

Cell Membrane Structure and Function

The **cell membrane**, **cytoplasmic membrane** or **plasma membrane** (a structural component of all living cells) is a living, dynamic layer that surrounds and limits the cell. It is sometimes referred to as an invisible surface layer because it is too thin to be visible with a light microscope. A typical cell membrane is about 8nm thick, so is considerably thinner than the skin on an apple or the colorful film forming the wall of a large soap bubble. The cell membrane forms a **selectively** and **differentially permeable** barrier, because it allows only certain types of substances to pass through (into or out of the cell) and because it changes over time. It is alive and changing rather than static.

Membrane Structure

Eukaryotic cell membranes are typically composed of lipids and proteins in a near 50:50 ratio, i.e., they contain about 50% lipids and 50% proteins of various types. Prokaryotic membranes contain 40% lipid and 60% protein. The most commonly accepted model for the structure of the cell membrane (the Fluid Mosaic Model) was developed by Seymour J. Singer and Garth L. Nicholson in 1972 and shows proteins "floating like icebergs in a sea of lipid". Most membrane illustrations are based on this model and show lipids arranged in a bi-layer with proteins floating in and sometimes penetrating through this layer.

The lipid bi-layer portion of a bacterial cell membrane is composed primarily of **phospholipids**. These are **amphipathic/amphiphilic** molecules, i.e., have both **polar** (hydrophilic) and **non-polar** (hydrophobic) portions and are arranged with their **hydrophobic tails** toward the inside of the membrane and their **hydrophilic heads** toward the watery environment either inside or outside the cell. The orientation of these molecules is influenced by their solubility in either lipid or water, and is a major factor maintaining the structural integrity of the membrane itself.

In eukaryotic cells, the lipid bi-layer is about 65% phospholipids, 25% sterols (cholesterol in animals, phytosterols in plants, ergosterol in fungi, etc.) and 10% other types of lipids. Since prokaryotic cells generally lack sterols (though some bacteria have sterol-like lipids) the cell membranes represented in most illustrations are prokaryotic (bacteria specifically). The cell membranes of Archaea are unique (do not contain phospholipids) and will be described later.

The proteins associated with cell membranes are usually globular in form and also **amphipathic/amphiphilic**. They can be divided into two categories based on their location and degree of interaction with the lipid bilayer. Proteins categorized as **integral proteins** (intrinsic proteins) extend into and sometimes all the way through the membrane, and cannot readily be removed without causing structural damage. Proteins categorized as **peripheral proteins** (extrinsic proteins) sit on the membrane surface (facing either the inside or the outside of the cell) and can be easily removed. Many of the proteins associated with cell membranes occur as complexes, and some are **glycoproteins**, i.e., proteins bound to polysaccharide chains. Glycoproteins found on external cell surfaces often serve as active or reactive sites involved in the regulation of cellular responses.

Membrane Functions

The cell membrane is a living, functioning portion of the cell and is associated with a number of cellular processes including:

1. **Separating the cell from the environment surrounding it.** Recall that the cell membrane contains and limits the cell.
2. **Controlling what types of materials enter and exit the cell.** Since the movements of materials into and out of cells are essential to cellular function, membrane transport mechanisms have been extensively studied. Some of the best-understood mechanisms are described below.

A. Diffusion – Diffusion can be defined as the movement of particles to fill an available space, and occurs due to the random activity of molecules. It may involve liquids, solids or gasses. Since it is a **passive transport** process, i.e., does not require the cell to expend energy, the net movement of particles will always be down a gradient, either a **concentration gradient** (chemical gradient) or an **electrical gradient** (or combination of these). A concentration gradient exists when there is a difference in the concentration of particles between one area and another. Although particles move at random, the net direction of movement will be from an area of high concentration to an area of lower concentration (from high to low) so the particles are said to travel **down the gradient**.

Charged particles (ions) are influenced by concentration, but also by the net charge existing between opposite sides of a membrane. Particles with different charges (cations and anions) are attracted to one another, while those with the same charge repel one another. Charged particles can be induced to move against their concentration gradient by a strong electrical gradient.

Diffusion can be categorized as **simple** or **facilitated** depending upon the types of particles moving, and how they pass through the membrane. **Simple diffusion** does not require a membrane, but can occur across one, while **facilitated diffusion** requires a membrane because integral proteins are necessary to facilitate the transport process.

Gasses such as oxygen and carbon dioxide are among those particles able to move into and out of cells via simple diffusion. Both can pass through the lipid portion of the membrane, but the direction they travel varies depending on the type of cell being considered. In the case of animal type cells, oxygen (O₂) tends to move inward while carbon dioxide (CO₂) moves outward. This is because much of the oxygen entering an animal type cell is quickly converted into water (keeping the oxygen concentration low) while carbon dioxide is constantly being formed through the catabolism of carbohydrates. In the case of plant type cells actively engaged in photosynthesis, just the opposite is true. Carbon dioxide will move inward because it is being converted into carbohydrate, and oxygen will diffuse outward because it is being produced within the cell as a waste gas (from the splitting of water molecules).

Ions (charged particles) can also move passively across cell membranes, but require a protein channel to do so. The proteins facilitate the diffusion process (make it easier), so the process is called **facilitated diffusion**. Channel proteins may be complexes, and are sometimes equipped with gates that if closed will restrict ion flow.

Small organic compounds such as monosaccharides, amino acids, nucleotides, etc. can also move across membranes by facilitated diffusion, but only down their concentration gradients. The proteins involved undergo conformational changes during the process (recall revolving door analogy). In some cases the proteins facilitating particle movement are specific, i.e., allowing only one type of molecule to pass, and in other cases they are more general, allowing a variety of similar molecules to pass. The term **permease** is sometimes applied to proteins involved in facilitated diffusion, but not all permeases allow passive transport.

B. Osmosis—Osmosis is sometimes defined as the diffusion of water through a membrane, but has a more technical definition. It is the movement of **solvent** (most often water in biological systems) from an area of low **solute** concentration (high water) to an area of higher solute concentration (low water) through a selectively permeable membrane, i.e., one permeable to the solvent but not to solute particles. This can be thought of as the movement of water from an area of high water concentration to an area of lower water concentration, or down a concentration gradient; however, chemically speaking, there is no such thing as water concentration.

Osmosis provides the mechanism by which water influences cell size and shape, because water entering a cell will cause it to swell up while water leaving a cell will cause it to shrink. In either case, excess water movement can cause cell damage and sometimes death.

Because the movement of water through cell membranes is influenced by the concentration of solute particles, we can think of these particles as exerting pressure. In reference to fluid environments surrounding cells, the term **tonicity** is equivalent to **effective osmotic pressure**, i.e., the pressure causing water to move by osmosis. (Though technically osmotic pressure is measured by preventing the movement of water.)

An environment is **isotonic** (iso = the same), if the concentration of solute particles is equal to that found within the cell. The osmotic pressure is equal on either side of the membrane and there is no net movement of water.

An environment is **hypotonic** – (hypo = under or beneath) if it has a solute concentration lower than that found within the cell, as would occur in a water environment. Cells placed into hypotonic environments will take on water through osmosis unless they are protected by cell walls. Water will readily enter human RBCs placed in hypotonic environments, and will cause them to rupture, but this doesn't happen to bacteria because they are protected by cell walls.

An environment is **hypertonic** – (hyper = over, above or excessive) if the solute concentration is greater than that found within the cell. In this case water will leave the cell and the cell will shrink, sometimes collapsing.

Exactly how water passes through cell membranes appears to vary depending on the cell type. Sometimes it “leaks” slowly through the lipid bilayer, and sometimes it moves rapidly. Rapid water flow occurs through channels created by integral membrane proteins called **aquaporins**, that occur in a wide variety of cells. Water molecules appear to pass in single file through such proteins, but when many exist, water movement overall is fast. Some cell membranes appear to prevent osmosis from occurring, while others cannot, probably because not all cell membranes have aquaporins.

C. Active Transport – Active transport is a process allowing cells to move particles through membranes against their concentration and/or electrical gradients. Like facilitated diffusion, it involves integral proteins, but unlike diffusion, it **requires energy**, i.e., it is not passive.

Adenosine triphosphate (ATP) is the high-energy compound most commonly used to drive active transport processes, but it may be used either directly (**primary active transport**) or indirectly (**secondary active transport**). When cells use **ATPase enzymes** to transport sodium (Na^+) or hydrogen (H^+) ions across membranes and **create gradients**, this is primary active transport. When they use these gradients to move other types of particles in symport or antiport with the cations (as they flow back across the membrane down their gradients), this is secondary active transport. The sodium-potassium pumps associated with cell membranes are ATPase enzymes (Na^+/K^+ ATPase) that pump three Na^+ out and two K^+ in for each ATP used.

ATP-synthase, the enzyme responsible for the synthesis of ATP during oxidative and photophosphorylation can also function as an ATPase, and can pump hydrogen protons (H⁺) across membranes to create gradients (both concentration and electrical). In this case, three H⁺ are transported for each ATP used. This enzyme complex might be called a **uniporter**.

The protein complexes involved in **secondary active transport** use the energy provided by **electrochemical gradients** to move particles through or across membranes. They are dependent on their ability to bind with two different types of particles, and they change their conformation to allow these particles to be either picked up or released. When these protein pumps move two different types of particles in opposite directions across membranes, they are called **antiporters** or **exchangers** (the process is called antiport or exchange). Sodium (Na⁺) and calcium (Ca²⁺) ions can be exchanged by **antiporters** that move two Ca²⁺ out for every three Na⁺ allowed to flow inward down an electrochemical gradient. The flow of Na⁺ ions down their electrochemical gradient drives the transport of Ca²⁺ ions against their gradient. When the pumps move two different types of particles in the same direction across membranes, they are called **symporters** or **cotransporters** (the process is called symport or cotransport). Glucose, amino acids and other small organic compounds can be moved in **symport** with either hydrogen or sodium ions. In this case, the flow of cations down their electrochemical gradient drives the transport of organic compounds against their concentration gradient.

Yeast cells placed in a 5% glucose solution can initially take in glucose passively through facilitated diffusion; however, when the glucose concentration outside the cells becomes lower than that inside, the yeast cells will switch to active transport.

Diffusion (both simple and facilitated), osmosis and active transport are used by both prokaryotic and eukaryotic cells, but some prokaryotes can also use another process called group translocation or group transport.

- D. Group translocation** – Group translocation (sometimes called group transport) is a mechanism allowing bacteria to move molecules through membranes down their concentration gradients by changing them into different types of molecules during the transport process. For example, bacteria taking in glucose molecules through group translocation, bind a phosphate group to each one as it passes through the membrane. The phosphorylated glucose (glucose-6-phosphate) cannot exit (the cell membrane is not permeable to it), so accumulates inside the cell. Because this mechanism requires energy, it is considered active, but it does not involve ATP directly.
- E. Endocytosis** – Endocytosis is a transport mechanism associated with eukaryotic cells primarily (*E. coli* cells have been made to carry out endocytosis under experimental conditions). It involves the invagination (inward folding) of a small section of the cell membrane, and the pinching off of that portion to form a vacuole or vesicle inside the cell. Typically the materials being taken in are bound to receptors on the outer cell surface, and this triggers the invagination process. Endocytosis can be divided into two categories based on the size of the particles being taken in. If the particles are large (cellular in size), the process is called **phagocytosis** or cell eating. If the particles being taken in are small (molecular in size), the process is called **pinocytosis** or cell drinking. Single-celled animal-like organisms known as protozoa typically consume food materials by means of phagocytosis. Phagocytosis is also the process used by human WBCs when they consume bacteria.
- F. Exocytosis** – Exocytosis is a process allowing cells to release various materials to the outside by joining vacuoles or vesicles with the cell membrane from the inside. Although this process is sometimes also called **emioctosis**, a term meaning cell vomiting, the materials being released

are not necessarily waste. Many cells release enzymes into their environments by this means, and enzymes have multiple different functions.

Both endocytosis and exocytosis are considered to be active transport mechanisms, because both require energy (ATP).

- 3. Influencing taxis – Taxis** is the directed movement of cells within their environment, and often involves receptors (usually glycoproteins) associated with the cell membrane. Cell membranes are equipped with various receptors telling the cell what is going on in the environment. Stimuli perceived by these receptors trigger internal responses resulting in cell movement. In the case of prokaryotic cells, movement also involves the cell membrane because prokaryotic flagella are driven by membrane "motors". If movement is directed toward a stimulus, it is called **positive taxis**, and if it is directed away from a stimulus it is called **negative taxis**. Different types of stimuli trigger different types of taxis as indicated below:

Phototaxis = movement directed by light. Organisms capable of using light as an energy source will frequently display positive phototaxis, i.e., will move toward light. Organisms preferring dark habitats will move away from light, so will display negative phototaxis.

Chemotaxis = movement directed by chemicals. Animal-like organisms such as protozoa display positive chemotaxis as they move toward a food source and negative chemotaxis as they move away from toxic chemicals or potential predators.

Magnetotaxis = movement directed by magnetic fields. Magnetotaxis involves structures called **magnetosomes** made up of magnetic crystals surrounded by cell membrane. Cells displaying positive magnetotaxis often travel toward iron deposits.

Geotaxis = movement directed by gravity. Organisms display positive geotaxis when they move downward or into a sediment layer, and negative geotaxis when they move upward or away from sediments.

- 4. Synthesizing ATP and facilitating other metabolic processes.** Although ATP synthesis occurs in association with internal organelles (mitochondria and chloroplasts) of eukaryotic cells, in prokaryotic cells much of it occurs in association with the cell membrane. The processes involved, **oxidative phosphorylation** and **photophosphorylation** involve the creation of **concentration gradients** (the proton motive force) and the movement of **hydrogen protons** through a type of enzyme called **ATP synthase** (unique to prokaryotic cells). These processes will be described in detail later in the semester.

Prokaryotic cell membranes also contain a variety of enzymes involved in other metabolic processes including the synthesis of cell wall constituents and portions of the cell membrane, the replication of DNA and formation of septa required for cell division, light production and some carbon dioxide fixation.

- 5. Quorum sensing** – Quorum sensing involves receptors in bacteria cell membranes sensitive to signaling molecules released by other bacteria. When enough signaling molecules (called autoinducers or **pheromones**) bind with membrane receptors, they trigger the activation of genes influencing a variety of cellular functions including the formation of more membrane receptors. Quorum sensing is involved in such bacterial activities as biofilm formation, light production, cell aggregation, release of toxins and production of enzymes required for digestion of nutrients.