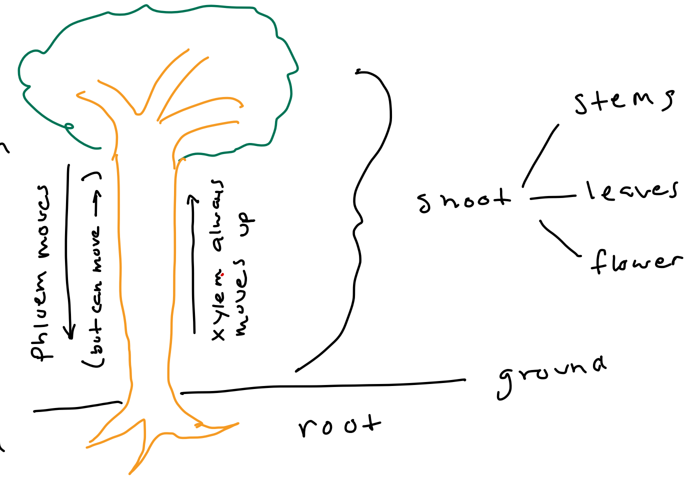
Plants move H_2O and solutes by **Bulk Flow**

1. Move H_2O and ↑ [sol] (mostly sucrose) from **source** (typically leaves) to **sink** (growing/storage cells) in the **Phloem**. The mechanism is **pressure flow**, which **Pushes** the H_2O



2. move water and small amount of solutes from root to shoot in the **Xylem**. The primary mechanism is **Transpiration**, which **Pulls** the water up the tree. A secondary mechanism is **root pressure**, which **pushes** H_2O up the tree.
3. pressure flow and root pressure arise from **turgor pressure**, which increases when H_2O moves into a cell due to **Osmotic pressure**. Osmotic pressure is a very different concept than turgor pressure
4. Transpiration is controlled by opening/closing **stomata** on leaves. This is also due to Osmotic pressure

water transport over very short (microscopic) distances due to both hydrostatic pressure and osmotic pressure.

Water flow in the Phloem and Xylem is via Bulk flow. Bulk flow is driven by a **difference in hydrostatic pressure**

upstream pressure

downstream Pressure

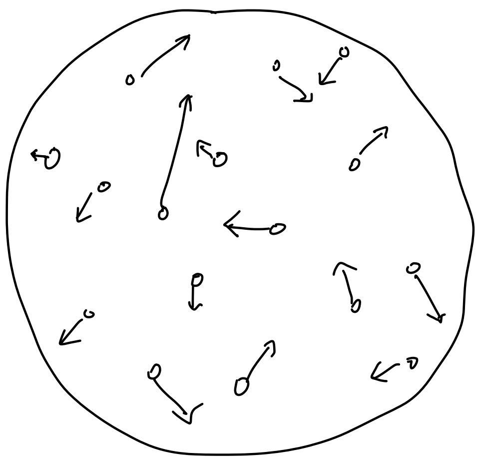
$$\text{Flow} = \frac{P_{up} - P_{down}}{R}$$

resistance to flow due to friction

Concepts of **Hydrostatic Pressure**

Pressure is force "standardized" by area: $P = \frac{F}{A}$

For gas mixtures like air:



- Pressure arises from the collisions of particles with the wall.

$P = \frac{F}{A}$ ← the time-average force due to collisions
← the surface area of the wall

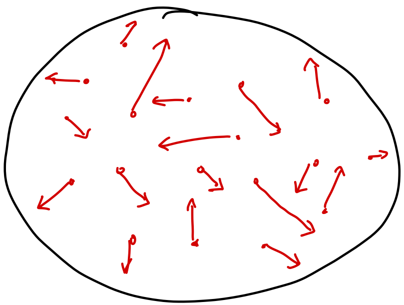
- Since the pressure arises by collisions with the wall, the direction of the pressure is always pointed into the wall, it's a *pushing* pressure

- The pressure of a real gas approximates closely an ideal gas:

$P = \frac{nRT}{V}$

- if the wall expands out, P↓
- if the wall is compressed, P↑

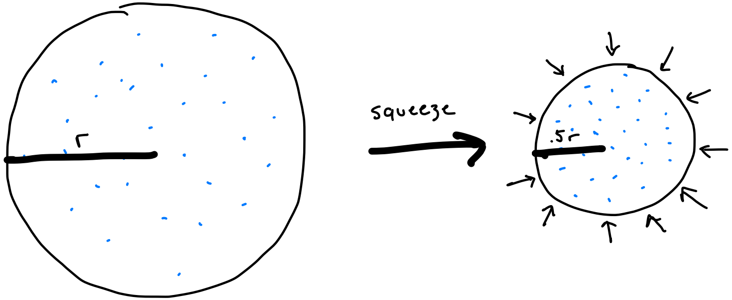
Compare this to pressure of water in a container



- like a gas, the molecules are moving at random speeds and directions
- like a gas, the molecules are colliding with the wall
- Unlike a gas, the molecules are interacting w/ each other via hydrogen bonds

This is huge!

gas mixture



$$PV = nRT \xrightarrow{\text{rearrange}} P = \frac{nRT}{V}$$

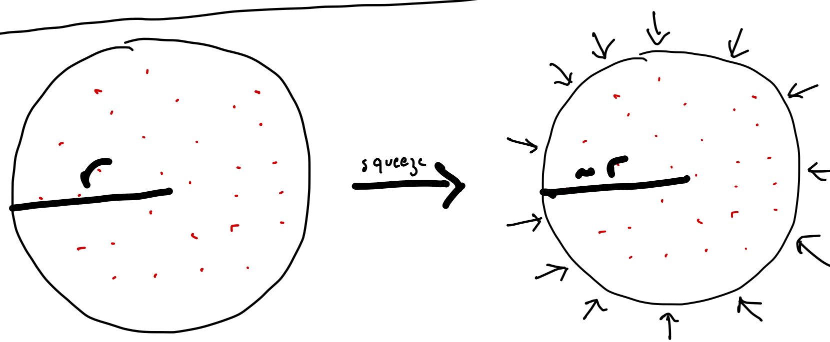
Apply Compressive Force → ↓volume → ↑rate of collisions w/ wall → ↑P

Apply Compressive Force → ↑ KE → ↑P

↑ KE → ↑T

- when a container of gas is squozen the gas is compressed and the volume of the gas shrinks. This increases rate of collisions w/ wall so ↑ P. Also it takes work ($W = F \cdot d$) to squeeze gas. This Energy goes into particles, increasing their KE. So ↑KE → ↑T

water

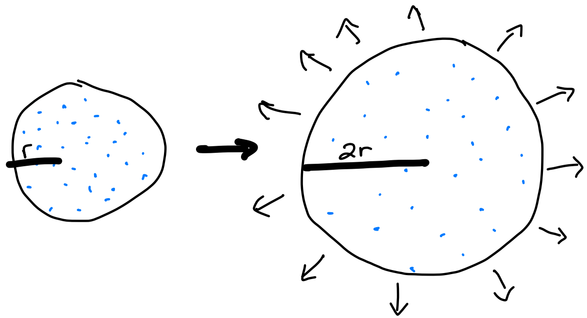


Apply Compressive Force → "Compress H bonds" (push H_2O closer to each other) → ↑ electrostatic resistance → ↑P

- Apply the same compressive force to a H_2O filled container and the container shrinks by only a *tiny* amount. But the Pressure of the H_2O increases to the same amount as if it were a gas. so $P \neq \frac{nRT}{V}$! why does pressure increase if volume is barely shrunk? because H_2O molecules are being forced closer and this forces atoms to be closer and the e^- interactions resist this → This is the source of the ↑ P

This gets weird when we apply a tensile force

gas mixture



Apply tensile Force → ↓ volume → ↓ rate of collisions w/ wall → ↓P

Apply tensile Force → ↓ KE → ↓P

↓ KE → ↓T

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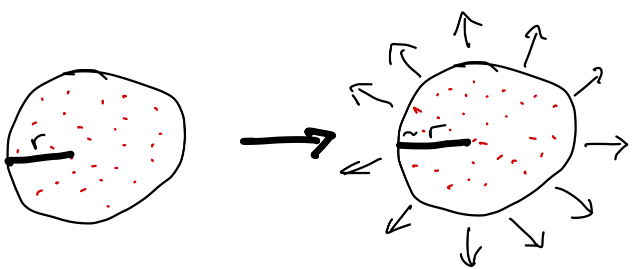
water



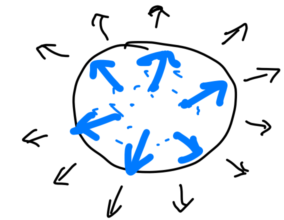
Apply tensile Force → "stretch" hydrogen bonds (pull H_2O molecules away from each other) → ↑ electrostatic resistance → ↑P

Huh? the Pressure goes up when H_2O is in tension?

Yes, it becomes bigger but More Negative

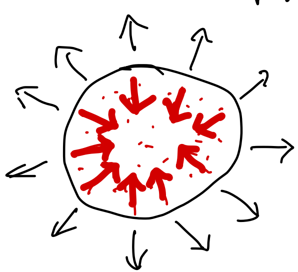
why this is weird

- in a gas, the pressure is always positive, the gas always **Pushes** on the wall. In a stretche Container, it simply pushes less



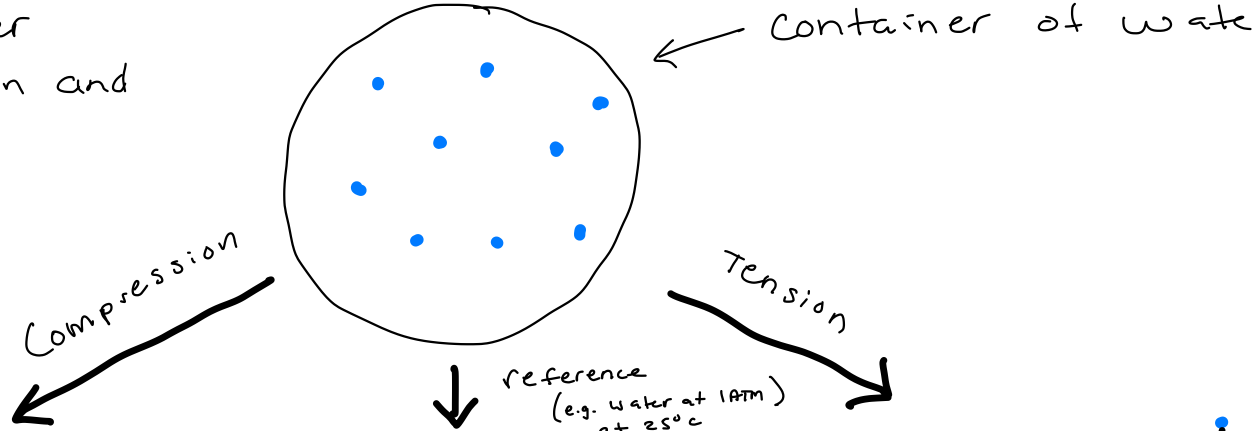
BUT

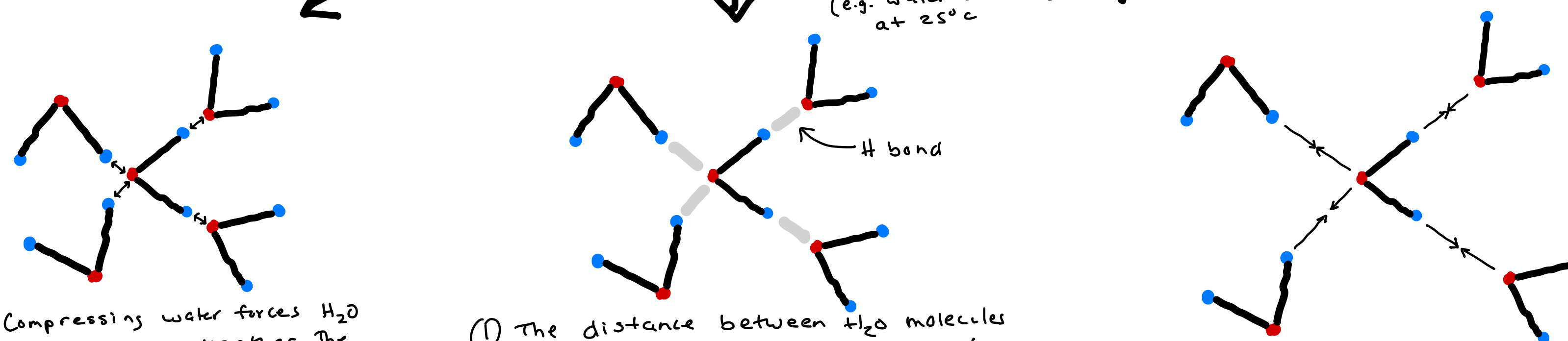
- In stretched water, the pressure can be negative, as in below Zero. This is not relative to something but true negative pressure.



The negative pressure in the container * **Pulls** * on the wall! It's a pulling force.

Water under compression and tension





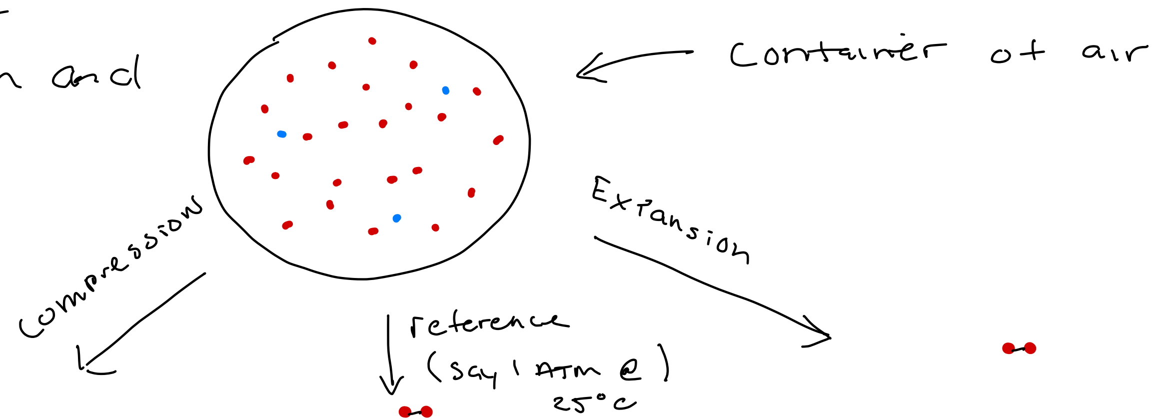
(2) Compressing water forces H_2O molecules closer together. The molecules resist this, or "push back".
Water in compression pushes

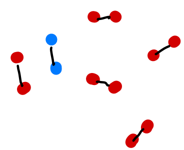
(1) The distance between H_2O molecules is a balance between attraction of H nucleus and O e^-, and H nucleus and O nucleus. The KE of H_2O affects this: $\uparrow KE \rightarrow \uparrow$ distance

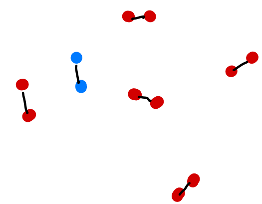
Water in tension forces H_2O molecules further apart. The H_2O molecules are attracted to each other so they "pull back"
water in tension pulls.

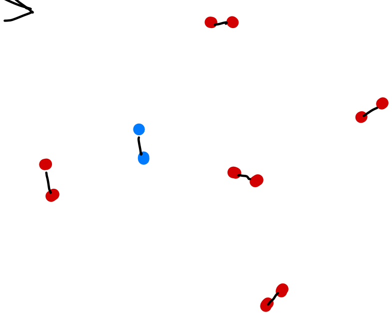
molecules (including H_2O) don't interact (form short term bonds) so don't behave this way.

Air under Compression and Expansion







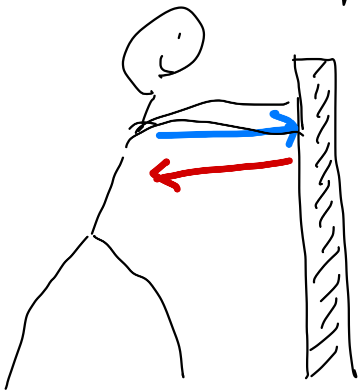


(1) gas molecules have too high KE to interact (form short-term bonds).

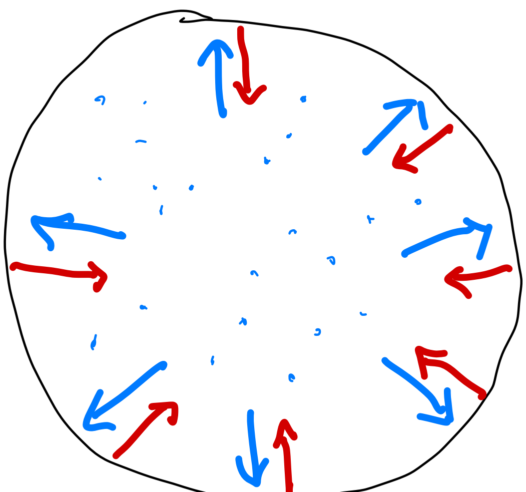
(2) in compressed gas, the volume shrinks considerably because the molecules are not repeling each other... there is no push back

(3) in expanded gas, the volume expands considerably because the molecules aren't attracting each other. Their is no pull

Remember – walls push (or pull!) back



If I push a wall with force F, the wall pushes back with force −F (equal magnitude, opp. sign)



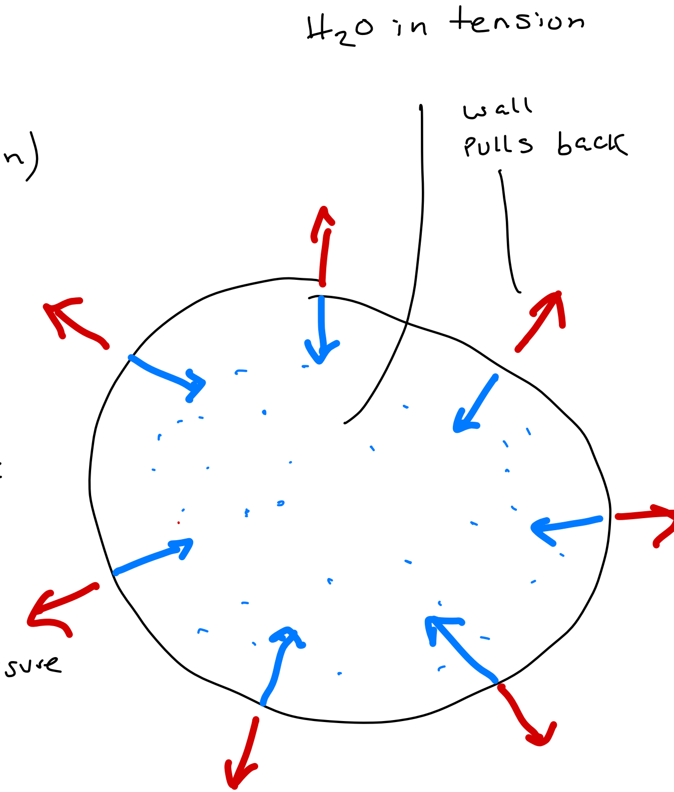
gas or H_2O

Force on wall

wall resistance F

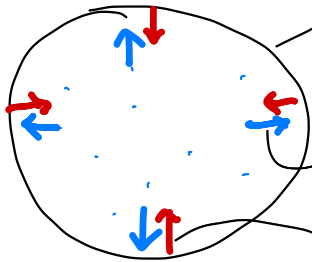
Since $P = \frac{F}{A}$

The fluid pressure is $\frac{\Sigma F}{A}$



H_2O only

Now instead of compressing or pulling the wall, let's add or remove fluid

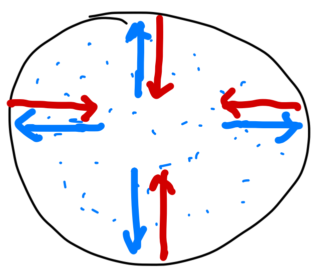


Stiff wall - remember stiffness is the resistance to deformation

H_2O pushes against wall

wall pushes back

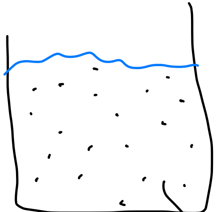
add water



Wall pushes back *more*. The pushing back compresses the H_2O. Because H_2O is extremely resistanto to compression, the resistance force rises very quickly. **The pressure of the H O in the container is:**

$$\frac{F}{A} \quad \begin{matrix} \rightarrow \text{resistance force} \\ \rightarrow \text{area of wall} \end{matrix}$$

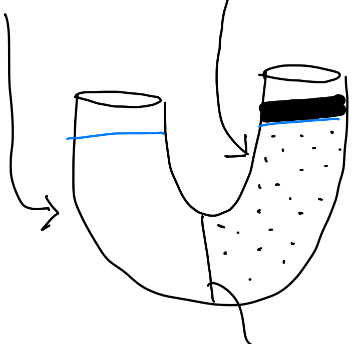
Now it is easier to understand osmotic pressure



here is a beaker of solution. What is the osmotic pressure of this solution?

1) place some volume of solution here

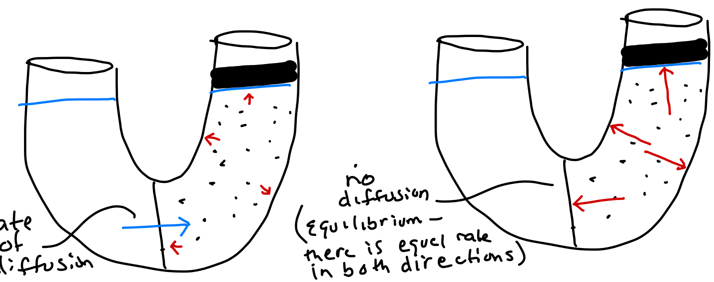
2) place equal volume of pure H_2O here



4) Cap the column of solution with a rigid ceiling

3) membrane that is
a) permeable to H_2O
b) not permeable to the solute

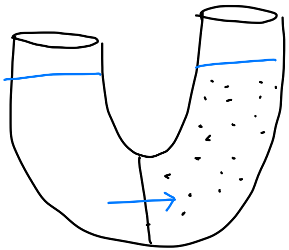
Because the concentration of H_2O is greater on the pure water side, H_2O will diffuse into the solution



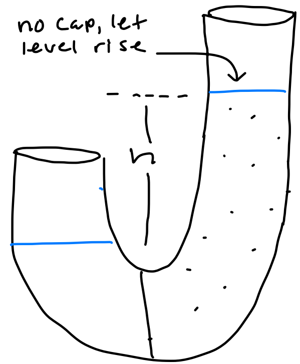
As H_2O molecules move into the solution, the hydrostatic pressure of the solution increases. At equilibrium, when there is no more diffusion of H_2O, the hydrostatic pressure of the solution is equal to the osmotic pressure of the solution (but the osmotic pressure has a negative sign)

continued →

Three conceptions of osmotic pressure (P_{sol})



no cap, let level rise



$$P_{sol} = \frac{P}{A} = \frac{W}{A} = \frac{m \cdot g}{A} = \frac{d \cdot V \cdot g}{A} = \frac{d \cdot h \cdot A \cdot g}{A} = d \cdot h \cdot g$$

acceleration due to gravity

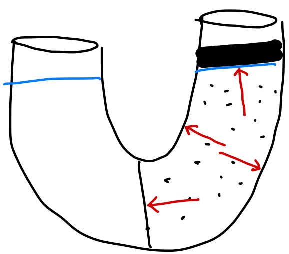
w is the weight of the extra water

m is the mass of the extra water

d = density

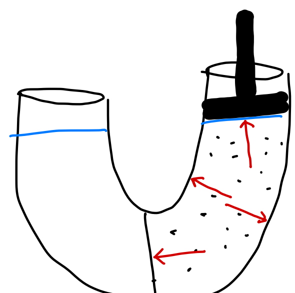
v = volume

h is height



P_{sol} is the hydrostatic pressure in the solution at Equilibrium

P_{sol}



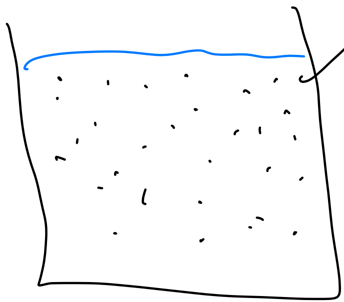
here, we don't let any water move, but instead use a piston to apply a pressure to the water.

P_{sol} is the pressure we'd need to apply to the solution to exactly balance the tendency of H_2O to move into the solution.

* A very small difference in [SOL] causes a big difference in height. for example if Δ[SOL] = .039 mol/L $\longrightarrow$ ~10 m difference in column height!

So osmotic pressure is a very weird kind of pressure

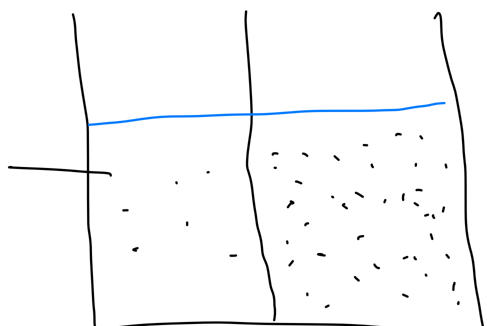
- If a pressure is a standardized force $\frac{F}{A}$, then osmotic pressure is weird because there is no force.



This solution has an osmotic pressure but what is the force?

Even in the context of a semipermeable membrane and osmosis, there is no force, there is simply a *NET* movement of H_2O up the sol concentration gradient.

$\downarrow [sol]$
$= \downarrow P_{sol}$



$\uparrow [sol]$
$= \uparrow P_{sol}$

A force causes acceleration. There is no acceleration of individual particles, just a net transfer of H_2O in one direction.

water potential (Ψ) - how plant physiologist speak

$\Psi = \Psi_p + \Psi_s$ (Ψ is greek letter psi pronounced "sign")

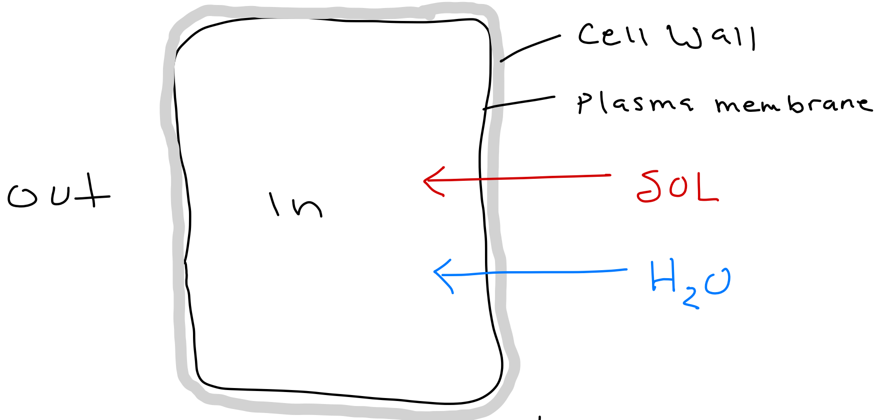
Ψ_p is the hydrostatic pressure. Ψ_p is always positive. A big Ψ_p is a big, positive number

Ψ_s is the osmotic pressure. Ψ_s is always negative. A big Ψ_s is a big, negative number.

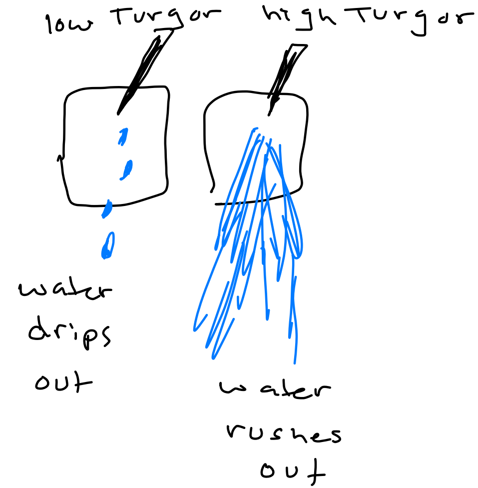
In Bulk Flow, we say Fluids move from high to low P, where P is hydrostatic Pressure

When using Ψ, in either bulk flow or osmosis, we say water flows from more positive Ψ to more negative Ψ.

Turgor Pressure



Poke a hole in cell w/



1. $\Psi_p^{in} + \Psi_s^{in} = \Psi_p^{out} + \Psi_s^{out}$ - System at equilibrium
2. Cell transports solutes in, so Ψ_s^{in} becomes more negative
3. water moves into cell, which pushes against cell wall
4. increases hydrostatic pressure on cell because cell wall resists expansion
5. This increased hydrostatic pressure is Turgor Pressure

Phloem loading and Unloading control phloem flow

↑ Ψ

load sugar

H_2O follows,

source: leaves that make sugar

H_2O

H_2O

H_2O enters from xylem along route

Sinks:

Unload sugar

H_2O follows

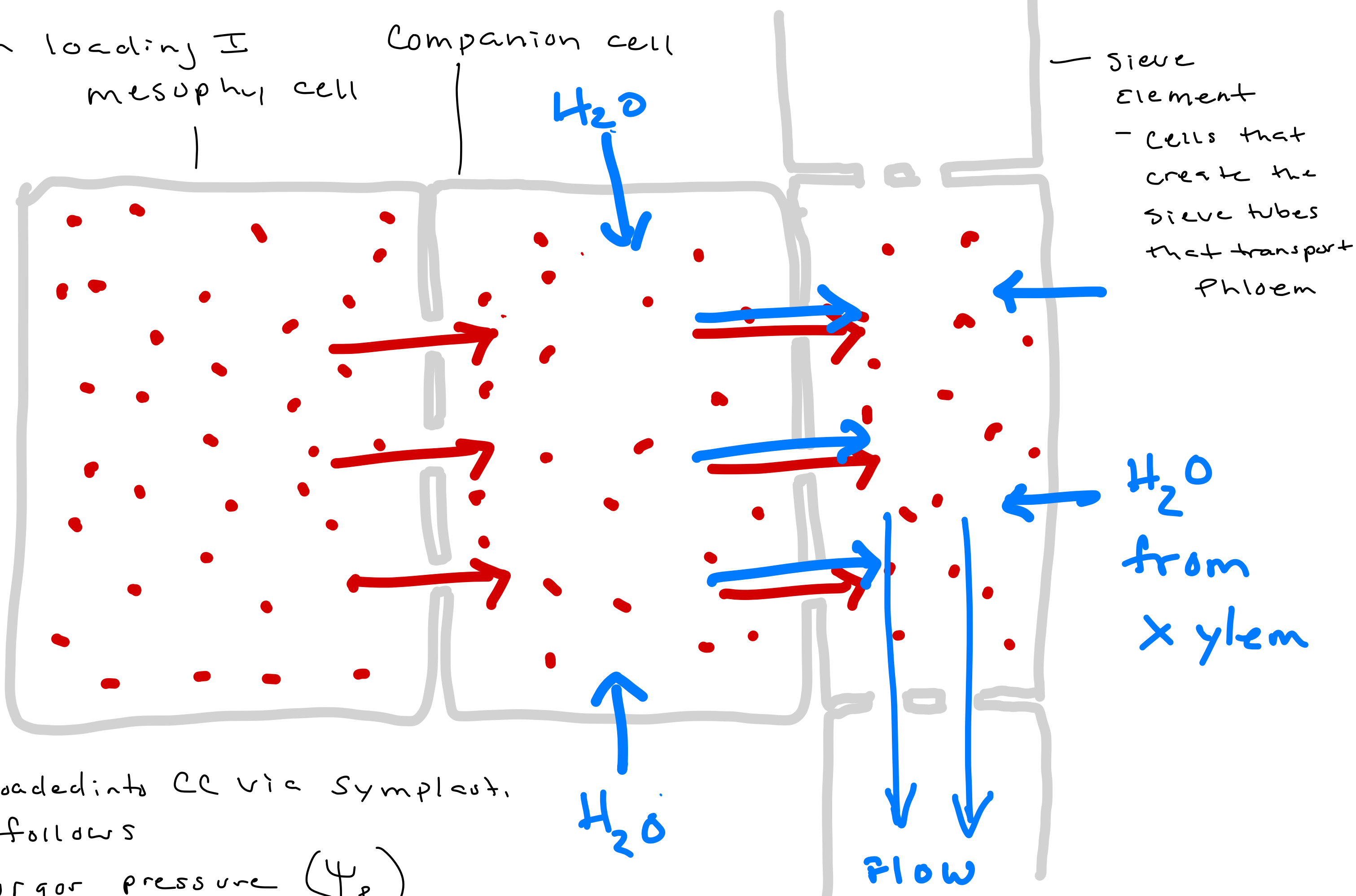
sugar unloads in stem for growth

Unload sugar

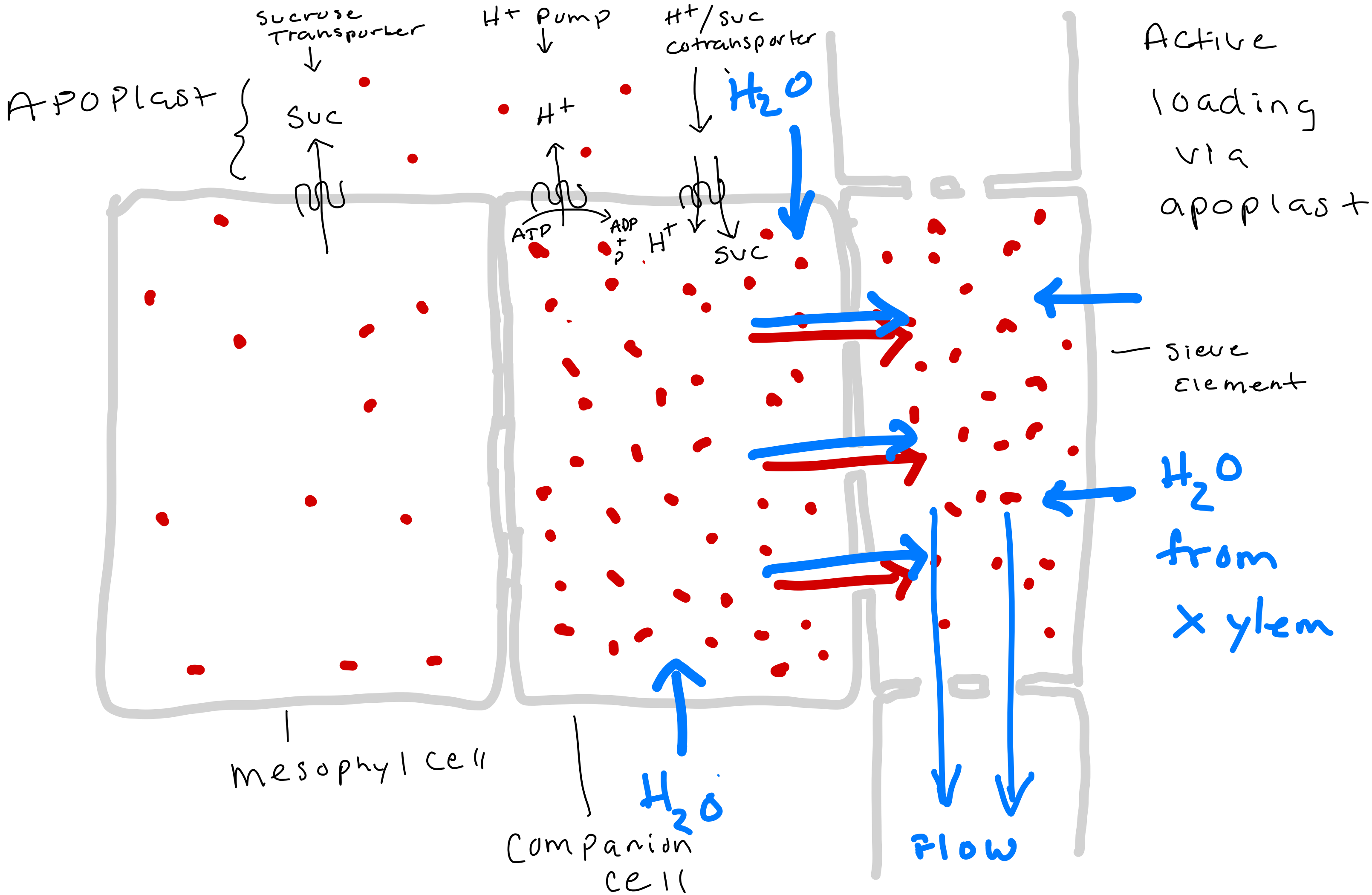
H_2O follows

and roots for growth / storage

Phloem loading I



1. Sugar loaded into CC via symplast.
2. H_2O follows
3. ↑ turgor pressure (Ψ_p)
4. Cause flow from ↑Ψ_p to ↑Ψ_p

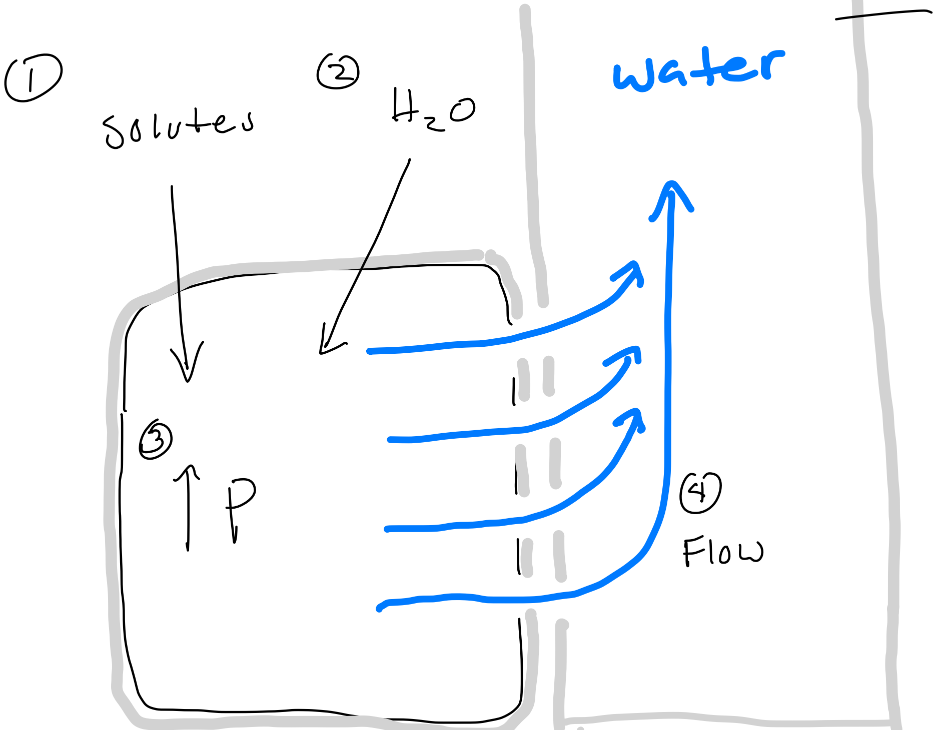


Active loading via apoplast
Apoplast
Sucrose Transporter
Suc
H+ pump
H+
H+/suc cotransporter
H_2O
ATP
ADP + P
H+
suc
sieve element
H_2O from xylem
mesophyl cell
Companion cell
H_2O
Flow

Passive loading requires mesophyl cells in leaves to maintain high [suc] to drive phloem. This is less Sucrose to do leaf stuff.

Active loading takes ATP but does not require mesophyl cells to maintain high [suc] so more sucrose to do leaf stuff

Root Pressure - Pushing water up

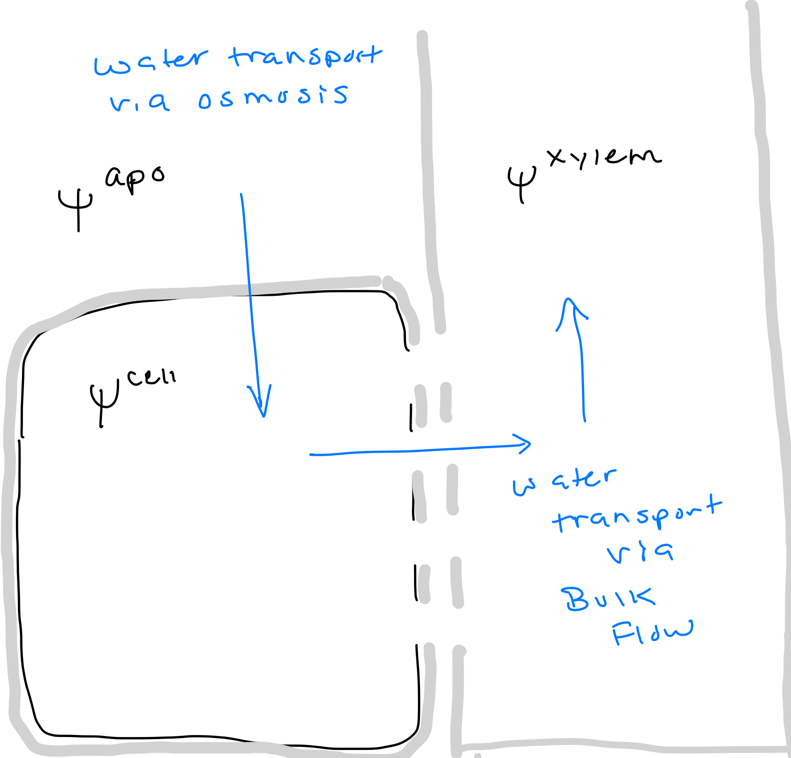


1) Solutes transported into cell via active transport

2) H_2O follows (into cell)

3) This increase turgor Pres. (hydrostatic pressure)

4) H_2O flows down pressure gradient into xylem



1. $\psi^{cell} = \psi^{apo} = \psi^{xylem}$

2. Transport solute into cell

$\psi^{cell} = \psi_s^{cell} + \psi_p^{cell}$

2a. increases solute potential (= more negative)

2b. This decreases ψ^{cell} relative to ψ^{apo}, so

3. H_2O moves from apoplast to cell

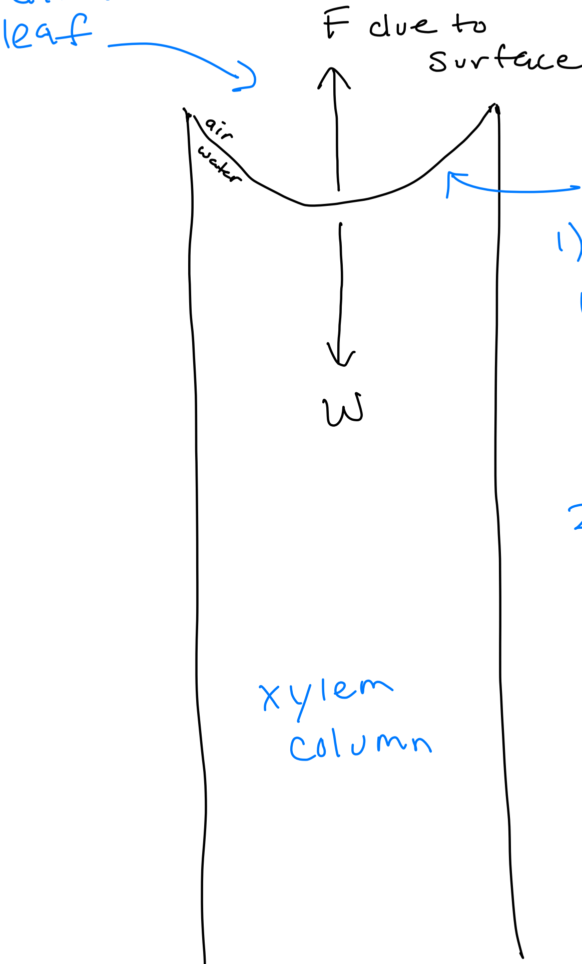
$\psi^{cell} = \psi_s^{cell} + \psi_p^{cell}$

3a. increase pressure potential

3b. This increases ψ^{cell} relative to ψ^{xylem}, so

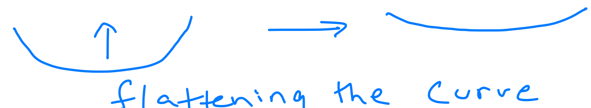
4. H_2O moves from cell into xylem

Transpiration - pulling water up

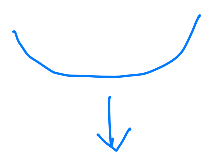


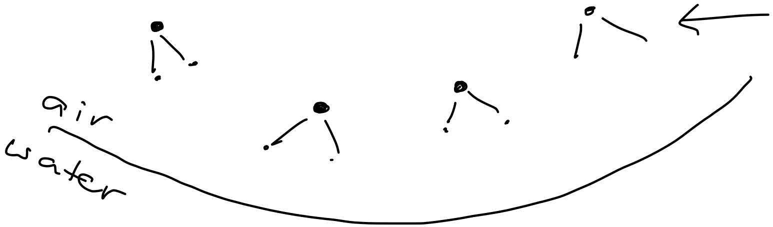
a stretched H_2O surface balancing

1) surface tension pulling up on surface to minimize surface area (flatten the curve)

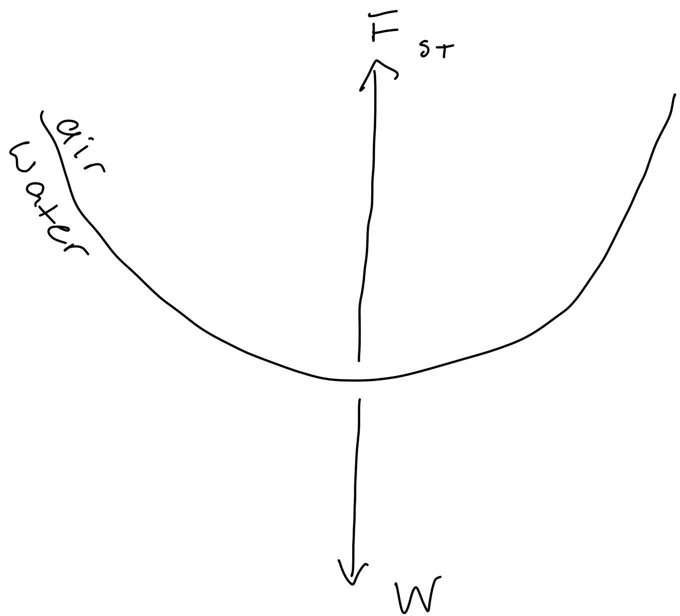


2. weight of the column of H_2O is pulling down on the surface





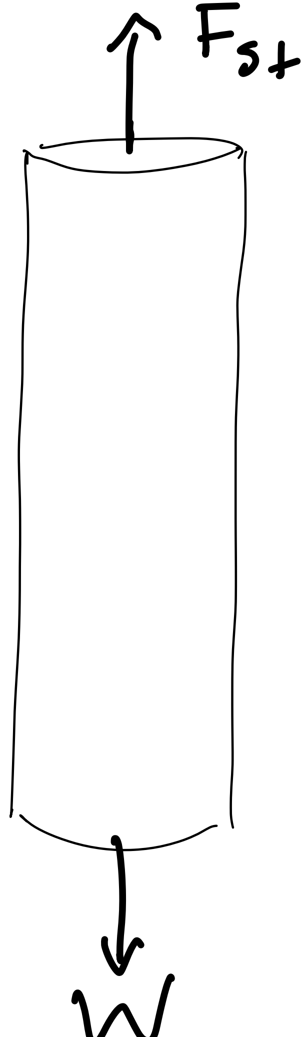
1. H_2O evaporates from surface due to Energy from sun increasing KE of surface molecules.



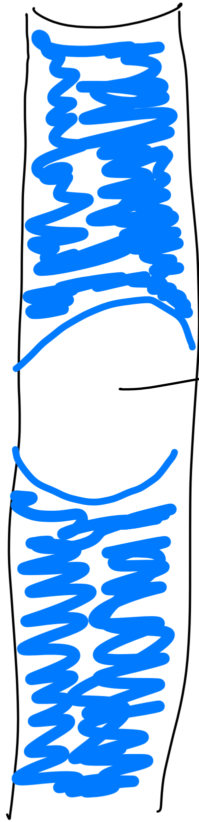
2. This increases curvature of surface, or increased surface area.

3. The H_2O resist "being stretched" which increases the Force due to surface tension

4. this pulls H_2O up the column



The column of water is in extreme tension. it is being pulled apart. The hydrostatic pressure of the xylem is truly negative - not just relative to something. This doesn't happen in gases or physics 101 textbooks.



gas bubble (embolism)

Plants have adaptations for avoiding cavitation – the formation of a gas bubble due to the column of water "ripping apart".