1.2



In order to respire aerobically, oxygen is required and carbon dioxide (a waste product) needs to be removed



Photosynthetic organisms release oxygen as a waste product and require carbon dioxide as a reactant in order to fix carbon

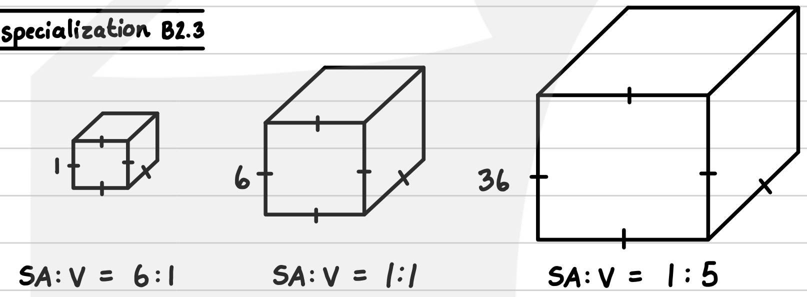
photosynthesis C1.3

↳ process becomes less efficient and more of a challenge the larger an organism becomes due to:

✗ reduction in surface area : volume ratio

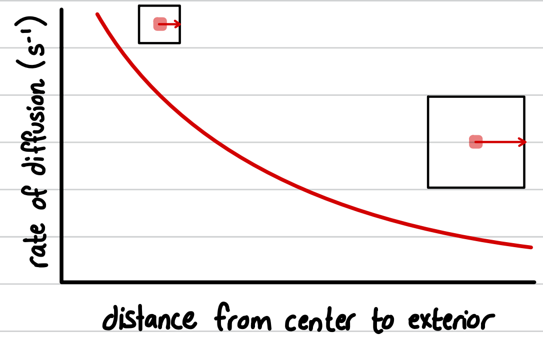
cell specialization B2.3

as an organism increases in size the square-cube law states that its volume (which dictates its metabolic rate and demand) increases faster than its surface area (which dictates its rate of exchange)



✗ increased distance for exchange

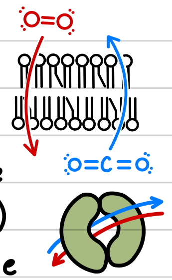
the larger an organism becomes the greater the distance from the center to its exterior, thus making exchange between the innermost cells and the external environment (via diffusion) slow and inefficient



↳ in order to maximize the rate of gas exchange, gas-exchange surfaces tend to have the following properties:

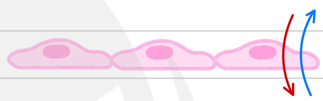
✓ **high permeability**

To quickly and efficiently transport gases across membranes they are freely permeable to O_2 and CO_2, moving passively via simple diffusion. Vascular plants have pores (stomata) on underside of leaves controlling this exchange



✓ **thin tissue layer**

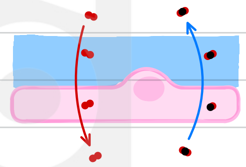
the shorter the distance gases need to diffuse for exchange, the greater the rate. Thus tissues are adapted to be very thin (1 layer thick and flat in shape)



ex: simple squamous epithelial cells make up lining of blood vessels, lung and lymph vessels

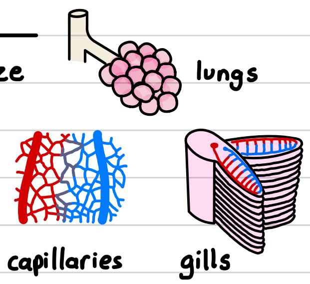
✓ **moist surface**

in order to promote gases to diffuse (facilitating exchange) respiratory surfaces in terrestrial animals are covered by a moist film ex: pulmonary surfactant in alveolar surface



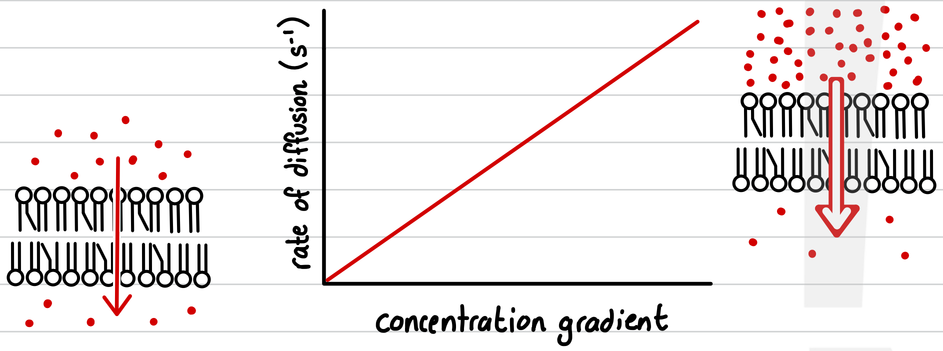
✓ **large surface area : volume**

respiratory surfaces maximize the SA: volume in order to increase the relative area of membrane, where gases will diffuse and be exchanged

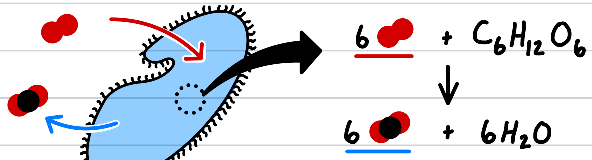


another crucial factor for efficient and continual gas exchange is the maintenance of a large concentration gradient at gas-exchange surfaces

↳ concentration gradient is directly proportional to rate of diffusion

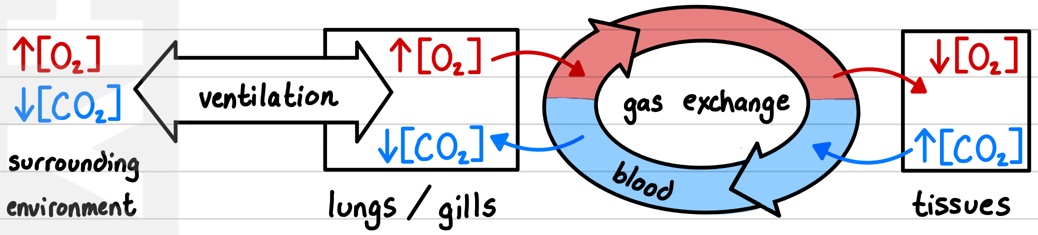


↳ in unicellular organisms, such as *Paramecium* a concentration gradient is maintained i.e. high O_2 outside cell, high CO_2 inside cell due to continual aerobic cellular respiration where O_2 is used and CO_2 produced, ensuring passive exchange of both respiratory gases

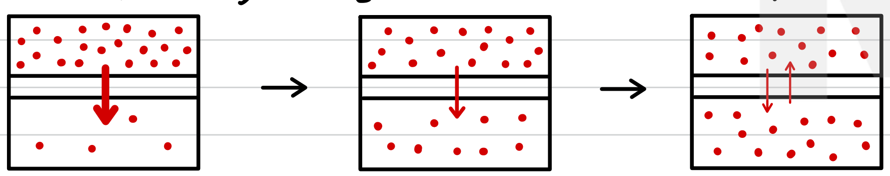


↳ in animals, [ ] gradient is maintained at gas-exchange surfaces:

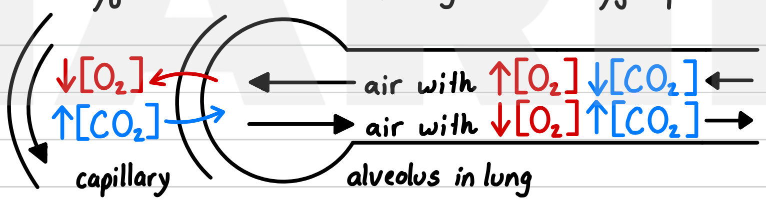
✓ ventilating gases in and out of the organism, preventing equilibrium
✓ continuous blood flow, preventing equilibrium
✓ dense network of blood vessels (capillaries) surrounding tissues



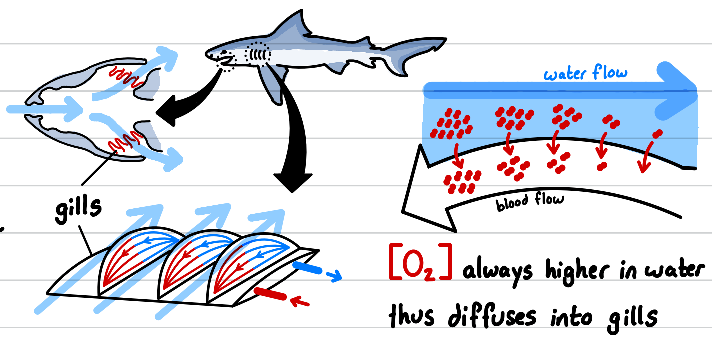
if there is no mechanism to maintain this gradient, diffusion will slow down, eventually resulting in no net movement due to equilibrium



• in mammals, blood flow and ventilation ensures air in lungs is oxygen rich and can be exchanged with oxygen poor blood



• in fish, oxygen rich water is ventilated through the gills. Water flows in the opposite direction of blood in gills, ensuring [ ] gradient is maintained and that gas exchange occurs continuously



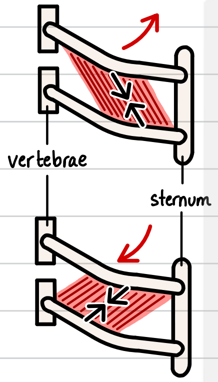
[O_2] always higher in water thus diffuses into gills

Ventilation: the movement of air in and out of the lungs

↳ In order to do this the volume of air within the chest cavity (thorax) is altered, causing a pressure differential

↳ this is accomplished using **antagonistic muscle pairs**, meaning when one muscle contracts, the other relaxes

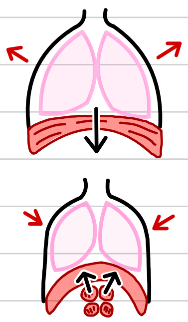
- Internal and external intercostal muscles



External intercostals contract pulling ribs up and out, internal intercostals relax

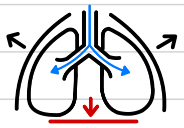
Internal intercostals contract pulling ribs down and in, external intercostals relax

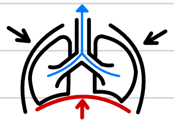
- Diaphragm and abdominal muscles



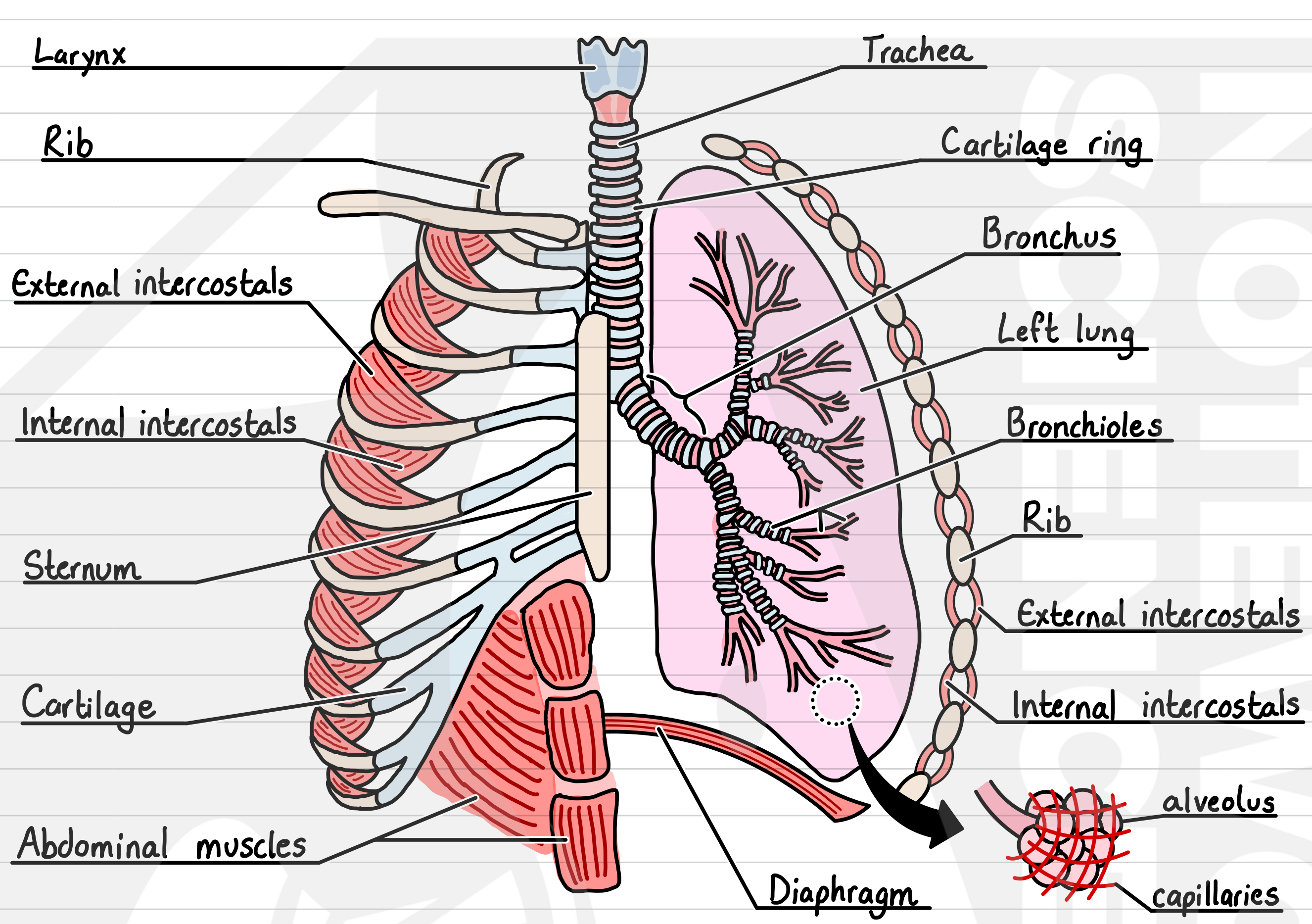
Diaphragm contracts and flattens, pushing relaxed abdominals out

Abdominals contract, pulling ribs down, pushing relaxed diaphragm up (domed)



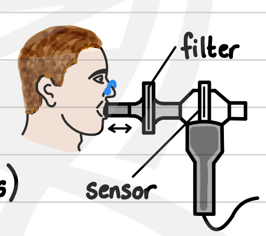


Inspiration	Expiration
Internal intercostals relax	External intercostals relax
External intercostals contract	Internal intercostals contract
↳ pull ribs up and out	↳ pull ribs down and in
Abdominal muscles relax	Diaphragm relaxes and domes
Diaphragm contracts	Abdominal muscles contract
↳ flattens and moves down	↳ pushing diaphragm up
▼	▼
Thoracic volume increases	Thoracic volume decreases
▼	▼
Pressure within thorax decreases below atmospheric pressure	Pressure within thorax increases above atmospheric pressure
▼	▼
Air flows outside → lungs down pressure gradient	Air flows lungs → outside down pressure gradient

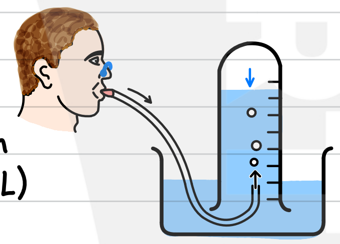


spirometry: test of lung function including lung volumes and ventilation rate

↳ digital spirometer
breaths are detected as change in pressure by screens in sensor → flow rate (L/s)



↳ bell jar spirometer
air from breaths displaces water within bell jar → volume (L)

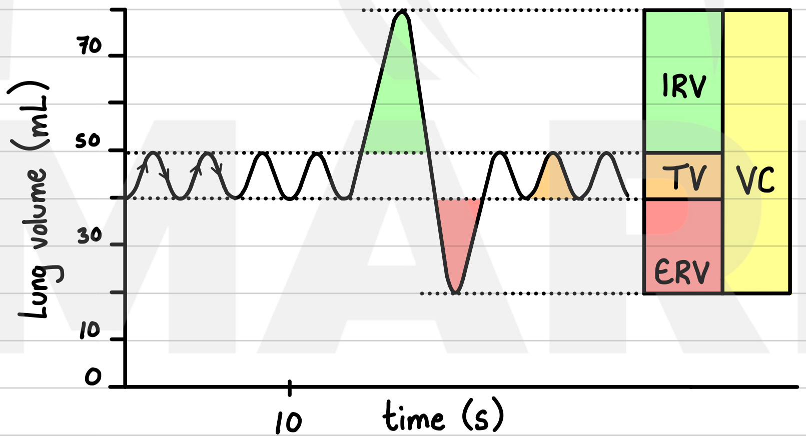


Tidal volume (TV): volume of air moved in and out of the lungs in normal ventilation

Inspiratory reserve volume (IRV): maximum of air that can be inhaled after normal inhalation

Expiratory reserve volume (ERV): maximum of air that can be exhaled after normal exhalation

Vital capacity (VC): total amount of air exhaled after a maximum inhalation (IRV + TV + ERV)



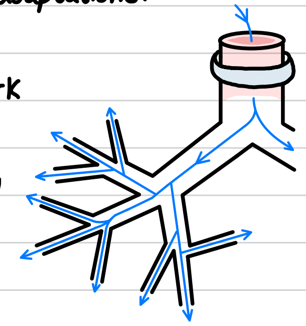
example graph analysis:

TV = 10L
IRV = 30L
ERV = 20L
VC = 10L + 30L + 20L = 60L
ventilation rate = 3 breaths / 10s
= 0.3 breaths / s
= 18 breaths / min

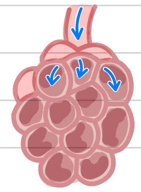
Gas exchange in lungs involves exchanging oxygen from the air in the alveoli with CO_2 from blood in capillaries via simple diffusion

↳ air is exchanged between the outside and the alveolar lung via the airways which has a number of adaptations:

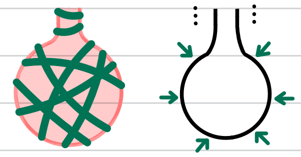
- The airways consist of a branched network of tubes: trachea → bronchi → bronchioles. This allows air to move around lungs evenly. Each tube is supported by cartilage rings which resists collapse from pressure drops



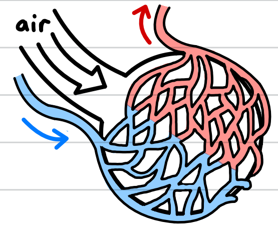
- Each bronchiole terminates in a cluster of spherical alveoli. Despite being small, the large number of these (100s of millions) provide enormous total surface area



- Each alveolus is surrounded by elastic fibres allowing it stretch during inhalation and recoil during exhalation, forcing air out

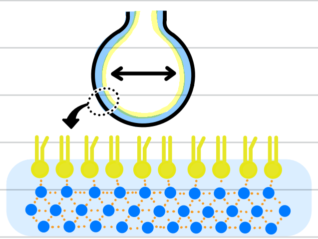


- Each alveolus is surrounded by an extensive capillary bed, providing close access and a very large surface area for gas exchange between air in alveolus and blood in capillary

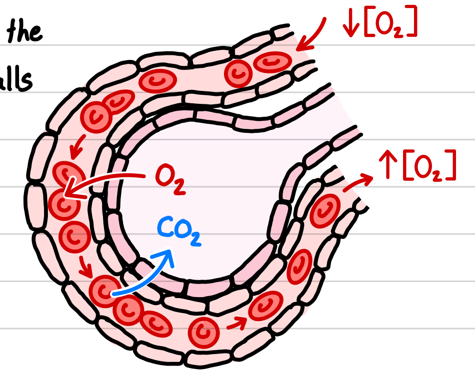


- The inside of alveoli are lined with a pulmonary surfactant. As its moist, it allows O_2 and CO_2 to dissolve and diffuse easier. It also contains phospholipids which decrease surface tension, preventing the alveolus from adhering and collapsing

cell specialization B2.3

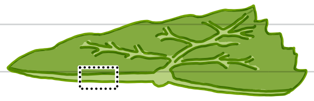


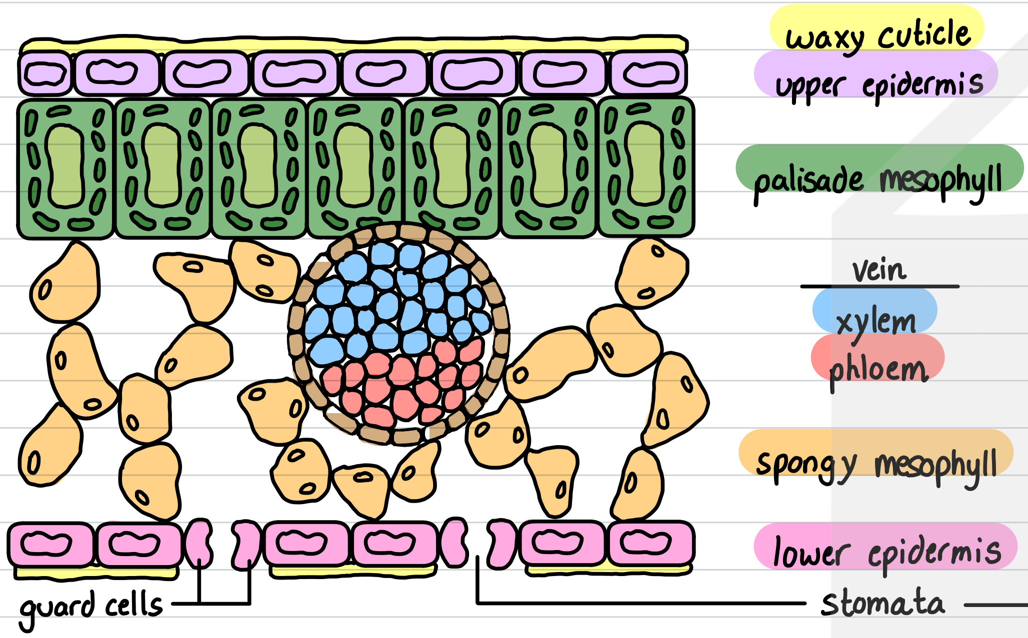
- Both gas exchange tissues in the lung: alveoli and capillaries walls are one cell thick, providing a very small diffusion distance from the inside of the lung to blood, greatly increasing the rate of gas exchange between them



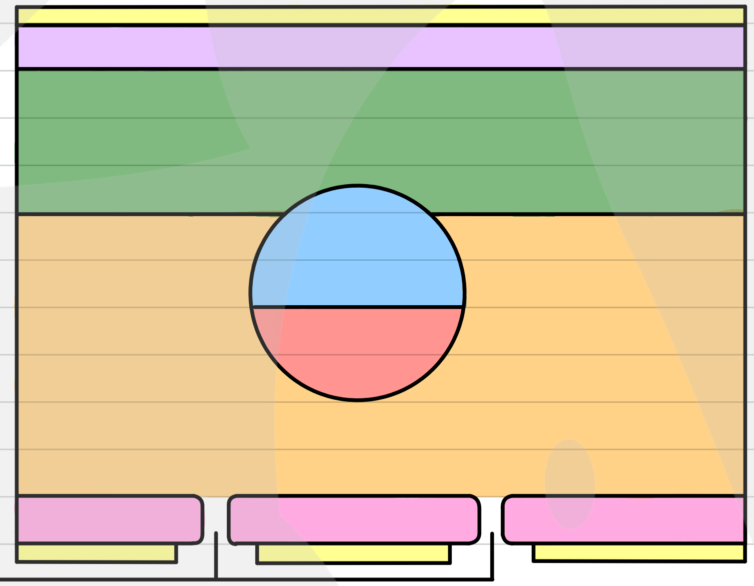
In vascular plants (angiosperms, gymnosperms, ferns) gas exchange occurs in the leaves

transverse cross-section of a dicotyledonous leaf:



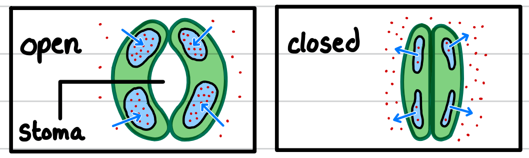


plan diagram of transverse of a dicotyledonous leaf:



leaf tissue gas exchange adaptations:

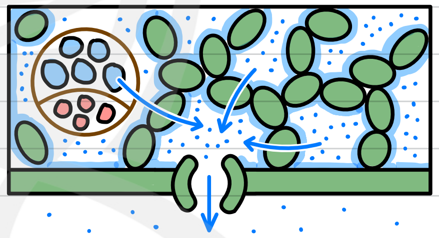
- waxy cuticle: the top of leaves as well as the underside (except for stomata) is coated by a layer of lipid wax which is hydrophobic and has low permeability to gases. This ensures that water loss and gas exchange is occurring at the stomata (which can be opened or closed)
- epidermis: secrete wax which forms waxy cuticle. Acts as protective layer. Lower epidermis has guard cells which form stomata and regulate gas exchange and water loss
- spongy mesophyll: contains many air spaces which provides a large moist surface area for diffusion and gas exchange (CO_2 in, O_2 out for photosynthesizing palisade mesophyll tissue)
- veins (vascular bundle): water is carried in Xylem vessels to leaves for use in photosynthesis and primarily to replace those lost via transpiration. Phloem transports nutrients such as sugars
- stomatal guard cells: pair of cells which regulate gas exchange and water loss via diffusion by either becoming turgid and forming stoma or flaccid and closing



Transpiration: movement of water through a plant from entering in roots and exiting as vapour via stomata through diffusion

↳ process occurs as a consequence of gas exchange in the leaf, i.e. so long as stomata are open and exchanging O_2 for CO_2:

1. water delivered to leaf via xylem, keeping spongy mesophyll moist for gas exchange
2. water within spongy mesophyll air spaces evaporates into water vapour
3. increases the relative humidity in air spaces until air is saturated
4. water diffuses out of leaf via stomata, dropping humidity within air spaces

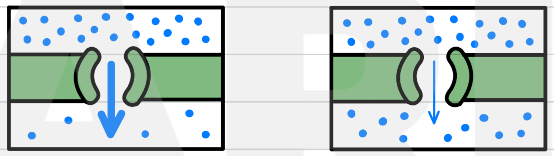


↳ rate of transpiration (i.e. water loss) is impacted by several environmental factors:

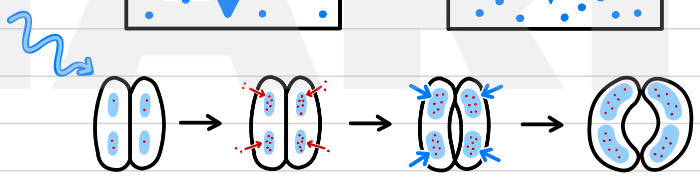
temperature: positive relationship: higher temperatures mean more kinetic energy to break hydrogen bonds between water molecules ∴ more evaporation and loss via diffusion ※ At extreme temperatures, stomata may close to prevent excessive loss

wind speed: positive relationship: higher wind speeds displaces more water vapour surrounding leaf away, reducing its relative humidity ∴ greater [ ] gradient between water vapour inside and outside the leaf ∴ greater rate of diffusion

humidity: negative relationship: higher humidity decreases [ ] gradient between water vapour inside and outside the leaf ∴ lower rate of diffusion

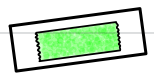


light intensity: positive relationship: guard cells swell in response to blue light, opening their stoma to allow gas exchange for photosynthesis
※ crucial factor as transpiration ceases in absence of light

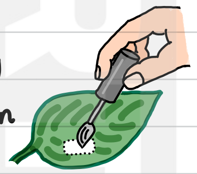


stomatal density: number of stomata per unit area (mm^{-2} or μm^{-2}) of a leaf surface.

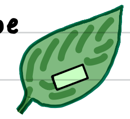
Procedure: use micrograph or take a cast of the lower epidermis of a leaf



1. Spread clear nail polish on section

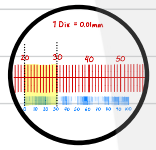


2. once dry, place clear tape overtop and press down



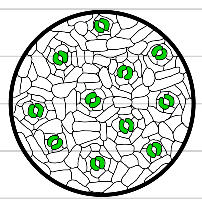
3. Pull tape off leaf and stick on glass slide

Analysis: view leaf lower epidermis micrograph or casting under microscope at high power



Cell structure A2.2

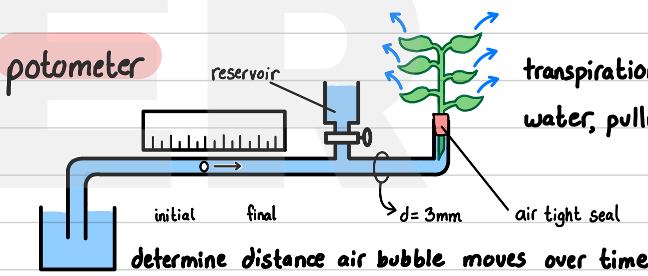
determine the actual field of view diameter using stage micrometer and then count stomata



at 400x, F.O.V. diameter = 0.56 mm
F.O.V. area = $\pi(0.28\text{mm})^2 = 0.25\text{mm}^2$
number of visible stomata / area
$= 11 / 0.25\text{mm}^2 = 44$ stomata per mm

NOS: mean stomatal density should be calculated from multiple micrographs or casts to increase reliability and to account for natural biological variation among specimens

potometer



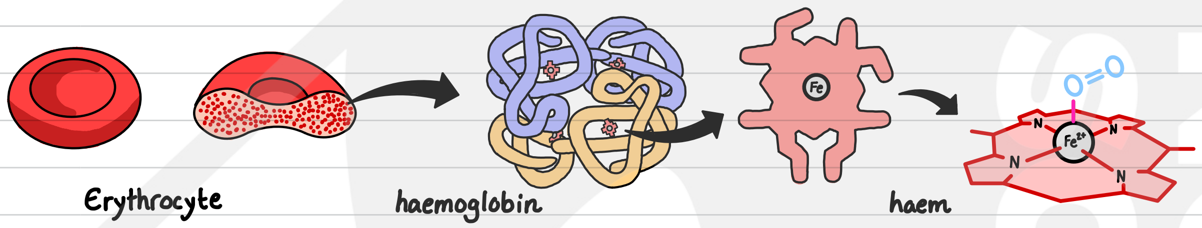
transpiration draws water, pulling bubble

distance bubble moved in 1 min = 0.51 mm

$$\text{transpiration rate} = \frac{\text{volume water (mm}^3)}{\text{time (min)}}$$

$$= \frac{\pi r^2 d}{t} = \frac{\pi(1.5\text{mm})^2(0.51\text{mm})}{1\text{min}} = 3.6\,\frac{\text{mm}^3}{\text{min}}$$

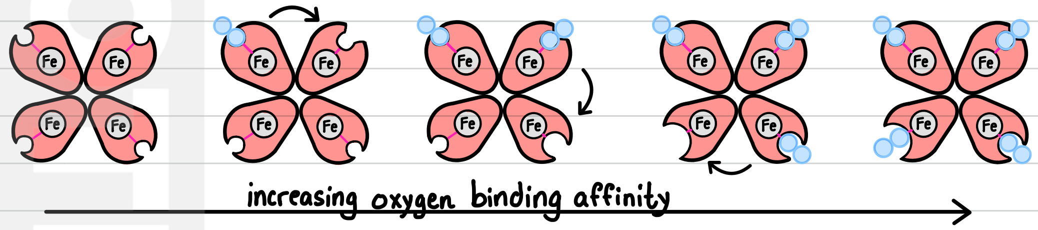
Erythrocytes (red blood cells) are adapted to carry respiratory gases (mainly O_2) through the blood stream by being packed full of the protein haemoglobin cell structure A2.2



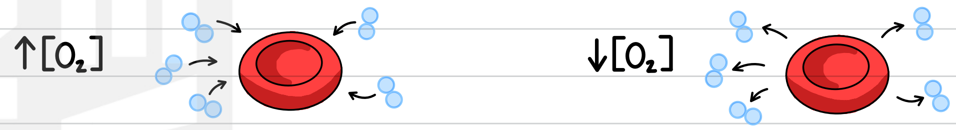
Haemoglobin is a conjugated quaternary protein composed of four subunits - each comprising a polypeptide and a haem group with a bound iron atom which binds reversibly with oxygen proteins B1.1

Cooperative binding of haemoglobin

↳ oxygen (O_2) binding at each of the four haem sites does not occur simultaneously but cooperatively: binding the first oxygen is difficult, but once an oxygen binds it induces a conformational change to the neighbouring chain within the haemoglobin, facilitating subsequent oxygen binding ∴ binding the first, second, third, and fourth oxygen molecule to haemoglobin becomes progressively easier and conversely, dissociation of oxygen reduces affinity in other haem groups making unbinding progressively easier ∴ 2 most probable states are Hb with no oxygen and with four



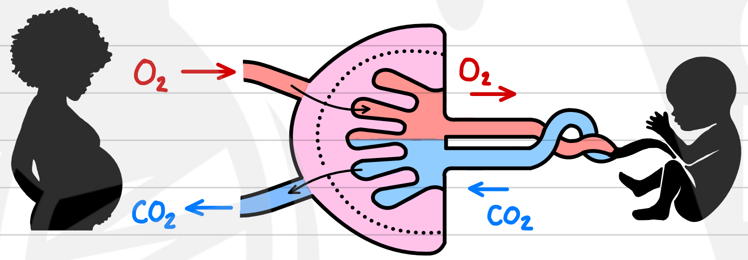
↳ this is adaptive: haemoglobin has a higher affinity for O_2 in oxygen-rich areas (such as the lung) → promoting oxygen loading
haemoglobin has a lower affinity for O_2 in oxygen-poor areas (such as muscles) → promoting oxygen unloading



Adaptations of foetal haemoglobin

reproduction D3.1

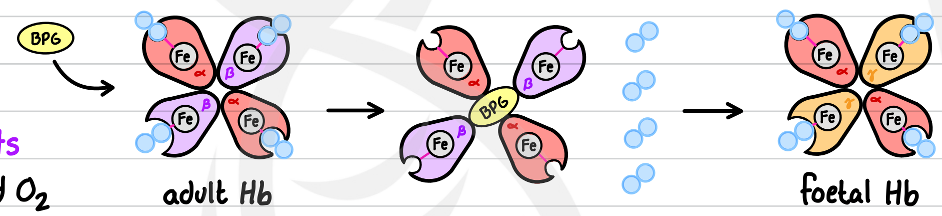
↳ During pregnancy, the foetus receives O_2 from the mother via the placenta where the mother's red blood cells unload O_2 in the placenta where it diffuses and binds to foetal red blood cells and is delivered via umbilical cord



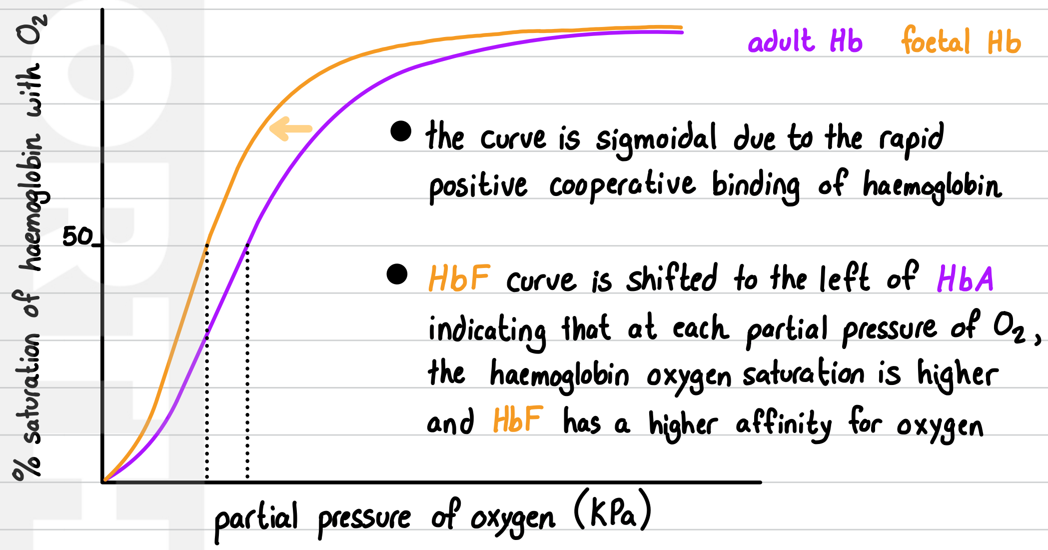
Problem: how/why does the oxygen bound to the mother's haemoglobin unbind, diffuse and then bind to foetal haemoglobin?

Solution: foetus uses a different haemoglobin (foetal haemoglobin, HbF) which has a higher oxygen affinity than adult haemoglobin

↳ a molecule (2,3-BPG) produced by placenta binds to adult Hb causing a drop in O_2 affinity and unloading
↳ HbF has 2 gamma subunits instead of 2 beta subunits which prevents 2,3-BPG from binding, allowing it to bind O_2



Oxygen dissociation curve: plots the oxygen saturation of haemoglobin over different partial pressures of oxygen

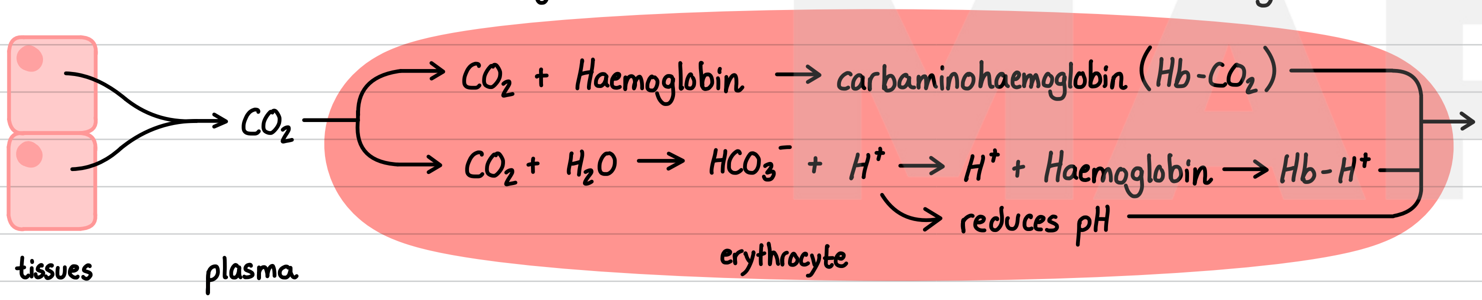


- the curve is sigmoidal due to the rapid positive cooperative binding of haemoglobin
- HbF curve is shifted to the left of HbA indicating that at each partial pressure of O_2, the haemoglobin oxygen saturation is higher and HbF has a higher affinity for oxygen

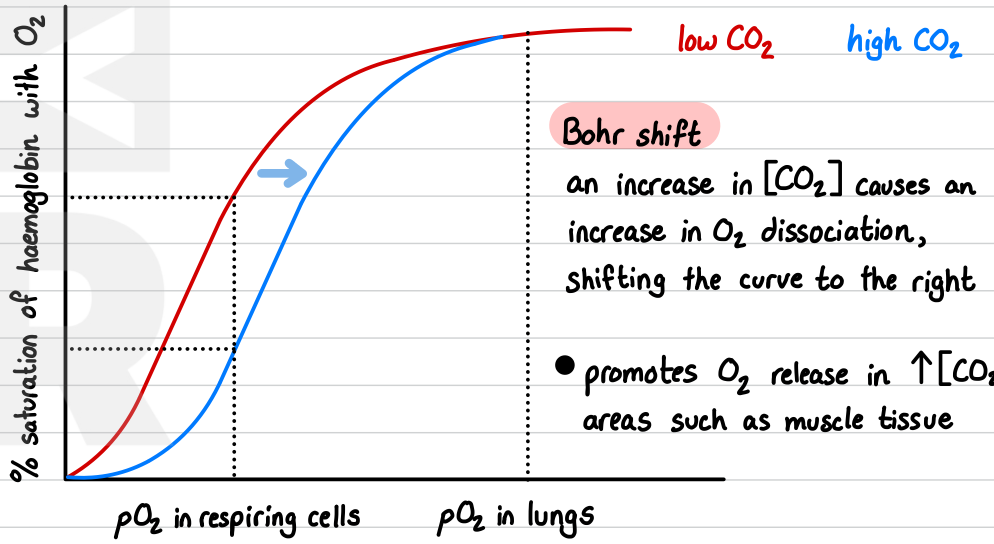
Impact of carbon dioxide - Bohr shift

↳ aerobically respiring tissues produce CO_2 which is released into the blood → decreases haemoglobin's affinity for oxygen → promotes oxygen offloading

Other substances can bind onto haemoglobin at a site other than the haem (allosteric binding) which causes a change in its conformation



adaptive as: O_2 is released and is able to be delivered to tissues in great need and CO_2 is able to be delivered to lungs by erythrocytes in order to be exhaled



Bohr shift
an increase in [CO_2] causes an increase in O_2 dissociation, shifting the curve to the right

- promotes O_2 release in ↑[CO_2] areas such as muscle tissue

BIBLIOGRAPHY