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Water Potential

IB Biology - Revision Notes

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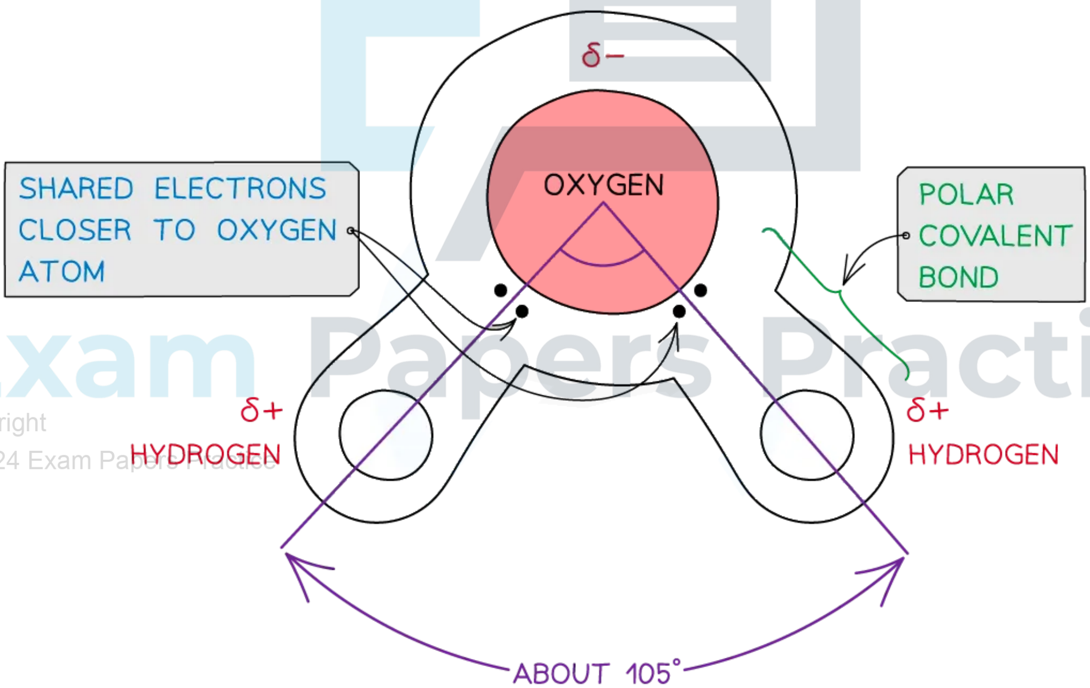
Osmosis

Solvation & Water

- A solution typically consists of a solute dissolved in a solvent
- Water is a **very good solvent** because it is dipolar
  - The hydrogen side of the molecule is slightly positive while the oxygen side is slightly negative
- This enables water molecules to form **hydrogen bonds** with other **polar** solute molecules and ions
- Hydrogen bonding between water molecules is also considered at the start of the course, the notes can be found here
- The interaction between a solvent, such as water, and a solute is known as **solvation**

Hydrogen bond and electron arrangement in water diagram

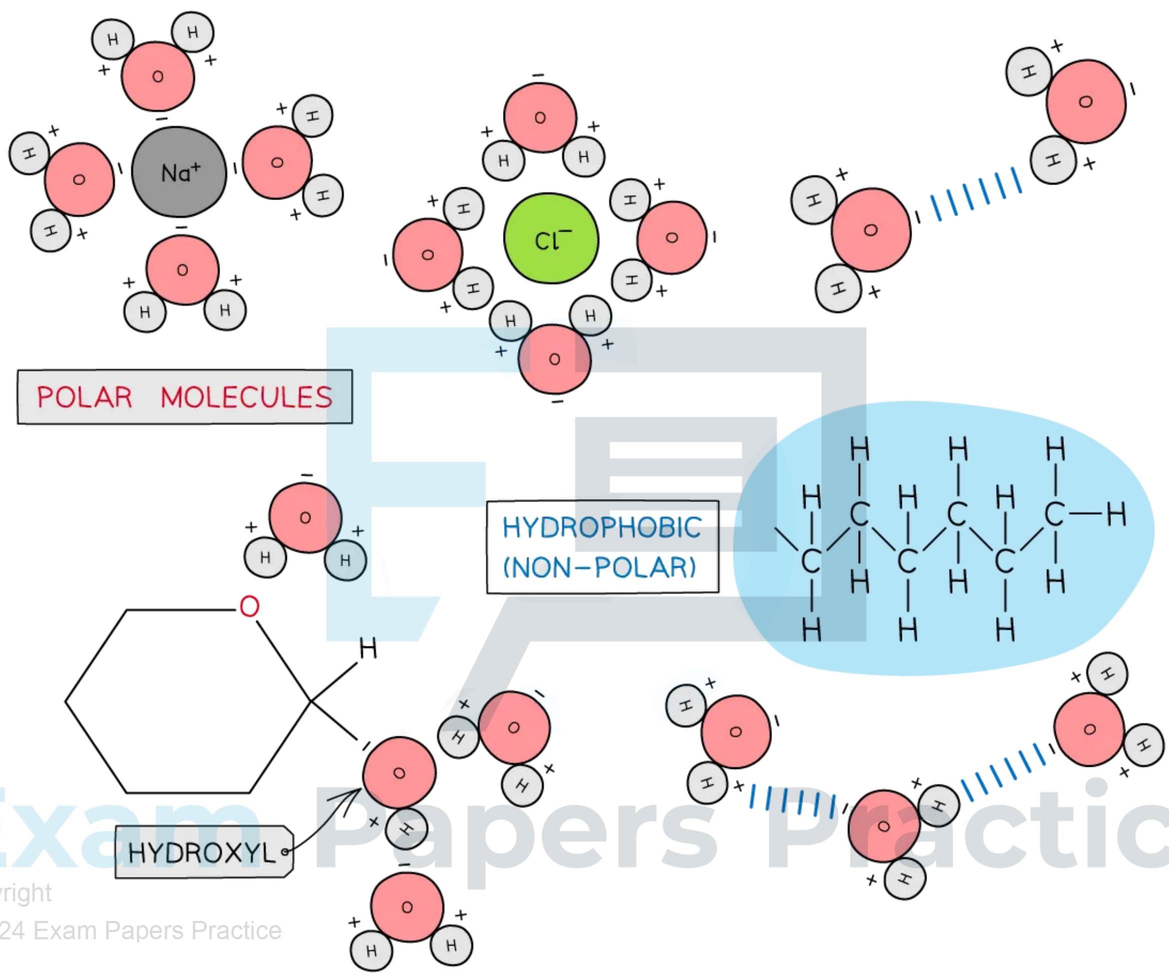


Water molecules are dipolar because electrons are distributed unevenly between the hydrogen and oxygen atoms

- Polar solvents, such as water, can orientate themselves towards polar solutes and ions to form hydrogen bonds or ion-dipole forces

- This creates **hydration shells** around each solute particle

Dipolar nature of water diagram

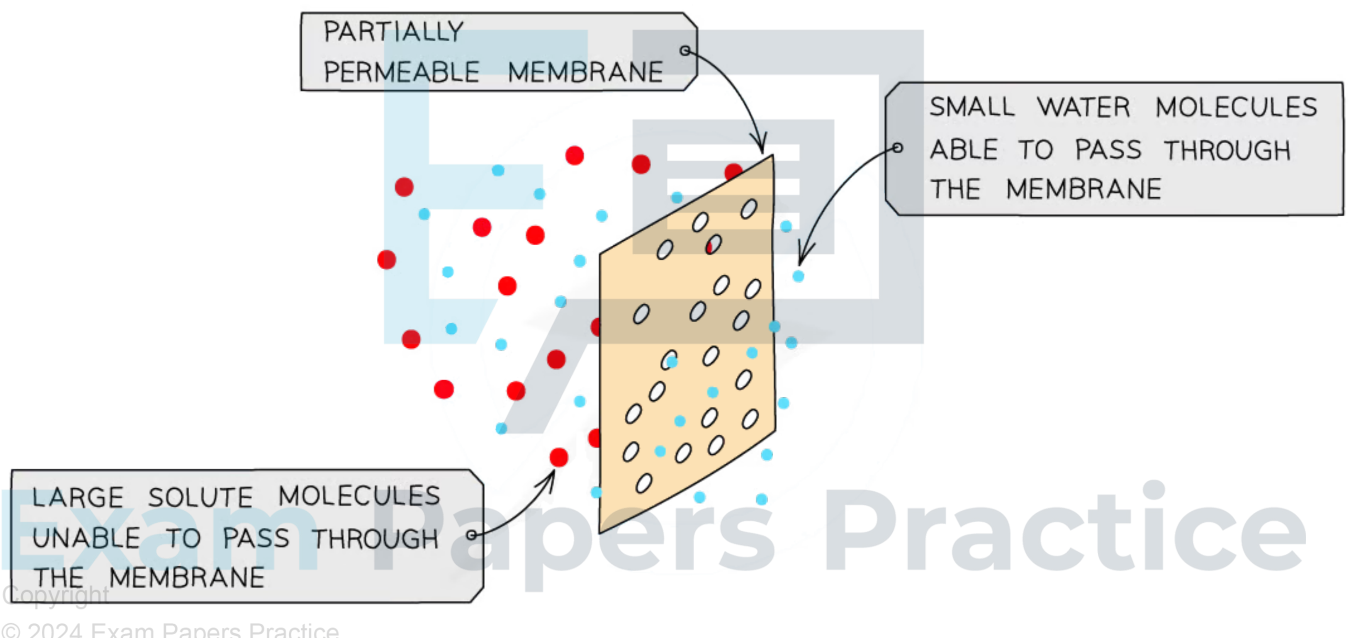


The dipole nature of water molecules allow them to form hydration shells around polar solutes and ions

Water Movement in Solutions

- All cells are surrounded by a cell membrane which is **partially permeable**
- Water can move in and out of cells by **osmosis**
- Osmosis is the **diffusion of water molecules** from a less concentrated (dilute) solution to a more concentrated solution across a partially permeable membrane
  - In doing this, water is moving down its **concentration gradient**
- The cell membrane is partially permeable which means it **allows small molecules (like water) through** but not larger molecules (like solute molecules)

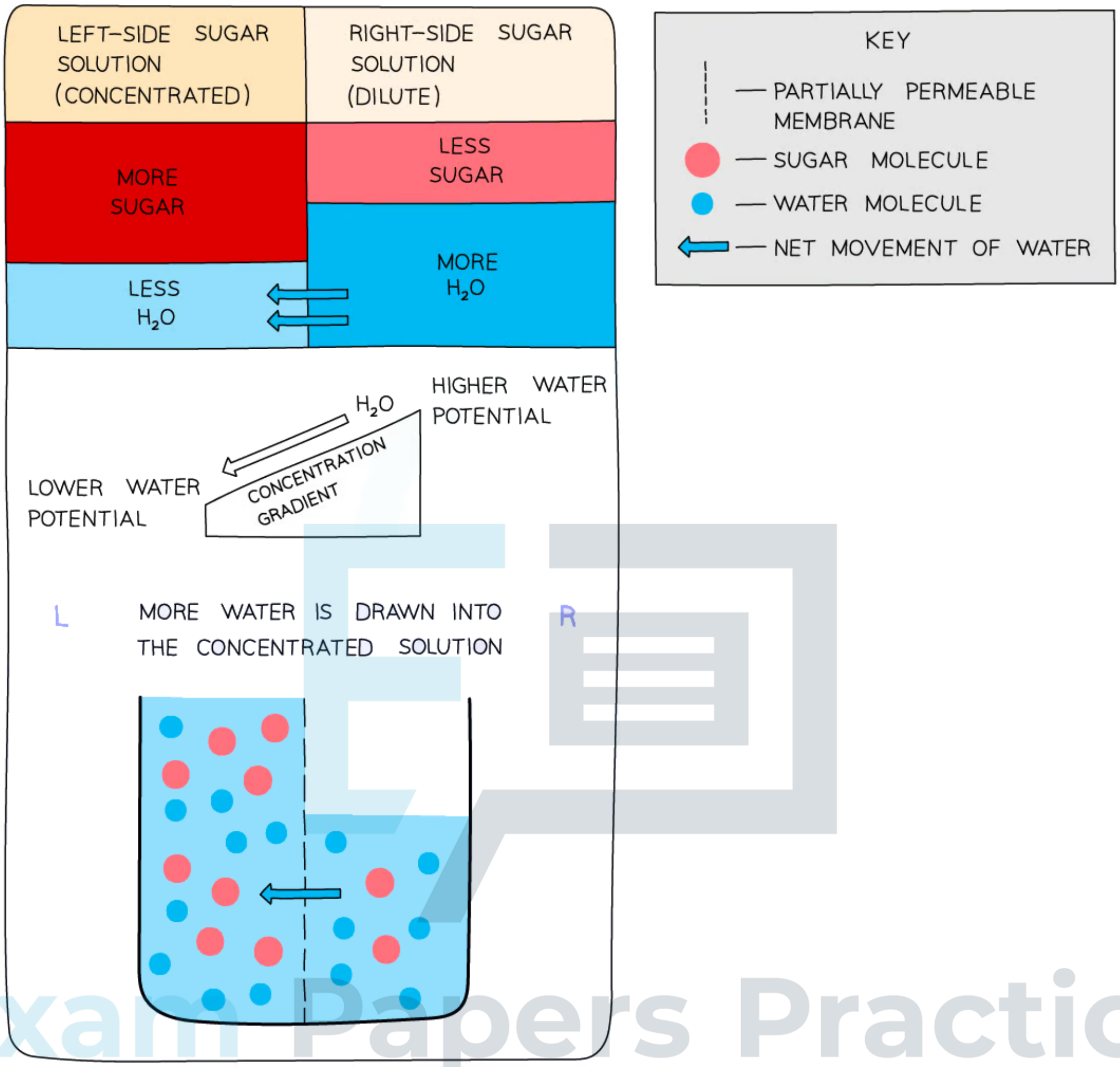
Partially permeable membrane diagram



Osmosis and the partially permeable membrane.

- Osmosis can also be described as the **net movement of water molecules** from a region of **lower solute concentration** to a region of **higher solute concentration**, through a partially permeable membrane

Movement of water diagram

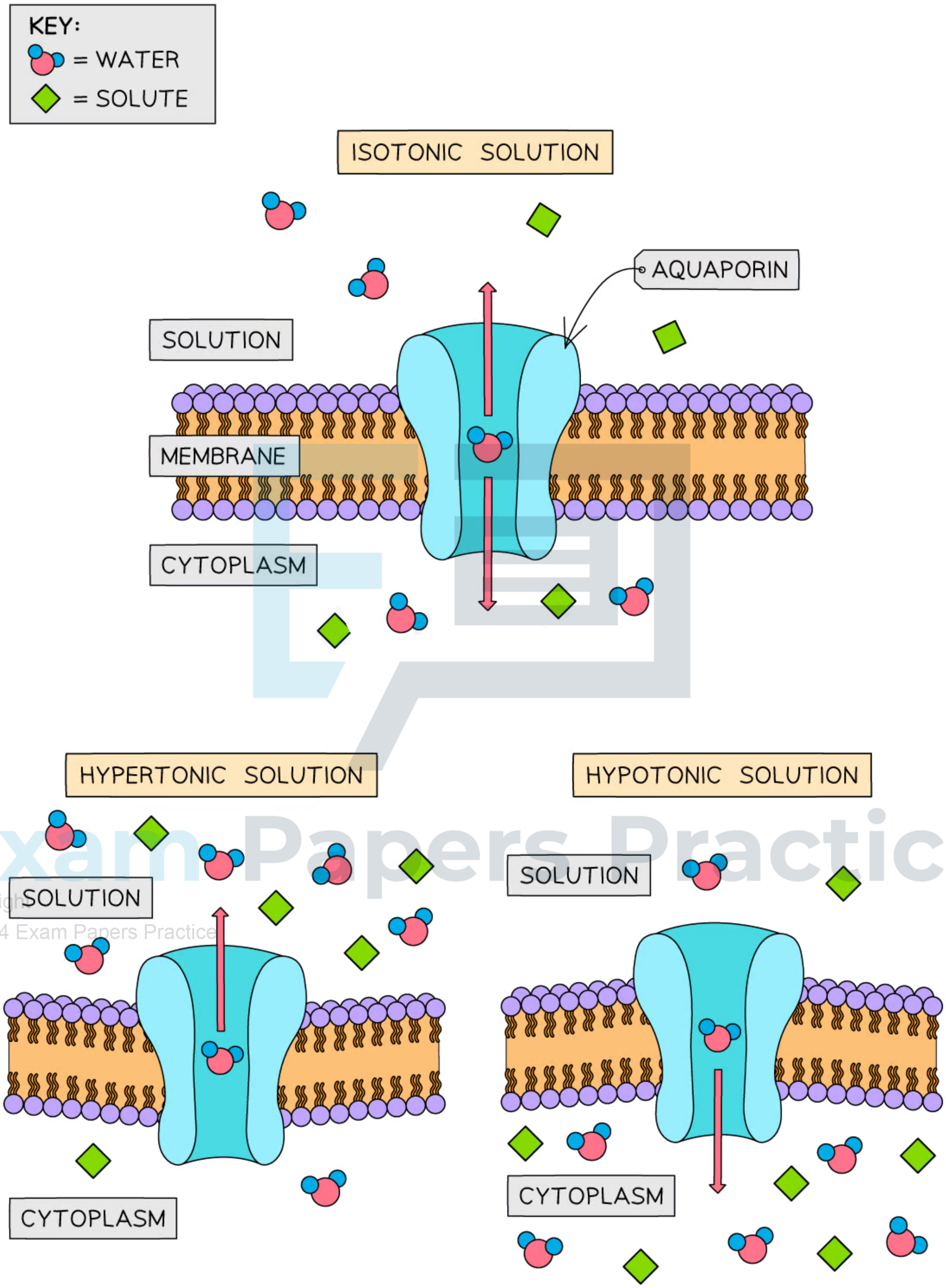


The water moves from the region of lower solute concentration (dilute solution) to the region of higher solute concentration (concentrated solution)

- If a cell is placed in a solution with a **lower solute concentration** (i.e. more dilute) than the cytoplasm of the cell, then there will be a **net movement** of water **into the cell** by osmosis
  - Solutions like this is referred to as being **hypotonic**

- If however, the solution outside the cell has a **higher solute concentration** (i.e. more concentrated) than the cytoplasm of the cell, then there will be a **net movement** of water **out** of the cell
  - These solutions are said to be **hypertonic**
- If the solute concentration is the **same** on both sides of the cell membrane, there will be **no net movement** of water into or out of the cell by osmosis
  - An solution with a similar concentration as the cytoplasm of a cell is referred to as an **isotonic** solution

Tonicity of solutions diagram



The net movement of water is determined by the relative solute concentration of the solution outside the cell

Exam Tip

Take note that water molecules are always moving into and out of cells due to the kinetic energy that the molecules possess. It is therefore incorrect to say that there would be no movement of water if a cell is placed in an isotonic solution. There would be no **net** movement of water in a particular direction in that case.

Osmosis in Cells

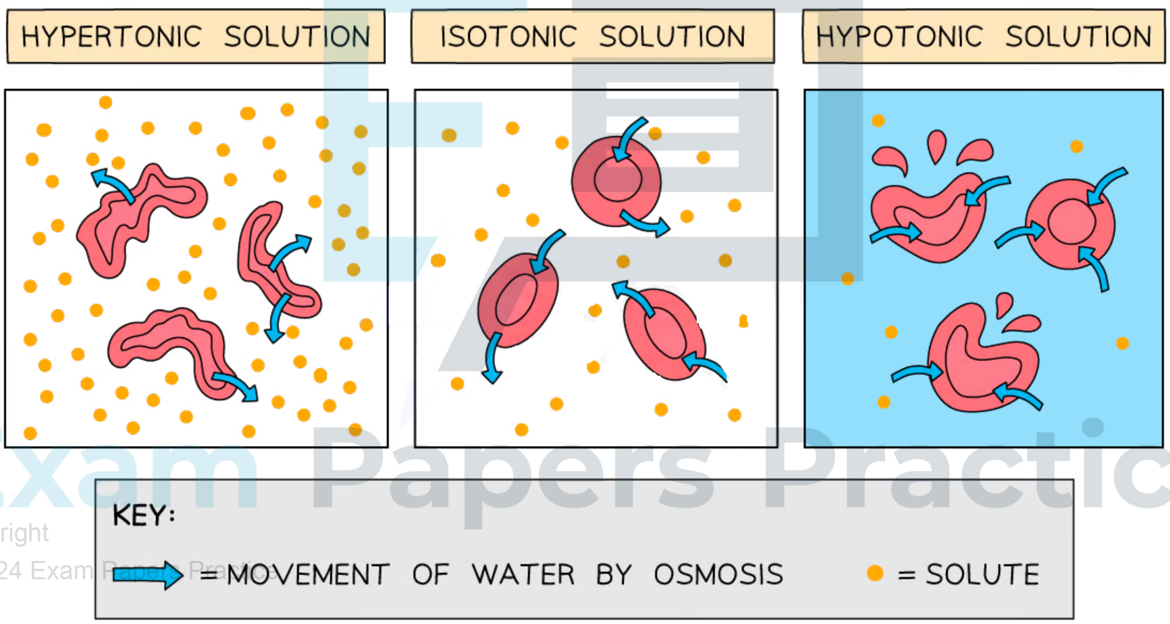
Water Movement & Cells

- The direction of the net movement of water will depend on whether a cell is placed in a **hypertonic** or **hypotonic** solution
  - In a **hypertonic** solution there will be a **net movement** of water **out** of the cell, as the cytoplasm is more dilute than the outside solution
  - In a **hypotonic** solution there will be a **net movement** of water **into** the cell because now the outside solution is more dilute than the cytoplasm
- In an **isotonic solution**, the movement of water into the cell will be balanced out by the movement of water out of the cell
  - There will therefore be **no net movement** of water into or out of the cell
  - The cell is now in **dynamic equilibrium** with the isotonic solution
  - It is especially important for animal cells to maintain their **osmotic concentration** as any deviation from this equilibrium may either cause the cell to shrink or burst

Effects of Osmosis on Cells Without Cell Walls

- **Animal cells** lose and gain water as a result of osmosis
- As animal cells **do not have a supporting cellulose cell wall**, the results on the cell are more severe than on plant cells
- If an animal cell is placed into a **hypertonic solution** (more concentrated than the cytoplasm of the cell), it will lose water by osmosis and become **crenated** (shrivelled up)
  - This may lead to the formation of blood clots as crenated red blood cells may become stuck while moving through capillaries
- If an animal cell is placed into a **hypotonic solution** (more dilute than the cytoplasm of the cell), it will gain water by osmosis and, as it has **no cell wall to create turgor pressure**, will continue to do so until the cell membrane is stretched too far and **it bursts**
- Multicellular organisms must therefore **maintain isotonic tissue fluid** around their cells to prevent these harmful changes from happening

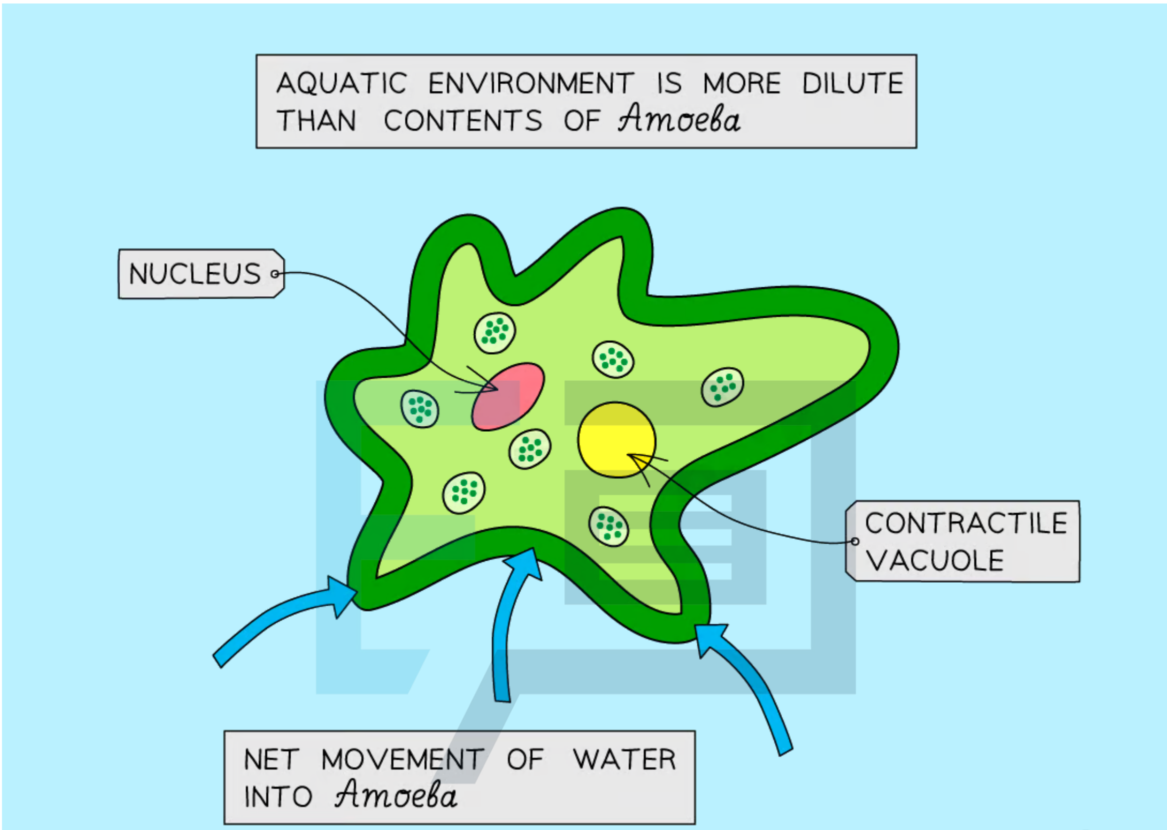
Osmosis in animal cells diagram



The effects of water movement on animal cells

- Some unicellular organisms, such as the protozoan ***Amoeba***, live in freshwater aquatic habitats that is **hypotonic** to their cytoplasm.
  - There will be a **constant net influx** of water into the organism by osmosis, which **increases** the internal pressure

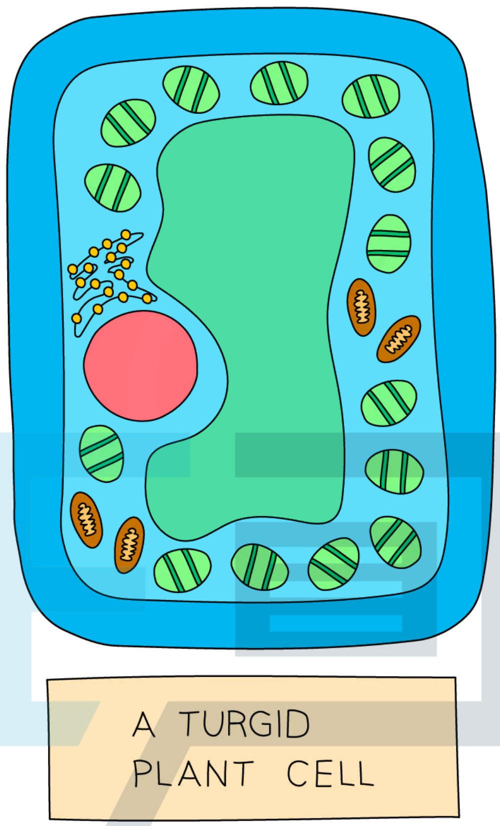
- To prevent these organisms from bursting, they contain structures called **contractile vacuoles** in their cytoplasm
  - Excess water will be continuously collected in the contractile vacuole and pumped out of the organism to maintain the osmotic concentration of the cytoplasm



The contractile vacuole is responsible for removing excess water from Amoeba to prevent them from bursting

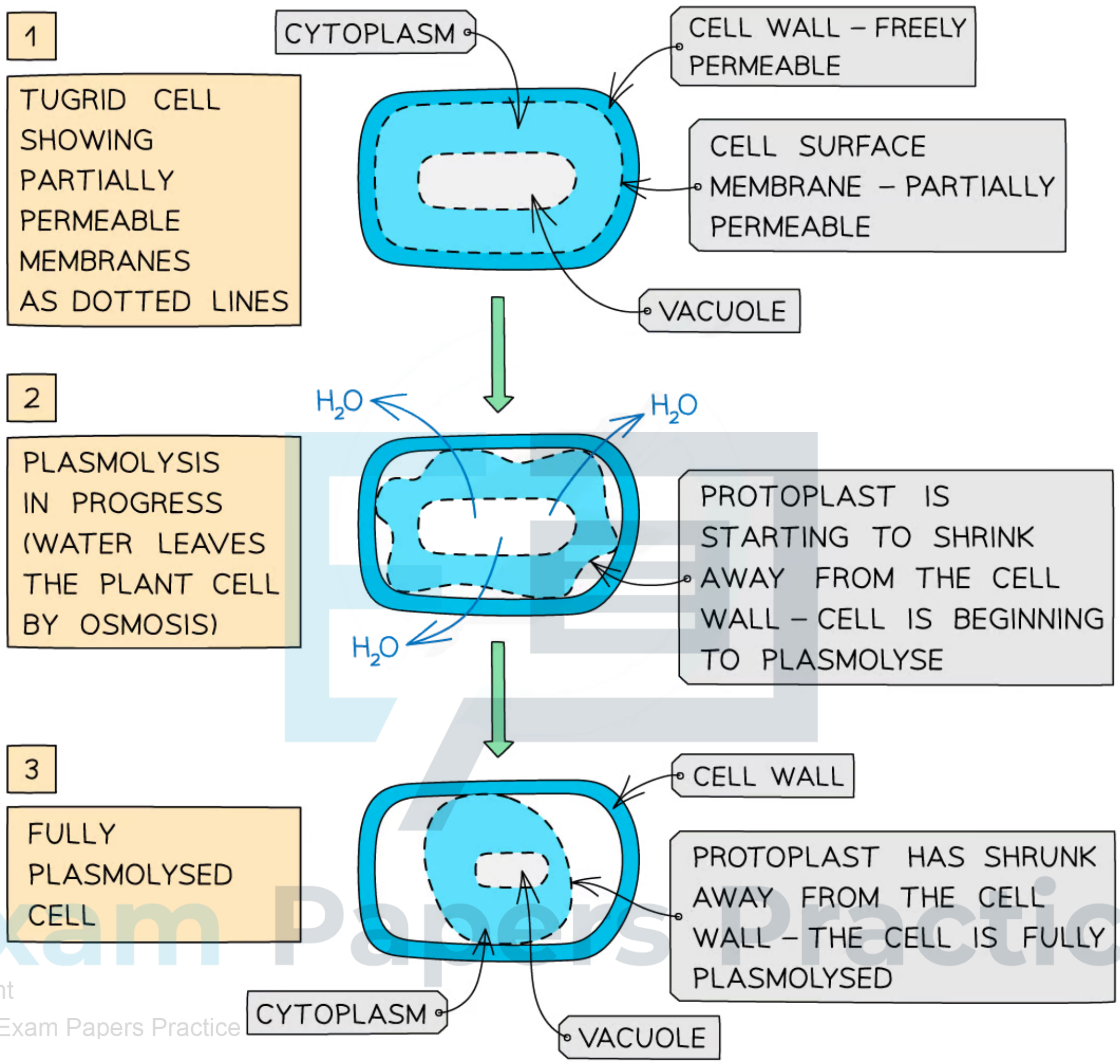
Effects of Osmosis on Cells With Cell Walls

- If a plant cell is placed in a **hypotonic solution**, water will **enter** the plant cell through its partially permeable cell surface membrane by **osmosis**, as the solution has a **lower solute concentration** than the plant cell
- As water enters the **vacuole** of the plant cell, the **volume** of the plant cell **increases**
- The expanding **protoplast** (living part of the cell inside the cell wall) pushes against the cell wall and **pressure builds up** inside the cell
  - This pressure is known as **turgor pressure**
  - The inelastic cell wall prevents the cell from bursting
- The pressure created by the cell wall also stops too much water entering and this also helps to prevent the cell from bursting
- When a plant cell is fully inflated with water and has become rigid and firm, it is described as fully **turgid**
- This turgidity is important for plants as the effect of all the cells in a plant being firm is to provide **support** and **strength** for the plant – making the plant stand upright with its leaves held out to catch sunlight
- If plants do not receive enough water the cells cannot remain rigid and firm (turgid) and the plant **wilts**



The net movement of water into a plant cell will increase the turgor pressure and result in a turgid cell

- If a plant cell is placed in a **more concentrated solution**, water will **leave** the plant cell through its partially permeable cell surface membrane by **osmosis**
- As water leaves the **vacuole** of the plant cell, the volume of the plant cell **decreases**
- The protoplast gradually shrinks and no longer exerts pressure on the cell wall
- As the protoplast continues to shrink, it begins to pull away from the cell wall
- This process is known as **plasmolysis** – the plant cell becomes **flaccid** and is said to be **plasmolysed**



Plasmolysis of a plant cell that has been placed in a solution with a lower water potential than the cell itself

Exam Tip

Remember – plant cell membranes are composed of a phospholipid bilayer and are partially permeable (only certain molecules can cross), whereas plant cell walls are made of cellulose and are freely permeable. Thus, in a plasmolysed cell, the external solution will be exerting pressure on the protoplast, that is, there is not an empty space between the cell wall and protoplast.

Application of Isotonic Solutions in Medicine

- In some cases, patients may require an **intravenous (IV) drip** to treat dehydration or to deliver medicine directly into the bloodstream
- It is important that the solution in the IV drip is **isotonic** in relation to blood plasma
  - The solution is usually a 0.9% sterile saline solution (saltwater)
  - If the solution was **hypotonic** then there would be a net movement of water into red blood cells **causing them to burst**
    - This would result in a **decrease** in the oxygen carrying capacity of blood
  - A **hypertonic** IV solution would result in a net movement of water out of the red blood cells causing them to **shrivel and become crenated**
    - This would **increase** the risk of blood clots forming as these red blood cells cannot move freely through capillaries
- Another important medical application of isotonic solutions is in the preparation of **donated human organs** for transplant surgery
  - These organs must be kept in an isotonic saline solution to **prevent damage** to the cells due to the net movement of water by osmosis

Osmosis: Skills

Changes in Plant Tissue due to Water Movement

Experimental design; accurate quantitative measurements in osmosis experiments are essential

- Planning is an essential part of experimental biology, it will help ensure that valid conclusions can be made
- **Preliminary** (meaning "to come before") **research** must be completed to ensure the experiment design considers:
  - The **results** that will be collected
    - **Quantitative data** allows more valid conclusions to be made
    - **Qualitative data** (descriptive) can be useful to support the conclusions
  - How **measurements** will be made so they are as precise and as **accurate** as possible
    - The choice of **apparatus** and **techniques** should be **based on the science** surrounding the issue being investigated
  - How many **repeats** will be undertaken to ensure the data collected is reliable
  - The **variables** that will be **tested** and need to be **controlled**
- Once the preliminary research has been completed then **preliminary studies** can be conducted to further aid the experimental design
- These studies are very important for:
  - Identifying additional variables that affect the experiment
  - Finding the best way to control these variables
  - Deciding on the quantities and volumes of substances that are needed so that you do not run out of reactants/reagents
- Any experiment conducted without preliminary research or studies is likely to be invalid as the other variables that affect the results in the experiment will not have been identified and controlled

Estimation of osmotic concentration in tissues by bathing samples in hypotonic and hypertonic solutions

- The **osmotic concentration** (or **solute concentration**) in tissues can be estimated by bathing samples of plant tissue in solutions of different tonicity
- A **hypotonic solution** has a **lower osmotic concentration** than the tissue being bathed in it (so the tissue will increase in mass or length) whereas a **hypertonic solution** has a **higher osmotic concentration** (so the tissue will decrease in mass or length)
- An **isotonic solution** will have the **same osmotic concentration** as the tissue (so the mass or length will remain unchanged)
- It is possible to investigate the effects of immersing plant tissue in **solutions of different osmotic concentrations** and to **use the results to estimate the osmotic concentration of the**

plant tissue itself

- The most common osmosis practical of this kind involves cutting **cylinders of potato** and placing them into solutions with a **range of different osmotic concentrations**
  - **Usually sucrose solutions of increasing concentration** – at least 5 different concentrations are usually required

Apparatus

- Potato x 2 (same variety)
- Cork borer (e.g. 5mm)
- White tile
- Scalpel
- 10cm ruler or vernier calipers
- Weighing balance (2dp)
- 10 cm^3 sucrose solution (0 mol/dm^3, 0.25 mol/dm^3, 0.5 mol/dm^3, 0.75 mol/dm^3, 1.00 mol/dm^3)
- 5 test tubes (in test tube rack)
- 10 cm^3 measuring cylinder
- Paper towels

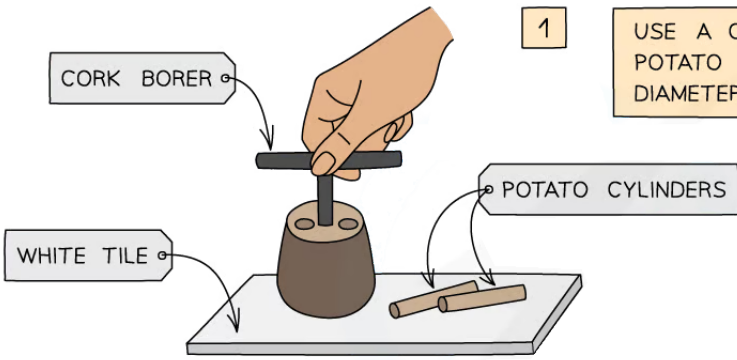
Method

- The required number of potato cylinders are cut
  - At least 5 for each of the solutions you are testing to ensure you have sufficient repeats
- They are all cut to the **same length** and, once blotted dry to remove any excess moisture, their **initial mass is measured and recorded** before placing into the solutions
- The potato cylinders are left in the solutions for a set amount of time (e.g. 30 minutes), usually in a water bath (set at around 30°)
  - The solutions are prepared by serial dilutions of a specific solute concentration determined during the preliminary research/trials)
- The cylinders are then removed and **dried**
  - This is done to **remove excess liquid**
- The **final length and mass** of each potato cylinder is then measured and recorded

OSMOSIS METHOD

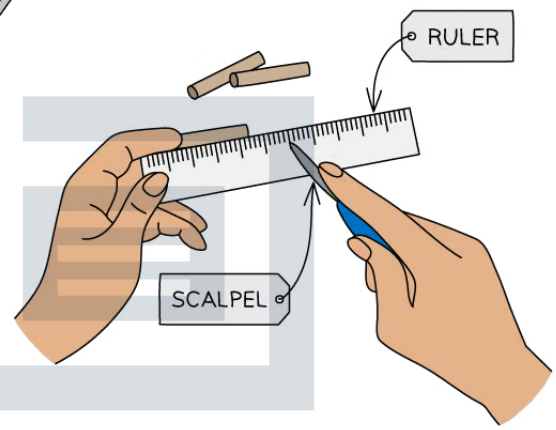
1

USE A CORK BORER TO CUT 5 POTATO CYLINDERS OF THE SAME DIAMETER



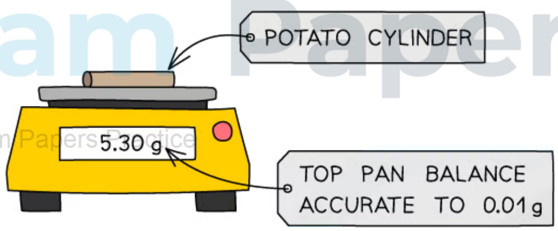
2

USE A SCALPEL AND RULER TO TRIM EACH POTATO CYLINDER SO THEY ARE ALL THE SAME LENGTH



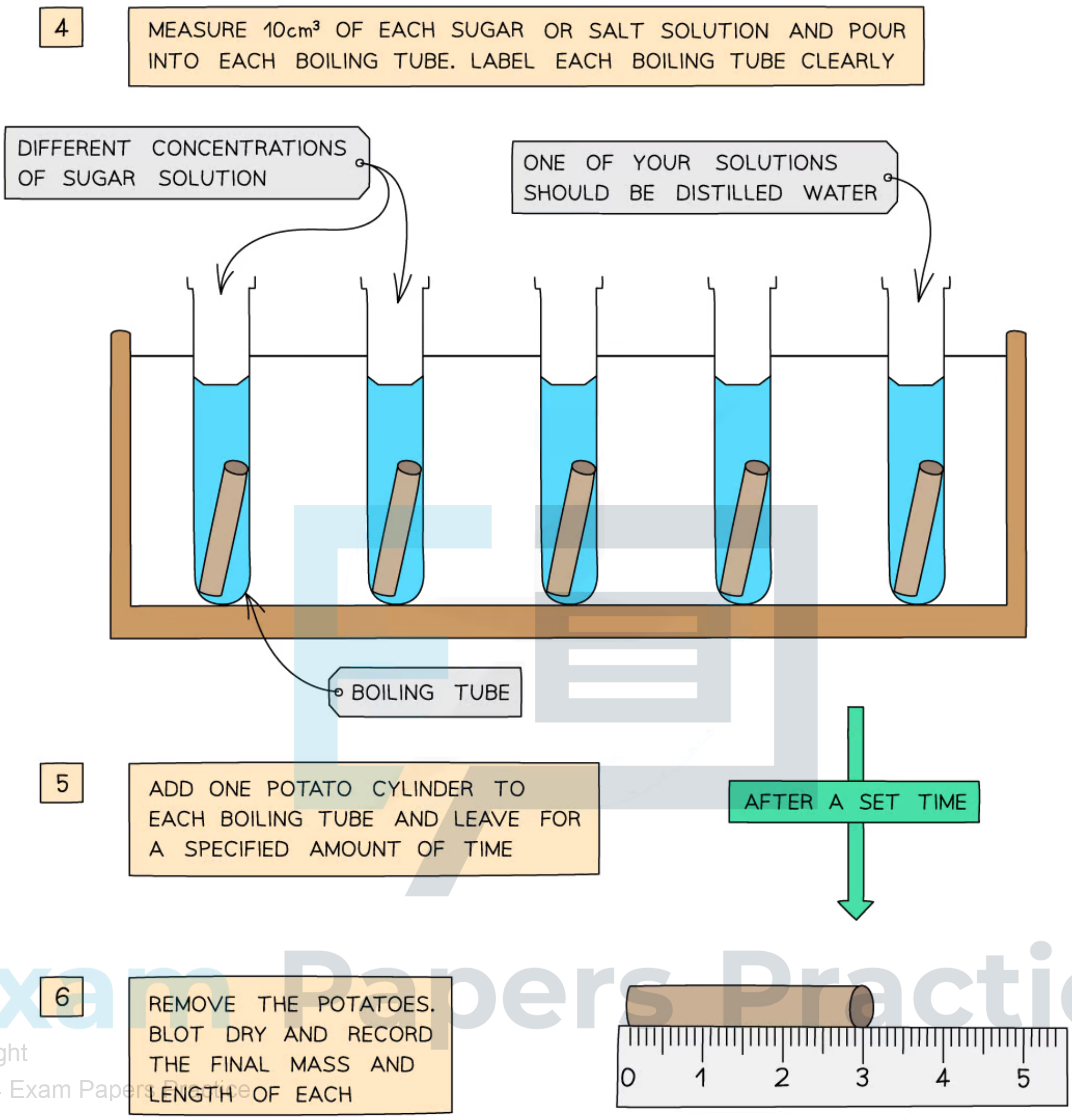
3

MEASURE THE MASS OF EACH POTATO CYLINDER AND RECORD IN A TABLE OF RESULTS



YOU WILL ALSO WANT TO RECORD THE INITIAL LENGTH (mm) IN A SIMILAR TABLE

Concentration of sucrose solution mol/dm^3	Initial mass (g)	Final mass (g)	Change in mass (g)	% change in mass
0 (distilled water)	5.30			
0.25	5.32			
0.50	5.29			
0.75	5.31			
1.00	5.29			



You will need to use apparatus appropriately to measure out the volumes of your solutions and record your measurements

Analysis

- The **percentage change** in mass for each potato cylinder is calculated and then plotted

OSMOSIS ANALYSIS

Concentration of sucrose solution mol/dm³	Initial mass (g)	Final mass (g)	Change in mass (g)	% change in mass
0 (distilled water)	5.30	5.80	+0.50	9.4
0.25	5.32	5.42	+0.10	?
0.50	5.29	5.24	−0.05	−1.0
0.75	5.31	5.11	−0.20	−3.8
1.00	5.29	5.02	−0.27	−5.1

1 CALCULATE THE PERCENTAGE CHANGE IN MASS FOR EACH CYLINDER

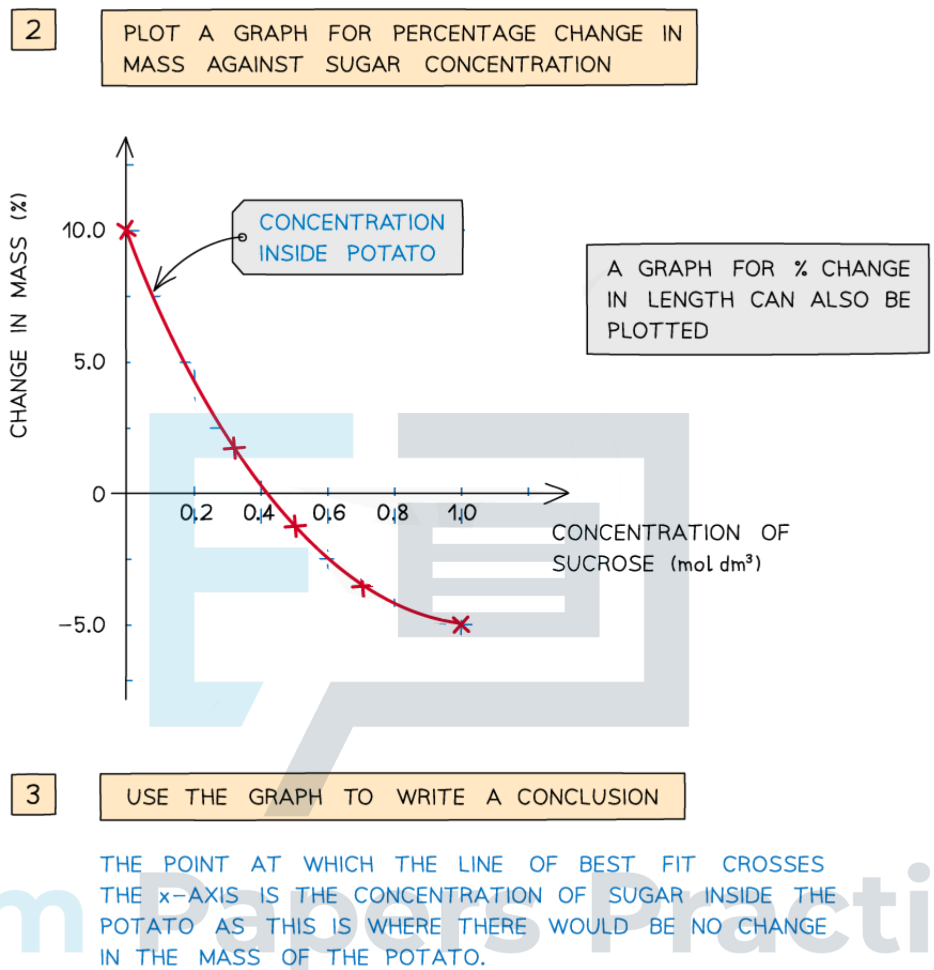
$$\frac{(\text{FINAL MASS} - \text{INITIAL MASS})}{\text{INITIAL MASS}} \times 100$$

e.g. FOR 0.25 mol dm³

$$= \frac{(5.42 - 5.32)}{5.32} \times 100$$

= 1.9%

To find the percentage change in mass, the change in mass must be divided by the initial mass and then multiplied by 100



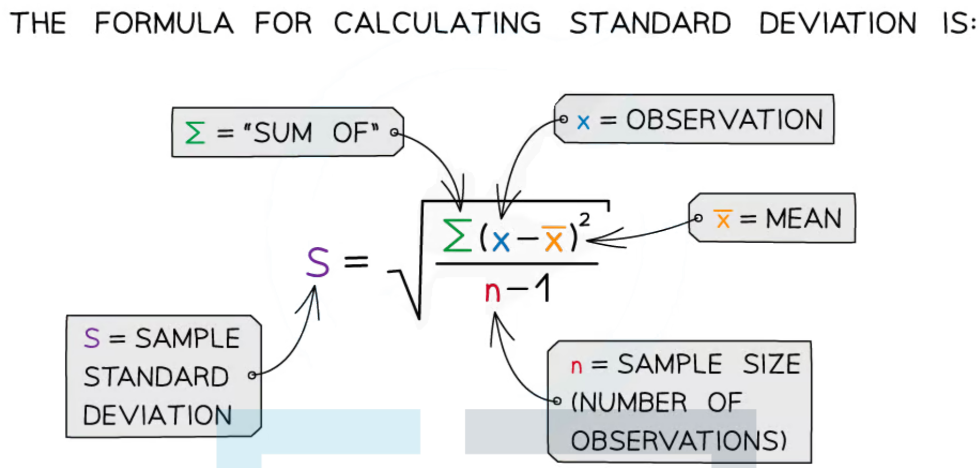
A positive percentage change in mass indicates that the potato has gained water by osmosis

- A **positive** percentage change in mass indicates that the potato has gained water by osmosis (net movement of water from the solution into the potato) meaning the **solution** had a **lower osmotic concentration** than the potato
  - The gain of water makes the potato cells **turgid,** as the water exerts turgor pressure (or hydrostatic pressure) on the cell walls – the potatoes will feel hard
- A **negative** percentage change suggests the opposite, that is, the solution had a **higher osmotic concentration** than the potato
  - The potato cylinder in the **strongest sucrose concentration** will have **decreased in mass** the most as there is the **greatest concentration gradient** in this tube between the potato cells (lower osmotic concentration) and the sucrose solution (higher osmotic concentration)

    - More water molecules will move out of the potato cells by **osmosis**, making them **flaccid** and decreasing the mass of the potato cylinder – the potato cylinders will feel floppy
    - If looked at underneath the microscope, cells from this potato cylinder might be **plasmolysed**, meaning the cell membrane has pulled away from the cell wall
- If there is a potato cylinder that has neither increased nor decreased in mass, it means there was **no overall net movement of water** into or out of the potato cells
- The solution that this particular potato cylinder was in had the **same osmotic concentration** as the solution found in the cytoplasm of the potato cells, so there was **no concentration gradient** and therefore no net movement of water into or out of the potato cells
- The concentration of sucrose inside the potato cylinders can be found if a graph is drawn showing how the percentage change in mass changes with the concentration of sucrose solution
- The point at which the line of best fit **crosses the x-axis** is the concentration of sucrose inside the potato cylinders
- Calculating the **standard deviation** and **standard error** for the results of this experiment would allow the reliability of the length and mass measurements to be compared

Standard deviation

- It is important to have sufficient repeats when conducting experiments, like the one above, in order to ensure **reliable results**
    - These repeat values can be used to calculate a **mean** mass for the potato cylinders in each sucrose concentration
- The mean is a more informative statistic when it is provided alongside **standard deviation**
- Standard deviation measures the **spread of data** around the mean value
    - This is very useful when comparing consistency between different data sets during data analysis
- The standard deviation can be calculated using the following formula:



Standard error

- The standard error gives an indication of how close the **sample mean** is to the **true population mean**
  - A large sample size results in a smaller standard error and the closer the sample mean will be to the true population mean
- Standard error (*SE*) can be calculated by dividing the standard deviation (*S*) by the square root of the sample size (*n*):

$$SE = \frac{S}{\sqrt{n}}$$

- When graphs of mean values are drawn, the standard error can be shown as **error bars** added to each plotted value
  - This demonstrate the **deviation** of the sample mean from the true population mean
  - Error bars will extend above and below the data points to indicate variability
- If error bars **overlap** then it suggest that the **difference** between the mean values is **not significant** while **non-overlapping** error bars indicate a **significant difference** between the means

Water Potential (HL)

Water Potential

- Water potential (Ψ) can be defined as follows:

  The potential energy of water, per unit volume, relative to pure water

  - Potential energy is the energy stored in an object due to its position in relation to other objects
  - In this instance it is the **energy stored in water molecules** due to their position in relation to other molecules, e.g. **molecules of a solute** in a solution
- The unit of water potential is usually **kilopascals**, or **kPa**
- Water potential is always stated **relative to pure water** at atmospheric pressure and 20 °C:
  - The water potential of **pure water** is given a value of **0 kPa**
    - Note that the water molecules in pure water do technically have potential energy, but it is **impossible to determine**, and this designated value of zero allows for a **simple comparison** with solutions
  - As **solutes** are added to a solution, the **water potential decreases** into **negative values**; solutions with a high solute concentration have a **lower water potential**
    - Energy is stored in hydrogen bonds between solute molecules and water molecules in a solution, meaning that **less energy is available as potential energy**
    - Water molecules in a solution with a higher solute concentration therefore have **less potential energy**

Water Movement & Water Potential

- Water potential describes **the tendency of water molecules to move** from a **dilute** solution to a solution with a **high solute concentration**
  - Solutions with a high water potential contain water molecules with a **greater potential energy for movement**, and therefore a greater tendency to move
  - Solutions with a low water potential contain many hydrogen bonds between water molecules and solute molecules, **reducing the potential energy for movement** of the water molecules, and therefore their tendency to move
- Water molecules move **from an area of high water potential to an area of low water potential**
  - It can also be said that:
    - Water molecules move from an area of higher potential energy to an area of lower potential energy
    - Water molecules move from an area of low solute concentration to an area of high solute concentration

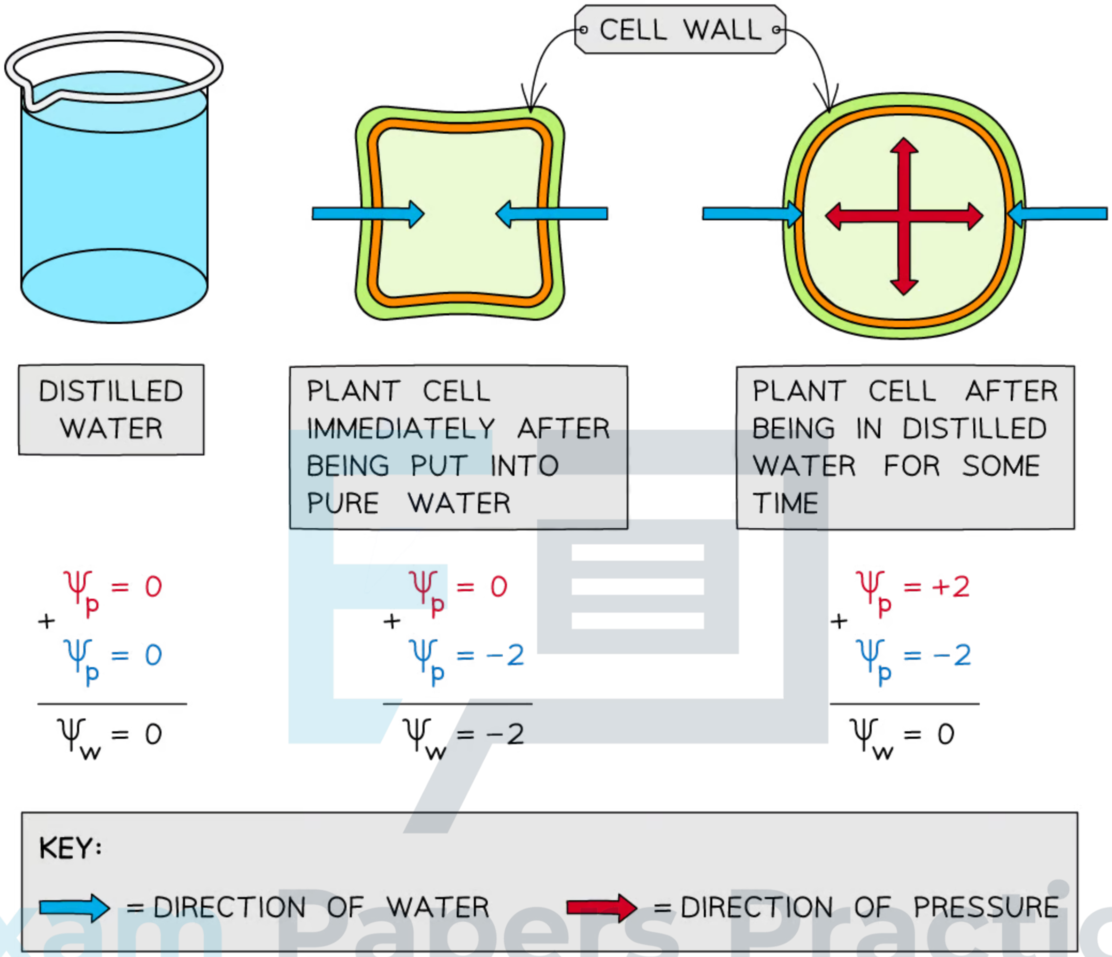
Water Movement in Plant Tissue (HL)

Solute & Pressure Potential in Plant Cells

- **Water potential** measures the **potential energy of water compared to pure water**
  - we use the symbol **ψ or ψw** to represent water potential
  - Pure water has a water potential of zero at standard temperature and pressure
- **Pressure potential** is the hydrostatic pressure **to which water in a liquid phase is subjected**
  - it is also referred to as turgor potential or turgor pressure and represented by **ψp**
  - **Pressure potentials are generally positive** inside cells, although negative pressure potentials occur in xylem vessels where sap is being transported under tension

- **Solute potential**, also called osmotic potential, is a component of water potential and is represented by the symbol Ψ_w
  - Solutes reduce water potential by consuming some of the potential energy available in the water, this results in a **negative solute potential**
  - Solute molecules can bind to water molecules using hydrogen bonds, this allows them to dissolve in water
  - The energy in the hydrogen bonds between solute molecules and water is no longer available elsewhere which is why the water potential is reduced, in other words the potential energy that was available in the water is transferred to the hydrogen bonds
  - Therefore **solute potentials can range from zero downwards as the concentration of solutes increases**
- The equation **ψw = ψs + ψp** can be used to summarise the interactions between solute potential, water potential and pressure potential
  - Water potential is directly proportional to the solute concentration and pressure potential

Water potential diagram



The water potential is affected by the solute potential and the pressure potential

Water Movement in Plant Tissue

- When plant tissue is bathed in either a hypotonic or hypertonic solution some changes occur
  - In a hypotonic solution plant cells will gain water and will have a higher water potential (closer to zero)
  - Plant cells will lose water in a hypertonic solution and will have a lower water potential (more negative)
- The reason for these changes is
  - In a **hypotonic solution**
    - **Pressure potentials increase** because there are a greater number of water molecules present in the cell and therefore more molecules to exert pressure
      - With more water molecules comes greater potential energy meaning more energy for molecules to move and and exert pressure on the cell membrane (the cell becomes turgid)
    - **Solute potentials decrease** (be more negative) because the number of solute molecules relative the number of water molecules is less
  - In a **hypertonic solution**
    - As water molecules move out of the cell the **pressure potential is decreased**
      - There are fewer water molecules in the plant cell and so decreased potential energy of water to move and exert pressure on the cell membrane (the cell becomes flaccid)
    - Solute potential increase because there are greater numbers of solute molecules relative to water molecules

Exam Tip

The terms hypotonic and hypertonic can be confusing, here's a silly tip to help you remember

- Hypotonic - think hippo (as in the animal!) which really like lots of water; hypotonic (hippotonic) solutions have lots of water molecules
- Hypertonic - think hyperactive, this is how some people can get after lots of sugar, which is a solute, so hypertonic solutions have lots of solutes (e.g. sugar)