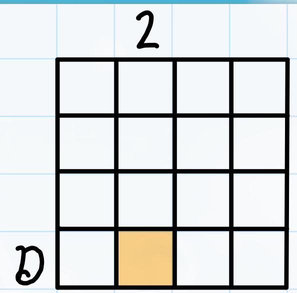
D2.3 Water Potential

Ver. 2

Guiding Questions
What factors affect the movement of water into or out of cells?
How do plant and animal cells differ in their regulation of water movement?

Linking Questions
What variables influence the direction of movement of materials in tissues?
What are the implications of solubility differences between chemical substances for living organisms?



Theme: Continuity + Change

Level of Organization: Cells

Written and drawn by:

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SL Learning Outcomes

D2.3.1	Solvation with water as the solvent	Include hydrogen bond formation between solute and water molecules, and attractions between both positively and negatively charged ions and polar water molecules.
D2.3.2	Water movement from less concentrated to more concentrated solutions	Students should express the direction of movement in terms of solute concentration, not water concentration. Students should use the terms "hypertonic", "hypotonic" and "isotonic" to compare concentration of solutions.
D2.3.3	Water movement by osmosis into or out of cells	Students should be able to predict the direction of net movement of water if the environment of a cell is hypotonic or hypertonic. They should understand that in an isotonic environment there is dynamic equilibrium rather than no movement of water.
D2.3.4	Changes due to water movement in plant tissue bathed in hypotonic and those bathed in hypertonic solutions	**Application of skills:** Students should be able to measure changes in tissue length and mass, and analyse data to deduce isotonic solute concentration. Students should also be able to use standard deviation and standard error to help in the analysis of data. Students are not required to memorize formulae for calculating these statistics. Standard deviation and standard error could be determined for the results of this experiment if there are repeats for each concentration. This would allow the reliability of length and mass measurements to be compared. Standard error could be shown graphically as error bars.
D2.3.5	Effects of water movement on cells that lack a cell wall	Include swelling and bursting in a hypotonic medium, and shrinkage and crenation in a hypertonic medium. Also include the need for removal of water by contractile vacuoles in freshwater unicellular organisms and the need to maintain isotonic tissue fluid in multicellular organisms to prevent harmful changes.
D2.3.6	Effects of water movement on cells with a cell wall	Include the development of turgor pressure in a hypotonic medium and plasmolysis in a hypertonic medium.
D2.3.7	Medical applications of isotonic solutions	Include intravenous fluids given as part of medical treatment and bathing of organs ready for transplantation as examples.

HL Learning Outcomes

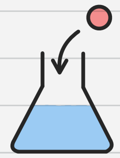
D2.3.8	Water potential as the potential energy of water per unit volume	Students should understand that it is impossible to measure the absolute quantity of the potential energy of water, so values relative to pure water at atmospheric pressure and 20°C are used. The units are usually kilopascals (kPa).
D2.3.9	Movement of water from higher to lower water potential	Students should appreciate the reasons for this movement in terms of potential energy.
D2.3.10	Contributions of solute potential and pressure potential to the water potential of cells with walls	Use the equation $\psi_w = \psi_s + \psi_p$. Students should appreciate that solute potentials can range from zero downwards and that pressure potentials are generally positive inside cells, although negative pressure potentials occur in xylem vessels where sap is being transported under tension.
D2.3.11	Water potential and water movements in plant tissue	Students should be able to explain in terms of solute and pressure potentials the changes that occur when plant tissue is bathed in either a hypotonic or hypertonic solution.

D2.3.1—Solvation with water as the solvent. D2.3.2—Water movement from less concentrated to more concentrated solutions. D2.3.3—Water movement by osmosis into or out of cells. D2.3.5—Effects of water movement on cells that lack a cell wall

Dissolve: process of solute passing into solution. Occurs when attractive forces between solvent and solute > attractive forces holding solute together

Solvation: interaction of a solvent with dissolved molecules or ions (solutes)

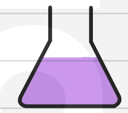
↳ **aqueous solution** is one where water is the solvent. This occurs when water is attracted and interacts with polar or charged solutes (🔗 water A1.1)



solute - substance being dissolved in solution

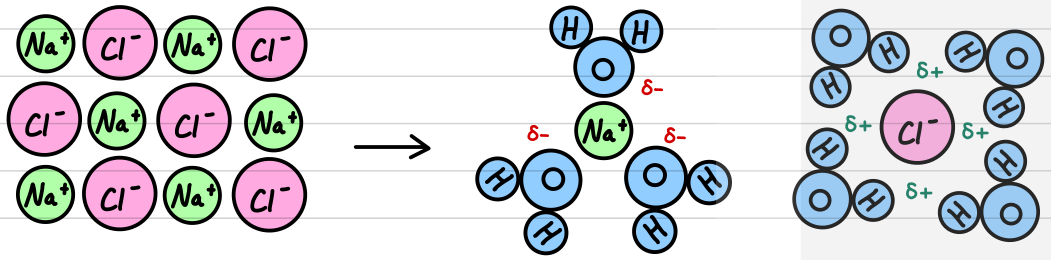
solvent - substance in which solute dissolves

→



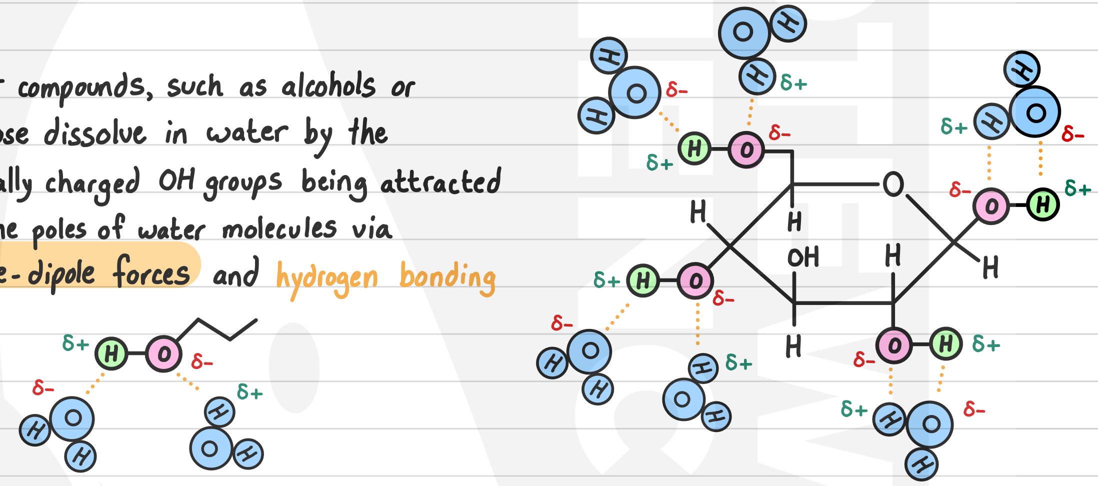
solution - homogeneous mixture composed of two or more substances

ex: ionic compounds such as sodium chloride (NaCl) dissolve in water by dissociating into ions and being attracted to the partially charged poles of water molecules via **ion-dipole forces**. Water molecules form 3-D hydration shells, isolating the ions



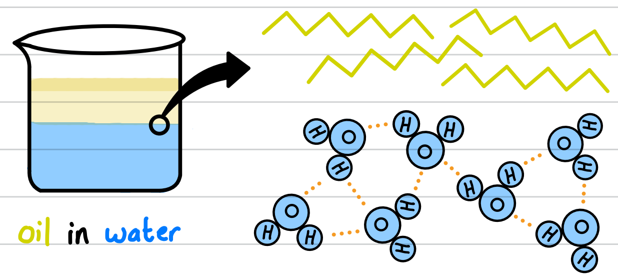
electrostatic force of attraction < ion-dipole interaction with water

ex: polar compounds, such as alcohols or glucose dissolve in water by the partially charged OH groups being attracted to the poles of water molecules via **dipole-dipole forces** and **hydrogen bonding**



glucose-glucose attraction < attractive forces between glucose and water

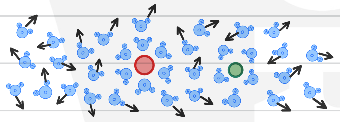
ex: non-polar molecules such as lipids cannot form hydrogen bonds or dipole interactions with water. Thus water molecules preferentially H-bond with each other, excluding non-polar molecules



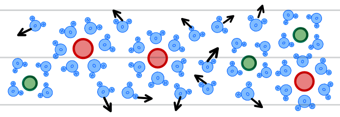
oil in water

Aqueous solutions involve the continual movement of both water and the solutes. In liquids, molecules are constantly breaking and forming intermolecular bonds.

↳ In solutions, attractive forces between solvent and solute > attractive forces between solute molecules
∴ the more concentrated the solution (more solute/solvent), the more the movement of water is restricted and reduced (viscous)



↓ solute [ ]
↑ free water movement



↑ solute [ ]
↓ free water movement

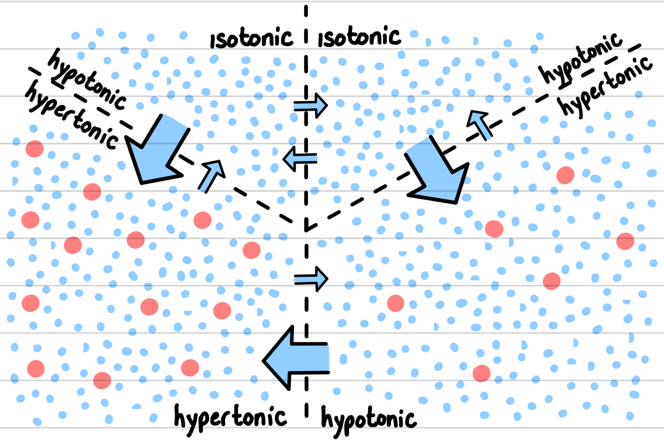
↳ The relative concentration of solutions can be compared and used to predict net water movement across membranes (from one solution to another)

※ water movement into and out of cells occurs primarily via aquaporins

isotonic: a solution of equal osmolarity (solute concentration) to another

hypertonic: a solution of higher osmolarity (solute concentration) to another

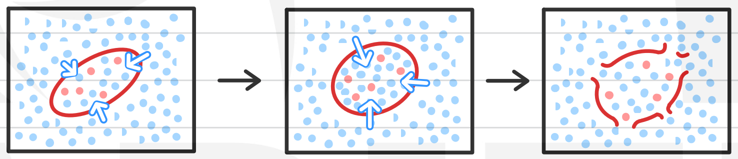
hypotonic: a solution of lower osmolarity (solute concentration) to another



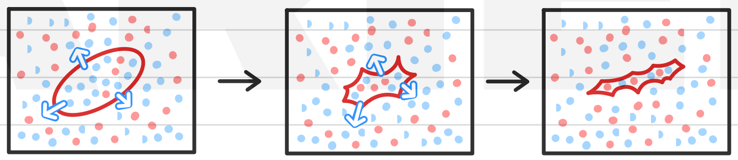
- if two solutions are isotonic, the rate of movement between them is equal (dynamic equilibrium) ∴ no net water movement
- more free water movement in a hypotonic solution, relative to a hypertonic solution ∴ net movement of water from hypotonic to a hypertonic solution (low to high solute concentration) via osmosis

In cells which lack a cell wall (ex: animals and protists), the influx or outflux of water can lead to cellular damage
∴ regulating cytosol osmolarity is a crucial constant homeostatic process (osmoregulation)

↳ cell in hypotonic solution will swell and potentially burst (cytolysis) due to net influx of water.

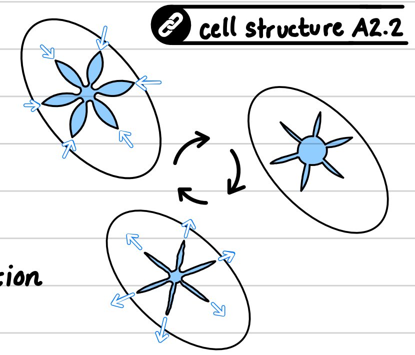


↳ cell placed in hypertonic solution will shrink and crenate, due to net outflux of water.

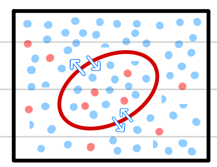


Ex: *Paramecium* reside in freshwater environments, thus water is constantly entering ∴ to prevent cytolysis, they use contractile vacuoles to actively remove water as a form of osmoregulation

🔗 cell structure A2.2



↳ cell placed in an isotonic solution will remain at a ~ constant size due to zero net water movement - which is ideal for cell function

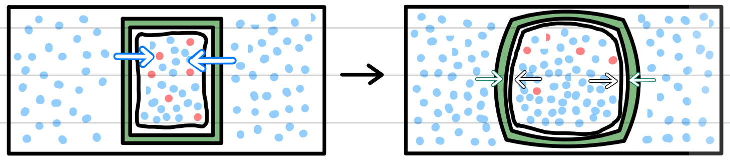


※ multicellular organisms regulate the extracellular fluid osmolarity, keeping it isotonic to cells
ex: Kidneys regulate blood plasma osmolarity

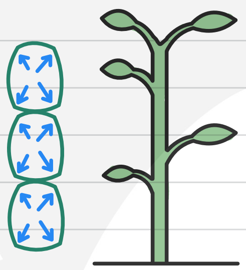
🔗 homeostasis D3.3

In cells that have a cell wall (ex: plants, fungi, bacteria) the influx of water in hypotonic solutions results in the cell swelling but not bursting - resulting in **turgor pressure**: force pushing plasma membrane against cell wall

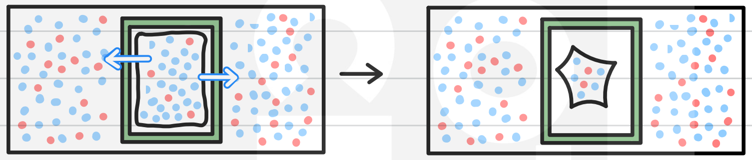
↳ cell in hypotonic medium will swell and become turgid as cell wall is able to resist internal hydrostatic pressure



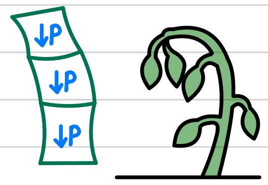
Ex: in multicellular plants, turgid cells provide support due to its strength under compression - allowing the plant to be upright without an endoskeleton



↳ cell in hypertonic medium cytoplasm volume drops, causing plasma membrane to pull away from cell wall - **plasmolysis**



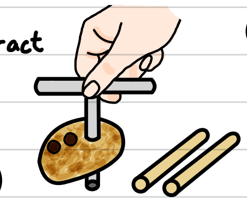
Ex: in multicellular plants, flaccid cells have very low hydrostatic pressure, reducing support and causes plant to wilt. Plasmolyzed cells typically die.



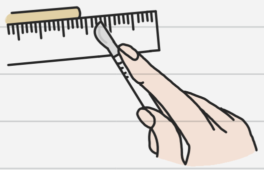
The **osmolarity** (solute particles per solution volume) of plant tissues can be deduced by bathing tissues in varying concentrated (hypertonic and hypotonic) solutions by determining the isotonic solute concentration

↳ Part A - preparing plant tissues

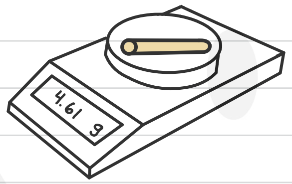
① using cork borer, extract cylindrical samples of chosen plant tissue (potato, carrot, squash)



② using ruler and scalpel cut all tubes to the same length



③ Using a scale, determine the mass of each plant cylinder



↳ Part B - preparing solutions

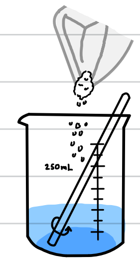
Create a range of solute solutions (NaCl or sucrose) from 0 moldm^{-3} and up (hypotonic to hypertonic)

ex: creating 100 mL of 0.5 moldm^{-3} solution of NaCl

$n = CV = (0.5\,\text{moldm}^{-3})(0.1\,\text{dm}^3)$

$= 0.05\,\text{mol} \times 58.44\,\text{g mol}^{-1}$

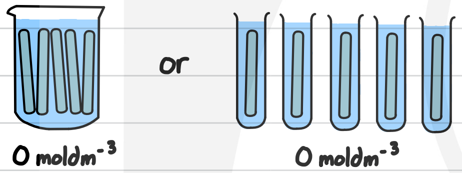
$= 2.92\,\text{g}$ of NaCl dissolved in water and made to final vol of 100 mL



↳ Part C - submerging tissues into solutions

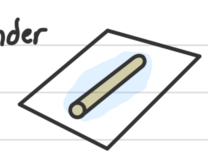
① submerge 5+ cylinders into each solution or place 1 cylinder in a test tube x 5

② wait 1-24 hours (depends on time availability)



↳ Part D - determining change in length and mass

① remove each cylinder and blot excess fluid using tissue



② Using scale and ruler, measure the mass and length of each cylinder

③ Calculate the % change in length and mass

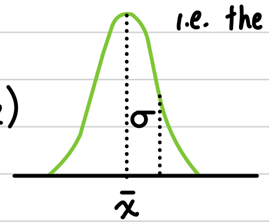
$$\%\ \text{change} = \frac{\text{final} - \text{initial}}{\text{initial}} \times 100$$

※ takes individual variances into account

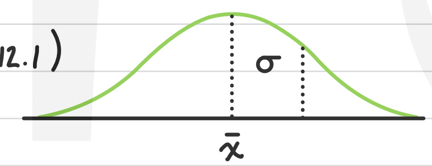
↳ Part E - data processing

- mean ($\bar{x}$) for each experimental group is calculated and graphed
- **standard deviation** (σ): amount of variation of values of a variable about its mean i.e. the dispersion of data in relation to its mean

ex: (10.1, 10.5, 11.0, 10.9, 11.2)
$\bar{x} = 10.7 \quad \sigma = 0.4$



ex: (2.5, 11.3, 11.9, 9.5, 12.1)
$\bar{x} = 9.5 \quad \sigma = 4.0$



data more clustered around mean = ↓σ

data more spread out around mean = ↑σ

- **standard error** (σ_M): how reliably the mean of a sample represents mean of whole population

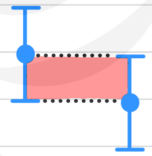
the larger the sample size (n), the smaller the standard error

$$\sigma_M = \frac{\sigma}{\sqrt{n}}$$

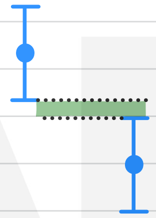
※ typically used if trial sample size >30

↳ Part F - analysis

- error bars represent $\pm 1\sigma_M$ or σ
- degree of overlap can be analyzed:

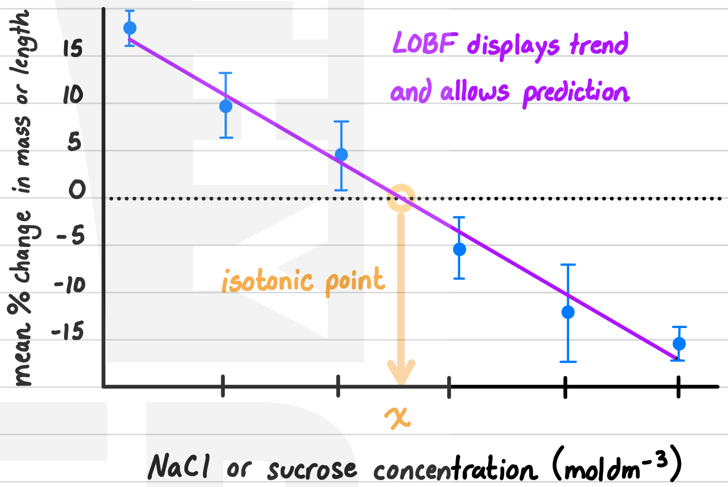


overlap suggests there is no difference between both means



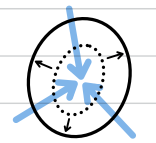
no overlap suggests there is a difference between both means

※ a statistical test needs to be done to confirm this (ex: ANOVA, t-test)



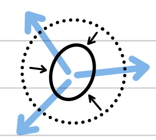
Positive change in mass or length indicates water entered plant tissue

∴ solution is hypotonic relative to plant



Negative change in mass or length indicates water left plant tissue

∴ solution is hypertonic relative to plant



- point x is the predicted concentration where the plant tissue did not gain or lose mass or length, i.e. the solution is isotonic and there is no net water movement due to osmosis ∴ this is the predicted osmolarity of the plant tissue
- experiment can be repeated at and around concentration x in order to confirm prediction

HL D2.3.8—Water potential as the potential energy of water per unit volume. D2.3.9—Movement of water from higher to lower water potential. D2.3.10—Contributions of solute potential and pressure potential to the water potential of cells with walls. D2.3.11—Water potential and water movements in plant tissue

Physics review

energy : the ability to do work. Can be held in different stores

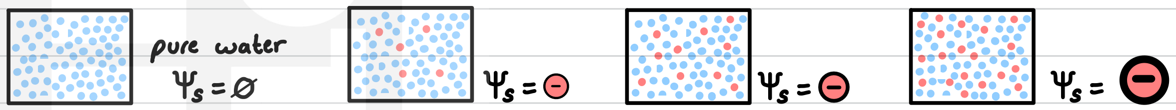
potential energy : energy held by something due to its relative position
ex: gravitational, elastic, electric, chemical

Water potential (Ψ): potential energy of water per unit volume, measured in kPa or MPa

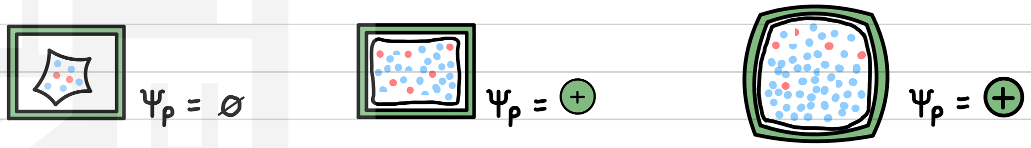
↳ the absolute quantity of potential energy cannot be determined, thus all values are relative to pure water (at 1atm, 20°C) which has a value of 0KPa

↳ can be calculated using the following formula: Water potential (Ψ_w) = Solute potential (Ψ_s) + pressure potential (Ψ_p)

Solute potential (Ψ_s) also called osmotic potential reduces water potential as energy is released during the solute-water bond formation during solvation ∴ reducing energy held by water. The more solutes dissolved in water, the more negative Ψ_s ∴ reducing water potential

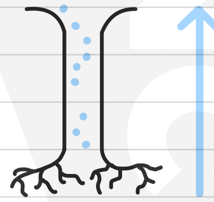


pressure potential (Ψ_p) increases water potential the higher it is as more pressure provides more potential energy in the system. The more turgid (positive pressure) the cell, the higher its pressure potential. ※ atmospheric pressure has Ψ_p of $\varnothing$



↳ while pressure potentials are generally positive inside cells (turgor pressure), they can also be negative under tension ex: during transpiration, water evaporates and exits leaves, causing a negative pressure potential inside xylem vessels where water and sap are being carried up the plant under tension ∴ water potential gradient from soil to leaves

outside Ψ_w = −100.0 MPa
leaves Ψ_w = −1.0 MPa
xylem Ψ_w = −0.7 MPa
soil Ψ_w = −0.3 MPa

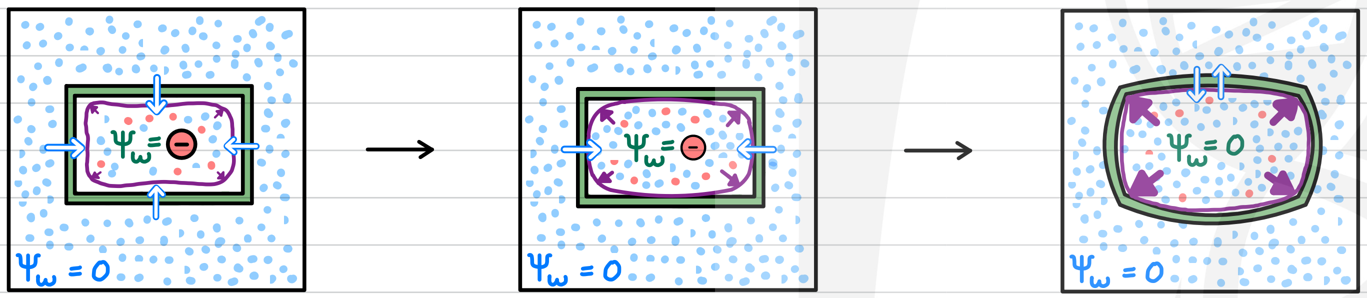


water during transpiration moves from regions of higher to lower water potential
soil → roots → xylem → leaf cells → leaf air pockets → outside via stomata
↳ ensure they are hypertonic to soil by actively moving solutes in (↓Ψ_w)

$\Psi_w = \Psi_s + \Psi_p$ explains the movement of water via osmosis, i.e. water moves from a region of higher water potential to lower water potential across a semi-permeable membrane

transport B3.2

Bathing plant tissue in a hypotonic solution (higher Ψ_w than cell)

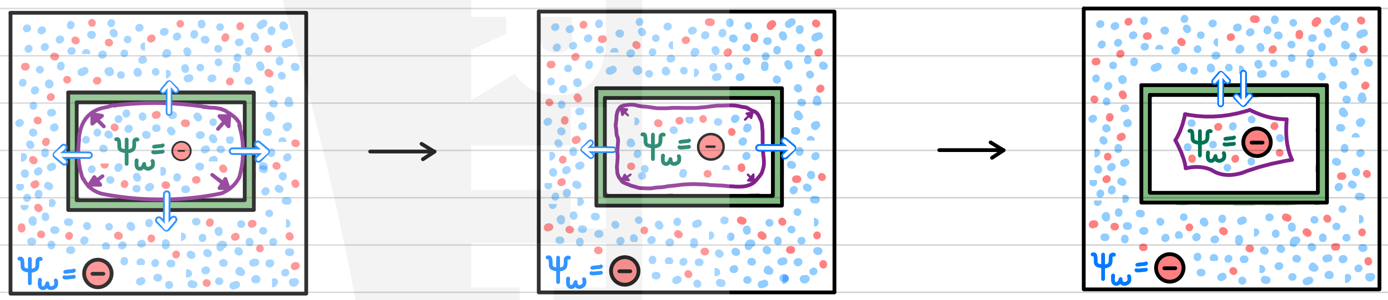


plant ⊖Ψ_s > ⊕Ψ_p
plant Ψ_w < solution Ψ_w
∴ water will move into plant

as water enters cell its Ψ_w is increasing:
Ψ_s is getting less negative (more dilute)
Ψ_p is getting larger (more turgor pressure)

Eventually Ψ_p rises so high that it causes Ψ_w to be 0 despite having solutes ($-\Psi_s = \Psi_p$)

Bathing plant tissue in a hypertonic solution (lower Ψ_w than cell)



plant ⊖Ψ_s > ⊕Ψ_p
plant Ψ_w > solution Ψ_w
∴ water will move out of plant

as water leaves cell its Ψ_w is decreasing:
Ψ_s is getting more negative (more concentrated)
Ψ_p is getting smaller (less turgor pressure)

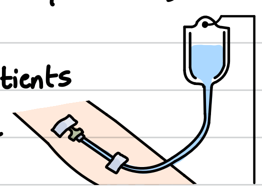
Eventually, Ψ_p falls to atmospheric (∅kPa) ∴ $\Psi_s = \Psi_w$, making plant cell Ψ_w very negative, matching solution

SL D2.3.7—Medical applications of isotonic solutions

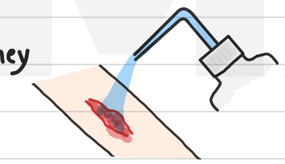
In isotonic solutions there is no net movement of water in/out of human cells, allowing their shape to remain ~constant and optimizing their function. In hypotonic solutions they may lyse and in hypertonic solutions may crenate

↳ in human medical procedures, solutions isotonic to human tissues are used (typically a 0.9% NaCl 'saline' solution)

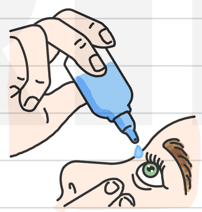
to rehydrate patients saline is given intravenously



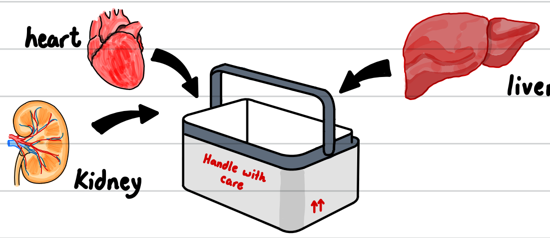
to clean wounds, they are rinsed using saline solution



to treat dry eyes, eye drops with concentration isotonic to eyes is used



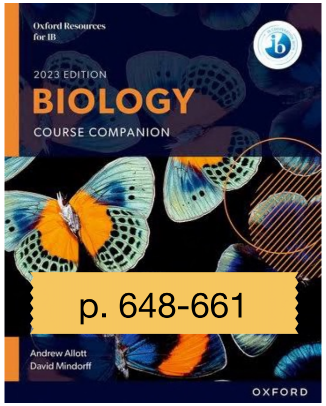
When moving organs for transplant, they are bathed in cool, isotonic solutions for preservation and cell integrity

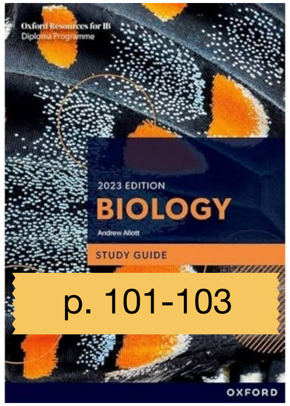


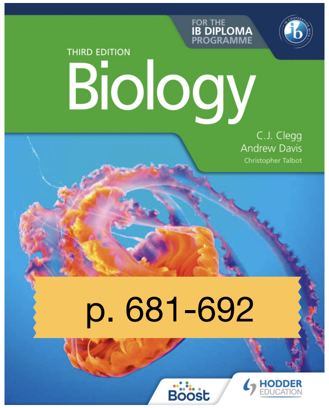
Resource Links

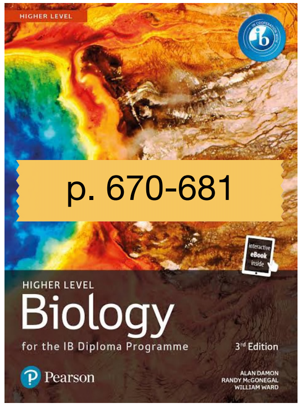
each resource is hyperlinked

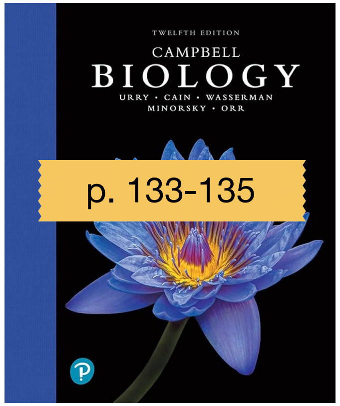
Textbooks



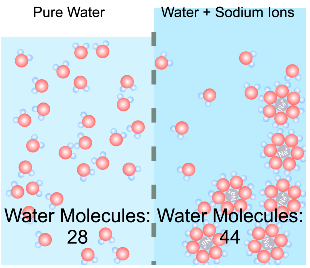




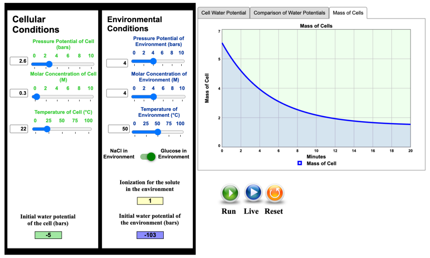




Simulators / Interactives

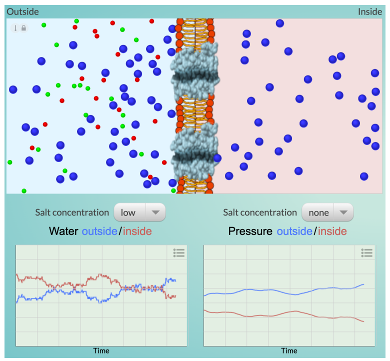


Osmosis

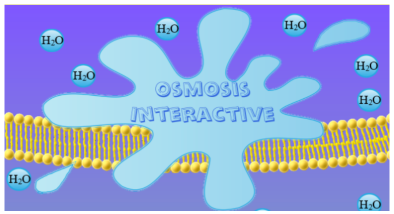


Water potential

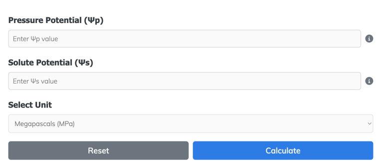
Transpiration and water potential



Osmosis, equilibrium and osmotic pressure



Osmosis game



Water potential calculator

Articles

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Novick, K. A., Ficklin, D. L., Baldocchi, D., Davis, K. J., Ghezzehei, T. A., Konings, A. G., MacBean, N., Raoult, N., Scott, R. L., Shi, Y., Sulman, B. N., & Wood, J. D. (2022). Confronting the water potential information gap. Nature Geoscience, 15(3), 158–164. https://doi.org/10.1038/s41561-022-00909-2