INVESTIGATION

National
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Science
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Science
Education
Standards
(NRC,
1996)
that
strongly
recommend
the
use
of
hands-on
inquiry
experiences
to
help
increase
students’
understanding
of
scientific
concepts.

Much
of
the
difficulty
in
understanding
osmotic
principles
appears
to
lie
in
understanding
and
remembering
terminology
(Odom &
Barrow,
2007).
For
example,
the
terms
hypotonic,
hypertonic,
and
isotonic
refer
to
the
relative
concentrations
of
solutions
separated
by
a
semipermeable
membrane.
Many
students
are
unable
to
state
that
water
will
move
into
a
cell
if
it
is
placed
in
a
hypotonic
solution
and
out
of
a
cell
that
is
placed
in
a
hypertonic
solution.
In
the
case
of
an
isotonic
solution,
students
can
state
that
there
is
"no
net
movement
of
water
across
the
cell
membrane,"
but
when
they
are
asked
to
explain
what
this
means,
it
becomes
apparent
that
they
do
not
understand
that
water
molecules
are
moving
through
the
membrane
in
both
directions;
they
think
that
water
molecules
stop
moving
across
membranes
(Odom,
1995).

Our
experiences
with
prospective
science
teachers,
as
well
as
many
in-service
teachers,
indicate
that
many
of
them
struggle
with
explaining
the
mechanisms
of
water
movement
that
accompany
osmosis.
Teachers,
as
well
as
most
textbooks,
tell
students
that
water
will
diffuse
into
a
cell
if
it
is
placed
in
a
hypotonic
solution.
This
statement
does
not
intuitively
fit
the
definition
for
diffusion
of
water
because
the
terms
refer
to
relative
solute
concentration.
Consequently,
teachers
explain
osmosis
in
terms
that
are
based
on
the
concentration
differences
of
water.
While
this
explanation
is
accurate
and
will
correctly
indicate
the
initial
direction
of
water
movement,
it
provides
no
information
about
the
mechanisms
driving
osmosis.
It
is
also
misleading
because
water
concentration
per
se
does
not
play
much
of
a
role
in
osmosis;
indeed,
it
is
the
solute
concentration
that
contributes
most
significantly
to
the
osmotic
process
(Salisbury &
Ross,
1992;
or
most
any
other
currently
available
plant
physiology
textbook).

Perhaps
an
even
more
perplexing
concept
with
which
students
and
even
teachers
struggle
is
that
of
osmotic
pressure.
Osmotic
pressure
is
classically
declared
as
the
hydrostatic
pressure
that
balances
the
osmotic
flow
of
water
across
a
semipermeable
membrane
caused
by
solute
concentration
gradients.
For
students,
this
process
appears
to
contradict
what
they
have
been
told
about
diffusion
and
concentration
gradients.
To
introduce
the
concept
of
osmotic
pressure,
a
teacher
will
often
show
students
a
traditional
osmometer
that
he/she
has
assembled,
or
more
likely,
a
diagram
of
an
osmometer
from
the
textbook.
The
teacher
explains
that
water
diffuses
across
the
membrane
from
the
hypotonic
side
of
the
system
into
the
osmometer,
raising
the
water
level.
As
the
water
level
rises,
the
water
column
exerts
a
downward
hydrostatic
pressure
resulting
from
the
force
of
gravity.
He/she
continues
to
explain
that
water
will
rise
in
the
osmometer
until
the
hydrostatic
pressure
prevents
the
net
flow
of
water
across
the
membrane.
This
can
be
especially
disconcerting
to
students
when
they
note
that
the
concentration
gradient
of
the
solute,
and
presumably
the
water,
is
still
present.
The
notion
of
osmotic
pressure
is
also
problematic
because
it
introduces
another
factor
(pressure)
into
the
osmotic
process
without
really
explaining
the
mechanism
behind
it.
Moreover,
osmotic
pressure
appears
to
contradict
the
idea
that
osmosis
is
governed
by
concentration
gradients.

It
is
important
for
students
to
be
exposed
to
the
concept
of
osmotic
pressure
for
a
variety
of
reasons.
The
force
that
is
attributed
to
osmotic
pressure
is
used
to
explain
why
animal
cells,
like
erthrocytes,
placed
in
hypotonic
solutions
will
burst
like
a
balloon
that
has
been
over-inflated.
This
phenomenon
(lysis)
can
be
observed
under
a
microscope,
and
its
practical
importance
can
be
discussed
in
terms
of
tonicity
of
fluids
used
in
intravenous
infusions.
Osmotic
pressure
is
very
important
in
the
functioning
of
plant
cells.
Cell
lysis
does
not
occur
in
plant
cells
because
they
have
rigid
cell
walls
that
resist
osmotic
pressure.
If
students
place
pieces
of
potato
tuber in distilled water, they are able to observe that the pieces gain weight and feel plumper than they did before soaking in the water. The plumpness or firmness is due to a buildup of osmotic pressure inside the cells, but students are being asked to infer that the plumpness is due to the increase in weight of the tissue.

In plant cells, the firmness associated with the tissue is referred to as turgor pressure, and the cells are said to be turgid. Turgor pressure is what makes salad crisp, or celery and asparagus "snap" when broken, and the lack of turgor pressure in leaf cells results in wilting. Turgor pressure also provides the force that allows plant cells to elongate before their cell walls are fully formed, and changes in turgor pressure in guard cells are responsible for opening and closing stomata. Loss of cell turgor is responsible for the rapid closing of Venus Flytrap leaves or the touch response that is commonly observed in Mimosa pudica. In addition to these examples of the importance of osmotic pressure, understanding this concept lays the foundation for deeper discussions that lead to more theoretical aspects of water movement associated with the concepts of free energy, water potential, osmotic potential, pressure potential, and osmotic adjustment.

The concept of osmotic pressure is usually taught through lecture, without opportunities for hands-on experiences, and if experiences are provided, they rarely have quantitative measurements associated with them. If students observe real cells or cell models in hypotonic solutions, they are not measuring osmotic pressure. Quantifying osmotic pressure in the classroom is not generally part of the curriculum because of time constraints or because of the availability and cost of equipment, although the costs of technology are dropping quickly. Studying osmotic pressure with hands-on, inquiry-based experiments may allow students to more fully appreciate and comprehend this important concept, as well as reinforce the basic principles of water movement across membranes.

Many biology classrooms may already be equipped with most of the necessary instrumentation to make measurements of osmotic pressure, or the teachers may be able to borrow it from their colleagues in chemistry or in physics. What the teachers lack is a simple, inexpensive osmometer that can be attached to that existing equipment. In this article, we describe a simple membrane osmometer made from readily-available items. When our device is coupled to a pressure transducer, a data acquisition interface, and a computer, students can quantitatively investigate the effects of different solute concentrations on the rates of change in osmotic pressure.

**Membrane Osmometer Design & General Procedure**

A membrane osmometer is a closed osmometer that uses a pressure transducer to directly measure the osmotic pressure generated by a solution; they are used in laboratories and industry to measure osmolality of solutions and molecular weights of macromolecules (Grattoni et al., 2008). These devices are expensive but in many ways they function like living cells and can be used to illustrate the osmotic principles that relate to teaching about osmotic pressure. The simple membrane osmometer that we describe in this article was constructed from a 60 ml syringe, a screw cap and threaded neck from a water bottle, a screw cap from another bottle, a disk cut from a piece of perforated aluminum sheet, and a flat piece of semipermeable membrane (Figure 1). Below is a step-by-step procedure for making one of the membrane osmometers as well as directions for filling it with test solution. This section is followed with descriptions and discussions of some basic experiments that use the device.

1. The threaded-neck portion of a 500 ml Propel® water bottle fits snugly around the barrel of a BD brand 60 ml Luer-Lok syringe. Cut the neck off of the bottle just below the threads and sever the syringe just below the flanges to remove them.

2. After "cleaning up" the edges of the cut pieces using fine-grit sandpaper and a 1" bevel cutter (Grizzly Tool Co.), glue the cut end of the syringe into the bottle neck with Loctite 496® adhesive (Figure 2).

3. Cut 1" holes into the centers of a 500 ml Propel® bottle top and a bottle cap from a 20 oz Gatorade® bottle using a gasket punch (Grizzly Tool Co.). The raised gasket portion of the Gatorade® bottle cap should be carefully removed using a scalpel in order to create a flat surface.

4. To assemble the osmometer cap, place a 1/4" disk, cut from a sheet of 0.05" aluminum, perforated with 7/32" holes, inside the Gatorade® cap and glue the smaller water bottle cap in place using Loctite 496® adhesive (Figure 2). The perforated aluminum disk supports the membrane and keeps it from bulging outward as osmotic pressure builds up within the osmometer. The water bottle cap fits snugly into the Gatorade® cap but it needs to be glued in place, otherwise the osmotic pressure will push the outer cap off, causing the system to fail.

5. To fill the osmometer, screw a Luer-Lok valve (Small Parts, Inc.) onto the end of the syringe and pour the test solution into the base-end until it almost overflows.
6. Place a precut 5 cm diameter piece of semipermeable membrane (Wards, Inc.), that has been soaking in water for about 15 minutes, over the base-end of the syringe and screw the cap tightly in place.

7. With the membrane and cap in place, turn the Luer-Lok end of the osmometer upright and remove the valve. Completely fill the osmometer with the test solution through the Luer-Lok tip of the syringe using another syringe containing the test solution and fitted with a 16-gage blunt needle (Small Parts, Inc.).

8. Once the osmometer is filled, check it for leaks by removing the blunt needle from the syringe and connecting the two syringes together with a short piece of plastic tubing fitted with Luer-Lok connectors (Figure 3). Remove air from the tubing by pushing some solution through it before connecting the two syringes. By pushing on the plunger of the syringe, students are able to apply considerable pressure to the membrane and fitting. If the seal between the top and the body of the osmometer leaks, it will be readily observable; generally tightening the top fixes the leak. This testing procedure creates a “teachable moment” as it demonstrates that water is virtually incompressible when pressure is applied to it in a confined space – an important concept with respect to plant cells.

Once the osmometer is completely filled, connect the pressure transducer to it using a 60 cm length of plastic tubing fitted with 1/16” Luer-Lok connectors and place the osmometer in a container of distilled water. The solution in the osmometer should be at the same temperature as the water in the bathing container to avoid air bubble formation during the experiment; the container should be large enough to allow the osmometer to remain in a vertical position while being covered with water. The pressure transducer should be positioned above the osmometer in such a fashion that the plastic tubing does not have any horizontal or descending loops (Figure 4).

We used a Vernier LabPro° interface to connect a pressure transducer to a laptop computer, and data were logged using Vernier Logger Pro° 3.6 software. This software is simple to use and allowed us to collect and plot data in real-time. We also recorded data using the Vernier LabQuest™ with equal success. We did not try other data acquisition systems readily available to schools (e.g., Pasco PASPORT°), but they should work equally well.

○ A Sample Experiment with Comments

The experiment described below addresses the question: What effects do solute concentration gradients have on the rates of osmosis and osmotic pressure? This experiment meets learning objectives associated with the NSES (NRC, 1996). As a result of completing the exercise, the students will be able to:

1. Explain the relationship between osmosis and osmotic pressure as water moves across the membrane of an osmometer.
2. Analyze data from four different sucrose concentrations and construct a computer-generated graph that compares the differences in the rates of osmosis in each concentration.
3. Predict the effect that the concentration gradient has on the rate of osmosis by using the computer-generated graphs.
4. Apply the concept of osmotic pressure to animal cell lysing.
5. Relate the concept of osmotic pressure to turgor pressure in plant cells.

○ Methods

Day One

1. Before starting the experiment, show students a diagram of the apparatus and explain how the system is designed to function. Ask students to make predictions about what might happen based on previous discussions and experiences (see Summary for an example of background that might be presented prior to working with the osmometer), and guide them toward an experimental design involving concentration gradients.

2. Students can work in groups of four since a Vernier LabPro’ unit has four input channels. By connecting a pressure transducer to each one, students can collect four sets of pressure data simultaneously. There are two classroom strategies for conducting an experiment. Each group can collect data on four different concentrations of sugar, or they can collect data from four repetitions of a single concentration and share the data with the rest of the class. We prefer the former approach (e.g., each group collects data...
for 0.5, 1.0, 2.0, and 3.0 M sucrose solutions) because it provides each group with a complete data set. Students can share data sets if the teacher wants to stress the importance of repetitions.

3. All experiments can be conducted at room temperature (see Results & Discussion), but the temperature of the solution in the osmometer and its bathing solution should be the same. If the bathing solution is warmer, air dissolved in the osmometer solution will come out of solution and form air bubbles as it warms. These bubbles will affect pressure measurements in the system.

4. To collect data, students should follow the basic procedures described in the manuals for the particular equipment they are using. For example, to set up a system using Vernier products, the LabPro® interface should be powered on and connected to the computer; the LoggerPro software should be running before the pressure transducers are attached to the interface. As the pressure transducers are connected, the software will automatically detect them and generate graphs and tables reflecting the sensors. We used an option to allow the data from each sensor to be plotted on a single graph.

5. The students will need to adjust the axes of the graph to reflect the time scale and number of data points collected. For our study, we collected samples every 10 minutes for 24 hours. The Y axis of the graph can be adjusted for visual effect.

6. After everything is assembled, the student should click the “Collect” button and clean up unused materials.

**Day Two**

1. Students should examine the osmometer and record qualitative observations. They should note that water has moved up into the connecting tubing and that the levels of water in the tubing of each concentration are not equal.

2. Turning their attention to the graph of the data generated by the software, students will observe the effects of solute concentration on pressure inside the osmometer. They can highlight a portion of each line and display its slope.

3. We preferred to copy the first 10 hours of raw data on the left-hand side of the screen into a MS Excel spreadsheet. This procedure allows students to create their own graphs and to statistically analyze the data. It also allows them to work with the data on computers that do not have the Logger Pro® software installed on them. All of the graphs presented in this paper were generated with MS Excel.

**Results & Discussion**

In our system, the osmometer is sealed with a pressure transducer, allowing us to measure the pressure buildup associated with the compression of the air column. This system directly measures the osmotic pressure caused by the water in the osmometer and not a hydrostatic pressure associated with a typical osmometer open to the atmosphere. The amount of water that flows into the closed osmometer over a specific time period is directly related to the change in pressure in the system. Consequently, the change in pressure per unit of time (e.g., kPa/hr) can be considered a measure of the rate of osmosis.

The results of an experiment that measured pressure changes in membrane osmometers containing different sucrose solutions (0.5, 1.0, 2.0, and 3.0 M) are depicted in Figure 5. As water moves into the osmometers, the volume of the solution in the osmometer increases and compresses the air in the tube connecting the osmometer to the
membrane. Thus, a change in pressure in the system is a measure of osmotic flow across the membrane. The rate of pressure buildup in the osmometers over the 10-hour period is directly related to solute concentration differences across the membranes; the larger the solute concentration gradient, the more rapidly the pressure increases inside the osmometer.

The slopes of each of the lines in Figure 5 are strongly linear ($R^2 > 0.98$), suggesting that—other than concentration of the solute—there are few factors, such as dilution effects or random variability, contributing to the pressure increase. It is important to note that as the pressures in the osmometers were increasing, some solution moves up the tube connecting the osmometer to the pressure transducer. This indicates that water is, indeed, moving into the model cell and applying pressure against the air in the tubing. The results of this experiment verify that pressure builds in an osmometer as a result of net water movement into the osmometer. They also illustrate the relationship between the rate of osmosis and varying the solute concentration gradient.

We analyzed the data in Figure 5 using Analysis of Covariance (GraphPad Prism®) to test the null hypothesis that all of the slopes were equal. We present this analysis to show that the results are significant, and we are not suggesting that students need to do similar analysis to understand the graphic results of the experiment. This analysis indicated that there were significant differences between the slopes of at least two of the four concentrations ($p < 0.001$). GraphPad Prism®, as well as most other statistical software programs, does not provide a methodology to determine which lines are statistically different from each other; however, this can be computed manually using procedures described by Zar (1996). Using Zar’s methods, we determined that there were significant differences in the rates of osmosis between all of the concentrations depicted in Figure 5 ($p < 0.001$). If comparisons are made of concentration gradients closer than 0.5 molar, it is likely to be harder to discern significant differences between slopes.

Another approach to determine if there are significant differences between the rates of osmosis and concentration gradients is to perform multiple trials at each concentration (Table 1). In this way, the slope values can be analyzed with ANOVA to test the null hypothesis that all of the slopes are equal. There was a significant difference between at least two of the rates of osmosis associated with specific concentrations ($p < 0.0001$), and a post-hoc Tukey-Kramer Multiple Comparisons Test revealed that the rates of osmosis for each of the sucrose concentrations were significantly different from each other ($p < 0.001$).

When the means of the slopes at each concentration are examined with regression analysis, a strong linear relationship is revealed between the rate of osmosis and the solute concentration gradient across the semi-permeable membrane (Figure 6). Almost all ($R^2 = 0.999$) of the variation in the rate of pressure change attributed to osmosis can be explained by the sucrose concentration gradient. This linear relationship between rates of pressure change and concentration of the osmotic gradient is consistent with linear predictions of diffusion rates using Fick’s Law. While it is beyond the scope of this article to mathematically relate units in Fick’s Law to changes in pressure in the system, there are analogous responses. For students, the results presented in Figures 5 and 6 can simply stand as vivid images that relate osmotic gradients to rates of osmosis that are consistent with predictions of mathematical models of diffusion and osmosis.

### Table 1. Average rate of osmosis measured at four concentration gradients. Each rate was significantly different from all of the other rates ($p < 0.001$).

<table>
<thead>
<tr>
<th>Concentration (M/L)</th>
<th>Number of Trials</th>
<th>Average Rate of Osmosis (kPa/h)</th>
<th>Standard Error of Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>8</td>
<td>1.656</td>
<td>0.067</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>3.665</td>
<td>0.179</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>7.904</td>
<td>0.133</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>11.959</td>
<td>0.643</td>
</tr>
</tbody>
</table>
Unfortunately, because of limitations in the pressure transducers, the system cannot be used to support the concept that net movement of water will stop when osmotic pressure reaches an equilibrium point. After 12 hours, the pressure in the osmometers containing 2.0 and 3.0 M solutions exceeded the maximum pressure (220 kPa) that could be measured by the transducer (data not shown). On a theoretical basis, both the 0.5 and 1.0 M concentrations should also exceed the pressure limit of the transducer. This did not occur during the 24-hour period in the osmometer containing the 0.5 M sucrose solution, for example, because the rate of pressure change in the osmometer was only 1.66 kPa/h. At this rate, it would take more than 78 hours for the pressure in the system to reach 220 kPa. We did not attempt to determine this prediction empirically.

Temperature Dependence

In an effort to determine if temperature played a significant role in osmosis, we measured the changes in pressure in osmometers containing 1 M sucrose solution at three temperatures (10, 20, and 30 °C). The rates at each temperature were not significantly different from each other (p<0.05); the average rates were within a 2.0 kPa/h range (Figure 7). These data suggest that tightly controlling temperature in a classroom setting is not critical to the outcome of the experiment. It is interesting to note that the $Q_{10}$ for osmosis, based on our measurements, is just slightly above 1; a value that is typical for a physical process such as diffusion. Solutes diffusing in water have a $Q_{10}$ between 1.2 and 1.4 (Salisbury & Ross, 1992).

General Evaluation of the System

Time is a consideration when using the apparatus. We found that it took about 45 minutes to set up an experiment if the teams were familiar with the Vernier equipment. Overall, the system produced reliable and reproducible data that is easy to collect with a computer or another electronic interface. The system allows students to investigate the relationships between rates of pressure increase in the osmometer and solute concentration gradients. Moreover, the system can be used to illustrate that osmotic pressure builds up in cells as water moves from a hypertonic solution into the cell.

The system also provides students with opportunities to investigate other factors that influence osmosis. For example, students can compare osmotic rates while holding concentration differences constant, or they can determine if the pressure in the osmometer will drop if it is placed in a hypertonic solution (it will). They could also investigate different types of solutes (e.g., glucose and sucrose) to determine if equal concentrations produce similar rates of osmosis. If the teacher can acquire membranes that are not permeable to ions such as sodium or chlorine (we have not been able to locate a source), students could investigate the effect of concentration of ionizing substances on osmotic pressure. These kinds of studies will help to reinforce the fundamental concepts of osmosis and osmotic pressure.

Assessment

Assessment of laboratory experiments using this apparatus can be approached using several different strategies. Prior to beginning the experiment, students can be asked to write hypotheses predicting the outcome of the laboratory exercise. Students can generate a lab report that describes a procedure that will answer a specific question and provide an explanation of the results based upon their understanding of osmotic principles. Using the data from the experiment, students can use computer software such as MS Excel® to generate graphs; these graphs can be evaluated by the teacher.

Along with using the experiment in a laboratory context, the students should be asked to compare the model system to an animal or plant cell. Some questions that teachers should ask include: Why is osmotic pressure important in living cells? What happens to an animal cell that is placed in a hypotonic environment? What role does osmotic pressure play in a plant cell?

If teachers would like to determine if the use of this apparatus, coupled with their own teaching techniques, increases the students' understanding of the osmosis, they could use the Diffusion and Osmosis Diagnostic Test (Odom, 1995) that has been used by a variety of authors to determine student understanding of these two processes (Odom & Barrow, 2007; Kose, 2007; Tekkaya, 2003; Odom & Kelly, 2001; Sanger et al., 2001) or they could try their hand at designing a similar two-tier pretest/posttest instrument.

Summary

Our membrane osmometer system is simple enough to implement in high school or college classrooms and has the advantage of incorporating technology into the classroom. We do not yet have experimental data to answer the question: Does using this apparatus help to clarify student misconceptions about osmosis? We are, however, in the process of evaluating student understanding of the concept of osmotic pressure as a result of experiences with the membrane osmometer that is coupled with an explanation of the osmotic process presented below.

Some Comments on Teaching About Osmosis

Over the years, we have struggled with ways to present the concepts of osmosis and osmotic pressure to students in a meaningful way—one that makes conceptual sense to the students yet can be presented in a visual fashion that accurately represents the process. These presentations require a compromise between a traditional water concentration gradient explanation presented in general biology classes and the more thermodynamic explanations used by plant physiologists. We have reached that compromise by using a particle approach to describe osmosis that is coupled with the concept of free kinetic movement of water molecules. We have found this explanation to be instructive and generally consistent with explanations of diffusion and osmosis. It also lends itself to an explanation of osmotic pressure that resolves some of the conflicts between solute concentration differences across membranes and the osmotic pressure that develops in both traditional osmometer and in cells. Some general biology textbooks hint at this mechanistic approach but do not provide detailed explanations. Our explanation also begins to hint at the thermodynamic aspects of osmosis that are commonly used in college physiology classes without using complex mathematical theory. Our explanation is not new or revolutionary, but it is much less mathematical than approaches presented by Lachish (2007) or Ben-Sasson and Grover (2003). The explanation provided below uses a Q&A format and is presented without the use of graphics; please be assured that we use graphics heavily in our classroom presentation of this material. We have inserted the words "graphic" and "animation" where they are appropriate.
What Effect Does Solute Have on Water as it Relates to Osmosis?

Water molecules in a container of pure water are relatively free to move throughout that container; their movement is primarily restricted by the hydrogen bonds that form between the water molecules (graphic). When a soluble substance like sucrose or sodium chloride is added to water, weak hydrogen bonds form between the solute and water molecules. This bonding results in the formation of hydration shells around the solute molecules keeping them in solution (graphic). However, this process also reduces the random free movement of the water molecules (animation). If more solute is added to the solution, the movement of more water molecules is restricted (graphic and animation). It is this reduction in free movement (free energy) of the water molecules that accounts for the solute effect in osmosis. As an aside, adding solute to a solvent decreases the chemical activity or free energy of water relative to its pure state. We interject this point here for the reader but we do not mention this to students (see any currently available plant physiology textbook for a discussion of this topic).

What Happens if Solutions of Different Solute Concentrations Are Separated from Each Other by a Semipermeable Membrane?

If an osmometer containing a sugar solution (graphic) is placed in a container of pure water, the solute in the osmometer is unable to pass through the semipermeable membrane. The water molecules in the container are free to move into the osmometer by diffusion but the water molecules in the osmometer are free to move into the container. This is because the solute molecules are trapped and continue to restrict the free movement of the water molecules (graphic or animation). The water molecules within the osmometer are moving into the container of pure water, but they are doing so at a lower rate than the water molecules from the container are moving into the osmometer (animation). This is an important point because students must understand that water molecules are moving bi-directionally through a membrane at all times, even when the system is in equilibrium. We keep stressing the concept of free movement.

If There Is a Net Flow of Water into the Osmometer, Isn’t the Volume of the Solution Going To Increase?

When water molecules enter the open osmometer, they do add volume to the solution, causing the solution level in the osmometer to rise (graphic). As the solution level rises, its weight applies hydrostatic pressure to the membrane and to the water molecules near the membrane. This hydrostatic pressure forces water molecules through the membrane in much the same way that water is forced to flow out of a faucet by pressure generated by a pump or a water tower. We have not found a good animation for this point so we rely on the students’ experiences.

Does the Hydrostatic Pressure Build Indefinitely?

No, eventually the hydrostatic pressure on the water molecules next to the membrane will increase to a point where the pressure is forcing water molecules out of the osmometer at a rate equal to the rate of water molecules entering the osmometer from the container by the diffusion process (animation). At this point, there will be no net movement of water molecules across the membrane and the system is in a state of dynamic equilibrium. This is more than just a subtle nuance; we are not simply telling students that osmotic pressure prevents net water flow into the osmometer, but we are explaining it (and demonstrating it) in terms of counter flows of water molecules. This type of presentation has important implications relating to student misconceptions about dynamic equilibrium concepts.

While we do not provide students with any mathematical explanations, we often tell them that the mathematical relationship between solute concentration and the osmotic pressure it can generate was described by van’t Hoff in 1887. For this work, van’t Hoff was awarded the first Nobel Prize in chemistry in 1901. We mention these facts in an effort to show students that concepts of chemistry and math have very important places in understanding important biological processes and to provide a historical background to the study of osmotic principles.

What Happens if a Pressure That Exceeds the Equilibrium Pressure Is Applied to the Osmometer?

In this case, the flow of water molecules out of the osmometer, due to the added pressure, will exceed the flow of water molecules into the osmometer driven by the relatively free movement of the water molecules associated with the solute concentration gradient. This is the principle behind water purification systems using reverse osmosis techniques and kidney dialysis devices (How et al., 2006). An analogous situation exists
in capillary beds within the human body where blood pressure in the capillaries forces water through the capillary walls into the interstitial fluids. This occurs against an osmotic gradient that would tend to drive re-absorption of water from the interstitial fluids back into the capillary.

**Is the Hydrostatic Pressure That Develops in an Osmometer Responsible for the Pressure That Develops in Cells?**

Osmotic pressure is responsible for lysis in animal cells and turgor in plant cells, but the term, as it is applied to biological systems, refers to the pressure created by water molecules striking the interior surfaces of the plasma membranes. Therefore, osmotic pressures that develop in cells are fundamentally different from, and should not be confused with, hydrostatic pressure in a traditional osmometer. This distinction is usually not made, perhaps out of tradition or because the end results are similar. When water molecules enter the confining volume of a cell, the water in the cell will apply greater pressure to the membrane because the molecules are striking the membrane more frequently (animation). The collisions with the membrane are more frequent because of the incompressibility of the cell’s fluid contents, and the more frequently that water molecules strike the membrane, the greater the chance that some of them will pass through the membrane. Eventually the pressure inside the cell will build to a point that the number of water molecules leaving the cell will equal the number of water molecules entering the cell because of the solute gradient’s effect (animation). Consequently, there will be no net water movement; that is, a dynamic equilibrium has been reached. This equilibrium is not because there is a cell pressure preventing water movement into the cell or because the solute concentrations are equal. It exists because the pressure-driven flow of water out of the cell is equal to the diffusion-driven flow of water into the cell. From a free water point of view, water molecules that are not being restricted by the solute in the cell are freer to pass through the membrane because they are simply striking the membrane more frequently. This latter point is somewhat difficult for students to grasp and often takes some time to get them to understand it.

**No Mention of Water Concentration**

Note that the answers to the above questions make no mention of water concentration, nor do they generally conflict with the fundamental thermodynamic principles that govern diffusion and osmosis. Lortie (1975) suggests that teachers teach as they were taught, using similar methods and examples unless there is a mediating experience to change the way they teach. An intervening experience with respect to teaching osmotic principles is not forthcoming from textbooks, nor dare we say from most college instructors, so it must come from the teachers themselves. We only have our own experiences to rely upon at this point, but they suggest that the above mechanistic approach to presenting osmotic principles to students is effective.

There are two Internet sites listed in the references (Watters & Patlak, 1998; Kottonau, 2008) that provide excellent animations that model many of our concerns and mechanistic explanations of osmosis. The sites are probably more appropriate for biology teachers and college level biology majors, but we do use some of the graphics to illustrate important points to non-majors as well.

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**References**


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