DIFFUSION
(A Self-Instructional Package)

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**INTRODUCTION**

Processes that result in the movement of molecules from one place to another are collectively known as transport processes. In this package we consider diffusion, the transport of molecules due to their random thermal (Brownian) motion. Later in the course other modes of transport, namely osmosis, facilitated transport, active transport, and ionic diffusion will be considered.

**OBJECTIVES**

1. State that diffusion occurs because of the random thermal movements of molecules and that diffusion results in the equalization of the concentration of the diffusion molecules.

2. Write Fick's First Law of Diffusion and identify the symbols in it.

3. Know that in the steady state $\frac{dc}{dx}$ in Fick’s First Law can be replaced by $\frac{\Delta c}{\Delta x}$. Be able to use the steady-state form of Fick's First Law to compute the rate of entry of a solute into a cell.

4. Be able to write Einstein's Relation: $(\Delta x)^2 = 2Dt$, and use it to calculate a rough estimate of how long it takes a particular molecule to diffuse a certain distance (or alternatively, how far a particular molecule will diffuse on the average in a given time interval.

5. State that the more lipid soluble (soluble in nonpolar solvents) a substance, the greater its permeability across most biological membranes. Know that for molecules of the same lipid solubility, permeability is inversely related to molecular weight.

6. State that very small water-soluble molecules such as water and methanol readily diffuse across most biological membranes.

7. State that most biological membranes are effectively impermeable to the diffusion of uncharged, water-soluble molecules with molecular weight above 200. Know that such molecules that do permeate do so by means of special transport mechanisms.

8. State that for ions in general the greater the charge, the smaller the permeability of the ion across the lipid bilayer part of the membrane. Know that ions permeate biological membranes primarily by means of more-or-less specific ion channels formed by membrane proteins.
PRACTICE CYCLE 1

Input
In order to illustrate the mechanism of diffusion, consider the following idealized situation. Two chambers of equal volume, A and B, are separated by a perforated partition.

Initially chamber A contains some molecules of which B is devoid. The random thermal motions (Brownian Movement) of the molecules will carry some of them into B. Since, initially, there are no molecules in B, none can diffuse from B to A.

A bit later the situation might look like this:

Since thermal motions are purely random, the probability that any particular molecule in A will move to B is exactly the same as the probability that a particular molecule in B will move to A. Because there is a larger number of molecules in A, there will be a greater number of molecules crossing from A to B, and thus a net flow of molecules from A to B. This is net diffusion of molecules from A to B.

Practice
(1) Why is there a net flow of molecules from A to B?
(2) When will net flow cease?

Feedback
Did you say something like:

(1) Because there are more molecules in A than B random thermal motion will result in more molecules moving from A to B than from B to A. Good.
(2) The net flow will cease only when the number of molecules in A and B are equal. Very good.

Only when the number of molecules in A equals that in B will the flow of molecules from A to B equal that from B to A. In this case there will be no net flow of molecules and we say the
system has reached diffusion equilibrium. We should note that this is a *dynamic equilibrium* in which some molecules diffuse from A to B, but the same number of other molecules diffuse from B to A in any given time period.

**PRACTICE CYCLE 2**

**Input**

In the last example the chambers were of equal volume and we spoke only of the numbers of molecules in each chamber. The relevant parameter is actually the concentration of molecules. Diffusion will proceed whenever the concentration of the diffusing molecules in one part of the system is higher than somewhere else in the system, provided there are no barriers to the diffusion of the molecules in question.

**Practice**

![Diagram](image1.png)

In the diagram above the concentration of the diffusing species is 1 M in chamber A and 0 in chamber B. Because the two chambers is perforated, diffusion proceeds. At equilibrium what will be the concentrations of the diffusing species in chambers A and B?

**Feedback**

Did you say 0.2 M will be the concentration in both chambers at equilibrium? Fine. At equilibrium the 1 mole of molecules that were initially in A (1 M = 1 mole/liter) will be distributed over the 5 liters of the entire box (A + B). 1 mole in 5 liters gives 0.2 M. Diffusion, as in this example, functions to equalize the concentration of the diffusing species. This is because diffusion is "driven" by concentration differences from one part of a system to another and it functions to do away with those differences.

**PRACTICE CYCLE 3**

**Input**

We just noted that concentration differences provide the driving force for diffusion. Consider the system shown below.

![Diagram](image2.png)
As we go from 0 to L, the molecules get progressively less concentrated, so net diffusion will proceed from 0 to L. If we consider the plane at b, the concentration is greater to the left of it and smaller to the right of it, so that net diffusion across the plane proceeds from left to right. The larger the concentration difference across the plane at b, the greater the net diffusion across the plane. Mathematically the concentration difference across the plane is expressed as the concentration gradient or the first derivative of the concentration with distance (the rate of change of concentration with distance). This is represented symbolically as \( \frac{dc}{dx} \) or as \( \frac{dC}{dx} \).

So that the net diffusion (J) of molecules across the plane at B is proportional to the concentration gradient at that plane. For example, at \( b \) in the figure above

\[
J(b) \propto \left. \frac{dC}{dx} \right|_{x=b}
\]

**Practice**

The concentration gradient is the slope of the graph of concentration vs. position. Let us say that in the diagram above concentration varies with position like this

(a) Compare the slope of the curve (concentration gradient) at a, b and c.
(b) Compare the net diffusional flux at a, b and c.

**Feedback**

Did you say

(a) The slope is steeper and thus the concentration gradient is greater at a than at b and greater at b than at c? Good.

(b) Since the net diffusional flux is proportional to the concentration gradient, the flux will be greater at a than at b than at c. That is \( J(a) > J(b) > J(c) \).

Note that in our example the slopes are negative in sign because concentration decreases as x...
increases. Yet diffusion proceeds in a positive direction (from smaller x to larger x). Conversely, when $dc/dx$ is positive (as shown above) diffusion proceeds in the minus x direction.

**PRACTICE CYCLE 4**

**Input**

Consider again our diagram

![Diagram](image)

The larger the area of the plane at b ($A_b$), the greater the net diffusion as well, so that

$$J(b) \propto A_b$$

Since $J(b)$ is proportional to both $A_b$ and $dC/dx$ at b,

$$J(b) \propto A_b \left. \frac{dC}{dx} \right|_{x = b}$$

which says that the net diffusional flux is directly proportional to the area available for diffusion and the concentration gradient that is the driving force for diffusion. Since this is true not only at b, but everywhere, we can write more generally

$$J(x) \propto A_x \left. \frac{dC}{dx} \right|_{x = x}$$

It was a German physician, physiologist, and physicist of the last century named Adolf Fick who first put forth the mathematical laws of diffusion. **Fick's First Law of Diffusion** is

$$J = -DA \left. \frac{dC}{dx} \right|$$

This is like our last expression in that it says that net diffusional flux is proportional to A and dc/dx, but it also has a proportionality constant (D). **D is called the diffusion coefficient.** The minus sign is there to show that when $dc/dx$ is positive, diffusion proceeds in the -x direction and vice versa. The diffusion coefficient is a measure of the diffusional mobility of a particular molecule. The larger the diffusion coefficient, the greater the diffusional flux caused by a given concentration gradient.
**Practice**

If diffusional flux is in moles/sec and the other quantities are in c.g.s. units, what are the units of D?

**Feedback**

Did you find that the units of D are cm²/sec? Great!

Here's how I did it:

\[
\text{Since } J = -DA \frac{dC}{dx}, \text{ then } D = \frac{-J}{A \frac{dC}{dx}}. \text{ Putting the various quantities in cgs units}
\]

\[
D = \frac{\text{moles/sec}}{\text{cm}^2 \cdot \text{moles/cm}^3} \cdot \text{This gives cm}^2/\text{sec for the units of D.}
\]

The magnitude of the diffusion coefficient depends on the diffusing molecule and on the medium in which it is diffusing. For spherical molecules that are much larger than the solvent molecules Einstein used an analogy to Stokes' Law to show that

\[
D = \frac{kT}{6\pi\eta r}
\]

This is called the **Stokes-Einstein Equation**. D is directly proportional to kT, which is proportional to the kinetic energy of the diffusing molecule. The denominator is proportional to the frictional resistance that opposes diffusion of the molecule. D is inversely proportional to \( r \) (the radius of the diffusing molecule) and to \( \eta \) (the viscosity of the medium). D is inversely proportional to \( r \). The volume of the spherical molecule, which is proportional to its molecular weight, is equal to \( \frac{4}{3}\pi r^3 \). Thus D is inversely proportional to the cube root of the molecular weight, so that a spherical macromolecule that is eight times larger in molecular weight diffuses only half as rapidly.

**PRACTICE CYCLE 5**

**Input**

Consider the diffusion of a particular substance through a plasma membrane. In order to use Fick's First Law to compute the flux at any point we need to know \( dc/dx \) at that point.
Unfortunately, we almost never know the concentration gradient of the substance at any point inside the membrane. What we do know are the concentrations in the aqueous compartments on the two sides of the membrane.

If the concentration at the outer surface of the membrane is $C_{\text{out}}$ and that at the inner surface is $C_{\text{in}}$, then even if we don't know $dc/dx$ anywhere within the membrane we do know that the average value of $dc/dx$ is

$$\frac{\Delta C}{\Delta x} = \frac{C_{\text{out}} - C_{\text{in}}}{\Delta x}$$

We can then use an approximation to Fick's First Law that allows us to calculate the diffusional flux across the membrane

$$J = -DA \frac{\Delta C}{\Delta x} = DA \frac{C_{\text{out}} - C_{\text{in}}}{\Delta x}$$

This equation allows us to deal with diffusion across a membrane using the concentrations of the diffusing substance at the two faces of the membrane. This equation is strictly true only when the flux is in a steady state, that is to say when the flux is constant in time. We will refer to the above equation as the steady-state form of Fick's First Law.

**Practice**

Urea is diffusing into a red blood cell. The diffusion coefficient for urea in the plasma membrane is $1 \times 10^{-7}$ cm$^2$/sec. The thickness of the membrane is 100 Å (10 nm). The concentrations in the cell and in the extracellular fluid are as shown. The area of the red cell membrane is about $1 \times 10^{-6}$ cm$^2$. What is the flux of urea into the red cell in µmoles/sec? (Hint: put all quantities into c.g.s. units, such as mM = mmol/1iter = µmoles/cm$^3$).

Feedback

Did you get $5 \times 10^{-8}$ µmoles/sec? If so, good! Here's how I did it.

$$J = -DA \frac{\Delta C}{\Delta x} = DA \frac{C_{\text{out}} - C_{\text{in}}}{\Delta x}$$

$D = 1 \times 10^{-7}$ cm$^2$/sec

$A = 1 \times 10^{-6}$ cm$^2$

$\Delta x = 100 \ \text{Å} = 10 \ \text{nm} = 1 \times 10^{-6}$ cm

$C_{\text{out}} = 1 \ \text{mM} = 1 \ \text{mmole/1} = 1 \ \text{µmole/cm}^3$

$C_{\text{in}} = 0.5 \ \text{mM} = 0.5 \ \text{µmole/cm}^3$
\[ J = (1 \times 10^{-7} \text{ cm}^2/\text{sec}) (1 \times 10^{-6} \text{ cm}^2)(0.5 \mu\text{mole/cm}^3)/(1 \times 10^{-6} \text{ cm}) \]
\[ = 5 \times 10^{-8} \mu\text{moles/sec} \]

**PRACTICE CYCLE 6**

**Input**

Fairly early in his career Albert Einstein was interested in diffusion. He considered the case of a large number of molecules being placed at \( x = 0 \) at time zero.

Einstein asked the question, given a time \( t \), how far will the average molecule diffuse. Since a molecule is equally likely to diffuse in a positive or negative \( x \)-direction, the average displacement \( (\Delta x) \) is zero. If one considers the average square of the displacement \( (\Delta x)^2 \), Einstein found that

\[ (\Delta x)^2 = 2Dt \]

where \( D \) is the diffusion coefficient and \( t \) is the time. We will call this equation *Einstein's Relation*.

Einstein's Relation applies exactly only to the situation described above. But since it is such a simple equation it is convenient to use Einstein's Relation as a rule of thumb in other situations. For example, let us say that a particular cell is 100 \( \mu\text{m} \) \((10^{-2} \text{ cm})\) from the nearest capillary. If the diffusion coefficient for glucose in the extracellular space is about \( 1 \times 10^{-5} \text{ cm}^2/\text{sec} \), about how long will it take glucose to diffuse from the capillary to the cell?

Solving Einstein's Relation for time and plugging in the appropriate values we obtain

\[ t = (\Delta x)^2/2D = (1 \times 10^{-2} \text{ cm})^2/(2 \times 10^{-5} \text{ cm}^2/\text{sec}) \]
\[ = 10^{-4} \text{ cm}^2 / (2 \times 10^{-5} \text{ cm}^2/\text{sec}) = 5 \text{ sec} \]

Given the metabolic time scale on which many cells operate, a 5 sec diffusion time from capillary to cell is tolerable.
**Practice**

If a cell were 1 cm from the nearest capillary, how long on the average would it take a glucose molecule to diffuse from the capillary to the cell? (Use the same diffusion coefficient as above.)

**Feedback**

Did you get $5 \times 10^4$ sec? Fine.

Here's how I did it: $t = (\Delta x)^2/2D = 1 \text{ cm}^2/(2 \times 10^{-5} \text{ cm}^2/\text{sec}) = 5 \times 10^4$ sec. Since there are 3600 sec in an hour, this amounts to 14 hours!

Even a pretty sluggish cell can't wait 14 hours for its next bite of glucose. The point to be emphasized here is that diffusion is quite fast over microscopic distances—the dimensions of most cells. But diffusion is quite slow on the macroscopic distance scale. (By macroscopic, I mean things one can see with the naked eye. The evolutionary consequence of the effective distance scale of diffusion is that any macroscopic organism has some sort of a circulatory system.

Note that Einstein's Relation tells us that the time required for diffusion increases with the square of the distance. Thus if on the average it takes 5 sec for molecules to diffuse 100 µm, the average molecule will require 20 sec to diffuse 200 µm, and 500 sec to diffuse 1000 µm. (To diffuse twice as far takes 4 times longer; to diffuse 10 times farther takes 100 times longer.)

**PRACTICE CYCLE 7**

**Input**

Let's return to the subject of diffusion across biological membranes. The lipid bilayer matrix of the membrane poses a diffusion barrier for most water soluble substances. For many vital, water-soluble compounds specific membrane proteins function to transport them across the membrane. The major characteristics of protein-mediated transport will be considered later in the course.

Substances whose passage across the membrane is not mediated by membrane proteins will tend to diffuse across the membrane. In order to do this these substances must essentially dissolve in the lipid bilayer, diffuse across the bilayer, and then come out of the lipid bilayer phase and move into the aqueous phase on the other side of the membrane.
Let us consider more in detail what may go on in the membrane. If the substance in question is assumed to equilibrate with the lipid bilayer, then it will partition into the lipid phase and its ultimate concentration in the lipid phase can be expressed in terms of a lipid:water partition coefficient ($\beta$). If, for example, we put some glucose into a flask with water and olive oil and then shake the flask for a long time, the final distribution of glucose between the two phases will tell us the partition coefficient.

\[
\text{olive oil:water partition coefficient} = \frac{[\text{glucose}]_{\text{oil}}}{[\text{glucose}]_{\text{water}}}
\]

for glucose

**Practice**

Consider the diagram of the membrane below

If a substance equilibrates with the membrane lipids with a lipid:water partition coefficient $\beta$,

(a) What will be the concentrations of the substance in the membrane lipids at $x = 0$ and $x = L$, $C_{m}(0)$ and $C_{m}(L)$, respectively, if the aqueous concentrations are $C_{0}$ and $C_{L}$ as shown in the diagram?

(b) Using these concentrations write the steady-state form of Fick's First Law for diffusion within the membrane.

(c) From this expression how does the rate of diffusion of the substance across the membrane depend on $\beta$, the partition coefficient?
Feedback

Did you say something like the following?

(a) $C_m(0) = \beta C_0$ and $C_m(L) = \beta C_L$

(b) $J = D_m A \beta (C_0 - C_L)/L$, where $D_m$ is the diffusion coefficient of the substance in the membrane lipids.

(c) The rate of diffusion is directly proportional to $\beta$.

If you got most of this, great! If not, here's how you might have done it.

(a) Just inside the membrane at 0 and L, we assume the concentration is in equilibrium with that in the water just outside the membrane at 0 and L, respectively. Since that equilibrium is expressed by the membrane:water partition coefficient: $\beta = C_m(0)/C_0 = C_m(L)/C_L$

Cross-multiplication gives $C_m(0) = \beta C_0$ and $C_m(L) = \beta C_L$

(b) The steady-state form of Fick's First Law is $J = -D A \frac{\Delta C}{\Delta x}$.

If the diffusion coefficient within the membrane is designated as $D_m$, and the membrane thickness is $L$, and the concentration difference within the membrane is $C_m(0) - C_m(L) = \beta (C_0 - C_L)$, then

$J = -D_m A \frac{\Delta C}{\Delta x} = -D_m A \beta \frac{C_0 - C_L}{L}$

(c) From the last equation we can see that the diffusional flux is directly proportional to the lipid:water partition coefficient ($\beta$). Thus, the more lipid soluble (i.e. soluble in nonpolar solvents) a substance, the greater its ability to diffuse through the membrane lipids, and the greater its membrane permeability.
PRACTICE CYCLE 8

Input

The relationship between the membrane permeabilities of various solutes and their lipid solubility was first demonstrated for algal cells by Collander and his associates. The figure below shows the classical data of Collander on the permeability of the alga *Chara ceratophylla*. They used the olive oil:water partition coefficient as a measure of lipid solubility of the various solutes.

Practice

From the data in the figure above, what can you say about

(a) What is the relationship between lipid solubility and membrane permeability?

(b) What is noteworthy about the permeability of water and methanol, which are very small water-soluble molecules?

Feedback

Did you say that:

(a) The greater the lipid solubility (as indicated by the olive oil:water partition coefficient), the greater the permeability.
(b) Water and methanol have much higher permeabilities than would be predicted from their olive oil:water partition coefficients. Lipid bilayers, with no proteins, have a higher permeability to water and other very small water-soluble molecules than would be predicted based upon partition coefficients. Many plasma membranes contain water channel proteins, called \textit{aquaporins}, that further increase the permeability to water.

Molecular weight or molecular size is also a determinant of permeability. In general, for molecules of similar lipid solubility, the larger the molecule, the smaller its permeability. This makes sense in terms of our earlier mention that the larger a molecule, the smaller its diffusion coefficient.

\textbf{PRACTICE CYCLE 9}

\textbf{Input}

The data in the last section is for substances with appreciable lipid solubility. For water-soluble substances some other factors need to be considered. Most cells are effectively impermeable to the diffusion of water-soluble molecules above a certain molecular weight. The plasma membrane of a typical mammalian cell is essentially impermeable to water-soluble molecules with molecular weight about 200 or greater. Thus, sucrose (MW 342) is often used to measure the extracellular space of a tissue because it fails to enter the cells but can distribute by diffusion in the interstitial fluid. A typical animal cell plasma membrane is significantly permeable to water-soluble molecules with MW less than 200, the smaller the molecule the greater the permeability.

Inorganic ions, because of their charge, are very insoluble in the lipid matrix of the membrane. The greater the charge on the ion, the smaller in general is its membrane permeability. Thus, lipid bilayer membranes have a very low permeability to Na\(^+\), Cl\(^-\), and other univalent ions and even lower permeabilities to Ca\(^{2+}\), SO\(_4^{2-}\), and other multivalent ions.

\textbf{Practice}

(a) For water-soluble molecules, what is the relationship between molecular weight and permeability by diffusion?

(b) For inorganic ions, how does membrane permeability by diffusion depend on the charge on the ion?

\textbf{Feedback}

Did you say that

(a) Most membranes are essentially impermeable to diffusion of water-soluble molecules with molecular weight above 200. For molecular weights less than 200, the smaller the molecule, the greater the permeability.
(b) The greater the charge on an ion, the smaller its ability to diffuse across the membrane.

It should be emphasized that certain ions and large water-soluble molecules do cross the biological membranes at appreciable rates. This transport occurs, however, not by the simple diffusion of the ion or large water-soluble molecule across the membrane, but with the assistance of more-or-less specific membrane proteins. These proteins form channels through the membrane or function as carriers for specific ions or molecules. Later in the course we will deal with membrane transport that is mediated by membrane proteins.

**POST-TEST**

1. Chamber A is separated from Chamber B by a removable partition. Chamber A contains many X molecules. Chamber B contains none. Then the partition is removed.
   
   (a) Describe the net flow of X molecules in the system. Why will this net flow occur?
   
   (b) Will the system reach equilibrium? Describe the equilibrium in terms of (i) the concentrations of X, (ii) the fluxes of X from A to B and B to A, and (iii) net flux of X.

2. Write Fick's First Law of Diffusion and identify the symbols in the equation.

3. (a) Write the steady-state form of Fick's First Law.
   
   (b) A human red cell has a membrane surface area of about 100 \( \mu \text{m}^2 \) \((1 \times 10^{-6} \text{ cm}^2)\) and a membrane thickness about 100 Å \((1 \times 10^{-6} \text{ cm})\). If the concentration of glycerol in the extracellular fluid is 10 mM, but its concentration in the intracellular water is 0, calculate the flux of glycerol in \(\mu\)moles/sec across the red cell membrane. Assume that the diffusion coefficient that applies is \(1 \times 10^{-8} \text{ cm}^2/\text{sec}\). (Watch your units!)

4. (a) Write Einstein’s Relation
   
   (b) During the course of a neurosurgical procedure a drug is applied to the surface of the brain in order to inhibit the activity of a group of neurons that lie 1 mm below the surface. Approximately how long will it take the drug to diffuse from the surface to those neurons. Assume the diffusion coefficient of the drug in brain tissue is \(1 \times 10^{-5} \text{ cm}^2/\text{sec}\).

5. (a) How does the lipid solubility of solute molecules affect their permeability to biological membranes?
   
   (b) For molecules of the same lipid solubility, how does the molecular weight affect permeability?

6. Water has a low lipid solubility
   
   (a) What can you say about its ability to permeate biological membranes?
   
   (b) Do other water-soluble molecules share this property? If so, what kinds of molecules?
7. With respect to the membrane permeability of molecules that are water soluble (i.e. have very low lipid solubility).

(a) What is the relationship between membrane permeability by diffusion and molecular weight?

(b) What is the molecular weight above which permeation by diffusion occurs at negligible rates?

(c) How, then, do water-soluble molecules larger than the molecular weight cut-off enter and leave cells?

8. (a) What is the relationship between the charge on an inorganic ion and its membrane permeability by diffusion?

(b) How do inorganic ions typically permeate cell membranes?

ANSWERS TO POST-TEST

1. (a) A net flow of molecules will occur from Chamber A to Chamber B. This net flow will occur because the number of molecules moving from A to B in a given time period will exceed the number moving from B to A.

(b) The system will ultimately reach equilibrium
   (i) At equilibrium the concentration of X will be the same in A and B.
   (ii) At equilibrium the flux from A to B equals that from B to A.
   (iii) At equilibrium the net flux is zero.

2. \[ J = -DA \frac{dC}{dX} \]
   where \( J \) is the net flow of solute (mole/sec)
   \( D \) is the diffusion coefficient (cm²/sec)
   \( A \) is the area (cm²)
   \( \frac{dC}{dX} \) is the concentration gradient [moles/cm³]/cm

3. (a) \( J = -DA \frac{\Delta C}{\Delta X} \)
   (b) \( J = (1 \times 10^{-8} \text{ cm}^2/\text{sec}) (1 \times 10^{-6} \text{ cm}^2) (10 \mu\text{mole/cm}^3)/(1 \times 10^{-6} \text{ cm}) = 1 \times 10^{-7} \mu\text{moles/sec} \)

4. (a) \( (\Delta x)^2 = 2Dt \)
   (b) \( t = (\Delta x)^2/2D = (0.1 \text{ cm})^2/(2 \times 10^{-5} \text{ cm}^2/\text{sec}) = 500 \text{ sec} \)
5. (a) In general, the more lipid soluble a molecule, the more permeable it is to biological membranes.

(b) For molecules of the same lipid solubility, the smaller the molecular weight, the greater the permeability.

6. (a) Water permeates most biological membranes much more rapidly than predicted from its lipid solubility.

(b) Yes. Other very small water-soluble molecules such as methanol are also very permeable. Water channel proteins, aquaporins, further increase the water permeability of membranes.

7. (a) For water-soluble molecules, the greater the molecular weight, the smaller the permeability.

(b) Water-soluble molecules larger than about 200 molecular weight are essentially impermeable to most biological membranes.

(c) Water-soluble molecules larger than 200 molecular weight may cross biological membranes via specific channels or carriers formed by membrane proteins.

8. (a) The greater the charge on an inorganic ion, the less it is able to diffuse across biological membranes.

(b) Inorganic ions do not diffuse readily across biological membranes but most cells have ion channels formed by specific membrane proteins.