Energy → physiological processes → plant growth
e.g. Energy → diffusion of water, gases, elements……*etc.* → all biochemical processes in plant → plant growth.

Laws of thermodynamics:-

0th Law: - Zeroth Law of Thermodynamics states that if two systems are in thermodynamic equilibrium with a third system, the two original systems are in thermal equilibrium with each other.

1st law: - The material cannot be destroyed nor created, but it could be changed from one state to another.

2nd law: - Can be used for determination of all biochemical processes and reactions that takes place spontaneously.

3rd law: - At absolute zero (-273^{0}C) the absolute change in entropy becomes zero.

In all physiological process in plant, the interest is concentrated on relative values of energy (but not the absolute values) in the beginning and end of chemical or physical reaction.

Free energy:

Amount of energy available to do work is called Gibbs free energy (G).

Water Potential.

Water potential is a measure of the energy state of water. This is a particularly important concept in plant physiology because it determines the direction and movement of water.

1. Free energy of water - energy available to do work (J = n m).
2. Chemical potential (μ) - free energy/unit quantity (usually per mole) (J mol^{-1}).
3. Water potential (Ψw) - chemical potential of water, compared to pure water at the same temperature and pressure. The units are in pressure because: (a) plant cells are under pressure; and (b) it is easier to measure pressure.
4. Derivation of units - Water potential is official defined as the chemical potential of water (J mol^{-1}). When divided by the partial molar volume (L mol^{-1}):

J mol^{-1}/ L mol^{-1} = J / liter = energy / volume = (weight x distance)/area x distance = force/area = pressure units.

Pressure is measured in MPa (mega pascals). 1 MPa = 10 bars = 10 atm. (1 atm = 760 mm Hg = 14. 7 lbs sq in^{-1} = 14.7 lbs in^{-2} = 760 mm Hg = 1.013 bars: typical tire pressure is 0.25 MPa.

Equation for water potential (must account for the factors that influence the diffusion of water).

$$\Psi w = \Psi p + \Psi s + \Psi m + \Psi g$$

Where **Ψw = water potential**;

Ψp = pressure potential;

Ψs = solute or osmotic potential;

Ψm= matric potential and

Ψg = gravity potential.

1- Solute (or osmotic) potential (Ψs).

This is the contribution due to dissolved solutes. Solutes always decrease the free energy of water; thus, their contribution is always negative. The solute potential of a solution can be calculated with the van's Hoff equation: $\Psi s = - miRT$ where m = molality (moles/1000 g); i = ionization constant (often 1.0); R = gas constant (0.083-liter x MPa/mol deg); and T = temperature (K).

2-Pressure (or Pressure Potential; Ψp).

Due to the pressure build up in cells. It is usually positive, although may be negative (tension) as in the xylem. Pressure can be measured with an osmometer.

Positive pressure potential is called turgor pressure.
Negative pressure potential is called tension.

3-Matric potential (Ψm).

This is the contribution to water potential due to the force of attraction of water for colloidal, charged surfaces. It is negative because it reduces the ability of water to move. In large volumes of water, it is very small and usually ignored. However, it can be very important in the soil, especially when referring to the root/soil interface.

* Cytoplasm is a colloid, made up largely of protein molecules dispersed in water.

*It is hydrophilic, i.e., attracts water molecules around them and prevents them to aggregate into large particles and settle out.

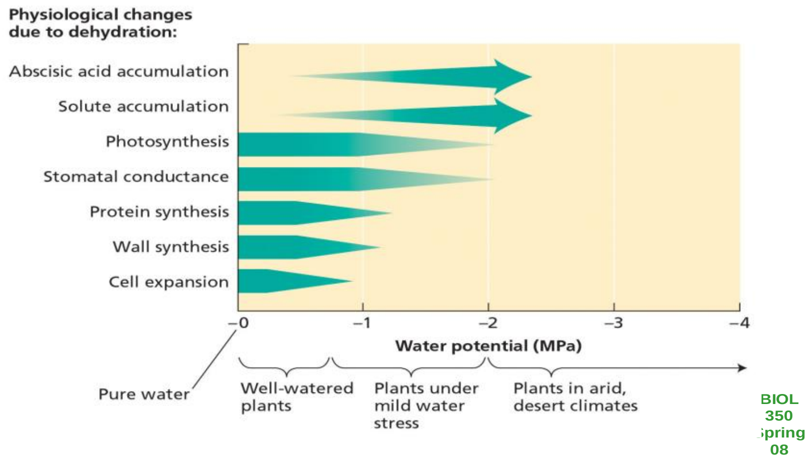
*Imbibition's is the processes by which water is absorbed by hydrophilic colloids inside seeds at the beginning of germination.

4. Gravity (Ψg).

A contribution of gravity is usually ignored unless referring to the tops of tall trees.

The water potential of pure water is zero. Water potentials in intact plant tissue are usually negative (because of the large quantities of dissolved solutes in cells).

The Water Potential Concept Helps Us Evaluate The Water Status of a Plant



Significance of osmosis to plant.

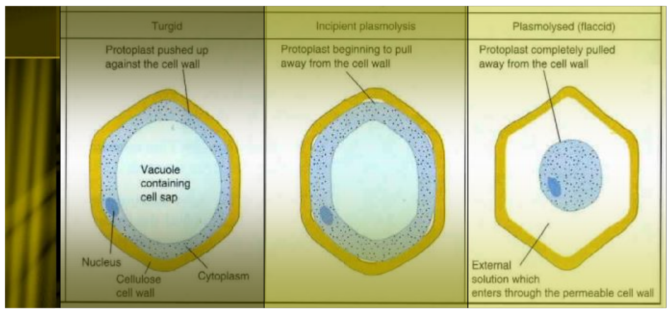
1. Maintenance of plant tissues in a state of turgidity where the tissues remain active metabolically.
2. Cause entrance of water into the plant, as well as transport and distribution of water within the plant.
3. Provide soft plant cells (as shoot tips for example) with strength and rigidity.
4. Enhances penetration of root tissues into the soil
5. Facilitate emergence of seedlings (i.e. sprouting) from the soil.

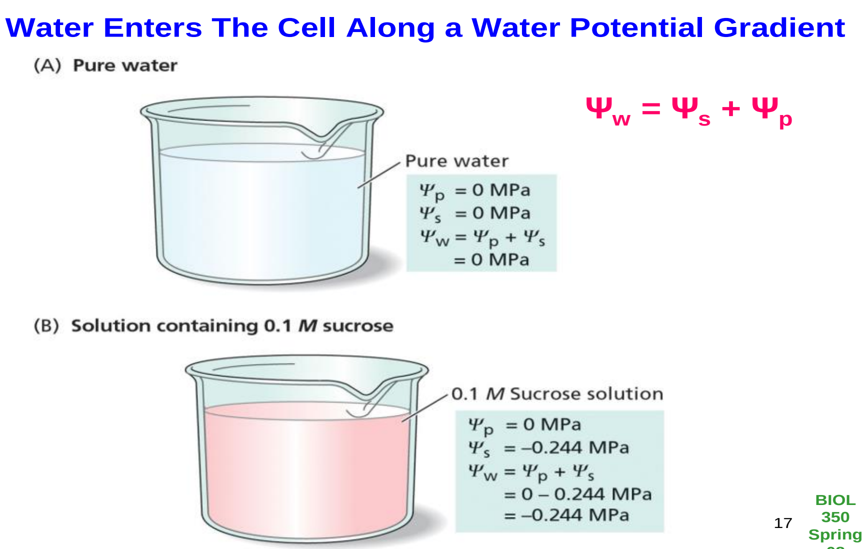
Hypertonic Solutions:- Contain a high concentration of solute (e.g. salts, sugars) relative to another solution (e.g. the cell's cytoplasm). When a cell is in a hypertonic solution, water diffuses out of the cell, causing the cell to shrivel (**plasmolysis**).

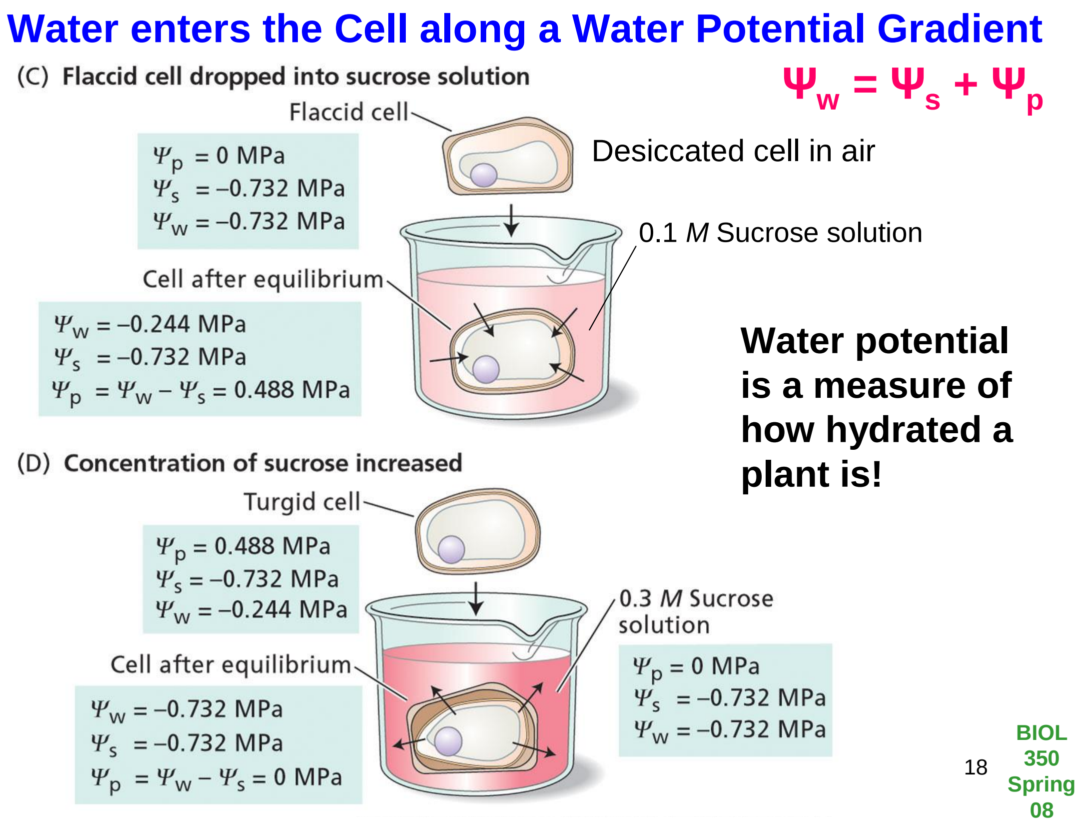
Hypotonic Solutions:- Contain a low concentration of solute relative to another solution. When a cell is in a hypotonic solution, water diffuses into the cell, causing the cell to swell and possibly explode (**Cytolysis**).

<u>Isotonic Solutions</u>:- Contain the <u>same concentration</u> of solute as another solution. When a cell is in an isotonic solution, water diffuses into and out of the cell at the same rate. The fluid that surrounds the cells is isotonic.

- **Incipient plasmolysis** is the point at which the protoplast of the cell just lost contact with the cell wall.
- **Plasmolysis** is a condition of the cell when the protoplast shrinks away from the cell wall due to osmosis.







Imbibition.

A special type of diffusion based on water movement according to the difference in water potential .e.g. seed imbibitions, xylem imbibitions. Imbibition is one of the causes of water movement inside the plants.

Conditions for imbibition's.

1. Presence of difference or gradient in water potential ($\Delta\Psi w$) between imbibed material and surrounding liquid (imbibition material).

2. Presence of attraction between them e.g. rubber imbibes by ether but does not imbibes by water. Other plant materials are less imbibed by ether.

Ψw for dry seeds = - 900 bar (or -90 Mpa).

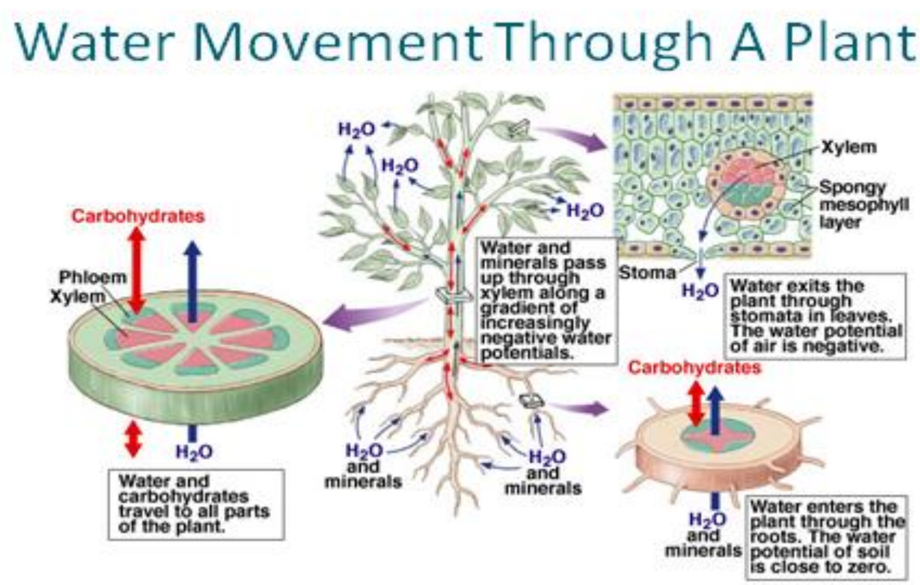
When seeds are placed in water, a sharp gradient is generated, and imbibition of water take place.

Factors affecting imbibitions.

1. **Temperature**: rate of imbibition's increases by increased temperature, but does not affect the amount of imbibed water.

2. **Osmotic potential**: affects both the rate of imbibition's and amount of imbibed water.

During imbibition's pressure is generated and called imbibition's pressure (currently called matric potential (Ψm).Imbibition's have a significant importance in seed germination. No germination takes place without imbibition's.



Water and soil.

1. Saturated - soil before drained. Gravitational water - water that drains and is not tightly bound; $\Psi = 0$ MPa
2. Field capacity - soil that holds all the water it can against gravity. Capillary water -water held by capillary action, water at field capacity; $\Psi = -0.015$ MPa
3. Permanent wilting percentage - soil moisture content at which plants can't get enough water. For most, $\Psi = -1.5$ MPa.

   a. between PWP and FC is the water available for a plant to use;
   b. clay holds more water than sand at any $\rightarrow\Psi$; and
   c. Clay holds water more tightly. Smaller particles in clay have a larger total surface and hence, have more charged surfaces that will bind water tightly.

Soil water potential is a function of osmotic potential (which is usually near zero except in saline soils) and mostly pressure (used to call it matrix potential; this refers to the tension generated because of the attraction of colloidal particles; i.e., adhesion).

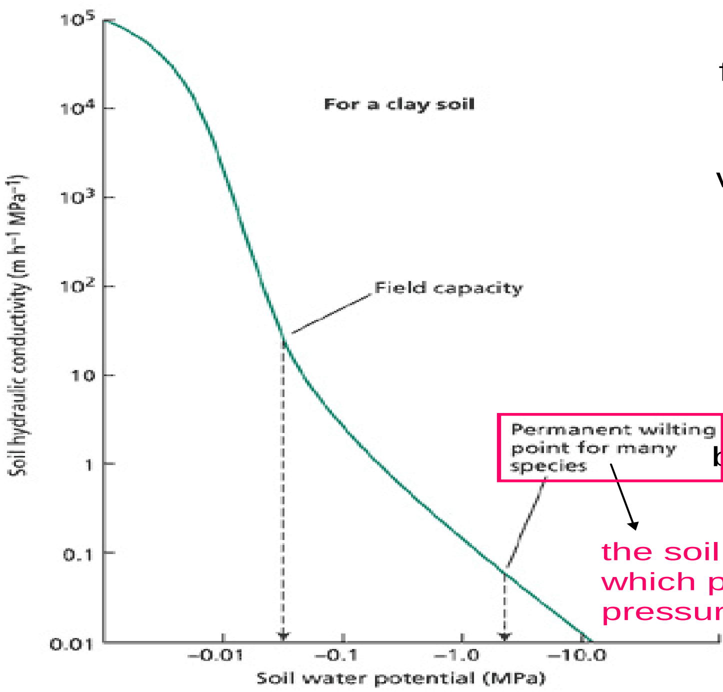
Water movement through soil - mostly is due to bulk flow as a result of pressure gradients with some diffusion.

- In addition, **diffusion** of water vapor accounts for some water movement.
- As water moves into root – less in soil near the root.
  - Results in a **pressure gradient** with respect to neighboring regions of soil.
  - So there is a **reduction** in Ψp near the root and a **higher** Ψp in the neighboring regions of soil.
- Water filled pore spaces in soil are interconnected, water moves to root surface by bulk flow down the pressure gradient.
- As water moves from soil into root the spaces fill with air
- This **reduces** the flow of water.

- **Permanent wilting point**
- At this point the water potential (Ψw) in soil is so low that plants cannot regain turgor pressure
- There is not enough of a pressure gradient for water to flow to the roots from the soil.

- **This varies with plant species.**
- The rate of water flow depends on:-
    - Size of the pressure gradient.
    - Soil hydraulic conductivity (SHC).
        - Measure of the ease in which water moves through soil.
- SHC varies with water content and type of soil.
    - Sandy soil high SHC.
        - Large spaces between particles.
    - Clay soil low SHC.
        - Very small spaces between particles.

Water Moves through Soil by Bulk Flow



- Soil hydraulic conductivity is a function of the water potential of the soil.
- Conductivity measures the ease with which water moves through the soil.
- As water content (and hence the water potential) decreases, the hydraulic conductivity decreases drastically (note logarithmic scale).
- Decrease in conductivity in drying soils is due to replacement of water by air, i.e. water flow becomes more difficult.

the soil water potential value at which plants cannot regain turgor pressure

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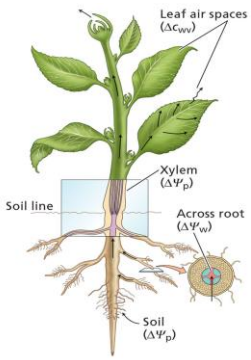
Water absorption and translocation.

The plant obtains water from the soil and absorbs it through its root system. Very little amount of absorbed water remain in the plant and used in growth, photosynthesis and other metabolic activities, while the greater amount of water is lost by transpiration. Absorption means movement of water from soil to root, while the process of translocation means the movement of food from "source" to "sink".

Main Driving Forces for Water Flow from the Soil Trough the Plant to the Atmosphere



Water potential in soil:
$\Psi_w = \Psi_s + \Psi_p$

Ψ_s – usually negligible, because solute concentrations are low (-0.02 MPa; soils with salts: -0.2 MPa).

Ψ_p – in wet soils: close to 0
– in dry soils: decreases, becomes negative

Where does the negative pressure in soil water come from?

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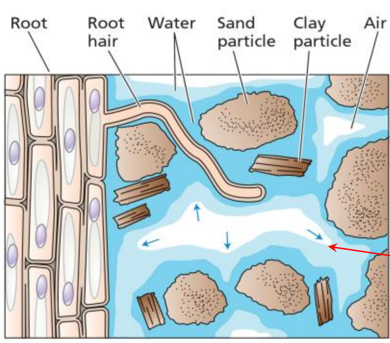
A Negative Hydrostatic Pressure in Soil Water Lowers Soil Water Potential



- root hairs increase plant surface area for water absorption

- soil is a mixture of particles, water, solutes, air

- as water is absorbed by plant, soil solution recedes into smaller pockets

- at air-water interface, this recession causes development of concave menisci, thus brings the solution into tension (negative pressure) by surface tension

- as more water is removed from soil, more acute menisci are formed, resulting in greater tension, i.e. more negative pressure

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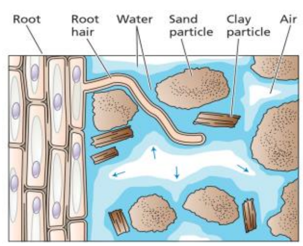
A Negative Hydrostatic Pressure in Soil Water Lowers Soil Water Potential



- Water under these curved surfaces develops a negative pressure:
  $\Psi_p = -2T/r$
- T – surface tension of water (7.28×10^{-8} MPa m)
- r – radius of curvature of air-water interface

Example: r = 1 μm (~ size of the largest clay particles) equals Ψp = -0.15 MPa (may reach -1 to -2 MPa in further dried-out soils)

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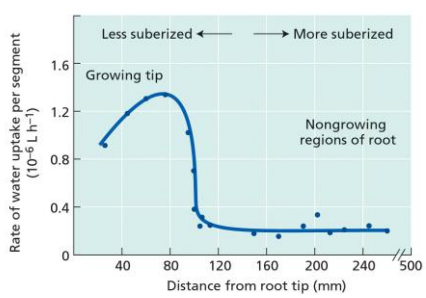
Water Moves in the Root via the Apoplast, Transmembrane, and Symplast Pathways



- Water moves through soil by **bulk flow.**
- Water enters root most readily near the root tip.
- Although it might seem counterintuitive, older root regions must be sealed off if there is water uptake from regions that are actively growing.
- This allows xylem tensions to extend further into the root system, allowing water uptake from distal (further away) regions of the root system.

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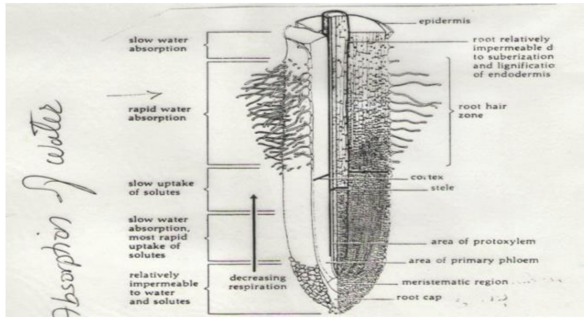
Most of the absorption takes place in root tips, mainly through the root hairs. Absorption is usually through osmotic forces as a result of difference in Ψw (from high Ψw region i.e. soil, to region of lower Ψw, i.e. root). This usually takes place spontaneously (termed passive absorption) without the need for metabolic energy. Available water for absorption is found in the soil between field capacity (FC) where (Ψw=0) and wilting point (WP) where Ψw= -15 bar).



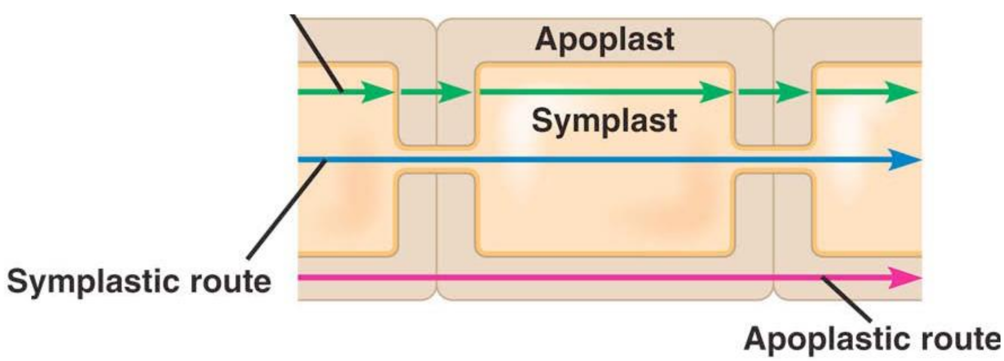
Water movement in the plant.

Absorbed water by the root hairs diffuses through the cell walls into the endodermis, which prevents the diffusion due to the presence of suberine layer (an impermeable to water) in Casparian strip. Therefore, the water goes into the protoplasm of the endodermis cells, then translocation to the xylem tissues.

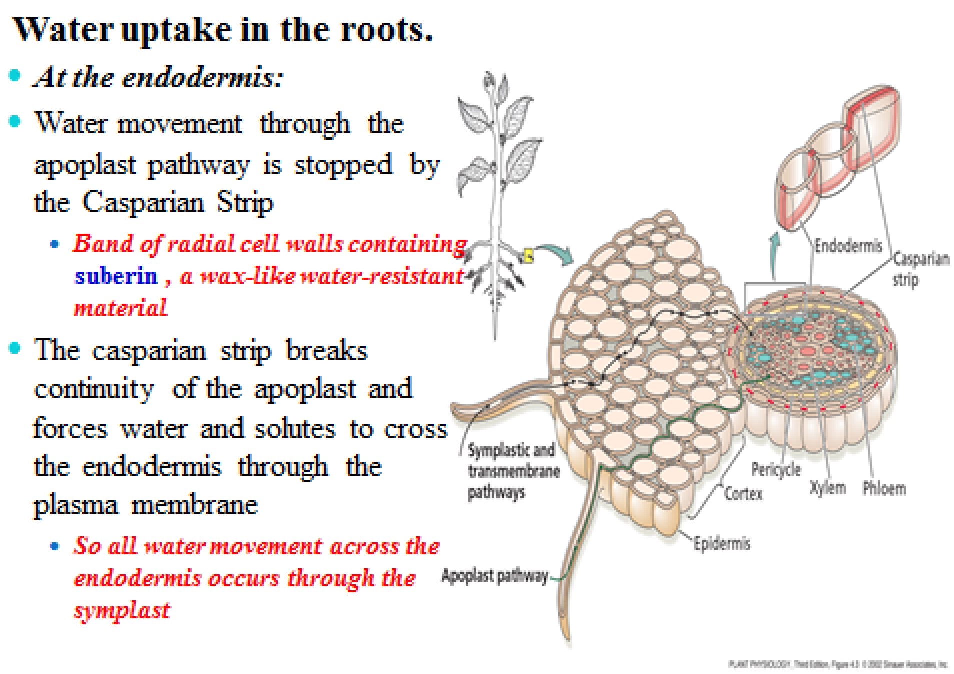
Transmembrane route.

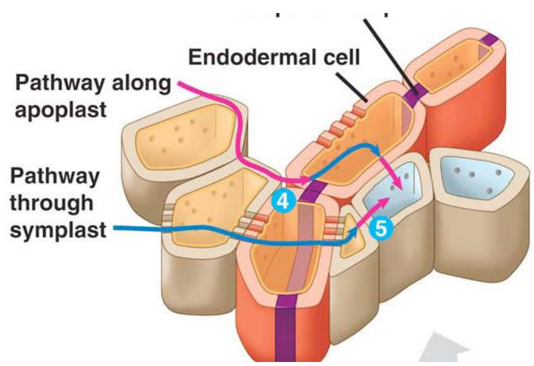
Apoplast: - Movement of water in continuous system between cell walls and intercellular spaces filled with air or water.

Simplest:- Movement of water through a continuous system that connects cell cytoplasm by plasmodesmata and forms a system for water and solute translocation.



Transmembrane: – The water moves from cell-to-cell crossing membranes as it goes.





Mechanism of water transport.

How does water moves up to high plant parts and organ that sometimes reaches more than a 100 meter? Water movement to the upper parts must be achieved either by pumping force or by pulling or lifting force (i.e. under tension). Several theories are available

Water movement through capillary vessels by capillary phenomena.

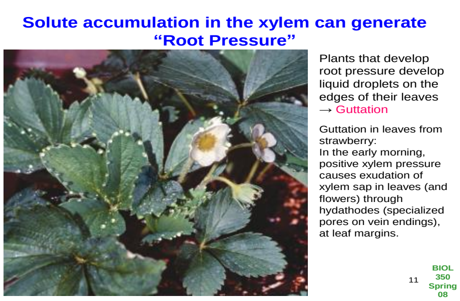
Movement by such force is not enough to support water movement for more than 1 meter. It is not accepted theory.

Root pressure theory.

If a stem of herbaceous plant is severed near the soil level, the xylem sap is seen to come out from the cut edge. This flow of sap is caused by root pressure that develops as a result of metabolic activities. This phenomenon is not observed when metabolic activities are repressed by respiration inhibitor, or lack of oxygen or by low temperature. Root pressure is generated as follows.

The ions are absorbed and accumulate in the xylem vessels (active absorption).Increased ion concentration in the xylem vessels leads to decrease the osmotic potential. This will lead finally to water movement towards the xylem vessels by osmotic forces. As a result of water entrance, pressure is generated.

- If the stem is severed (cut off), the sap will come out or **exudation** to the outside.
- If a manometer is placed on the cut surface, root pressure can be observed and measured.
-Root pressure occurs when soil water potential is high and transpiration is low.



Water transport cannot be explained according to this theory for the following reasons:-

Some plants (for example: conifers) does not show or generate root pressure, nevertheless water moves up in such plants.

Root pressure is not enough to push the water up to more than few meters (max. root pressure can reach about 2 bars only, while more than 20 bars are required for tall plants).

Rate of flow of xylem sap is less than the rate of transpiration, which means that the xylem sap is under tension rather than pressure.

In some plants: root pressure causes the appearance of water drops on leaf edges under low transpiration rate conditions (e.g. in humid weather). In such cases the root pressure will be high, and causes the exit of water drops from special openings or pores at the end of veins called hydathodes. This Guttation usually observed at night time.

Cohesion- tension theory :(Cohesion – Adhesion theory).

The force needed for water translocation to the top of a high tree might reach 10-15 bars or even higher. This force is available only as a result of force of evaporation (or: transpiration). Under fast transpiration rate condition, transpiration pull (Tn-pull) is responsible for water movement.
Elements of cohesion- tension theory.

1. Driving force (or pulling force): water movement from soil to root stem, then to the leaf and later to stomata and to the air is based (or dependent) on reduction in water potential gradient.

2. Adhesion force between water molecules and cell walls of hydrophilic nature by hydrogen bonds.

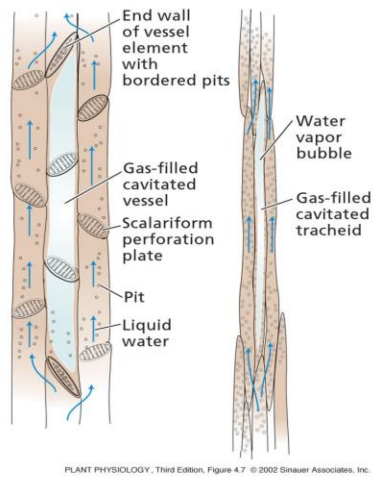
3. Cohesion force between water molecules by hydrogen bonds.

- Roots can develop positive hydrostatic pressure in their xylem → root pressure.

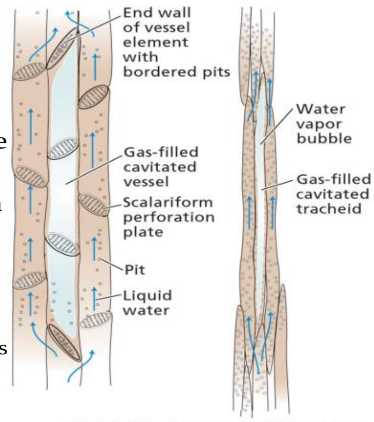
- However, root pressure is less than 0.1 MPa and disappears when transpiration rate is high → would not be enough to move water up a tall tree.
- Water at top of trees develops large tension = negative hydrostatic pressure (suction).
    - This tension "pulls" water through the xylem
    - This mechanism is called **cohesion-tension theory of sap ascent**
- Requires cohesive properties of water to sustain large tensions in the xylem water columns.

Water transport through xylem

- Such breaks in the water column are not unusual.
- Impact minimized by several means
    - Gas bubbles can not easily pass through the small pores of the ***pit membranes***.
    - Xylem are interconnected, so one gas bubble does not completely stop water flow
- Water can detour blocked point by moving through neighboring, connected vessels.



- Gas bubbles can also be eliminated from the xylem.
  - At night, xylem water pressure increases and gases may simply dissolve back into the solution in the xylem.
  - Many plants have secondary growth in which new xylem forms each year. New xylem becomes functional before old xylem stops functioning
    - As a back up to finding a way around gas bubbles.

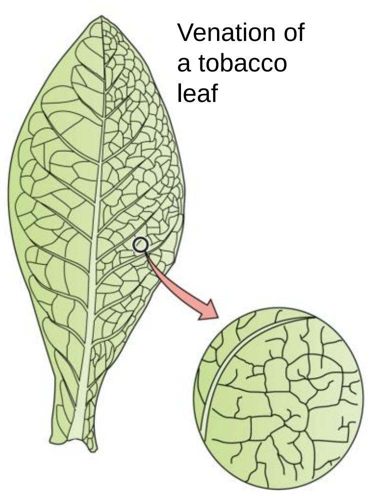


PLANT PHYSIOLOGY, Third Edition, Figure 4.7 © 2002 Sinauer Associates, Inc.

Xylem Transport of Water in Trees Faces Physical Challenges Problems:-

1) Water under tension transmits an inward force to walls of xylem → tendency to collapse → wall thickenings
2) As tension in water increases → tendency for air to be pulled in (air seeding) → air bubble will expand (cannot resist tensile forces) → **cavitation/embolism** → continuity of water column breaks**.**

Water Evaporation in the Leaf Generates a Negative Pressure in the Xylem

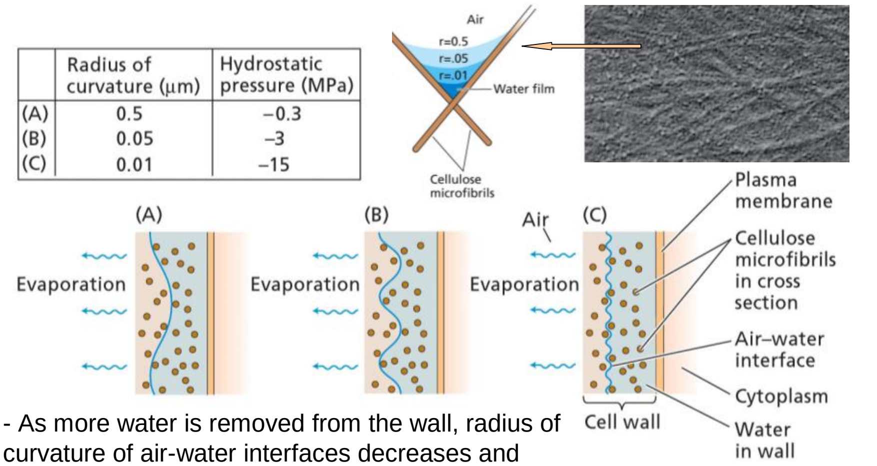


Venation of a tobacco leaf

- Water transported through vascular bundles into leaves
- venation is very fine: most cells are within 0.5 mm of a minor vein
- negative pressure that causes water to move up through xylem develops at surface of cell walls in leaf (similar to situation in soil)
- cell wall acts like a fine capillary wick soaked with water
- cells within leaf are in contact with atmosphere through intercellular spaces

Water Evaporation in the Leaf Generates a Negative Pressure in the Xylem

	Radius of curvature (µm)	Hydrostatic pressure (MPa)
(A)	0.5	−0.3
(B)	0.05	−3
(C)	0.01	−15



- As more water is removed from the wall, radius of curvature of air-water interfaces decreases and pressure of the water becomes more negative.

→ Motive force for xylem transport is generated in the air-water interfaces within the leaf

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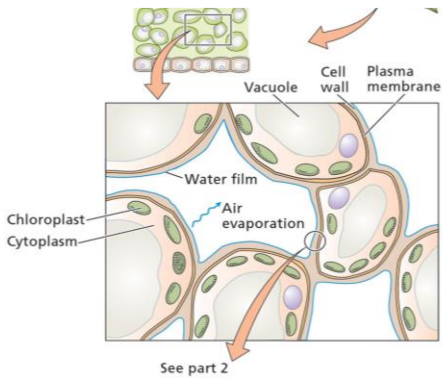

spaces.

- As water is lost to air, surface of the remaining water is drawn into interstices of the cell wall forming curved air-water interfaces.

- Because of high surface tension of water, curvature of these interfaces induces tension (negative pressure) in the water.

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Diffusion of water out of the leaf is very fast
Diffusion is much more rapid in a gas than in a liquid
Transpiration from the leaf depends on two factors:-

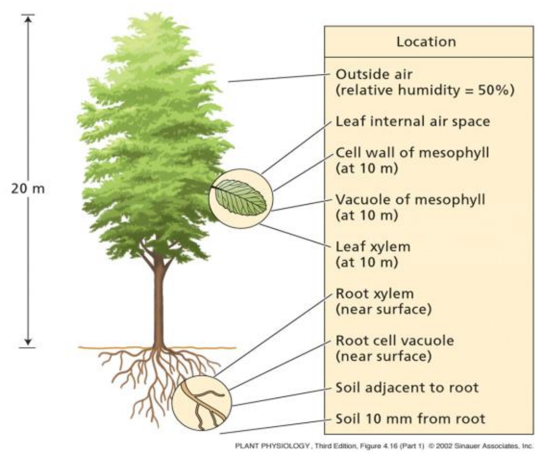
ONE: Difference in water vapor concentration between leaf air spaces and the atmosphere.

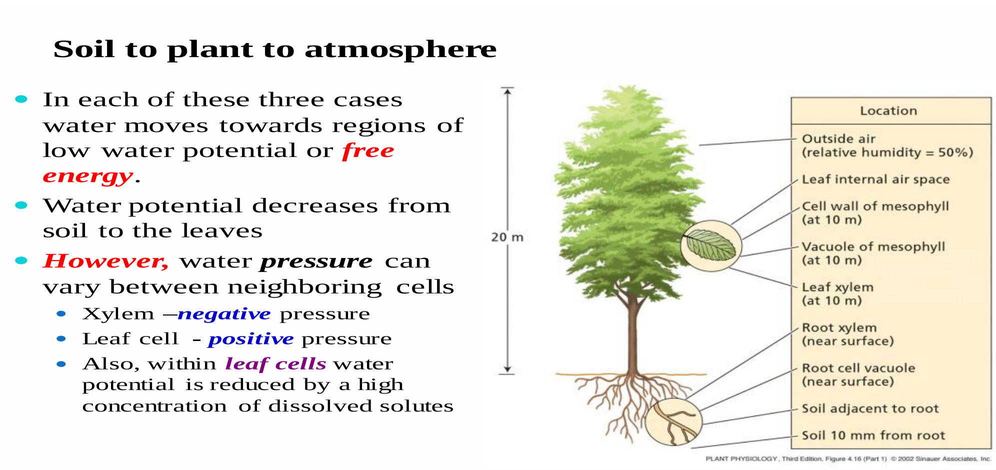
TWO: The diffusion resistance of the pathway from leaf to atmosphere.

**The diffusion resistance of the pathway from leaf to atmosphere has two components:
Leaf stomata resistance (rs) associated with diffusion through the stomata pore and resistance due to a layer of unstirred air next to the leaf surface Boundary layer resistance.

Soil to plant to atmosphere

- Soil and Xylem:
  - ***Water moves by bulk flow***
- In the vapor phase:
  - ***Water moves by diffusion – until it reaches out side air, then convection occurs***
- When water is transmitted across membranes
  - ***Driven by water potential differences across the membrane***
  - ***Such osmotic flow due to cells absorb water and roots take it from soil to xylem***





Factors affecting water absorption.

Several factors can affect this process as follows:-

1. Soil temperature: the rate of absorption is increased with increased temperature of soil.

and decreased with its reduction because:-

A-Water viscosity increase with reduction in temp.

B-Permeability of membranes decreased with reduction in temp.

C- Biological activities in general, as well as root growth are reduced with reduction in temperature.

2. Availability of soil water between field capacity (FC) and permanent wilting point (PWP).

3. Osmotic potential of soil solution leads to increase in water potential (Ψw), which subsequently increases the Ψw gradient between soil solution and cell sap, which further leads to increased absorption.

In Halophytes (i.e. plants adapted to grow under saline conditions), their Ψs might reach -200 bars, gradient is generated in Ψs between cell sap and water, thus they absorb water as a result of Δ Ψs.

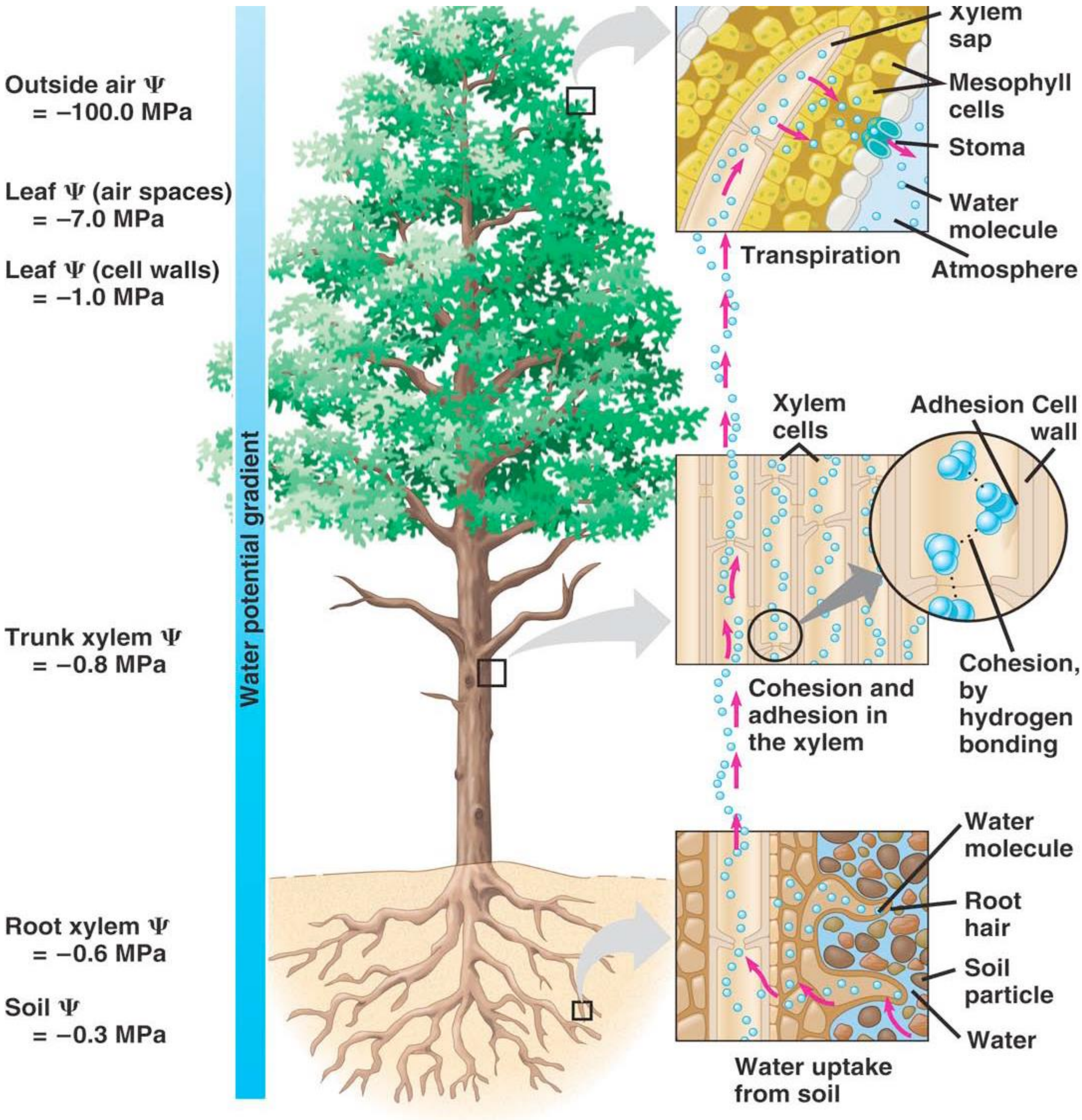
4- Soil aeration: Good soil aeration leads to a fast water absorption, while bad soil aeration causes reduction in absorption of water through reduction of oxygen availability, and subsequent reduction in metabolic activities such as respiration, reduced ion uptake, and finally reduced water absorption. Similarly, bad aeration causes carbon dioxide accumulation, which increases protoplasm viscosity, which further reduces the permeability of membranes to water, and subsequently reduces water absorption.

5- Rate of transpiration: high rate of transpiration cause more negative Ψw in the leaves, which increases the transpiration pull (Tn-pull) and cause increased water absorption.

6- Root characteristics: tap root system may absorb less water than fibrous root system due to increased surface area. Tap root system may go deeper into the soil searching for water to absorb. Absorption of water by areal part is very limited and depends upon.

a. Ψ w of leaf cells.

b. Permeability of cutin layer of the epidermis to allow water penetration.



Outside air Ψ = −100.0 MPa
Leaf Ψ (air spaces) = −7.0 MPa
Leaf Ψ (cell walls) = −1.0 MPa
Trunk xylem Ψ = −0.8 MPa
Root xylem Ψ = −0.6 MPa
Soil Ψ = −0.3 MPa
Water potential gradient
Xylem sap
Mesophyll cells
Stoma
Water molecule
Atmosphere
Transpiration
Xylem cells
Adhesion
Cell wall
Cohesion, by hydrogen bonding
Cohesion and adhesion in the xylem
Water molecule
Root hair
Soil particle
Water
Water uptake from soil