Edexcel International Advanced Level (IAL) Biology Revision Series

2A: Membranes and Transport Mechanisms

Topic 2: Membranes, Proteins, DNA and Gene Expression

COMPREHENSIVE HIGH-YIELD LECTURE NOTES & SPEC COMPANION

BIOLOGICAL NICHE STUDY: OSMOREGULATION IN AMOEBA PROTEUS

The single-celled eukaryotic organism *Amoeba proteus* lives in freshwater environments. Its cytoplasm contains dissolved minerals and sugars, creating an internal hypertonic state relative to its dilute environment. Because its outer cell surface membrane is partially permeable, water continuously moves inward by **osmosis**, a passive process common to all living cells. To prevent swelling and bursting, *Amoeba proteus* utilizes a specialized organelle called a **contractile vacuole**. This organelle actively pumps ions internally to draw excess water out of the cytoplasm, contracting to expel it from the cell via energy-dependent transport mechanisms.

1. Structure and Component Topology of the Cell Membrane

The core structural matrix of all biological membranes is defined by the **Fluid Mosaic Model**. The membrane is not a rigid barrier, but a dynamic, fluid bilayer built from amphipathic lipid molecules embedded with various functional proteins and carbohydrates.

The Phospholipid Bilayer Matrix

Membranes are predominantly composed of **phospholipids**, which are specialized amphipathic lipid molecules containing two distinct structural regions:

- **Hydrophilic Head:** Formed by a negatively charged polar phosphate group covalently linked to a glycerol backbone. This region face outward, interacting directly with aqueous extra-cellular fluids and intra-cellular cytoplasm.
- **Hydrophobic Tails:** Composed of two non-polar fatty acid hydrocarbon chains that project inward, facing each other away from water. This creates an isolated hydrophobic core that acts as a highly selective barrier against water-soluble substances.

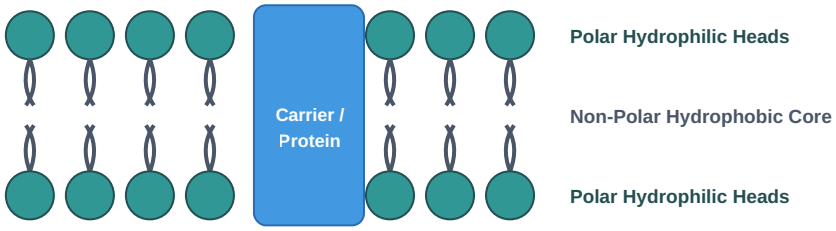

Figure 1: Cross-sectional structure of the fluid mosaic phospholipid bilayer with an integrated transport protein.

Alternative Core Structural Membrane Elements

Beyond the primary phospholipid substrate, other components are integrated into the membrane matrix to modulate its fluid traits and control cell interactions:

Membrane Component	Structural Association	Specific Functional Core Role
Cholesterol	Tucked between phospholipid hydrophobic tails.	Regulates membrane fluidity. Interacts with fatty acid tails to stabilize the membrane at higher body temperatures, while preventing crystallizing packing at low temperatures.
Intrinsic Proteins (Integral Transmembrane)	Span completely across the bilayer membrane.	Act as specialized carrier proteins or hydrophilic protein channels that allow large, charged, or polar particles to cross the hydrophobic core.
Extrinsic Proteins (Peripheral)	Bound superficially to either the inner or outer surface layers.	Serve as membrane enzymes, structural anchors for the cell cytoskeleton, or signaling sites that link to intracellular pathways.
Glycoproteins & Glycolipids	Carbohydrate chains covalently bound to proteins or lipids.	Function as cell surface antigens and receptors. Essential for cellular recognition, binding signaling hormones, and cell adhesion to form tissues.

2. Passive Transport: Diffusion & Facilitated Diffusion

Passive transport mechanisms move molecules down a concentration gradient without requiring metabolic energy input (ATP) from the cell. This movement is driven entirely by the natural kinetic energy of the particles.

Simple Diffusion

Simple diffusion is the net movement of particles from a region of higher concentration to an area of lower concentration. Because molecules move randomly, they naturally distribute evenly across a space over time. Small, non-polar molecules (such as oxygen, O_2, and carbon dioxide, CO_2) dissolve easily in lipids and diffuse directly through the phospholipid bilayer matrix.

Facilitated Diffusion

Large, highly polar molecules (such as glucose and amino acids) and fully charged inorganic ions cannot cross the hydrophobic core of the bilayer via simple diffusion. Instead, they require the assistance of specialized transmembrane transport proteins, moving down their concentration gradient through **facilitated diffusion**. This pathway is highly selective, as each transport protein is shaped to accommodate only a specific molecule or ion. Facilitated diffusion uses two primary types of transport proteins:

- **Channel Proteins:** Fixed, water-filled pores that span the membrane, allowing specific charged ions to bypass the hydrophobic core. Many channel proteins are gated, opening or closing in response to specific chemical or electrical signals.
- **Carrier Proteins:** Possess a specific binding site configured for a target solute molecule. Binding triggers a reversible shape change in the protein, shifting the solute across the membrane barrier to release it on the opposite side.

> **EXAM HINT: THE RATE-LIMITING PLATEAU EFFECT**
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> While the rate of simple diffusion increases linearly with solute concentration, the rate of facilitated diffusion hits a maximum plateau at high solute concentrations. This occurs because the system becomes rate-limited once all available transmembrane channel or carrier proteins are fully saturated with solute molecules.

3. Osmosis and Water Potential Dynamics

Osmosis is a highly specialized form of passive diffusion, defined as the net movement of water molecules from a region of higher water potential to an area of lower water potential through a partially permeable membrane.

The Principles of Water Potential

Water potential, represented by the Greek letter Psi (ψ), measures the free kinetic energy of water molecules in a system, quantified in pressure units of kilopascals ($ext{kPa}$):

- **Pure Water:** Has maximum water potential, arbitrarily assigned a baseline value of $0\ ext{ kPa}$.
- **Solutions:** Adding solute particles attracts water molecules, reducing their freedom of movement. This lowers the free kinetic energy of the system, giving all solutions a negative water potential value ($\psi < 0\ ext{ kPa}$). Water always moves down a water potential gradient, flowing from less negative areas toward more negative solutions.

Osmotic Effects on Animal Cells

Because animal cells lack a rigid cell wall, maintaining osmotic balance within extracellular fluids is essential for survival:

- **Hypotonic Environment:** If an animal cell is placed in a solution with a higher water potential than its own cytoplasm, water moves continuously into the cell. This causes the cell to swell and eventually burst (**lysis**).
- **Hypertonic Environment:** If placed in a solution with a lower water potential than its cytoplasm, water flows out of the cell. The cytoplasm shrinks, causing the cell membrane to shrivel and wrinkle (**crenation**).

4. Energy-Dependent Active Transport Mechanisms

Cells often need to move substances against their concentration gradient, accumulating ions or metabolic resources inside or outside the cell. This direction of movement cannot happen passively; it requires **active transport**, an energy-dependent mechanism driven by the hydrolysis of **adenosine triphosphate (ATP)**.

Primary Active Transport Mechanics

Active transport relies on specialized transmembrane carrier proteins called **pumps**. These proteins feature an active binding site for the target solute and a catalytic site for ATP binding. The active transport sequence follows a precise mechanism:

1. The specific target ion or molecule binds to its receptor site on the open side of the carrier pump.
2. An ATP molecule binds to the protein's catalytic site and undergoes hydrolysis, splitting into Adenosine Diphosphate (ADP) and an inorganic phosphate group (P_i).
3. The released phosphate group attaches directly to the pump protein (phosphorylation), transferring energy that triggers a major shape change in the carrier structure.
4. The carrier opens to the opposite side of the membrane, reducing its affinity for the solute and releasing it against the concentration gradient.
5. The phosphate group detaches, causing the pump to revert to its original shape, ready to repeat the transport cycle.

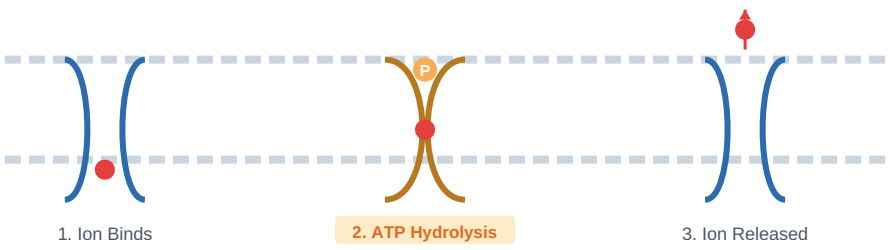

Figure 2: Step-by-step phosphorylation cycle driving an active transport carrier pump mechanism.

5. Bulk Transport: Endocytosis and Exocytosis

When a cell needs to move macromolecular packages or large quantities of material across its membrane at once, it utilizes vesicle-mediated bulk transport pathways. Because these mechanisms require large-scale rearrangements of the cell membrane, they depend heavily on metabolic energy input (ATP).

Endocytosis (Bulk Inward Transport)

Endocytosis moves large materials or fluid volumes into the cell by wrapping them in a vesicle formed from the cell membrane. The process follows a clear structural sequence:

1. The target extracellular material makes contact with the outer surface of the cell membrane.
2. The cell membrane invaginates, sinking inward to form a pocket around the target substance.
3. The edges of the membrane fuse together, pinching off the pocket to create an intracellular vesicle that detaches and migrates into the cytoplasm.

Endocytosis includes two primary forms: **phagocytosis** (the uptake of solid particles, such as a white blood cell engulfing a bacterium) and **pinocytosis** (the uptake of extracellular fluid packages).

Exocytosis (Bulk Outward Secretion)

Exocytosis operates in the reverse direction, export packages or cellular waste out of the cell. This process is essential for secreting hormones, digestive enzymes, and extracellular matrix proteins:

1. Secretory proteins are synthesized in the rough endoplasmic reticulum and packaged into spherical membrane vesicles within the **Golgi apparatus**.
2. These secretory vesicles are transported along the cell cytoskeleton toward the cell membrane.
3. The vesicle membrane makes physical contact with the cell membrane, and the lipid bilayers fuse together.
4. This fusion opens the vesicle to the extracellular space, releasing its contents outside the cell while incorporating the vesicle membrane into the cell membrane.