

### Activity 3.6: Osmosis and Water Potential

A more rigorous explanation of the movement of water through tissues uses the concept of water potential. In fact any rigorous description of the movement of matter uses the concept of potential. Matter will move from regions of high potential to lower potential. For example, elevated objects have higher gravitational potential than those on ground level. Consequently, elevated objects may fall or roll down an incline and move to a lower gravitational potential. Analogous thinking is used to describe the movement of materials through a fluid. Matter will diffuse from a region of higher potential to a region of lower potential. The need for this more rigorous approach is due to a simple yet fundamental difference between animal and plant cells.

In the past we have used differences in concentration to determine the direction of movement of particles by diffusion. In the case of the animal cell, knowing whether the extra-cellular fluid is hypertonic or hypotonic is sufficient to predict the direction of the flow of water. In other words, the direction of osmosis can be predicted by comparing the solute concentration within the cell to that outside. If for instance, the solute concentration is greater in the cytoplasm than in the extra-cellular fluid then the cytoplasm is described as being hypertonic to the extra-cellular fluid and water will enter the cell by osmosis. Water enters the cell in this case because the water concentration outside the cell is greater than inside. This state of affairs is illustrated in Figure 1.

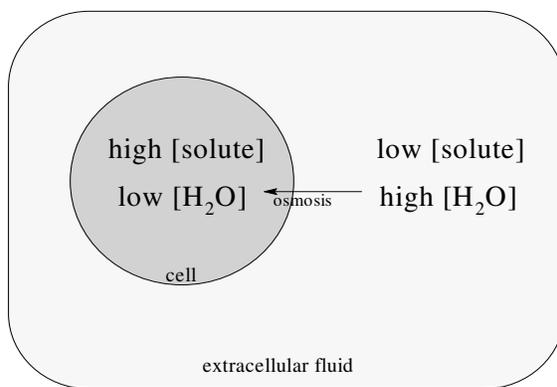


Figure 1: A cell in a hypotonic environment. Water moves from a region of high concentration (extra-cellular fluid) to a region of low concentration (the cytoplasm). The cell cytoplasm is hypertonic to the extra-cellular fluid. The intensity of the shading in the figure is used to represent solute concentration.

Thus in animal cells a comparison of the solute concentration on either side of a membrane is sufficient to predict the direction of the osmosis of water. This movement of water is solely due to the presence of solutes and is referred to as the solute potential. The solute potential, sometimes called the osmotic potential, is a measure of the effect that dissolved solutes have on the movement of water.

In plant, fungal and bacterial cells, however, the situation is complicated by the presence of a rigid cell wall. As water enters a plant cell, pressure builds inside the cell. This pressure, or pressure potential, increases as more and more water enters the cell. As pressure builds the entry of more water is resisted. Thus the pressure potential and the solute potential together determine the movement of water by osmosis.

Together the solute and pressure potential define the water potential:

$$\text{water potential} = \text{solute potential} + \text{pressure potential}.$$

If potential is represented by the Greek letter psi ( $\psi$ ) then the above equation can be rewritten as:

$$\psi = \psi_s + \psi_p$$

where  $\psi$  = water potential

$\psi_s$  = solute potential, and

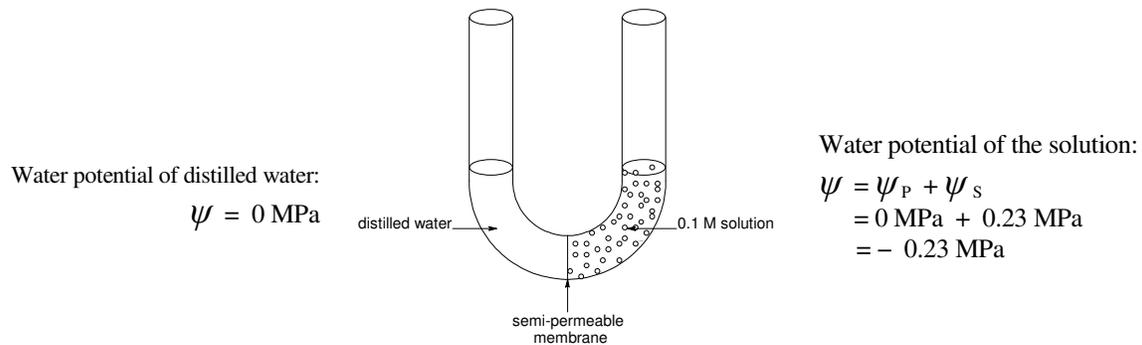
$\psi_p$  = pressure potential

Since the pressure potential ( $\psi_p$ ) tends to oppose the influx of water due to the solute potential ( $\psi_s$ ) these potentials have opposite signs. The pressure potential is positive while the solute potential is negative.

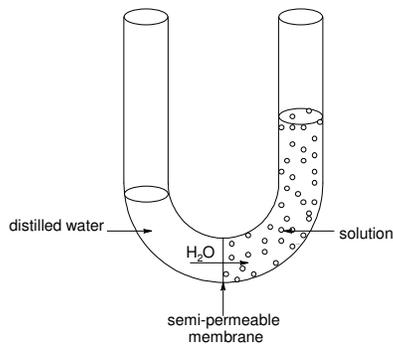
### Using the Osmometer to Illustrate the Concept of Water Potential.

The osmometer is a device that separates two solutions with a semi-permeable membrane. It is a useful device to explain the concept of potential and to illustrate the effect that solute and pressure potentials have on the movement of water by osmosis.

Figure 2: The Effect of a Solute on Water Potential and the Movement of Water.



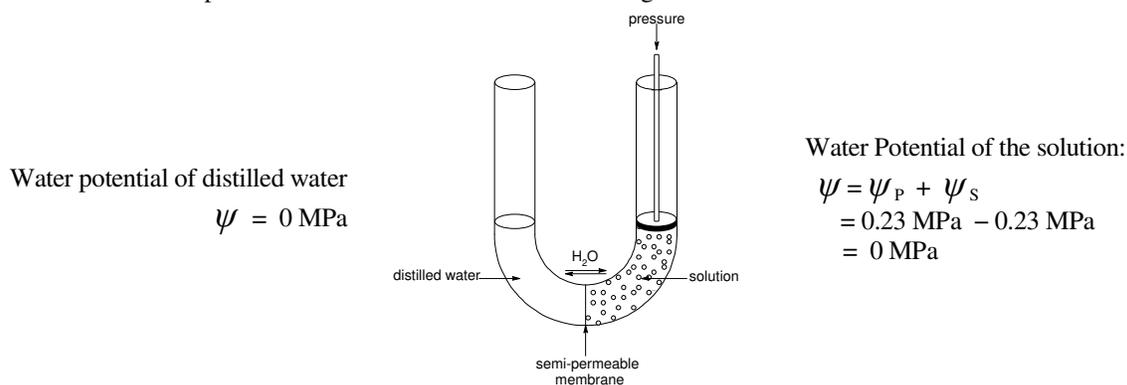
a) Initial conditions: In the U-tube illustrated above, a semi-permeable membrane separates pure water from a 0.1 M solution. The membrane is impermeable to the solute but permeable to the water. The diagram and calculation of the water potential ( $\psi$ ) on both sides of the membrane are given for initial conditions before any net movement of water. By definition, the water potential of distilled water is zero. For the solution on the right side of the membrane the pressure potential ( $\psi_P$ ) is zero because no pressure is being applied to the solution. The solute potential ( $\psi_S$ ) is  $-0.23 \text{ MPa}$ . (See the section "Derivation of the Water Potential Equation by van't Hoff" for the calculation which shows that a 0.1 M solution has a solute potential of  $-0.23 \text{ MPa}$ .) A solute reduces the water potential of a solution. This reduction accounts for the negative sign.



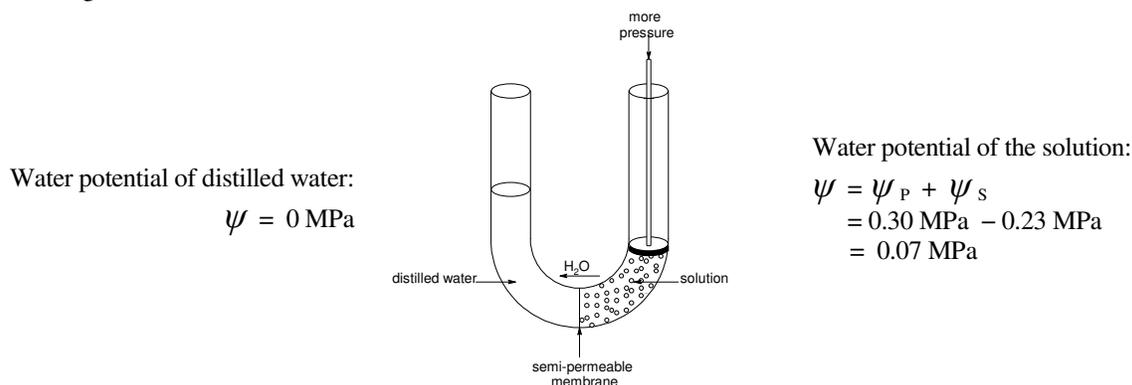
b) Final conditions:

The initial conditions described in Figure 2 a) above sets up a difference in water potential on either side of the membrane. The distilled water on the left side of the membrane has a water potential of  $0 \text{ MPa}$ . The solution on the right of the membrane has a water potential of  $-0.23 \text{ MPa}$ . Since the membrane is permeable to water, water will move from the region of greater potential to the region of lower potential. That is, water diffuses through the membrane and dilutes the solution on the right as shown in the figure. The difference in the height of the water columns in the two arms of the U-tube will introduce a pressure potential. The effect of pressure potential is described in Figures 3 and 4.

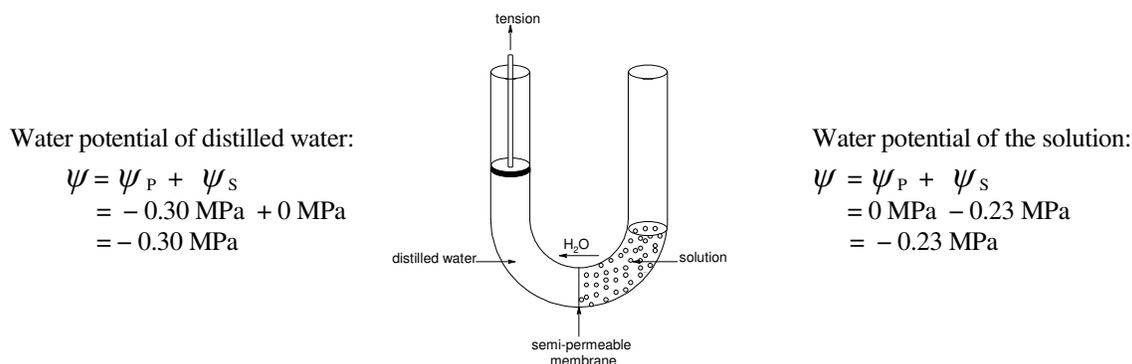
Figure 3: The effect of pressure on the movement of water through a membrane



a) Applying pressure to balance the solute potential: In the figure above, a piston is used to apply pressure to the solution. The solute potential of  $-0.23 \text{ MPa}$  causes water to diffuse into the solution. Applying pressure to the solution has the opposite effect and causes water to diffuse out of the solution. Adding a downward pressure of  $0.23 \text{ MPa}$  would balance the solute potential and equalize the water potential on both sides of the membrane causing no net movement of water through the membrane.



b) Applying pressure greater than the solute potential: If pressure is increased beyond  $0.23 \text{ MPa}$  to  $0.30 \text{ MPa}$  for example, then the water potential on the right side of the membrane has increased sufficiently to reverse the flow of water. Again the mathematics illustrates that water will flow from a region of high potential to a region of lower potential. Pressure increases the water potential of a solution.



c) Tension reduces water potential: Using a plunger to pull upward on the solution on the left creates tension or negative pressure. Tension reduces water potential. A tension of  $-0.30 \text{ MPa}$  "draws" water from the solution which has a water potential of  $-0.23 \text{ MPa}$ . Again, water flows from a region of greater to lesser potential. This situation is analogous to the movement of water up the xylem in a tree. Evapotranspiration at the leaves creates tension in the water column causing water to diffuse from the soil into the root hair.

### Applying the Concept of Water Potential to Cells

The above concepts are readily applied to tissues and cells in solution. When potato cores (i.e. cells) are immersed in distilled water (Figure 4 a) potato cytoplasm is separated from distilled water by a selectively permeable membrane. Distilled water has a water potential of zero. The cytoplasm in the potato core, however, is a region of negative water potential due to the presence of solute. (Assume for the sake of this illustration that the solute potential is  $-1.0$  MPa. How the solute potential is calculated is presented in the next section.) This difference in water potential dictates that water will flow into the cell by osmosis from regions of higher to lower potential. Osmosis causes the cell to swell as the cell contents push against the cell wall and increase the pressure potential. Plant physiologists call this turgor pressure. At equilibrium (Figure 4 b) there is no further net influx of water by osmosis and water potentials on both sides of the membrane are equal. This fact permits calculation of the size of the pressure potential at equilibrium. In other words, a pressure potential of  $1.0$  MPa is sufficient to counteract the effect of the solute potential of potato cytoplasm.

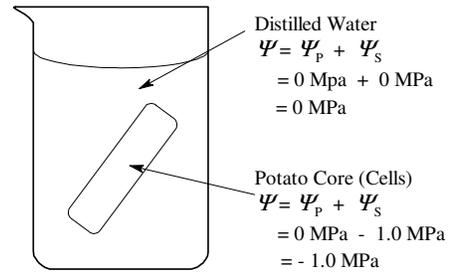


Figure 4 a): Initial water potential, pressure and solute potentials when potato cells are immersed in distilled water.

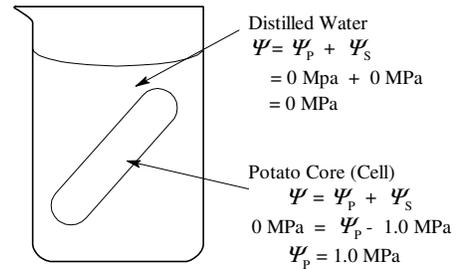


Figure 4 b): Equilibrium potentials when there is no net movement of water.

## Calculating Water Potential from Experimental Data

The solute potential of a solution is given by the equation:

$$\psi_s = -i c R T$$

where  $i$  = the ionization constant. For non-electrolytes  $i = 1$ . Note that the ionization constant is non-dimensional.  
 $c$  = molar concentration expressed in mol/L.  
 $R$  = the universal gas constant ( $R = 8.314 \text{ kPa L/mol K}$ )  
 $T$  = the absolute temperature.

Note that  $\psi_s$  has units of pressure. Hence the solute potential can also be thought of as a pressure.

Sample Problem:

Calculate the solute potential of a 1.0 M sucrose solution at 25 °C and standard atmospheric conditions.

Sample Solution:

Since sucrose is a non-electrolyte,  $i=1$ . For non-electrolytes the above equation simplifies to:

$$\begin{aligned}\psi_s &= -c R T \\ &= -1.0 \text{ M} \times 8.314 \frac{\text{kPa L}}{\text{mol K}} \times 298 \text{ K} \\ &= -2.5 \times 10^3 \text{ kPa} \\ &= -2.5 \text{ MPa}\end{aligned}$$

Hence the solute potential of a 1.0 M sucrose solution is  $-2.5 \text{ MPa}$  at  $25^\circ\text{C}$ . In the last activity, potato cores were immersed in solutions of various sucrose concentrations. Analysis of the data permitted estimation of the concentration of potato cytoplasm. That is, the potato cores are in an isotonic environment when the mass of the cores does not change.

1. State the estimated value of the concentration of potato cytoplasm.
2. Calculate the solute potential  $\psi_s$  of this equilibrium sucrose solution. Assume the experiment was conducted at room temperature of  $22^\circ\text{C}$ .
3. What assumptions are being made when performing this calculation.
4. Calculate the turgor pressure (pressure potential)  $\psi_p$  of potato cytoplasm.
5. If potato cores are allowed to dehydrate, would the water potential of the potato cells increase or decrease?
6. If a cell has higher water potential than its surroundings, is the cell hypertonic or hypotonic to its surroundings?

## Appendix: Derivation of the Water Potential Equation by van't Hoff

The solute potential of a solution is given by the equation:

$$\psi_s = -i c R T$$

where  $i$  = the ionization constant. For non-electrolytes  $i = 1$ . Note that the ionization constant is non-dimensional.  
 $c$  = molar concentration expressed in mol/L.  
 $R$  = the universal gas constant ( $R = 8.314 \text{ kPa L/mol K}$ )  
 $T$  = the absolute temperature.

Note that  $\psi_s$  has units of pressure. Hence the solute potential can be thought of as a pressure. For non-electrolytes the above equation simplifies to

$$\psi_s = -c R T$$

Van't Hoff, a Dutch chemist, derived the above equation over 100 years ago from the Ideal Gas Law as follows:

$$P V = n R T$$

Where  $P$  = pressure in kPa  
 $V$  = volume in L  
 $n$  = quantity in mol  
 $R$  = the universal gas constant ( $R = 8.314 \text{ kPa L/mol K}$ )  
 $T$  = the absolute temperature

Rearranging the Ideal Gas Law yields:

$$P = \frac{n}{V} R T$$

Since the ratio  $n/V$  is an expression of concentration ( $c$ ) with units mol/L then the equation becomes:

$$P = c R T$$

Since van't Hoff used the Greek letter pi ( $\pi$ ) to represent pressure the equation becomes:

$$\pi = c R T$$

This equation was found to apply to very dilute solutions of osmotically active non-electrolytes. Solving the van't Hoff equation for 0.100 mol/L sucrose solution yields a potential or pressure of:

$$\begin{aligned}\pi &= \frac{0.10 \text{ mol}}{\text{L}} \times \frac{8.314 \text{ kPa L}}{\text{mol K}} \times 273 \text{ K} \\ &= 230 \text{ kPa} \\ &= 0.23 \text{ MPa}\end{aligned}$$

Modern terminology uses  $\psi$  instead of  $\pi$  and the negative sign is inserted because the addition of a solute lowers the water potential.