The essential role of water in plant life processes is dependent upon the capacity of water molecules to perform work. Water molecules in plant cells participate in dissolving solutes, sustaining colloidal systems and suspensions, transporting assimilates, and exerting turgor pressure needed for cell and organ support and growth. A thermodynamic expression of the capacity of water to perform this kind of work is the chemical potential ($\mu_w$). Chemical potential ($\mu$) of any substance equals the Gibbs Free Energy per mole of the substance. Water potential ($\Psi_w$) is the chemical potential of water per mole ($18 \text{ cc H}_2\text{O/mole}$) expressed as pressure, and compared with the chemical potential of pure water which is assigned a value of zero at atmospheric pressure, same temperature and height.

In plant physiology, the water potential of water in a system is usually manifested as pressure, so pressure units are meaningful. Thus, a force of 1 newton over an area of 1 meter$^2$ represents a pressure (force per unit area) of one Pascal (Pa). The megapascal ($10^6$ Pa) is the unit that is preferred in modern plant physiology. One megapascal (MPa) equals 10 bars, and 1.01 bars equal 1 atmosphere (14.7 lb/in$^2$).

![Diagram of Osmometer](image)

Figure 1. Diagrammatic representation of an osmometer.

The osmometer is an apparatus for measuring the osmotic potential of a solution. To understand the workings of an osmometer, assume that Solution A is a sucrose-water solution, and B is pure water. Solution A is enclosed by a differentially permeable membrane (DPM). The DPM is permeable to water but impermeable to sucrose. If no force is applied to the piston, water will cross the DPM by osmosis, and exert pressure (doing work) against the piston. The osmotic potential ($\pi$), also called solute potential ($\Psi_s$), is a measure of the degree to which solutes lower the water potential of the system. Thus, the osmotic potential of Solution A in the osmometer, expressed in megapascals, will determine the amount of osmosis that will occur before equilibrium is reached with Solution B. As water enters and work is done against the piston, the pressure will rise within the osmometer until pressure equivalent to the osmotic potential is reached. This pressure is called the
pressure potential \((\Psi_p)\) (or pressure, \(P\)) of the solution. The pressure potential may also be considered as the pressure that must be applied to the piston prior to osmosis to prevent a net osmosis of water into Solution A.

In 1887, Van't Hoff discovered an empirical relationship between the number of moles of solute \((n)\) per unit volume of solvent \((V)\) and the osmotic (or solute) potential by plotting osmotic potentials directly from osmometer readings. The relationship is as follows:

\[
\Psi_s = \frac{n}{V} - iRT \quad \text{(Equation 1)}
\]

where \(i\) is the ionization constant (equal to 1 unless the solute is ionic and dissociates), \(R\) is the universal gas constant \((0.00831 \text{ liter MPa mol}^{-1} \text{ K}^{-1})\), and \(T\) is the temperature. Since \(n/V\) is, by definition, molality [a 1 molal \((1 \text{ m})\) solution has one mole of solute per liter of solvent], our equation becomes

\[
\Psi_s = -miRT \quad \text{(Equation 2)}
\]

Molality is more recently being expressed as moles of solute per kilogram of water, instead of moles per liter \((1 \text{ liter of water equals } 1 \text{ kilogram})\). Therefore, \(R\) is expressed as \(0.00831 \text{ kg MPa mol}^{-1} \text{ K}^{-1}\).

Note that since there is no pressure in addition to normal atmospheric pressure upon the solution, then \(\Psi_p = 0\) and \(\Psi_w = \Psi_s\).

**Problem 1.** Outline the approach you would take to make the following sucrose solutions (F.W. of sucrose = 342.3):

(a) One liter of a 1 molar \((1 \text{ M})\) sucrose solution.

(b) One liter of a 1 molal \((1 \text{ m})\) sucrose solution.

NOTE: Show all calculations.

**Problem 2.**

(a) Calculate the \(\Psi_s\) of a 1\text{ m} sucrose solution at 20 C (i.e. 293 K; must use degrees K).

(b) What pressure would have to be applied to prevent water from diffusing into such a solution across a DPM from pure water?

(c) What will be the \(\Psi_w\) of Solution A at equilibrium?

(d) Answer Part (b) for a condition where pure water was replaced with a solution with \(\Psi_s = -1\text{ megapascal}\).

We can see that water diffuses from a region of low solute content (purer water) to a region of higher solute content, unless pressure is applied in sufficient quantity to cancel the effect of solutes. Therefore, in order to determine the overall potential of water to do work (water potential) we must consider two components as shown in the following relationship:

\[
\Psi_w = \Psi_p + \Psi_s \quad \text{(Equation 3)}
\]
Here $\Psi_s$, the osmotic potential, represents the extent to which solutes lower the water potential. Osmotic potential is expressed in MPa, and has a negative sign. The pressure potential ($\Psi_p$) comprises the effect on water potential due to the real pressure in the part of the system being considered. Thus, $\Psi_p$ has a positive value unless a negative pressure or tension exists. As noted earlier, the $\Psi_w$ of pure water (no solute) in an open beaker (i.e. no positive pressure when exposed to the atmosphere) equals zero MPa, by convention, since the absolute free energy of water cannot be determined.

Since pure water does not exist in plant cells or in soils, water potential values are negative in these systems. If $\Psi_s$ and $\Psi_p$ are known, $\Psi_w$ can be calculated (Equation 3). One can then predict the direction of diffusion of water from one location to another based upon the relative differences in $\Psi_w$. Water diffuses from a solution or cell with a higher (less negative) water potential to a lower (more negative) water potential.

**Problem 3.** Given that Solution A in Figure 1 has an osmotic potential of -0.8 MPa and a pressure potential of 0.2 MPa,

(a) what is the water potential of Solution A?

(b) The $\Psi_s$ of Solution B is -0.3 MPa. What is its initial $\Psi_w$?

(c) Given time to equilibrate, which way will water move, and what will be the resultant $\Psi_s$, $\Psi_p$, and $\Psi_w$ of each solution at equilibrium? Assume B had a large volume, and that A does change in volume?

**Problem 4.** A plant cell has an osmotic potential of -1.6 MPa and a pressure of 1.0 MPa due to pressure exerted by the cytoplasm against the cell wall.

(a) What is the cell water potential?

(b) If this cell was surrounded by pure water, explain the result and how this would change the cell $\Psi_w$ when cell and solution reach equilibrium.

**Problem 5.** A cell with a $\Psi_s$ of -1.0 megapascal is placed in solution with $\Psi_w$ of -0.5 MPa. What will be the $\Psi_s$, $\Psi_p$, and $\Psi_w$ of the cell at equilibrium?

**Problem 6.** Two cells are in direct contact. Cell A has an osmotic potential of -1.0 MPa and a pressure of 0.4 MPa. The respective values for Cell B are -0.6 and 0.3 MPa.

(a) Which way will water move, and why?

(b) If Cells A and B were root hair cells, which cell would be best able to absorb water from the soil solution if soil $\Psi_w$ = -0.5 megapascals.

**Problem 7.** A cylinder taken from a fresh turnip root is placed in a 0.3 molal sucrose solution and allowed to equilibrate at 27 C. What will be the $\Psi_w$ of the turnip cells when equilibrium with the solution is reached?