A1.1 WATER

Ver. 2

Guiding Questions
What physical and chemical properties of water make it essential for life?
What are the challenges and opportunities of water as a habitat?

Linking Questions
How do the various intermolecular forces of attraction affect biological systems?
What biological processes only happen at or near surfaces?

1

A

Theme: Unity and Diversity

Level of Organization: Molecules

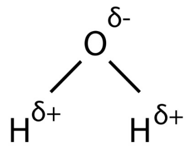
Written and drawn by:

Peter Marier

NOTEWORTHY SCIENCE

MARIER

SL LEARNING OUTCOMES

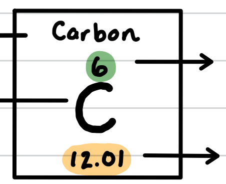
A1.1.1	Water as the medium for life	Students should appreciate that the first cells originated in water and that water remains the medium in which most processes of life occur.
A1.1.2	Hydrogen bonds as a consequence of the polar covalent bonds within water molecules	Students should understand that polarity of covalent bonding within water molecules is due to unequal sharing of electrons and that hydrogen bonding due to this polarity occurs between water molecules. Students should be able to represent two or more water molecules and hydrogen bonds between them with the notation shown below to indicate polarity. The following diagram is provided in the data booklet. 
A1.1.3	Cohesion of water molecules due to hydrogen bonding and consequences for organisms	Include transport of water under tension in xylem and the use of water surfaces as habitats due to the effect known as surface tension.
A1.1.4	Adhesion of water to materials that are polar or charged and impacts for organisms	Include capillary action in soil and in plant cell walls.
A1.1.5	Solvent properties of water linked to its role as a medium for metabolism and for transport in plants and animals	Emphasize that a wide variety of hydrophilic molecules dissolve in water and that most enzymes catalyse reactions in aqueous solution. Students should also understand that the functions of some molecules in cells depend on them being hydrophobic and insoluble.
A1.1.6	Physical properties of water and the consequences for animals in aquatic habitats	Include buoyancy, viscosity, thermal conductivity and specific heat capacity. Contrast the physical properties of water with those of air and illustrate the consequences using examples of animals that live in water and in air or on land, such as the black-throated loon (*Gavia arctica*) and the ringed seal (*Pusa hispida*). *Note: When students are referring to an organism in an examination, either the common name or the scientific name is acceptable.*

HL LEARNING OUTCOMES

A1.1.7	Extraplanetary origin of water on Earth and reasons for its retention	The abundance of water over billions of years of Earth's history has allowed life to evolve. Limit hypotheses for the origin of water on Earth to asteroids and reasons for retention to gravity and temperatures low enough to condense water.
A1.1.8	Relationship between the search for extraterrestrial life and the presence of water	Include the idea of the "Goldilocks zone".

Chemistry review

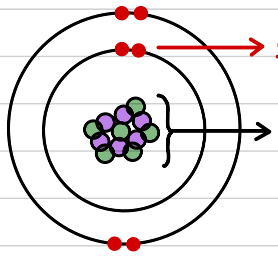
chemical name ←
chemical symbol ←



atomic number
→ number of protons (p^+) in nucleus
ex: carbon has 6 protons

relative atomic mass (A_r)
→ average mass of an element's isotopes (nucleus only)
* electrons are not considered as too light (0.0005)

mass number (A) : protons + neutrons



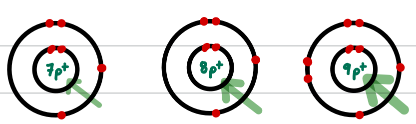
→ **electrons** : negative subatomic particle located around atom's nucleus
※ if lost / gained → ion ※ do not orbit but reside in 'cloud'

→ nucleus : contains :
↳ **neutrons** : neutral subatomic particle
↳ **protons** : positive subatomic particle

electronegativity : tendency of a nucleus to attract bonding electrons ($\bar{e}$)
i.e. the more it attracts, the more electronegative

↳ depends on number of protons in nucleus

ex:

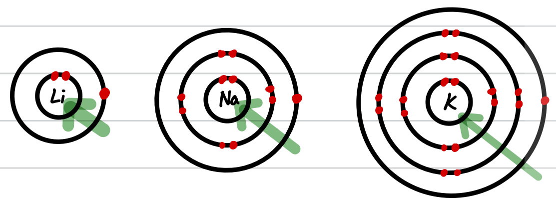


more protons in nucleus → stronger pull

increasing electronegativity →

↳ depends on distance between nucleus and bonding pair of electrons

ex:

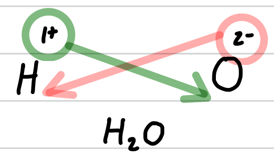


greater distance from nucleus (more orbitals)
→ weaker attractive force

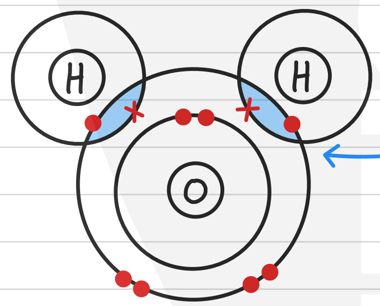
decreasing electronegativity →

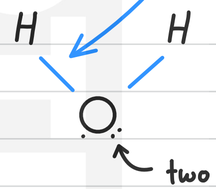
※ Difference between electronegativities of two atoms determines type of bond :
↳ very large (>1.7 Pauling scale), one atoms pulls $\bar{e}$ from another = **ionic** (between ions)
↳ small (0-0.4 Pauling scale), $\bar{e}$ equally shared between atoms = **non-polar covalent**
↳ moderately large (>0.4 - <1.7 Pauling scale) $\bar{e}$ unequally shared = **polar covalent**

Oxygen has 6 valence electrons, thus 'needs' 2 more to have full valence and be stable.
Hydrogen has 1 valence electron, thus 'needs' 1 more to have full valence and be stable.

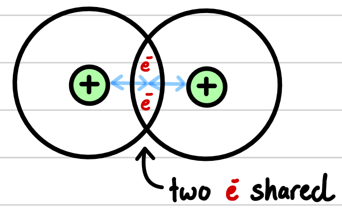


∴ one Oxygen atom can share 2 electrons with 2 Hydrogen atoms **covalently** as water

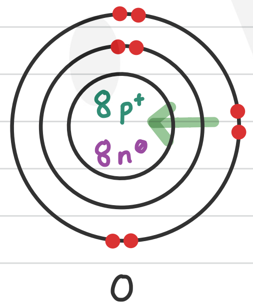




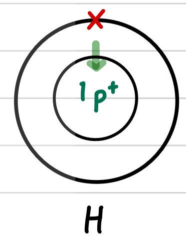
→ electrostatic attraction between positive nuclei and shared pair of electrons

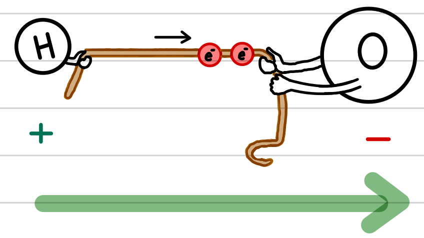


But Oxygen has a higher electronegativity than Hydrogen

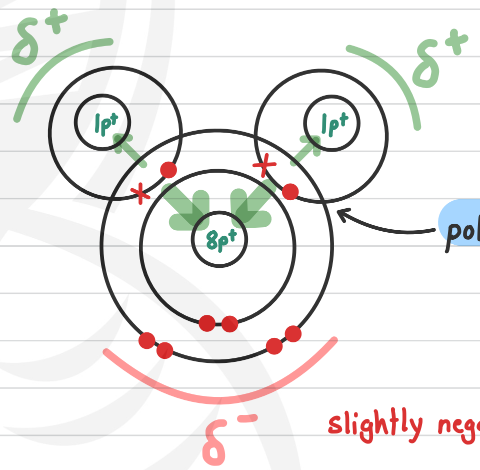


↳ 8 protons vs 1 proton
↳ O nucleus has stronger pull on electrons than H
↳ electrons spend more time closer to O than H





↓ causes



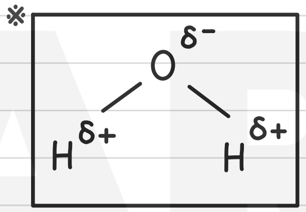
slightly positive charge (δ^+) around Hydrogen end of water due to lower electron density

polar covalent bond : Unequal sharing of electrons pairs leading to unequal distribution of electrical charge and polarity. Water comprises 2 polar covalent bonds
↳ when a molecule has 2 different electrical charges

slightly negative charge (δ^-) around Oxygen end of water due to higher electron density

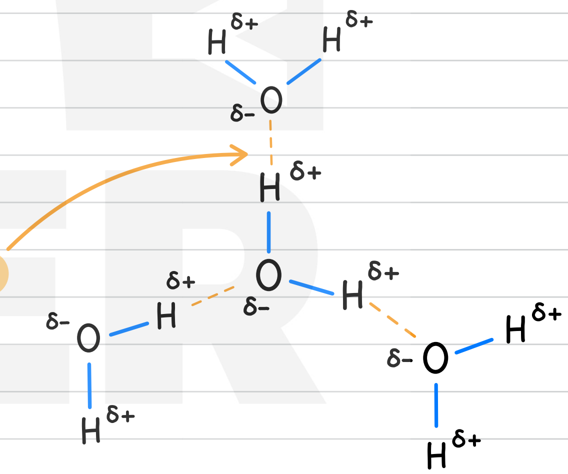
How to draw :

※



※ found in data booklet

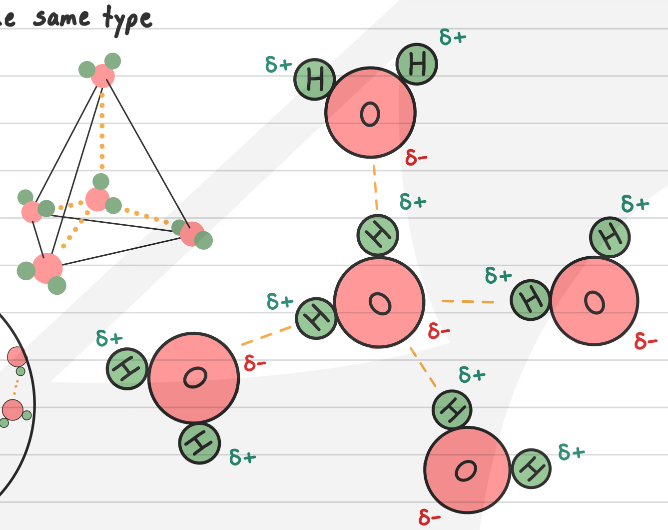
As water is polar, the slightly positive hydrogen is attracted to the slightly negative oxygen and forms a **hydrogen bond** (a weak intermolecular force of attraction)

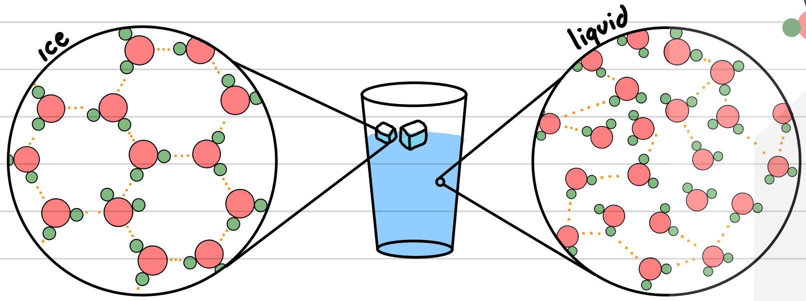


※ **Covalent bonds** are within a water molecule - intramolecular
↳ very strong and stable
↳ represented by ——

hydrogen bonds (dipole-dipole) are between water molecules - intermolecular
↳ weak, but stronger in large numbers
↳ constantly forming, breaking and re-forming
↳ represented by - - - or ....

Cohesion: the attraction of a molecule to another of the same type
i.e. water attracted to another water molecule
↳ every water molecule can form hydrogen bonds with up to 4 others in a tetrahedral formation

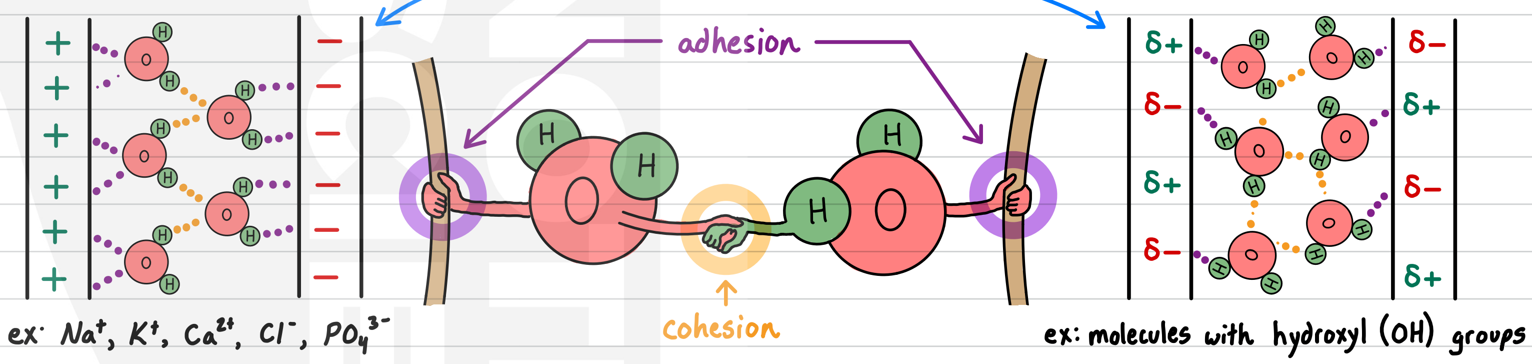




when frozen solid, water molecules have less energy, causing hydrogen bonds to become stable, arranging water in a crystalline lattice
↳ lowers density, causing ice to float

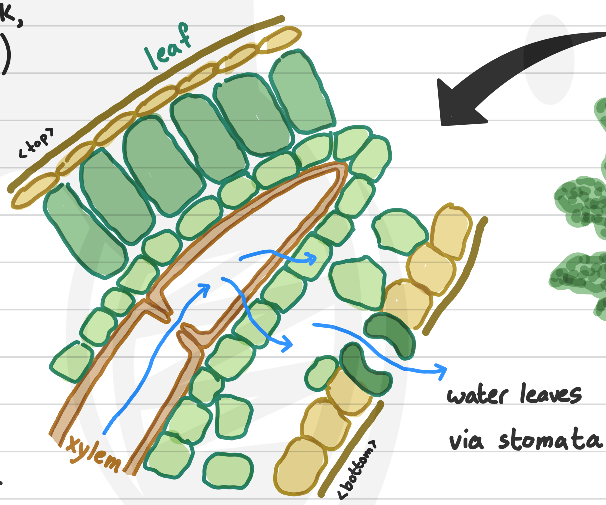
as liquid, water molecules move more, causing hydrogen bonds to form, break, and reform very frequently (ephemeral)
↳ shape undefined

Adhesion: the attraction of a molecule to a different type
i.e. water attracted to a charged or polar material (which is not water)

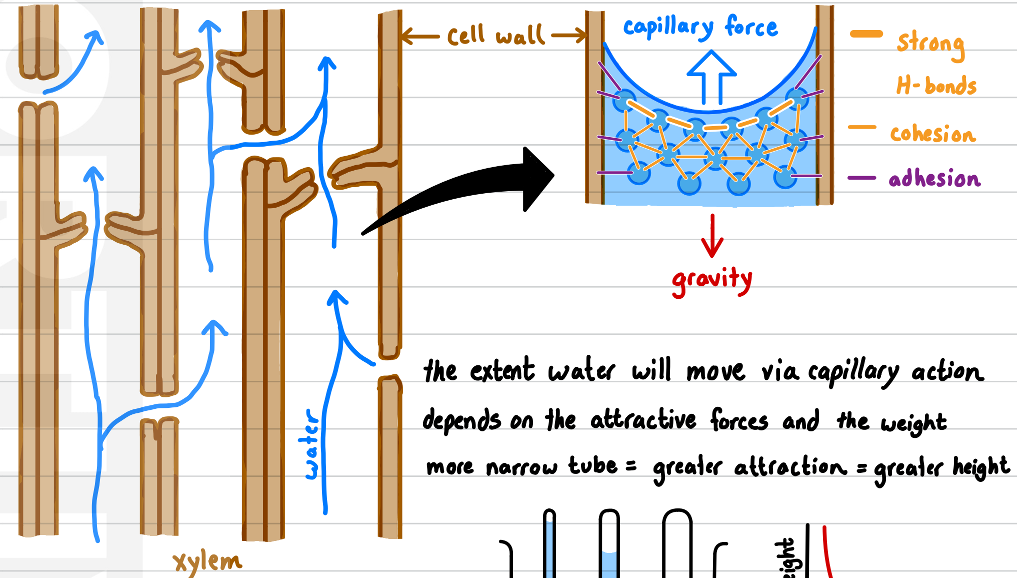


Capillary action: when water ascends up a narrow tube due to adhesion, cohesion and surface tension

ex: in vascular plants, water is carried by xylem which attract water due to their cellulose cell wall, allowing adhesion. water is pulled up via transpiration and adhesion prevents water from falling down.

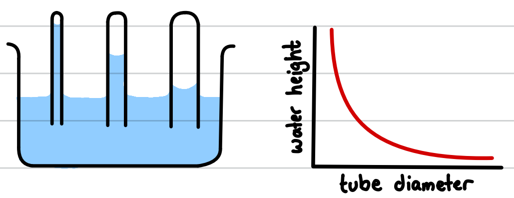


gas exchange B3.1

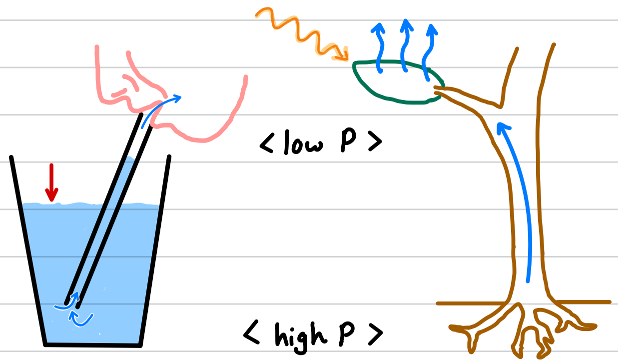


transport B3.2

the extent water will move via capillary action depends on the attractive forces and the weight
more narrow tube = greater attraction = greater height

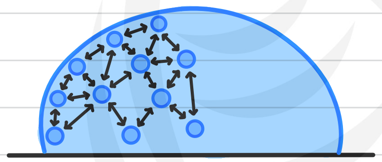


Transpiration stream: flow of water from roots to leaves in plants
like sucking water up a straw, water moves up due to a suction force, going from an area of higher pressure to lower pressure

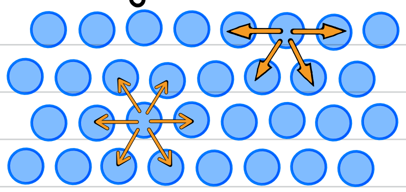


Sun evaporates water from leaves, pulling on the top of the water column. This puts water in xylem under tension (negative pressure - below atmospheric) Cohesion holds column together, so whole chain is pulled up: root → leaves

Surface tension: tension of the surface film of a liquid caused by cohesion molecules with in the surface layer which minimizes surface area

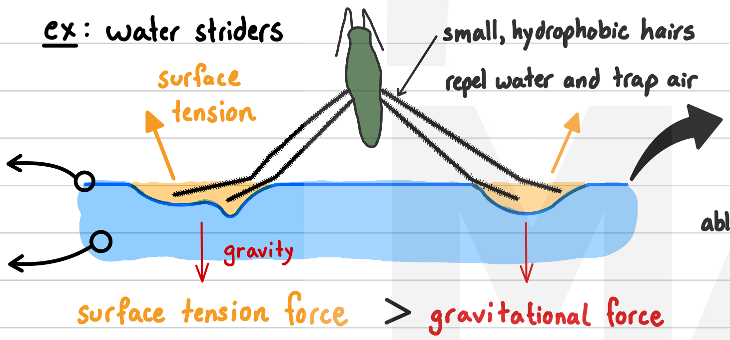


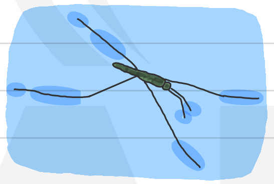
as there are no water above, water forms fewer, stronger hydrogen bonds with its neighbors at the surface



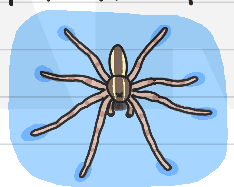
results in a stronger, film-like surface which resists breaking

ex: water striders





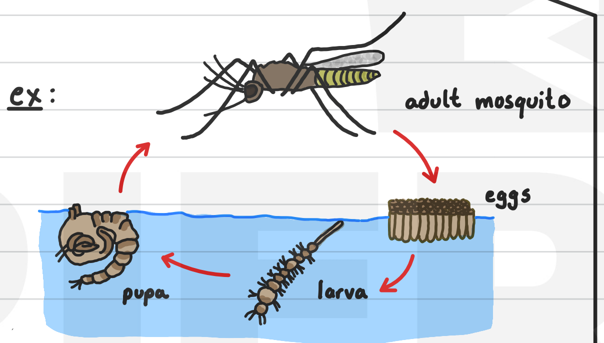
able to move on top of water's surface



raft spider (*D. fimbriatus*)

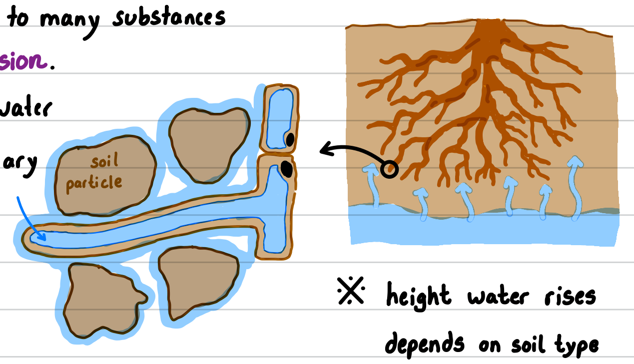
※ water surface can act as habitats for some animals

ex:



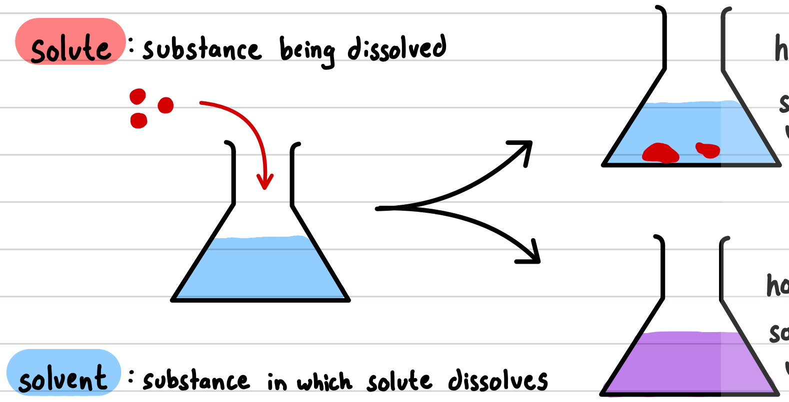
mosquitoes take advantage of surface tension by laying eggs on water surface and their young developing just below surface

ex:
water is attracted to many substances within soil via adhesion.
If soil is porous, water moves up via capillary action through small channels, making it available for roots of plants



※ height water rises depends on soil type

Chemistry review



Solute: substance being dissolved

solvent: substance in which solute dissolves

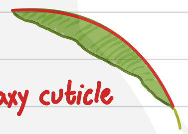
heterogeneous mixture: solution with non-uniform composition
↳ solute doesn't interact with solvent

homogeneous solution: solution with uniform composition
↳ solute dissolves in solvent

Substances that do not dissolve in water are **hydrophobic** → non-polar, uncharged (ex: lipids)

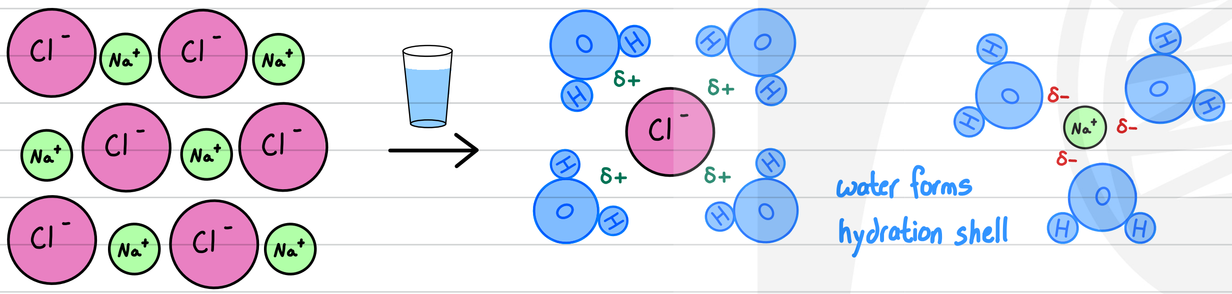
Substances that dissolve in / attracted to water are **hydrophilic** → polar, charged

→ why is water such a good solvent?



the surface of leaves have hydrophobic waxy cuticle preventing water loss

- it dissolves ionic / charged substances (ex: NaCl)

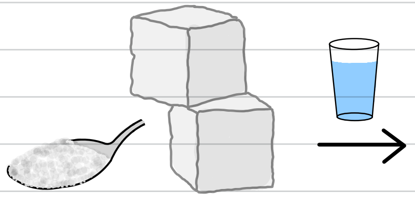


water forms hydration shell

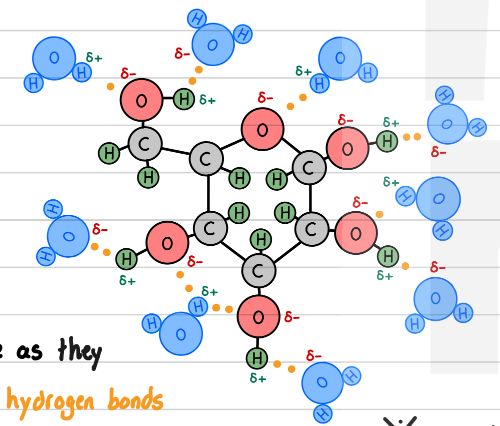
An ionic substance is held together with ionic bonds (electrostatic attraction) between cations (+) and anions (−)

the cation (+) becomes attracted to the δ− oxygen end of water and the anion (−) becomes attracted to the δ+ hydrogen end of water (ion-dipole interaction)
→ compound separates and dissolves in **aqueous solution**

- it dissolves polar compounds (ex: glucose) — water potential D2.3



Sugars are polar substances — carbohydrates B1.1



the various polar regions (OH groups) within the glucose molecule ($C_6H_{12}O_6$) are attracted to water, making it hydrophilic, allowing it to readily form hydrogen bonds with water and dissolve

※ polysaccharides are less soluble as they form many inter/intra chain hydrogen bonds resulting in fewer free −OH for a hydration shell

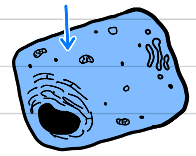
※ dissolving is a solvent property, not adhesion

water as a medium for metabolism

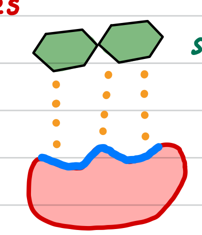
In order for a chemical reaction to occur (reactant(s) → product(s)) there must be a successful collision and sufficient energy – activation energy.
↳ Majority of chemical reactions occurring in organisms are regulated by enzymes — enzymes C1.1

Enzymes: proteins that function as biological catalysts (a substance that increases the rate of a chemical reaction without being changed or used up) by lowering the activation energy

Metabolism: complex network of interdependent and interacting chemical reactions occurring in living organisms
↳ the inside of cells, cytoplasm, is where most cellular chemical reactions occur
Cytoplasm is mostly made up of water which is an ideal medium for metabolism:

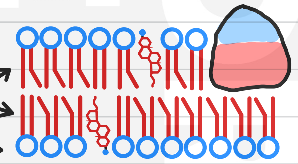


- many enzymes require a certain amount of water in their structures, allowing to maintain their shape and work effectively
- most substrates dissolve in aqueous cytoplasm, allowing them to collide more readily with enzymes
- hydrogen bonds form readily in water and allow the substrate to bind more readily with enzymes
- water can absorb heat from exergonic reactions and maintain constant ideal temperature



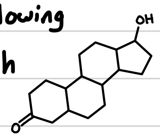
- some substances are hydrophobic and don't dissolve. This is important for their functions:

↳ cell membrane is composed of non-polar sections and polar sections making it stable and semi-permeable — membranes B2.1



↳ proteins embedded in cell membrane have hydrophobic parts to keep them attached and hydrophilic for interaction — proteins B1.2

↳ hormones like testosterone are hydrophobic, allowing them to pass through membrane easily

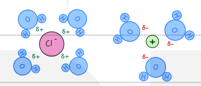


lipids B1.1

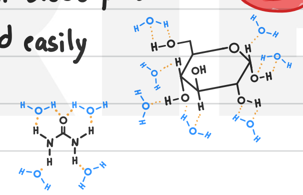
water as a medium for transport — transport B3.2

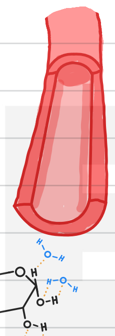
↳ In humans substances are carried in the liquid portion of blood (plasma), which is mostly water and thus aqueous

Ionic substances
dissolve into ions in aqueous plasma (Na^+, Cl^-, K^+, Ca^{2+})

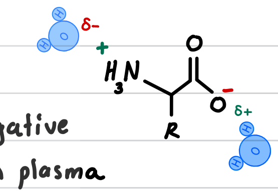


Polar substances
dissolve in blood plasma and carried easily
ex: glucose
urea

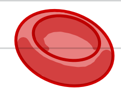




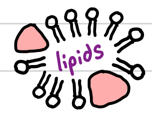
Amino acids
have both positive and negative charges so will dissolve in plasma



Oxygen (O_2) non-polar but small size allows it to dissolve, but sparingly.
Haemoglobin in red blood cells bind O_2 and greatly increases capacity of blood to deliver O_2

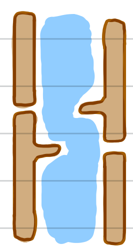


Lipids non-polar and hydrophobic.
Must be carried within lipoproteins

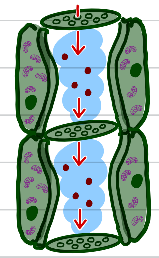


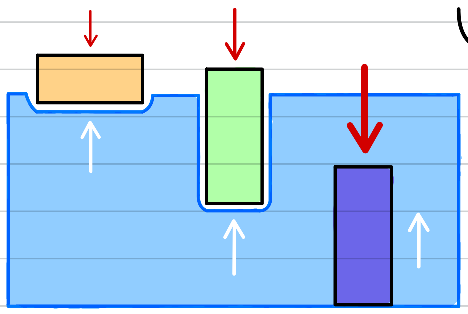
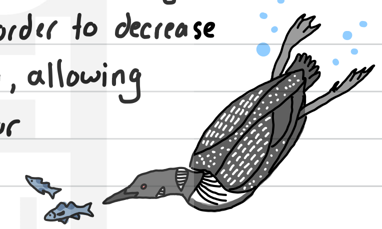
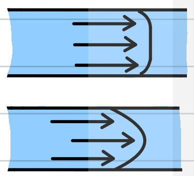
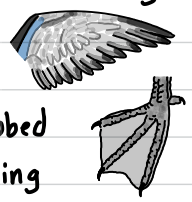
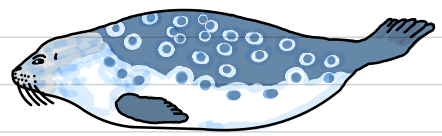
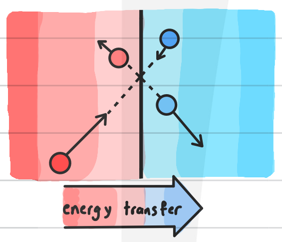
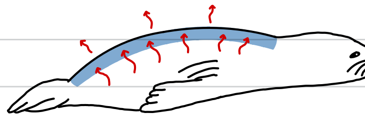
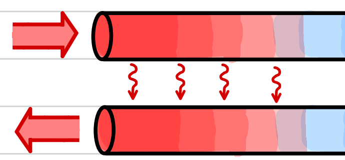
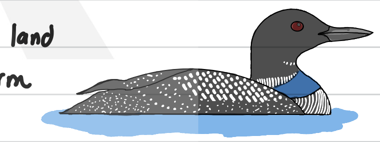
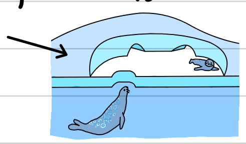
↳ In vascular plants, substances are carried in 2 main vessels:

Xylem
mineral ions are dissolved are carried in xylem sap



Phloem
Sucrose and other products of photosynthesis carried in phloem sap

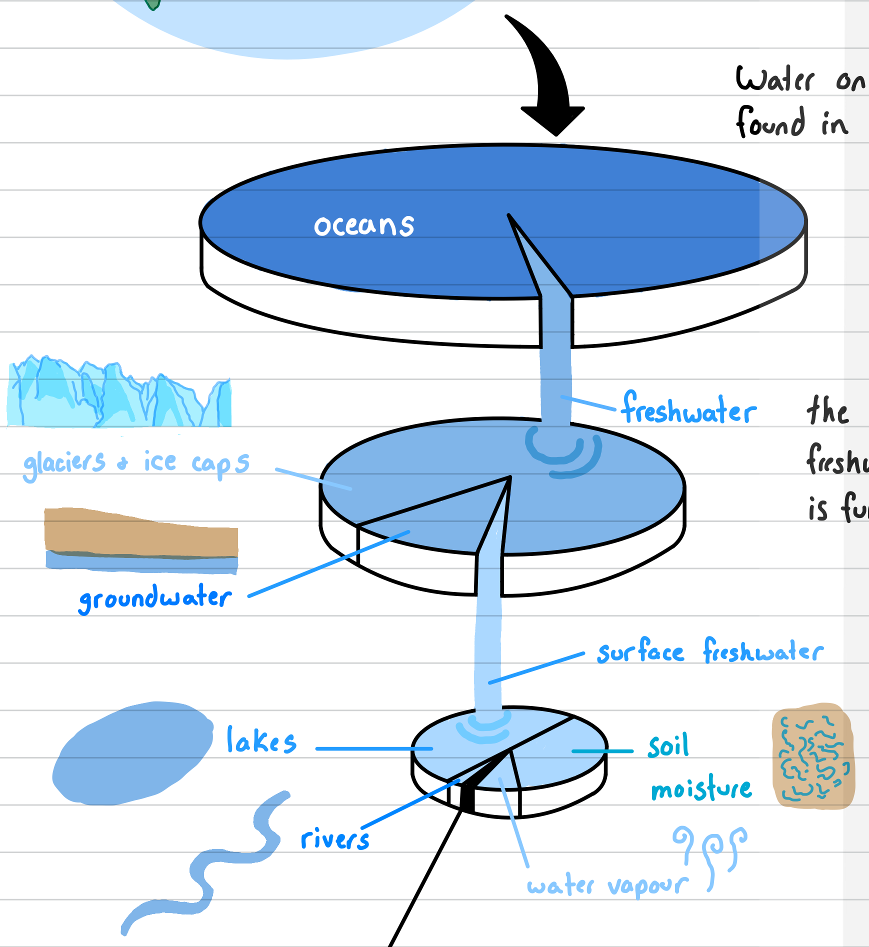


Physical Property	Water	Air	*Gavia arctica* adaptations	*Pusa hispida* adaptations
Buoyancy: the ability of any fluid (liquid or gas) to provide vertical upwards force on an object placed in or on it  ↳ the force is equal to the weight of the fluid displaced by the object object density < fluid density object density = fluid density object density > fluid density	density = 998.21 kgm^{-3} living organisms have an overall density close to water and tend to float, making water a suitable habitat ※ ice is less dense and floats on liquid water	density = 1.204 kgm^{-3} Air has a much lower density than living organisms, thus much energy is required to generate lift and fly	black-throated loon has large wings to generate lift in less buoyant air has solid bones (unlike other birds) to increase its weight and to compress air in its lungs and feathers in order to decrease its buoyancy, allowing it to dive for underwater prey 	Ringed seal is quite heavy so diving is not an issue but floating is more difficult. Large fat reserves, blubber, is stored under the skin to increase its buoyancy (making it close to that of water). Also, seals use floating ice as habitats. 
Viscosity: the resistance to a flow of a fluid (gas or liquid) ↳ viscosity is due to the internal friction caused when one part of a fluid moves relative to another  ↳ more viscous = more friction = more resistance to flow	viscosity = 1.0×10^{-3} $kgm^{-1}s^{-1}$ as a liquid, viscosity is due to cohesive forces and water forms hydrogen bonds so is more viscous than air but less so compared to other liquids	viscosity = 1.8×10^{-5} $kgm^{-1}s^{-1}$ as a gas, viscosity is due to collisions. Air has far lower viscosity than water as it is far less dense	Bird plummage is adapted to hold and deflect air for lift and flight They are aerodynamic to reduce drag and friction during flight Hydrodynamic to move through water easily. Webbed feet propel it during swimming 	Streamlined body is hydrodynamic to reduce drag through the water Seal uses flippers to propel itself through water 
Thermal conductivity: the ability of a substance to transfer heat when there is a temperature difference ↳ how quickly is heat being transferred across a material depends on collisions and electrons  ※ conductor = fast insulator = slow	therm. con. = 0.598 $Wm^{-1}K^{-1}$ water generally has a low thermal conductivity (compared to metals) but much higher than air as particles in liquids are closer and can transfer easier	therm. con. = 0.025 $Wm^{-1}K^{-1}$ air is a thermal insulator and conducts heat poorly as particles are far apart and collisions and transfer occur less frequently	air is trapped in the loon's feathers acting as an insulator and preventing heat loss, maintaining body temperature. loons can easily lose heat in water so they have an oil gland and using their beak, rub it on their feathers as an insulator as it is hydrophobic	To prevent heat loss in water, seals have large stores of blubber which act as an insulator. Huddle in groups to reduce surface area and heat loss on land  lipids B1.1
Specific heat capacity: heat required to raise 1Kg of material by 1K ↳ how much energy is needed to change the temperature of something ↑ specific heat capacity = a lot of energy is needed as it absorbs a lot ※ heat capacity = amount of heat energy required to change a substance 1K specific heat capacity = amount of heat energy required per unit mass ∴ it is independent of mass or volume	sp. heat = 4.184 $KJKg^{-1}K^{-1}$ Water has a very high specific heat capacity due to its hydrogen bonds. To warm up, the H-bonds need to be broken and when it cools, H-bonds are formed and release energy. ∴ Water can absorb a lot of energy without changing temp and is stable in differing conditions	sp. heat = 1.005 $KJKg^{-1}K^{-1}$ Air has a far lower specific heat capacity compared to water as the particles are more spread out and thus temperatures can easily change as there are no intermolecular bonds that need to be overcome	The blood of both birds and mammals are mostly water, so heat is able to be well distributed in the body and it helps maintain constant body temperature. water's temperature is relatively stable year-round  As water will remain relatively warmer in cold temperatures compared to the air, loons spend a lot of time on the water rather than land to stay warm 	Seal young (pups) do not have large blubber stores so can cool quickly. To keep them warm, pups are raised in insulated ice lairs where air can be easily warmed 

There is ~ 1.4 billion km^3 of water on Earth!

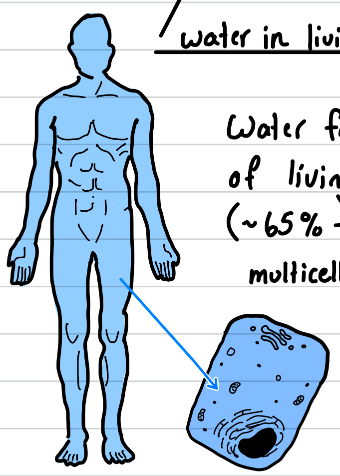
Over 70% of Earth's surface is water! Hence our nickname, 'The Blue Planet' as it appears blue from space

Water on Earth is mainly found in oceans (97%)



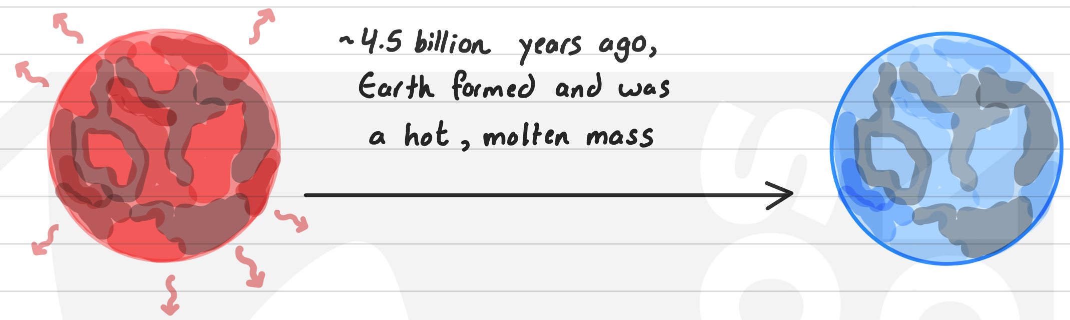
the 3% left is freshwater which is further subdivided

water in living organisms



Water forms a large proportion of living organisms (~65% - 95% by mass for most multicellular plants and animals)

~80% of our cells consist of water!



~4.5 billion years ago, Earth formed and was a hot, molten mass

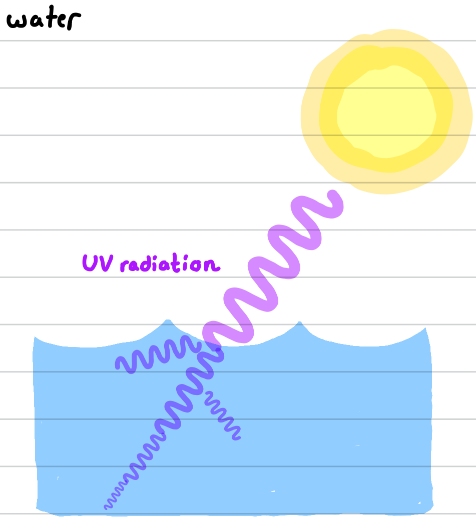
~ Earth cooled and ~ 3.8 billion years ago, Earth had water

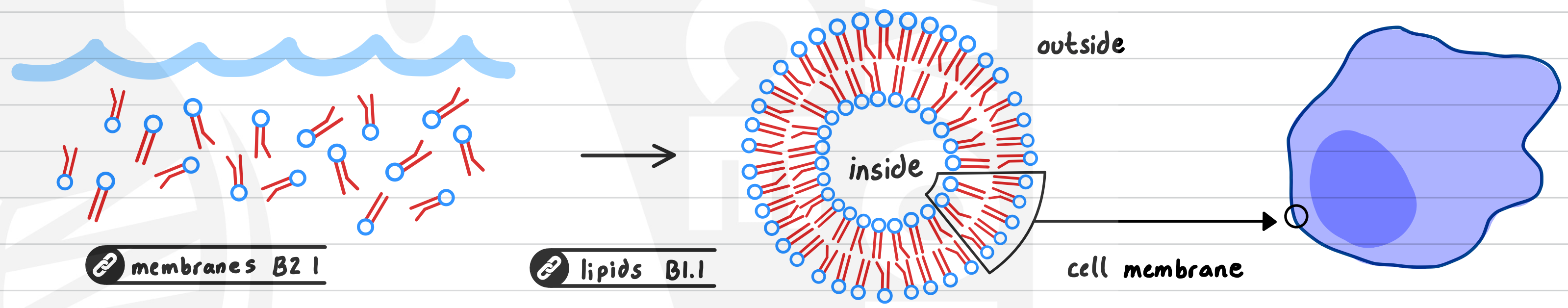
extended in HL →

life started in the oceans

origin of cells A2.1

- Early Earth did not yet have an ozone (O_3) layer to block harmful UV from the Sun but as UV enters the oceans, it dissipates and becomes less harmful with increasing depth - protecting organisms below and allowing life to thrive
- The early cells evolved membranes to separate their insides (cytoplasm) from the ocean water. Bilayers naturally form in water.





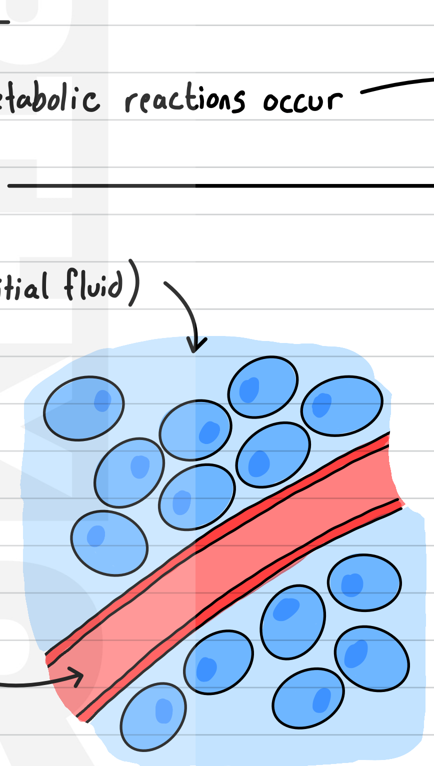
membranes B2.1

lipids B1.1

Water acts as an important solvent and is crucial for organisms

- makes up the fluid (cytoplasm) in all cells where all metabolic reactions occur
- makes up the fluid inside the organelles in cells
- is found between cells of multicellular organisms (interstitial fluid)
- allows transport of substances into and out of cells
- main component of blood (plasma)
- has a high heat capacity, allowing it to act as a temperature buffer and leads to stable environments
- necessary for the proper folding of proteins - allowing correct shape and function of many enzymes crucial for metabolism
- has high latent heat of vaporization, allowing evaporative cooling

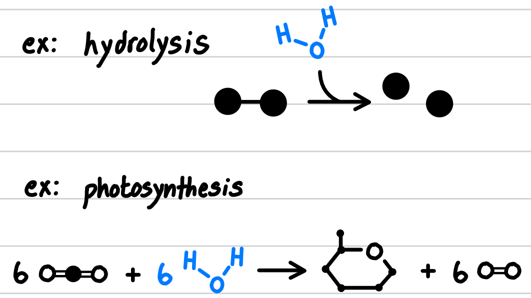
homeostasis D3.3



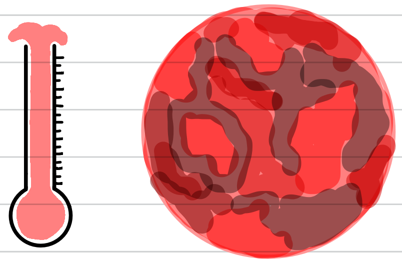
involved in many chemical reactions

ex: hydrolysis

ex: photosynthesis



without water, life would not exist on Earth

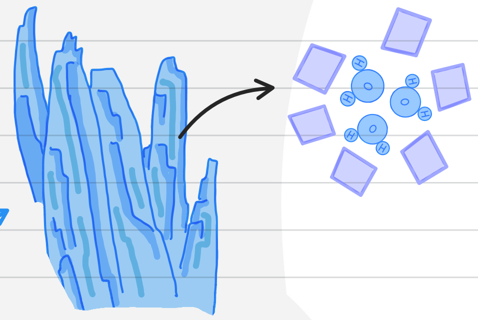


When Earth first formed it was far too hot for water to condense into a liquid, so most of it would have been lost to space as a gas and dispersed → water likely has an extraplanetary (outside of planet, Earth) origin

※ there are competing hypotheses for the origin of water on Earth, a prominent one is asteroids:

Asteroid hypothesis for origin of water on Earth

↳ the hypothesis states that during Earth's early history, once it started to cool, water was delivered to Earth via many colliding asteroids from space in the form of hydrated minerals



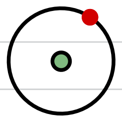
↳ while currently there aren't many collisions, billions of years ago during Earth's formation, there is estimated to have been many collisions over millions of years, which would account for the large amount of water currently present today

※ asteroids analyzed today don't contain a lot of water but over time water would evaporate due to the Sun so most collisions likely occurred early and contained more water proportionally

Evidence

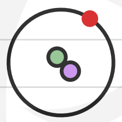
↳ Atoms naturally exist in different forms (isotopes) where they may have different number of neutrons in their nucleus as thus, atomic mass

ex: Hydrogen-1, ^{1}H (Protium)



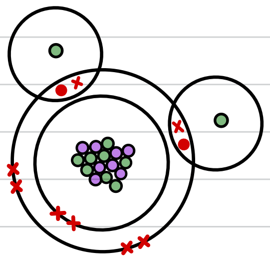
0 neutrons

Hydrogen-2, ^{2}H (Deuterium)

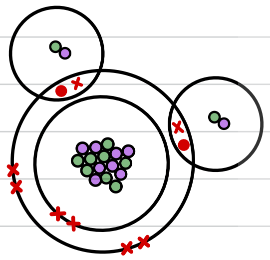


1 neutron

↳ Water can have different forms depending on what isotope of hydrogen it is comprised



'normal' water is most common



'heavy' water is rare

Water bodies are comprised of both and a ratio of the two can be determined

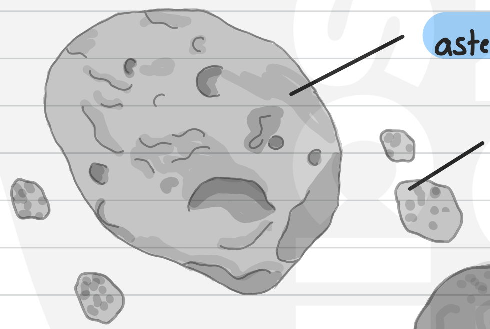
↳ Scientists have analyzed the ratio of Deuterium to Protium in the Earth's oceans and on asteroids that have passed through the Earth's orbit and meteorites

results:

D/P ratio, 1.56×10^{-4}, was found to be extremely similar for the ocean and many samples of asteroids and meteorites such as the carbonaceous chondrites. This supports the idea that asteroids were the source of water on Earth

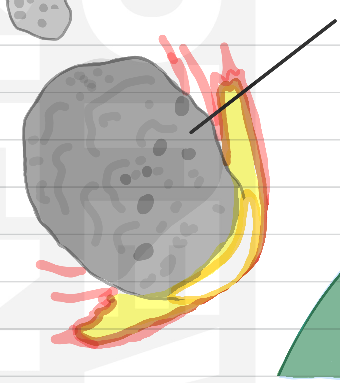
※ precise source still debated (Piani et al. 2020)

Definitions

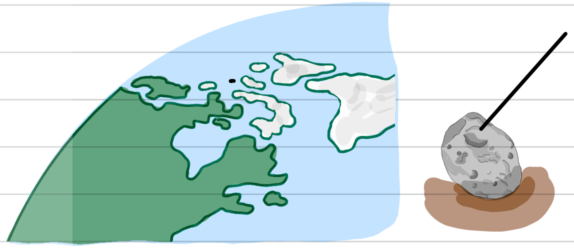


asteroid: rocky body orbiting the Sun

meteoroid: fragment of an asteroid or comet



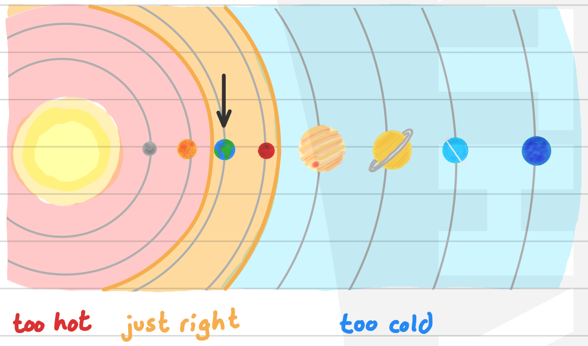
meteor: when a space fragment enters Earth's atmosphere and heats up



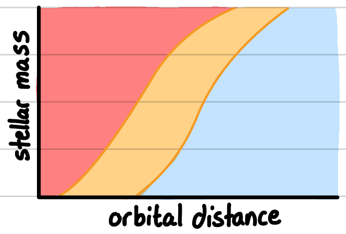
meteorite: a meteor that has landed on Earth's surface

How did water stay on Earth after its delivery?

- Due to the Earth's size, its gravity holds oceans to its surface as well as gases (the atmosphere)
  ↳ if Earth were smaller, its lower gravitational pull could not keep water at its surface
- After Earth received water, due to its proximity to the Sun, water remained as liquid, which due to cohesion and hydrogen bonding, is easier to hold to its surface than vapour.



Goldilocks zone: aka habitable zone. The distance away from the Sun where the amount of solar energy is not too hot to vapourize, or too far away to freeze but 'just right' to allow water to remain in a liquid state on the planet's surface

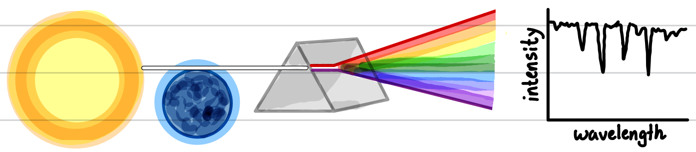


Search for extraterrestrial life

→ particularly exoplanets (those outside the Earth's solar system)

When searching for life on other planets, a key feature to look for is liquid water as it is essential for life as we know it → Planets therefore must be in a similar Goldilocks zone

↳ to determine if an exoplanet has water we can use transit spectroscopy which analyses the absorbance of light that passes through its atmosphere as it passes in front of its star. Analysis can determine if water is present

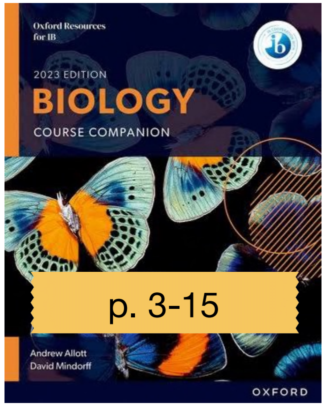


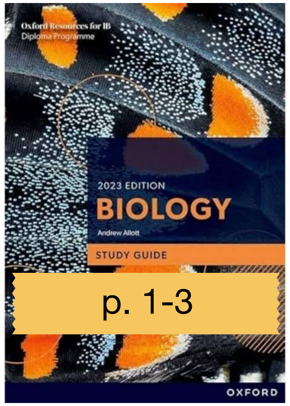
Resource Links

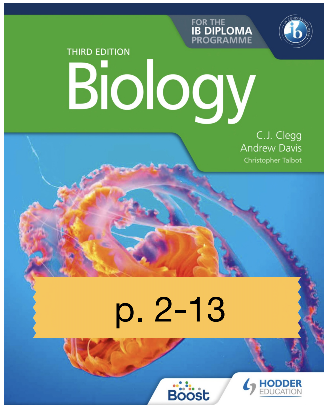
each resource is hyperlinked

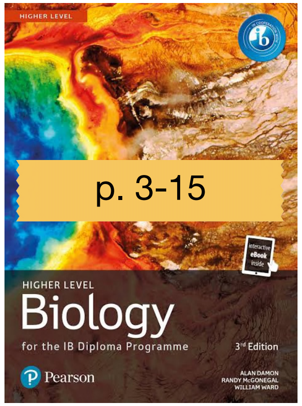
NOTEWORTHY SCIENCE
MARIER

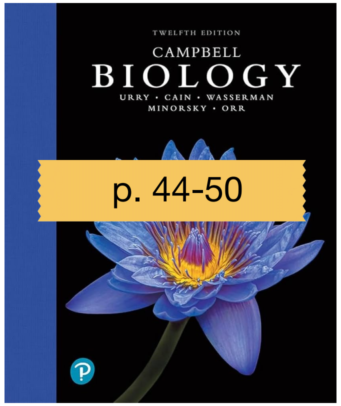
Textbooks











Simulators / Interactives

PhET INTERACTIVE SIMULATIONS

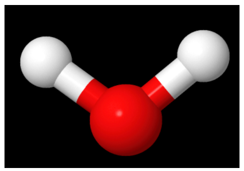
Molecule polarity

The Concord Consortium

Hydrogen bonding

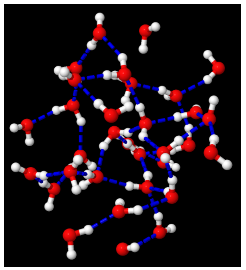
Specific heat | Javalab | Surface tension

3D models

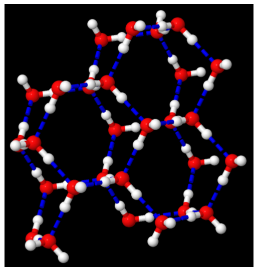


Water

BioTopics.co.uk



Liquid water



Ice

Articles

Biological Roles of Water: Why is water necessary for life? (2019, September 26). Science in the News. https://sites.harvard.edu/sitn/2019/09/26/biological-roles-of-water-why-is-water-necessary-for-life/

Luo, H., Dorn, C., & Deng, J. (2024). The interior as the dominant water reservoir in super-Earths and sub-Neptunes. Nature Astronomy, 8(11), 1399–1407. https://doi.org/10.1038/s41550-024-02347-z

Piani, L., Marrocchi, Y., Rigaudier, T., Vacher, L. G., Thomassin, D., & Marty, B. (2020). Earth's water may have been inherited from material similar to enstatite chondrite meteorites. Science, 369(6507), 1110–1113. https://doi.org/10.1126/science.aba1948