B2.1 Membranes and membrane transport

Form and function—Cells

Standard level and higher level: 4 hours

Additional higher level: 2 hours

Guiding questions

• How do molecules of lipid and protein assemble into biological membranes?

• What determines whether a substance can pass through a biological membrane?

SL and HL

B2.1.1—Lipid bilayers as the basis of cell membranes

Phospholipids and other amphipathic lipids naturally form continuous sheet-like bilayers in water.

- Cell membranes are composed of **phospholipid bilayers**
- Phospholipids are **amphipathic** molecules that contain hydrophilic & hydrophobic regions
  - The **phosphate head/group** is hydrophilic/polar & **attracted to water**
  - The **fatty acid tails/chains** are hydrophobic/non-polar & **repel water**
- Amphipathic lipids naturally form **continuous sheet-like bilayers** in water;
  - Fatty acid chains attract each other via **hydrophobic interactions**
  - Phosphate groups are attracted to water molecules via **hydrogen bonds**
- Bilayers minimize disruption to the hydrogen-bonding network of water, ensuring **energetically stability**

B2.1.2—Lipid bilayers as barriers

Students should understand that the hydrophobic hydrocarbon chains that form the core of a membrane have low permeability to large molecules and hydrophilic particles, including ions and polar molecules, so membranes function as effective barriers between aqueous solutions.

- Membranes function as effective **barriers** between aqueous solutions due to the inner hydrophobic core
  - Small or large **hydrophilic (polar)** particles are **unable** to **freely** diffuse across the membrane
  - Small or large **hydrophobic (non-polar)** particles **freely diffuse** across the membrane

B2.1.3—Simple diffusion across membranes

Use movement of oxygen and carbon dioxide molecules between phospholipids as an example of simple diffusion across membranes.

- **Simple diffusion** is the movement of particles from a region of high concentration to a region of low concentration (i.e. down the concentration gradient) without membrane proteins or ATP
- The ability of a particle to undergo simple diffusion across membranes depends on:
  - **Size**: smaller particles (like O_2 and CO_2) have a higher simple diffusion rate than larger ones
  - **Polarity**: more non-polar / less polar particles diffuse faster than more polar/hydrophilic ones
  - **Concentration gradient**: the greater the difference in concentration of the particle is across the two sides of the membrane, the faster the diffusion rate

B2.1.4—Integral and peripheral proteins in membranes

Emphasize that membrane proteins have diverse structures, locations and functions. Integral proteins are embedded in one or both of the lipid layers of a membrane. Peripheral proteins are attached to one or other surface of the bilayer.

- **Proteins** are major components of cell membranes that allow for diverse membrane functions
  - **Integral proteins** can be embedded in one or both of the lipid bilayers of a membrane
    - **Transmembrane proteins** are integral proteins that are embedded in both of the lipid bilayers
    - The **outer surface** of transmembrane proteins is hydrophobic in order to embed itself in the hydrophobic core of the membrane
    - All **transport proteins** are transmembrane proteins
  - **Peripheral proteins** can be attached to one surface of the bilayer or to lipids , hydrocarbon chains & integral proteins
- Membrane proteins have diverse functions:
  - **Catalysis** through enzymatic activity
  - **Attachment** to other cells or to the extracellular matrix
  - **Transport** of ions & polar particles
  - **Reception** of signalling molecules in chemical and neural signalling
  - **Junctions** that connect the cytoplasm of two cells together
  - **Recognition** of markers for cell identification (e.g. immunity)

B2.1.6—Channel proteins for facilitated diffusion

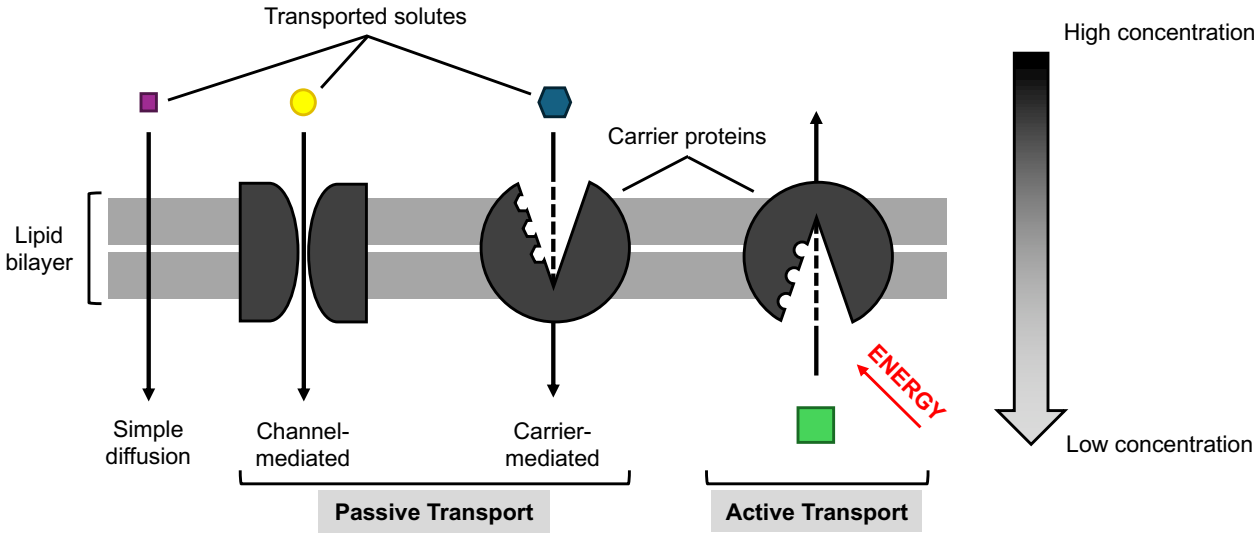
Students should understand how the structure of channel proteins makes membranes selectively permeable by allowing specific ions to diffuse through when channels are open but not when they are closed.

- **Passive transport** (**facilitated diffusion**) is the movement of particles **down their gradient** across membranes by **transport proteins** without using any energy (ATP)
  - Enables polar particles to diffuse across the membrane at higher rates than by simple diffusion
  - Allows cells to control the entry of polar particles by opening/closing transport proteins
- Channels and carriers are **two** types of transport proteins that can carry out passive transport
  - **Channels** can **only** perform passive transport
    - Contain a **hydrophilic pore (opening)** that allows polar particles to diffuse through it
    - The **outer surface** of the channel is **hydrophobic** because it is embedded in the hydrophobic core of the lipid bilayer
    - Opening/closing of some channel pores can be regulated by **ligands** or **voltage**
  - **Carriers** can perform **both** passive and active transport
    - Contain a **solute-binding site** that attaches to specific solutes
    - Binding of solute causes a **conformational change** in the protein structure of the carrier, which **translocates** the solute across the lipid bilayer & **releases** it on the other side
    - When involved in passive transport they are commonly referred to as carriers, but when performing active transport they are called pumps

B2.1.7—Pump proteins for active transport

Students should appreciate that pumps use energy from adenosine triphosphate (ATP) to transfer specific particles across membranes and therefore that they can move particles against a concentration gradient.

- **Active transport** is the movement of particles **against their gradient** across membranes by **transport proteins** that use energy (usually ATP)
  - Enables cells to acquire nutrients that exist in low concentrations outside of the cell
  - Allows cells to establish/maintain gradients for specific functions (e.g. neural signalling)
- **Pumps (carriers)** are the only transport proteins that perform active transport
  - Specific solutes attach to the solute-binding site
  - **ATP hydrolysis** causes a **conformational change** in the protein structure of the carrier, which **translocates** the solute across the lipid bilayer (against its gradient) and releases it



B2.1.8—Selectivity in membrane permeability

Facilitated diffusion and active transport allow selective permeability in membranes. Permeability by simple diffusion is not selective and depends only on the size and hydrophilic or hydrophobic properties of particles.

- Transport proteins in passive & active transport allow selective permeability in membranes
  - **Channels**: the **size of the pore** and the **amino acids lining its inner surface** provide specificity to the type of polar particles that can diffuse through it
  - **Pumps**: the solute-binding site is composed of **specific amino acids** that are selective for the solute they bind to
- Permeability by simple diffusion is **not selective** and depends only on the size and hydrophilic or hydrophobic properties of particles

B2.1.5—Movement of water molecules across membranes by osmosis and the role of aquaporins

Include an explanation in terms of random movement of particles, impermeability of membranes to solutes and differences in solute concentration.

- Water particles move randomly in all directions because they have kinetic energy
- Water moves very slowly by simple diffusion across membranes because it is small but polar
- Water movement is affected by **unequal distribution of solutes** across the membrane
  - Substances become dissolved in water (i.e. solutes) because they form hydrogen bonds with water
  - Areas with low solute concentration have more free water molecules (high water potential) than areas with high solute concentration (low water potential)
  - This causes **osmosis**: the movement of water molecules from an area of **high water potential** (low solute concentration) to an area of **low water potential** (high solute concentration)
- **Aquaporins** are **transport channels** that enable water to move across the membrane by osmosis
  - The amino acids lining the inner pore are selective for water molecules

B.2.1.9—Structure and function of glycoproteins and glycolipids

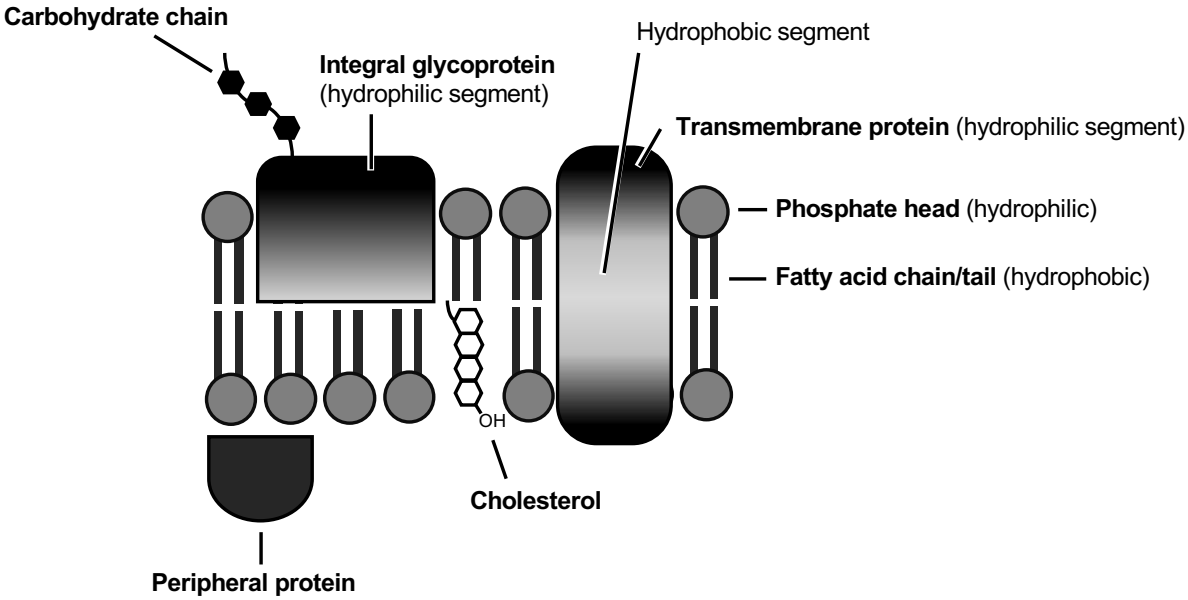
Limit to carbohydrate structures linked to proteins or lipids in membranes, location of carbohydrates on the extracellular side of membranes, and roles in cell adhesion and cell recognition.

- **Glycoproteins** are proteins attached to carbohydrates
- **Glycolipids** are lipids attached to carbohydrates
- Both glycoproteins & glycolipids are found on the **outer cytosolic leaflet (extracellular side)**, which supports their functions of:
  - **Cell adhesion**: the carbohydrate chains on adjacent cells can bind together to keep tissue intact
  - **Cell recognition**: the carbohydrate chains attached to proteins/lipids act as **receptors** that recognize & identify other cells (e.g. in the immune system)

B2.1.10—Fluid mosaic model of membrane structure

Students should be able to draw a two-dimensional representation of the model and include peripheral and integral proteins, glycoproteins, phospholipids and cholesterol. They should also be able to indicate hydrophobic and hydrophilic regions.

- The **fluid mosaic model** is the most strongly support model of membrane structure
- "**Fluid**" because the proteins & lipids within the membrane can **move/diffuse laterally** across the bilayer
- "**Mosaic**" because the membrane is composed of **highly diverse** lipids, proteins, and carbohydrates



Additional higher level

B2.1.11—Relationships between fatty acid composition of lipid bilayers and their fluidity

Unsaturated fatty acids in lipid bilayers have lower melting points, so membranes are fluid and therefore flexible at temperatures experienced by a cell. Saturated fatty acids have higher melting points and make membranes stronger at higher temperatures. Students should be familiar with an example of adaptations in membrane composition in relation to habitat.

- **Membrane fluidity** is how freely proteins/lipids can diffuse laterally within the bilayer (i.e. **viscosity**)
- Fatty acid composition is a major determinant of membrane fluidity
  - **Saturated fatty acids** have **higher melting points** because their linear structure maximizes surface area for intermolecular attractions
    - **Reduce** membrane fluidity/flexibility & permeability
  - **Unsaturated fatty acids** have **lower melting points** because the **kinks** in their structure reduce the surface area available for intermolecular attractions
    - **Increase** membrane fluidity/flexibility & permeability
- The **ratio** of saturated to unsaturated fatty acids in the bilayer determines overall membrane fluidity
  - Organisms with more saturated fatty acids are adapted for habitats with higher temperatures
  - Organisms with more unsaturated fatty acids are adapted for habitats with lower temperature
  - The ratio can be **regulated** by organisms to maintain homeostasis

B2.1.12—Cholesterol and membrane fluidity in animal cells

Students should understand the position of cholesterol molecules in membranes and also that cholesterol acts as a modulator (adjustor) of membrane fluidity, stabilizing membranes at higher temperatures and preventing stiffening at lower temperatures.

- **Steroids** like **cholesterol** are a major class of lipids in the membranes of animal cells
- Cholesterol's structure is **amphipathic**:
  - The **4 fused rings** and the **hydrocarbon chain** are hydrophobic
    - Embedded within the hydrocarbon chains/tails of the phospholipid bilayer
  - The **hydroxyl** (–OH) group is hydrophilic
    - Attracted to the phosphate heads of phospholipids
- Cholesterol acts as a **modulator (adjustor)** of membrane fluidity
  - Stabilizes membranes at higher temperatures by decreasing fluidity
  - Prevents membrane stiffening at lower temperatures by increasing fluidity

B2.1.13—Membrane fluidity and the fusion and formation of vesicles

Include the terms "endocytosis" and "exocytosis", and examples of each process.

- **Bulk transport** is the movement of large materials or large amounts of material across membranes
  - Specialized mechanisms are needed (i.e. vesicles) since they cannot be moved by carriers/channels
- **Vesicles** are small, spherical, fluid-filled membrane sacs enclosed by a lipid bilayer
  - Used for bulk transport into the cell, out of the cell, or around the cell (i.e. between membrane-bound organelles like the ER, Golgi apparatus, endosomes, & lysosomes)
  - Thus, fluid composition inside vesicles depends on the initial membrane compartment
- **Endocytosis** is a general term for bulk transport **into** the cell
  - The material to be internalized is surrounded by an area of the plasma membrane, which buds/pinches off inside the cell to form a vesicle containing the ingested material
  - Can be used to internalize pathogens/bacteria (**phagocytosis**) or nutrients (**pinocytosis**)
- **E<u>x</u>ocytosis** is a general term for bulk transport **out** of the cell (material **e<u>x</u>ists**)
  - Similar mechanism to endocytosis but in the reverse direction
  - Can be used to secrete proteins or waste in a **constitutive** (continuous) or **regulated** manner
- Both exo/endocytosis are **ATP-dependent** and use proteins (like **clathrin**) to assist with vesicle formation
- Vesicle formation depends on membrane fluidity in order to form their spherical structures

B2.1.14—Gated ion channels in neurons

Include nicotinic acetylcholine receptors as an example of a neurotransmitter-gated ion channel and sodium and potassium channels as examples of voltage-gated channels.

- **Gated ion channels** can open/close their pores in response to different signals
- **Ligand-gated ion channels** open their pore upon binding of a ligand (signalling molecule), like nicotinic acetylcholine receptors
  - **Acetylcholine** (neurotransmitter, a type of ligand) binding to the receptors (channels) causes a conformational change in the channel that opens the pore & allows facilitated diffusion of Na^+ ions
  - Ligand/neurotransmitter release/unbinding leads to pore closure
  - Nicotine can also bind to the receptors instead of acetylcholine to induce a similar response
- **Voltage-gated ion channels** open their pore upon a change in the voltage of the membrane, like sodium & potassium ion channels (both have similar mechanisms)
  - A change in the voltage/potential of the membrane causes a conformational change in the structure of the sodium or potassium ion channels that opens their pores & allows rapid ion diffusion
  - When voltage returns to its initial value, the channels change conformation & the pore closes
  - Since both Na^+ and K^+ ions are positively charged ions, the size & amino acid properties of their channel pores impose selectivity

B2.1.15—Sodium–potassium pumps as an example of exchange transporters

Include the importance of these pumps in generating membrane potentials.

- **Sodium-potassium pumps** are found in all animal cells to maintain Na^+ and K^+ gradients
  - They are **exchange transporters** that exchange Na^+ ions for K^+ ions;
    - An **ATP molecule** binds to the inwards-facing side of the pump
    - The pump is initially open to the intracellular side & has **high affinity** for Na^+ ions, so 3 Na^+ bind
    - This causes **ATP hydrolysis** & **phosphorylation** of the pump (a phosphate group binds the pump)
    - This leads to a **conformational change** that translocates the 3 Na^+ ions across the membrane
    - The pump loses affinity for Na^+ ions once it faces the extracellular side so the 3 Na^+ ions are released into the extracellular matrix/fluid
    - Affinity for K^+ ions when the pump is facing the extracellular side is high, so 2 K^+ ions bind
    - Binding of K^+ ions causes **dephosphorylation** of the pump (release of phosphate group)
    - This causes the pump to change to its original conformation & translocates the K^+ ions across the membrane
    - The pump loses affinity for K^+ ions once it faces the intracellular side so K^+ are released into the cytoplasm
  - There are distinct binding sites for Na^+ ions, K^+ ions, ATP, & the phosphate group
- Na^+/K^+ pumps move Na^+ and K^+ against their gradients, maintaining a **high Na^+ concentration out** of the cell and a **high K^+ concentration inside** the cell
- Since 3 Na^+ ions move out of the cell and 2 K^+ ions move into the cell, there is a **net loss of 1 positive charge** from the cell, which makes the cytoplasm more negative than the extracellular fluid
  - The difference in charge (voltage) between each side of the bilayer is the **membrane potential**
  - Generation of membrane potential by the Na^+/K^+ pump enables neural signalling

B2.1.16—Sodium-dependent glucose cotransporters as an example of indirect active transport

Include the importance of these cotransporters in glucose absorption by cells in the small intestine and glucose reabsorption by cells in the nephron.

- There are different types of active transport:
  - **Primary/Direct active transport** uses direct ATP hydrolysis to move particles against their gradients
  - **Secondary/Indirect active transport** uses the energy stored in electrochemical gradients established by primary active transport to move particles against their gradient
- Different types of pumps can carry out secondary active transport:
  - **Symporters** transport both solutes in the same direction, but one is moving down its gradient & the other is moving against its gradient (e.g. sodium-dependent glucose cotransporters; SGLTs)
  - **Antiporters** transport solutes in opposite directions, but one is moving down its gradient & the other is moving against its gradient
- **SGLTs** are **symporters** that move glucose & Na^+ ions into cells;
  - A sodium gradient is established by the Na^+/K^+ pump; sodium concentration outside the cell is higher
  - **2 Na^+ ions** bind to the extracellular side of the SGLT, which exposes the **glucose-binding site**
  - Glucose binding causes a conformation change in the SGLT, triggering translocation into the cell
  - Release of Na^+ ions & glucose returns the SGLT to its original, outward-facing conformation
- SGLTs are used to transport glucose into the cell when its concentration is low outside of the cell
  - In the nephron, SGLTs are used to reabsorb glucose from the filtrate
  - In the small intestines, SGLTs are used to absorb digested glucose from food

B2.1.17—Adhesion of cells to form tissues

Include the term “cell-adhesion molecules” (CAMs) and the understanding that different forms of CAM are used for different types of cell–cell junction. Students are not required to have detailed knowledge of the different CAMs or junctions.

- **Cell adhesion molecules (CAMs)** are transmembrane proteins that enable cells to adhere to other cells or to the extracellular matrix
- Different forms of CAMs are used for different types of cell-cell junctions
  - Some CAMs **mediate immune cell adhesions** during immune reactions
  - Other CAMs keep **tissues intact** (including cancerous tumors) by cell adhesions

Linking questions

• What processes depend on active transport in biological systems?

• What are the roles of cell membranes in the interaction of a cell with its environment?

Review questions

SL and HL

- Distinguish between carriers and pumps. [1]
- Outline the roles of glycolipids and glycoproteins. [2]
- Explain why phospholipids form continuous sheets in water. [2]
- Outline the diverse functions of membrane proteins. [3]
- Explain the role of aquaporins in osmosis. [3]
- Explain why facilitated diffusion and active transport are selective mechanisms. [3]
- Compare and contrast passive and active transport. [4]
- Explain the role of membrane proteins in mediating interactions between a cell and its environment. [7]
- Draw the fluid mosaic model of membrane structure. [8]

Additional Higher Level

- Define indirect active transport. [1]
- Outline the role of cell adhesion molecules (CAMs) in organisms. [2]
- Explain the role of cholesterol in regulating membrane fluidity. [3]
- Describe how large materials are transported in and out of cells. [4]
- Explain how fatty acid composition regulates membrane fluidity. [4]
- Describe how sodium-dependent glucose cotransporters function in different tissues. [4]
- Describe how cells move small and large substances across their membranes. [7]

References

Ann Clark, Mary, et al. *Biology 2e*. E-book, OpenStax, 2018, https://openstax.org/books/biology-2e/pages/1-introduction. OpenStax.

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