UNIT-3: CELL BIOLOGY (10HRS)

- This unit possesses the following main contents:
  - **Cell theory**
  - **Types of cell**
  - **Parts of the cell and their functions**
  - **The cell and its environment**
  - **Cellular respiration**

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3.1 Cell Theory

- **Learning objectives**- by end of this section you'll recap the following:
  - **Definition of the cell**
  - **Discovery of the cell**
  - **Basic concepts of cell theory**
- ***Cell conceptualization***:
  - **Cell** is the structural and basic building blocks of life.
  - Many important organisms are **very small** and biologists need to be able to see them.
  - The scientists need to be able to see cells to **understand living organisms**.
  - Today it is noted that living things are made of **cells**.
  - **Billions of cells** in the case of **human** beings, just **one cell** in the case of organisms like **amoeba.**
  - **All living organisms** have certain characteristics, which they carry out regardless of whether they have one cell or millions

❖The **seven life processes** that are common to most living organisms are:

1. ***Nutrition*** **–** all living organisms need food to provide them with the energy used by their cells (***autotrophic*** and ***heterotrophic***).
2. ***Respiration*** **–** the process by which living organisms get the energy from their food.
3. ***Excretion*** **–** getting rid of the waste products produced by the cells.
4. ***Growth*** **–** living organisms get bigger. They increase in both size and mass, using chemicals from their food to build new material.
5. ***Irritability*** **–** all living organisms are sensitive to changes in their surroundings.
6. ***Movement*** **–** all living organisms need to move to get near to things they need or away from problems. Animals move **using muscles**, plants move more **slowly using growth**.
7. ***Reproduction*** **–** producing offspring is vital to the long-term survival of any type of living organism.

- Everything we know about the structure of cells has depended on the development of the ***microscope***.
- ***Microscope*** is an instrument used to see organisms and cellular structures that unable to be seen by naked eyes.
- There are **two** main types of microscopes in use, the **light microscope** and the **electron microscope**.
- The **light microscope** uses a **beam of light** to form the image of an object.
- The **electron microscope** uses a **beam of electrons** to form an image.
- The reason microscopes are so useful is because they **magnify things**, making them look bigger.
- ***Magnification*** means increasing the size of an object.

- The best **light microscopes** will magnify up to around **2,000 times**.
- An **electron microscope** can give a magnification of **2,000,000 times**.
- Using **electron microscopes** makes to learn a lot more about cells and the ways in which they become specialized for particular functions.
- **Resolution** is the ability to distinguish between two separate points and it is the resolving power of a microscope that affects how much detail it can show.
- The **greater the resolving power of the microscope, the more detail it can show.**

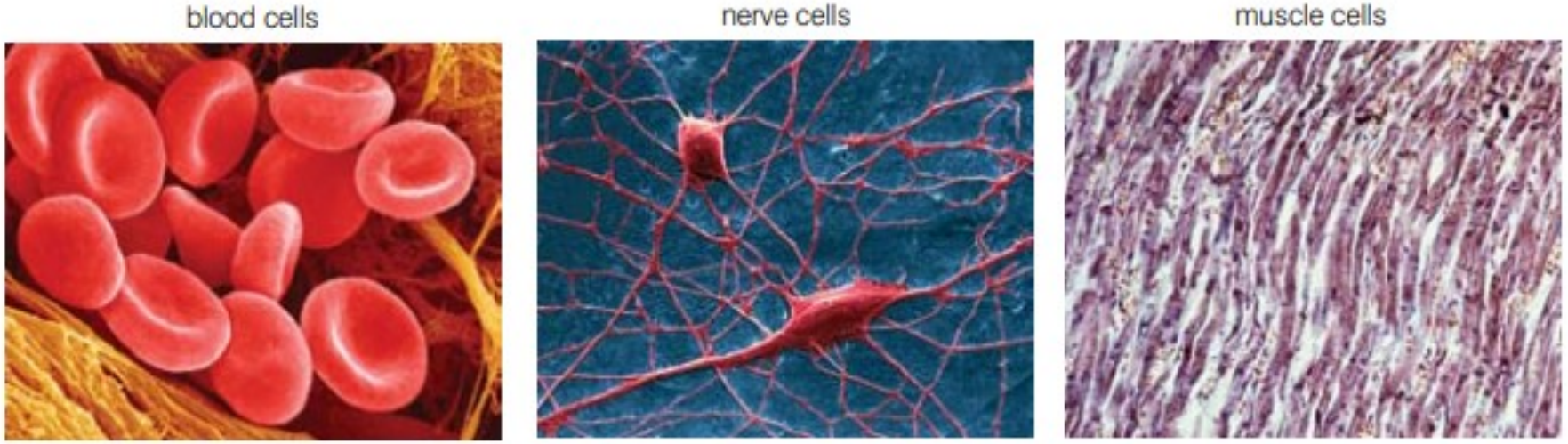


Figure 4.1 *Some of the different cells in our bodies*

There is only one cell in *Amoeba* and in *Vorticella*.

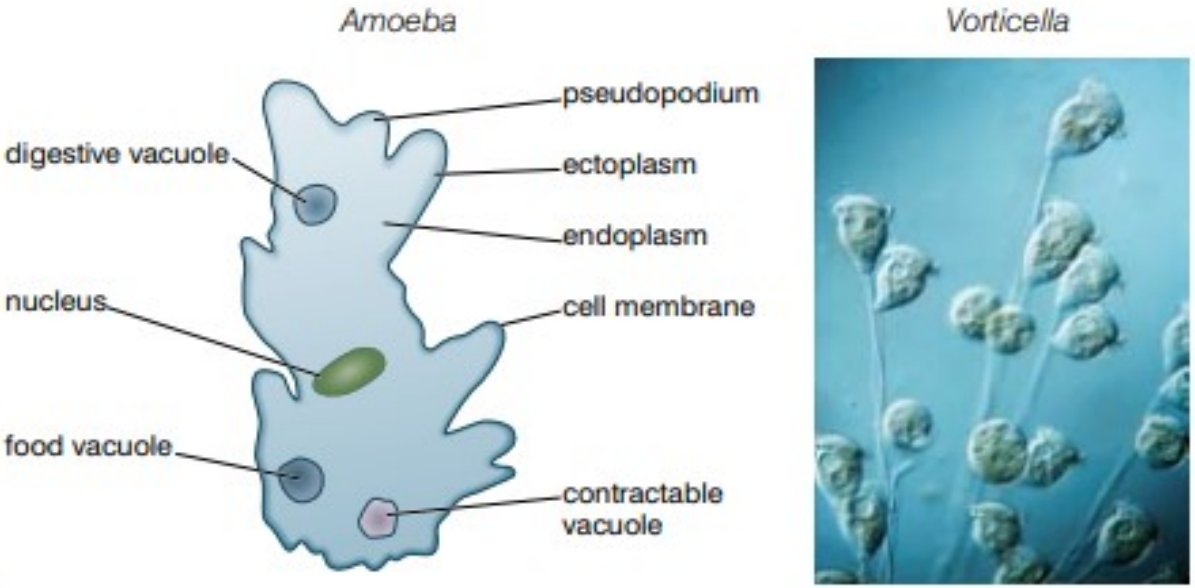


Figure 4.2 *The unicellular organisms* Amoeba *and* Vorticella

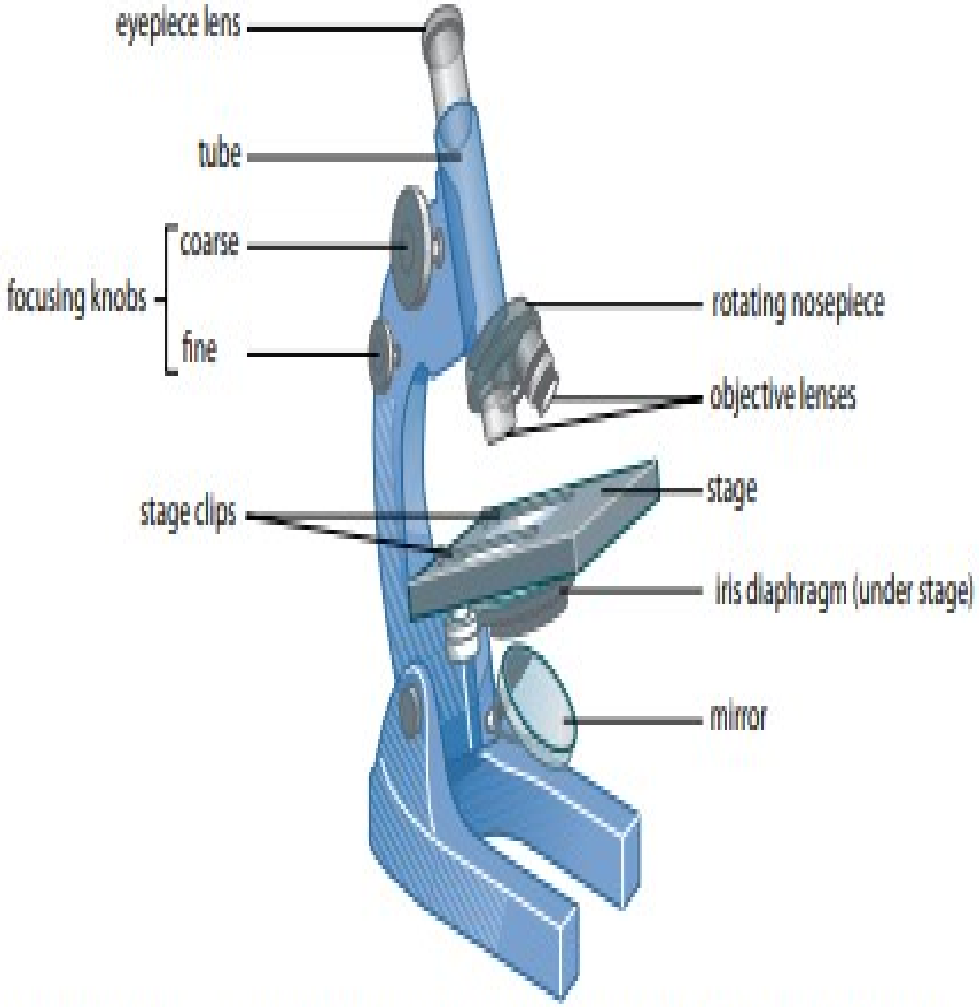


Figure 2.3 *A compound microscope has two sets of lenses (objective and eyepiece lenses) which are used to magnify the specimen. These microscopes are widely used for looking at cells.*

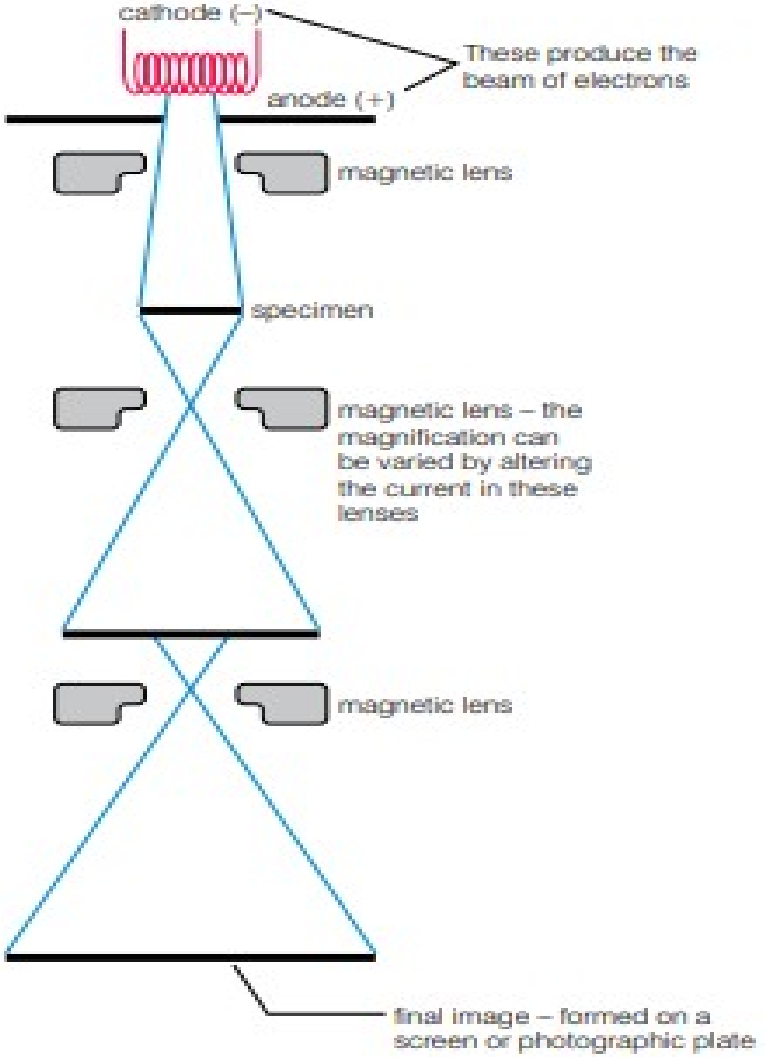


***Figure 2.8** A diagram of an electron microscope and how it works*

Discovery of the cell

- Only a few hundred years ago, cells had **not been discovered.**
- Their discovery had to wait for the development of **reliable microscopes** that could **magnify sufficiently** to show the **cellular structure of living organisms**.
- Many biologists and other scientists contributed to the **discovery of cells** and the statement of the very first cell theory.

The timeline below shows some of the major contributors:

Table 4.1 *Key events in cell biology*

	Event
1595	Jansen builds the first compound microscope.
1626	Redi postulates that living things do not arise from spontaneous generation.
1665	Hooke describes 'cells' in cork.
1674	Leeuwenhoek discovers protozoa.
1833	Brown describes the cell nucleus in cells of an orchid.
1839	Schleiden and Schwann propose a cell theory.
1857	Kolliker describes mitochondria.
1858	Virchow states *omnis cellula e cellula*.
1869	Miescher isolates DNA.
1879	Fleming describes chromosome behaviour during mitosis.
1898	Golgi describes the Golgi apparatus in cells.
1939	The first transmission electron microscope.
1953	Watson and Crick propose the double-helix structure of DNA.
1965	The first scanning electron microscope.
2000	Human genome DNA sequence draft.

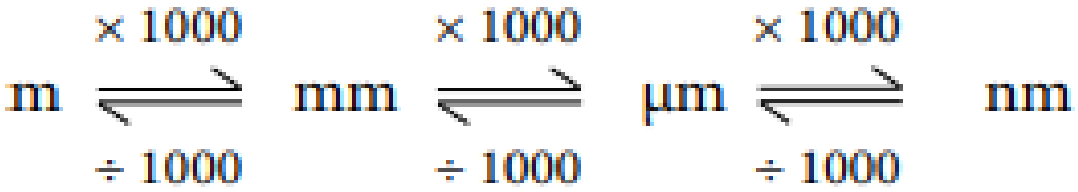
Basic concepts of cell theory

- **Cell theory** refers to the idea that cells are the basic unit of structure in every living thing.
- Many biologists and other scientists made discovery of cells and the statement of the very first ***cell theory***.
- **Matthias Schleiden** and **Theodor Schwann** put forward the first clearly stated cell theory.
- **Rudolf Virchow** completes the first accepted version of the cell theory.
- Modern cell theory concludes the following:
  - All known **living things** are made up of **cells**
  - The **cell** is a **structural** and **functional** unit of all living things
  - All cells come from **pre-existing cells by division** (there is no spontaneous generation of cells)
  - Cells contain **hereditary information** which is passed from cell to cell during cell division
  - All cells have basically the same **chemical composition**
  - All energy flow (the **metabolism** and **biochemistry** of life) occurs within cells

  i.e., "***Cell is the center of biochemical processes of all organisms"***

Cell size and its measurement

- **How big are cells?** ⇌ It all depends on what kind of cell you are measuring.
- For instance, the contents of a chicken's egg are just one huge cell packed with food.
  - – it's a pretty big cell, up to **5 cm (0.05 m) in length**.
- On the other hand, the smallest bacterial cells are only just over **100 nm** in length.
- **What units shall we measure cells in?** ⇌ There are three smaller units commonly used:
  - ***Millimeters (mm)*** – **1/1000** of a meter
  - ***Micrometers (μm)*** – **1/1000** of a millimeter, and **1/1 000 000** of a meter
  - ***Nanometers (nm)*** – **1/1000** of a micrometer, **1/1 000 000** of a millimeter, and **1/1000 000 000** of a meter. These measurement units have conversion form:



3.2 Types of cell

- Cells are grouped into two by their **possession of nucleus**:
  1. ***Prokaryotic cell***
  2. ***Eukaryotic cell***
- A **prokaryotic cell** is a type of cell that **does not** have a nucleus.
- The word prokaryotic is derived from the Greek ***pro*** (before) and ***karyos*** (nuclear).
- The **eukaryotic cell** is a type of cell that **has a nucleus**.
- The word eukaryotic is derived from the Greek ***eu*** (true) and ***karyos*** (nuclear).
- It can be as a **single cell** or **many cells** by its structural complexity.
- The organism possesses either of that cells called:
  - ***Unicellular organisms*** ▭ single-celled organisms (microorganisms).
  - ***Multicellular organisms*** ▭ many-celled organisms (larger organisms).

- Many biologists believe that **prokaryotic cells** were the first type of cells to be formed when life first evolved.
- **Prokaryotic cells** are much smaller and simpler than **eukaryotic cells**.
- These cells must carry out all the same functions that a eukaryotic cell carries out in order to survive.
- There is therefore some **division of labor** within the cell.
- **Division of labor** is the specialization of different parts to carry out certain functions.
- There are specialized regions for certain functions (***organelles***).

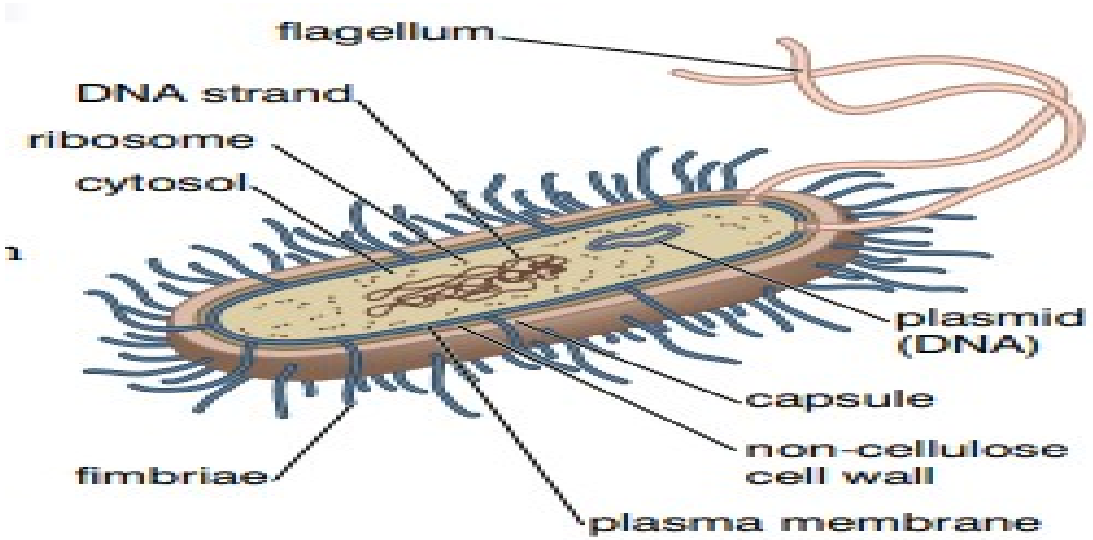


Figure 4.14 A generalised prokaryotic cell

❖There are **different types of the eukaryotic cell**, but all of them have a number of features in common.

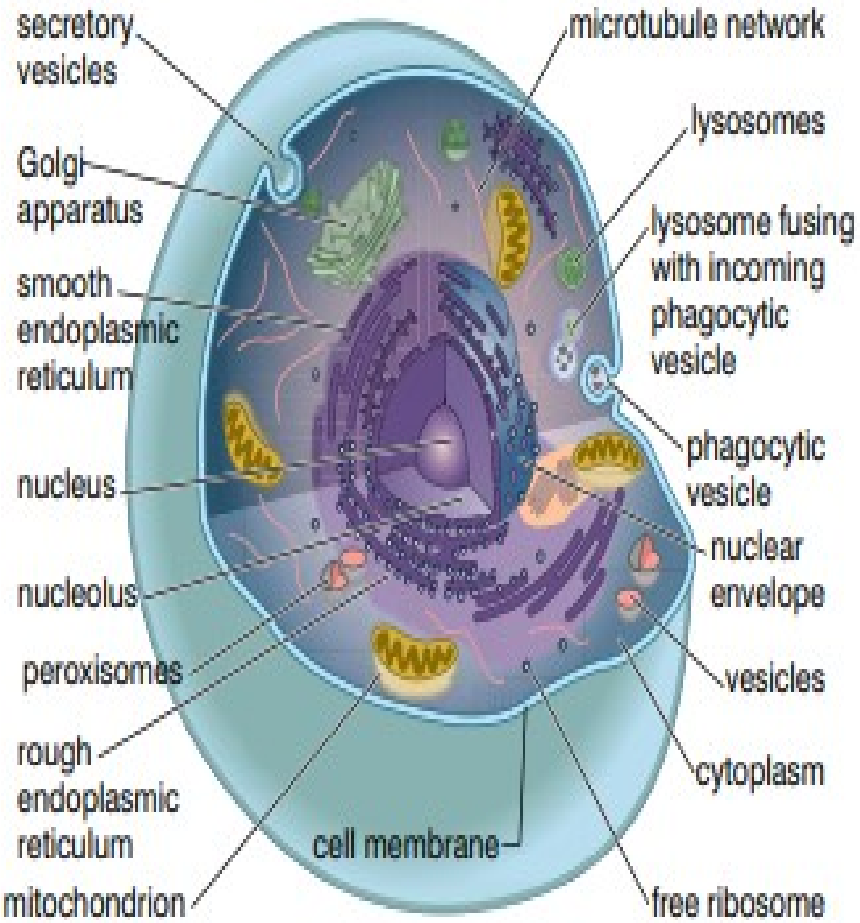


Figure 4.15 *A generalised animal cell*

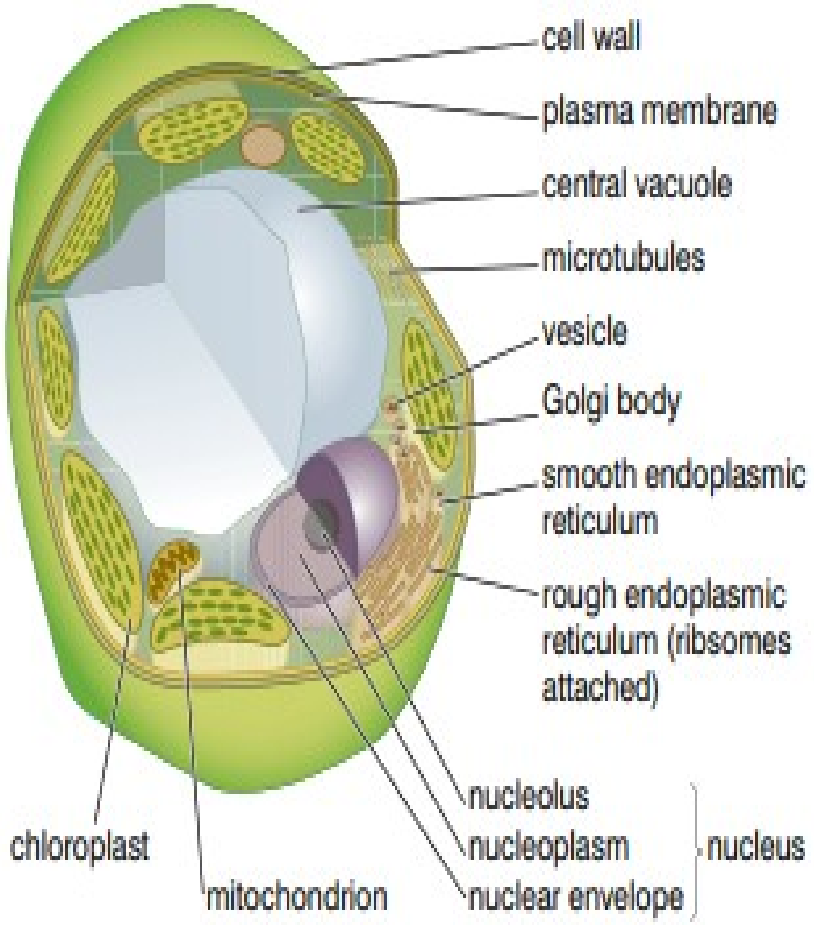


Figure 4.16 *A generalised plant cell*

- Eukaryotic cells are clearly much **more complex cells** than prokaryotic cells.
- What is really different about them is that there are many more different individual structures, called **organelles**.
- There are many more membranes in the cell that form the complex membrane system called the **endoplasmic reticulum**. Several of the organelles are surrounded by membranes; so-called ***membrane-bound organelles***:
  - ***Nucleus***
  - ***Mitochondria***
  - ***Chloroplasts*** (present in the plant cell)
  - ***Lysosomes***
  - ***Golgi apparatus***
- The theory that states the origin of eukaryotic cells is called the ***endosymbiont theory*** and was first proposed by the biologist ***Lynn Margulis***.

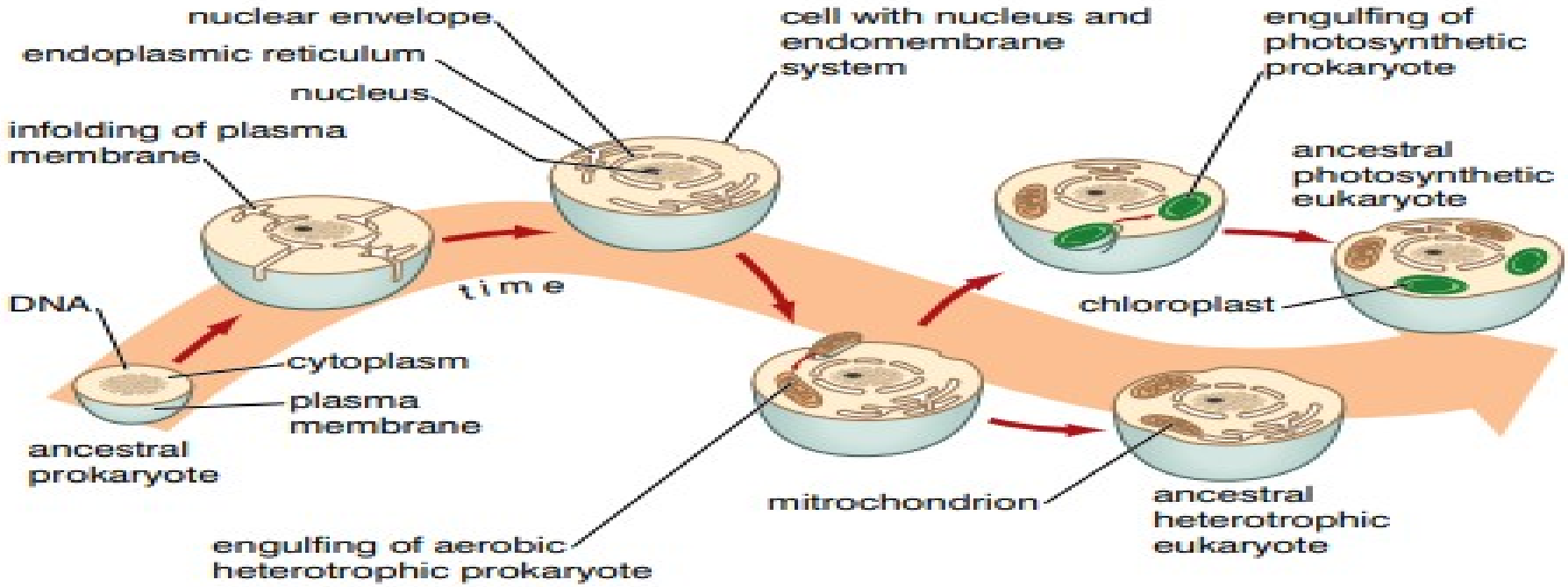


Figure 4.17 *The origin of eukaryotic cells*

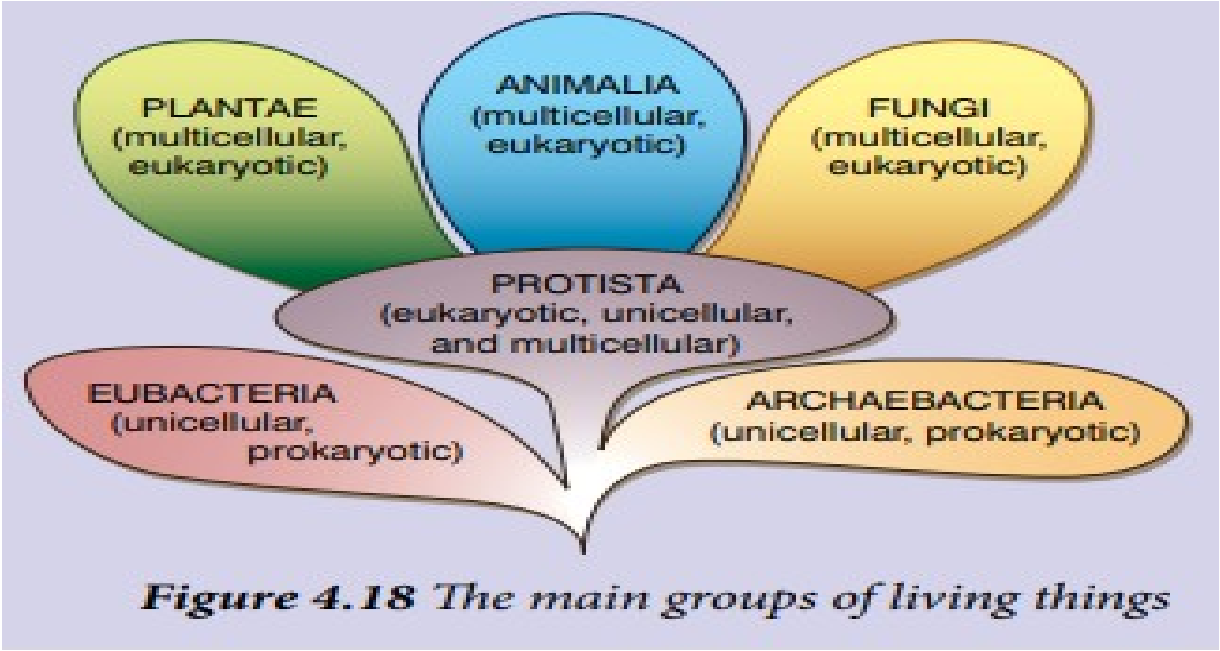


Figure 4.18 *The main groups of living things*

Table 4.2 *A summary of the main differences between prokaryotic and eukaryotic cells*

Feature	Prokaryotic cells	Eukaryotic cells
Size	1–10 µm	10–100 µm
Nucleus	No membrane-bound nucleus	Nucleus surrounded by nuclear envelope
DNA	• In a continuous loop • Not associated with protein to form chromosomes	• Linear DNA • Associated with histone proteins in chromosomes
Mitochondria	Absent	Present
Chloroplasts	Absent (but some prokaryotic cells contain a kind of chlorophyll and can photosynthesise)	Present in some cells (some plant cells and some algal cells)
Ribosomes	Present, but smaller than in eukaryotic cells (**70S**)	Present, but larger than in prokaryotic cells (**80S**)
Cell wall	• Always present • Not made from cellulose (often made from peptidoglycan)	• Present in plant cells, algal cells and fungal cells • Cellulose in plant cells, various materials in other cells

70S *and* **80S ribosomes** *the 'S' stands for 'sedimentation coefficient' and is a measure of their mass*

3.3 Parts of cell and their functions

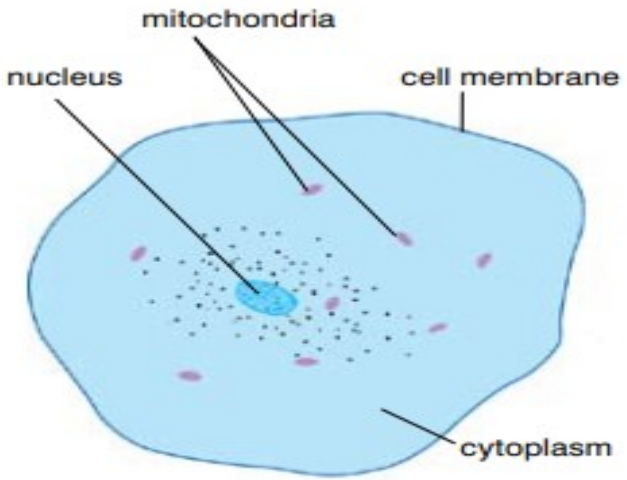
- There are some **basic similarities** between all cells, animal and plant alike.
- For example, almost all cells have:
  - A ***nucleus*** = controls all cell activity and contains chromosomes
  - A ***cell membrane*** = controls the movement of substances in and out
  - ***Mitochondria*** = carry out cellular respiration/energy powerhouse
  - ***Ribosomes*** = organelles involved in protein synthesis
  - ***Endoplasmic reticulum*** = links the nucleus with the cell membrane
  - ***Cytoplasm*** = liquid gel which contains all the organelles of a cell

Structures and functions in unspecialized animal cells

- Cells contain small units called **organelles** that have enzymes and chemicals to carry out specialized jobs within the cell.
  - **The nucleus:**
    - Controls all the activities of the cell
    - contains the instructions for making new cells or new organisms in the form of long threads known as chromosomes.
    - This is the genetic material.
  - **The cytoplasm:**
    - It is a liquid gel in which most of the chemical reactions needed for life take place.
    - About 70% of the cytoplasm of a cell is actually water!
    - It contains all the other organelles of the cell where most of the chemical reactions take place.

- **The cell membrane:**
  - It forms a barrier like a very thin ‘skin’ around the outside of the cell.
  - It controls the passage of substances such as **carbon dioxide**, **oxygen** and **water** in and out of the cell.
  - Because it lets some substances through but not others it is known as **selectively permeable**.
- **The mitochondria (singular: mitochondrion):**
  - They are the **powerhouse of the cell**.
  - They carry out most of the reactions of respiration, whereby energy is released from the food in a form your cells can use.
  - Whenever cells need a lot of energy – such as muscle cells and secreting cells – you will see a lot of mitochondria (**b/c there is a need of high energy production**).

- **<u>The endoplasmic reticulum</u>**:
  - it is a **three-dimensional system** of tubules that spreads right through the cytoplasm.
  - It links the **nucleus** with the **cell membrane**.
  - It bands off into ***<u>rough</u>*** and ***<u>smooth endoplasmic reticulum</u>***.
- **The ribosomes**:
  - They are found on the endoplasmic reticulum in your cells (particularly, **on the rough endoplasmic reticulum**).
  - They are vital for **protein synthesis**, the process by which your body makes all the enzymes that control the reactions of your cells.



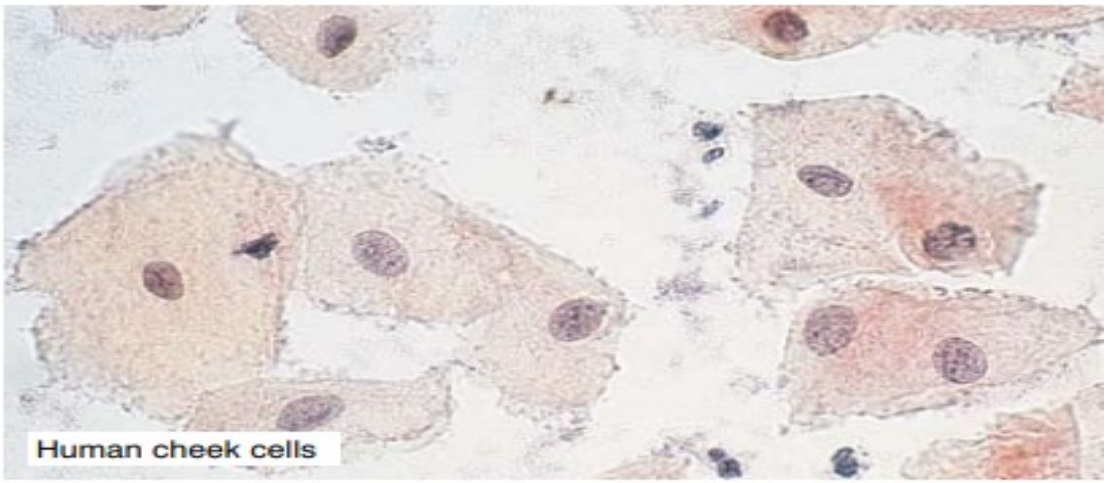


Figure 2.11 *A simple animal cell like this shows the features that are common to almost all living cells. Mitochondria, endoplasmic reticulum and ribosomes cannot be seen easily with a light microscope. They are much clearer using an electron microscope.*

Why do cells have organelles?

- All of the processes of life take place **within a single cell**.
- But this is the level of chemical activity going on in **a cell at any one time**.
- **Cell chemistry works** because:
  - ✓ Each reaction is controlled by an enzyme, a protein designed to **control the rate of a very specific reaction** and
  - ✓ Ensures that it takes place **without becoming mixed up** with any other reaction.
  - ✓ So, the enzymes involved in **different chemical** processes are usually **found in different parts** of the cell.
  - ✓ **Example**:--
    - Most of the enzymes controlling the reactions of **respiration** are found in the **mitochondria**.
    - The enzymes controlling the reactions of **photosynthesis** are found in the **chloroplasts**.
    - The enzymes involved in **protein synthesis** are found on the surface of the **ribosomes**.

Structures and functions in unspecialized plant cells

- Plants are very different from animals –
  - They do not move their whole bodies about
  - They make their own food by photosynthesis
  - They have common organelles with animals
  - They also have structures that are needed for their very different way of life.

- **The cell wall:**
  - It is made mainly of a carbohydrate called cellulose
  - It strengthens the cell and gives it support.
  - It is found outside the cell membrane.
  - Its structure contains large holes so substances can move freely through it in either direction ***– it is freely permeable*** (not semi-permeable like plasma membrane).

- **Chloroplasts:**
  - are found in all of the green parts of the plant.
  - They contain the green pigment chlorophyll, which gives the plant its colour.
  - As a result of the chlorophyll they can absorb energy from light to make food by photosynthesis.
- **A permanent vacuole:**
  - It is a space in the cytoplasm filled with **cell sap**, a **liquid containing sugars**, **mineral ions** and other **chemicals** dissolved in water.
  - It is important for **keeping the cells rigid** to **support the plant**.
  - The vacuole pushes the **cytoplasm against** the cell wall, which keeps the **whole structure firm**.
  - A permanent vacuole is often a **feature of mature (adult) plant cells**.

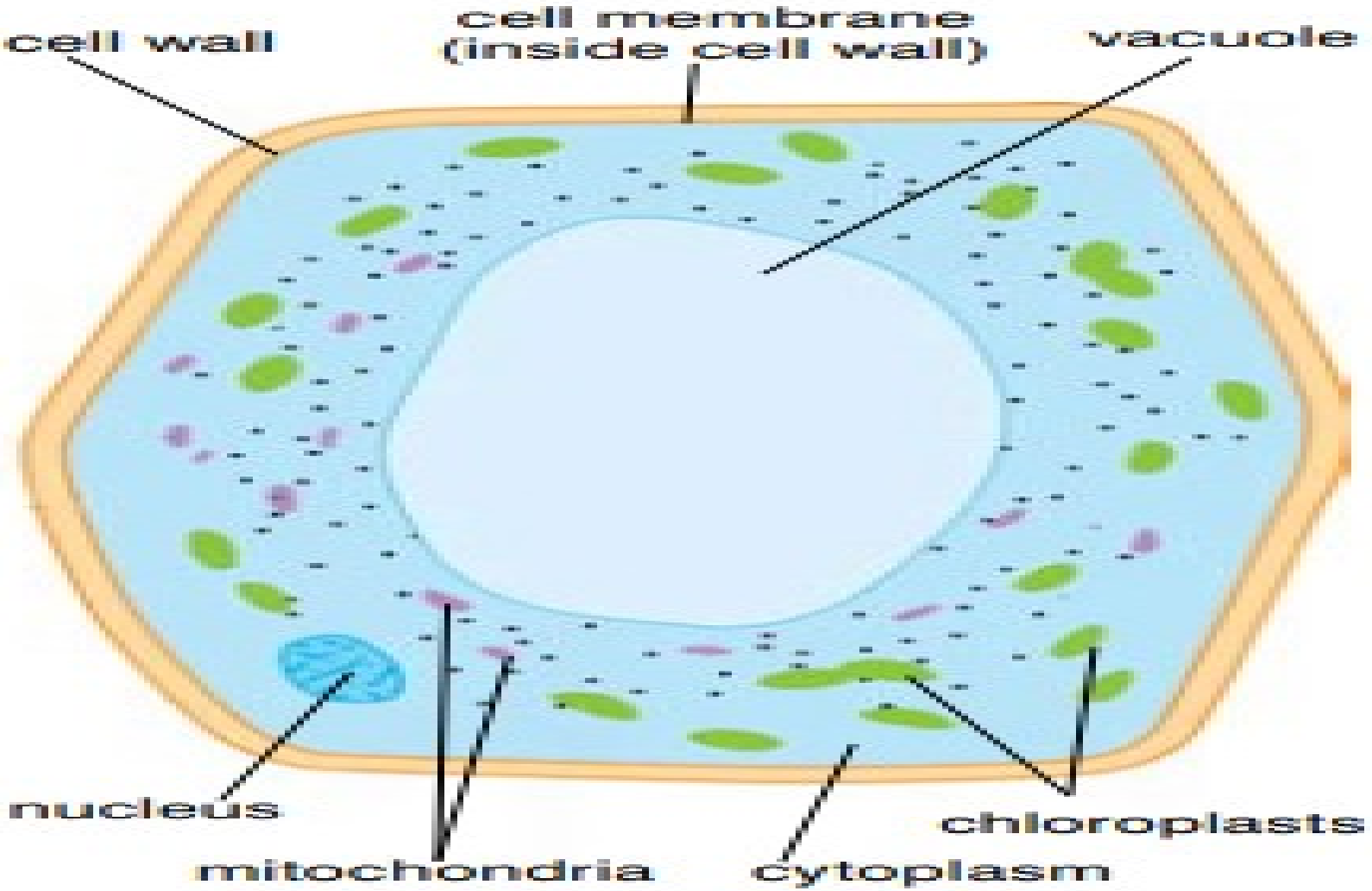


Figure 2.13 A photosynthetic plant cell has many features in common with an animal cell, but others that are unique to plants.

What is the importance of the cell membrane?

- The membrane that surrounds and encloses a cell is sometimes called the **cell surface membrane**, but most biologists now refer to it as the **plasma membrane**.
- It has little mechanical strength to support the cell,
- It plays a crucial role in:
  - **Controlling** what enters and leaves the cell;
  - **Moves substances** in and out of the cell by:
    - → ***Simple diffusion***
    - → ***Facilitated diffusion***
    - → ***Osmosis***
    - → ***Active transport***
    - → ***Bulk transport***:
      - → **Endocytosis –**
        - ***Phagocytosis***
        - ***Pinocytosis***
        - ***Receptor mediated endocytosis***
      - → **Exocytosis**

- **Cell signaling** ⇨ Various molecules in the membrane allow the **cell to be recognized** by:
  - **Hormones**
  - The **immune system** (in animals) and
  - **Growth regulator substances**, such as auxins (in plants).

❑ What is the plasma membrane like?

- ❖ The basis of plasma membranes is a **phospholipid bilayer**.
- ❖ There have been **several models** of the structure of the plasma membrane.

Table 4.3 Key events

Year	Event
1665	Robert Hooke discovers cells, but only sees dead cells and has no idea of a cell membrane.
1895	Charles Overton shows that the cell membrane is composed of some kind of lipids.
1905	Langmuir proposes a lipid monolayer as the basic membrane structure.
1910–1920	Evidence accumulates to show that the lipid in the membrane must be a phospholipid.
1925	E Gorter and G Grendel suggest that the plasma membrane is a phospholipid bilayer.
1935	Davson and Danielli know that proteins are also found in plasma membranes and suggest a 'sandwich' model.
1959	Based on electron microscope evidence that appears to support the Davson–Danielli model, J D Robertson proposes the unit membrane model – he suggests that all membranes are essentially the same.
1972	S J Singer and G L Nicholson propose the fluid mosaic model of membrane structure. As more and more supporting evidence accumulates, this is essentially the model we accept today.

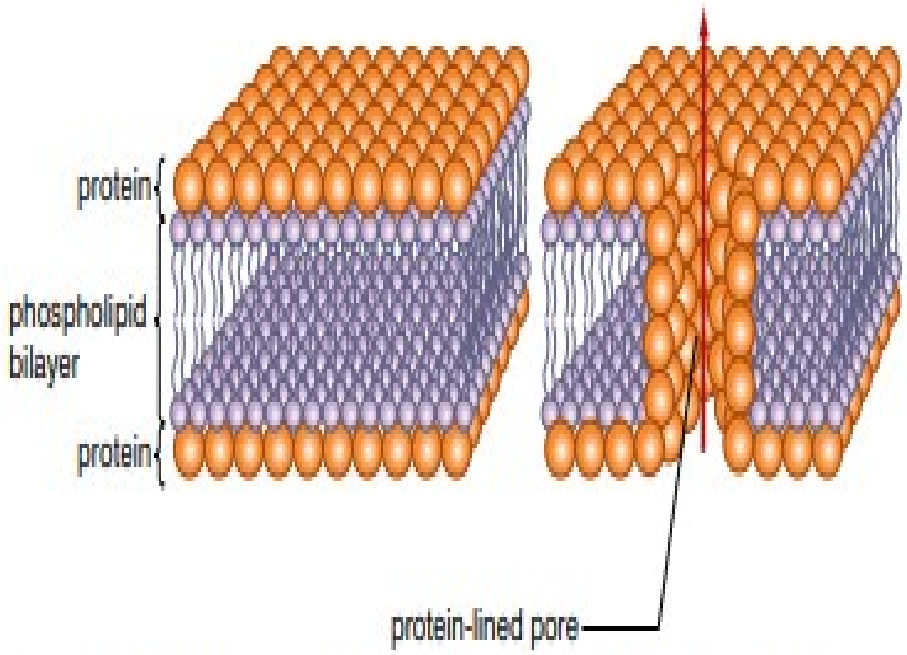


Figure 4.20 The Davson–Danielli models of 1935 and 1954

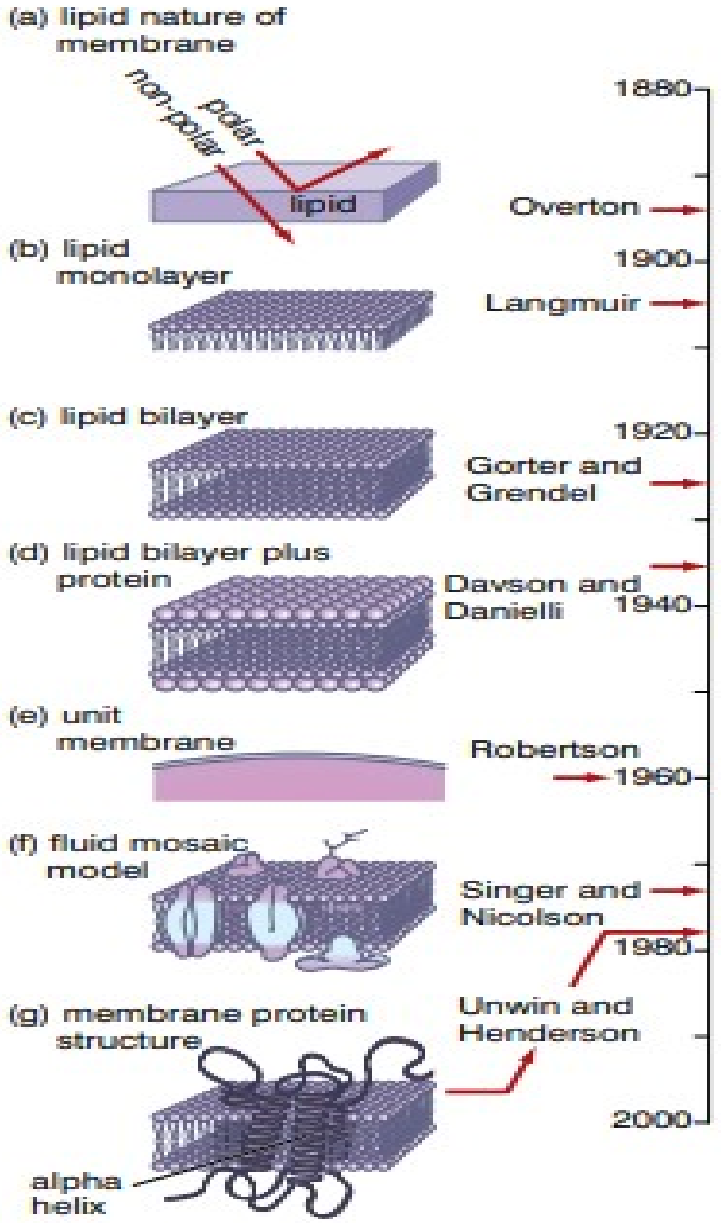


***Figure 4.19** A timeline of the development of our understanding of the structure of the plasma membrane*

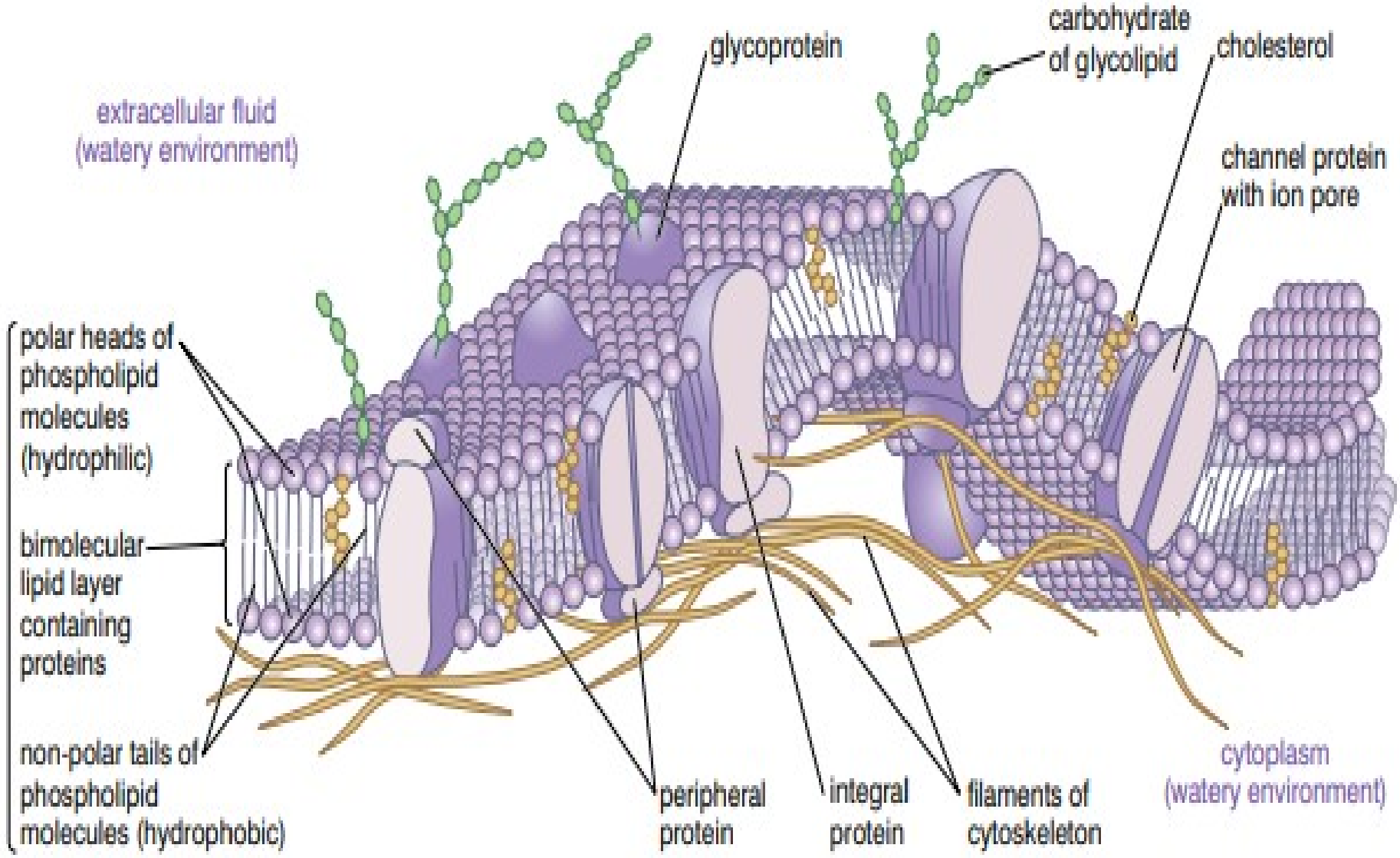


Figure 4.22 The current fluid mosaic model of membrane structure

❖The key features of the model as we currently understand it are:

- **The phospholipid bilayer** as the basis for the membrane
- **Integral proteins** (also known **as intrinsic proteins** and **transmembrane proteins**) that span the membrane.
  - ✓Some of these proteins play an important role in moving substances across the membrane.

❖There are **three** main types of these transport proteins: –

- **Channel proteins** – these proteins have a channel through them along which a specific ion can pass.
  - ✓There are different channel proteins for different ions.
- **Carrier proteins** – these proteins act in a more sophisticated way to move larger molecules through the membrane by facilitated diffusion or active transport.
  - ✓The ones involved in active transport are often referred to as **pumps.**

- **Peripheral proteins** (also known as **extrinsic proteins**) that span only one layer (or sometimes less) of the membrane.
  - ✓ They have a range of functions:
    - Some are enzymes,
    - Others anchor integral proteins to the cytoskeleton

❖ **Glycoproteins and glycolipids** – protein and lipid molecules that have carbohydrate chains attached to them and often serve as signals to other cells.

- They also act as receptor sites for hormones and drugs.
- The carbohydrate component of each can be cell specific and so allow identification of the cell by the immune system.

❖ **Cholesterol** – reduces the fluidity of the membrane.

Cell specialization in humans

- In multicellular organisms like human beings, most cells become **specialised** – that is, **they are adapted to carry out a particular function**.
- For instance, when an **egg** and a **sperm** combine to form an **embryo**, a **single cell** is formed.
- This cell divides many times to form a mass of similar ***undifferentiated cells*** (cells that have not yet assumed their final functional characteristics).
- Each of these cells (known as **embryonic stem cells**) carries all of the genetic information of the individual.
- As the embryo develops, the cells become **differentiated** – they **specialize** to carry out a particular function.
- For example, some cells differentiate to become **red blood cells** and **carry oxygen**, some become **muscle cells** and others become **neurones (nerve cells).**
- This differentiation takes place as some of the genetic material (**genes**) in the nucleus of the cells is switched on and others are switched off.

3.4 The cell and its environment

- In all other living organisms, dissolved substances can move into and out of the cells across the cell membrane in **three** different ways:
  - by **diffusion:** ***simple + facilitated diffusions***
  - by **osmosis** and
  - by **active transport**.
- **Diffusion** is the net (overall) movement of particles from an area of high concentration to an area of lower concentration.
- **Concentration** is a way of measuring how much (how many particles) of a substance is in one place.
- Diffusion takes place because of the **random movements of the particles** of a **gas** or of a **substance** in solution in **water.**
- Diffusion is a **relatively slow process**.

- **Not all particles** can actually pass through a plasma membrane **unaided** (it is **semipermeable** membrane).
- This is because of the largely lipid nature of the membrane.
- **Simple diffusion**: in fluids – liquids and gases – the particles that make up the fluid are free to move around. This kinetic energy is what drives diffusion.
- To pass through the plasma membrane by simple diffusion particles must be:
  - **Small**
  - **Lipid soluble** and
  - **Non-charged**
- This **excludes** particles such as:
  - **Ions** (they are charged),
  - **Sugars** and **amino acids** (they are not lipid soluble and are not small particles) and
  - Any of the really large particles, such as **proteins**.

❖The processes by which substances cross plasma membranes grouped into **two main types**:

- **Passive processes –** these processes rely only on:
  - the kinetic energy of the particles of the substances and
  - concentration gradients;
  - ✓they need no extra energy from the cell's metabolism.
- **Active processes –** these require energy from the cell's metabolism in the form of ATP to drive the transport.

Table 4.4 *The transport process*

Passive processes		Active processes	
Process	**Brief description**	**Process**	**Brief description**
Simple diffusion	Particles move from a high concentration to a low concentration.	Active transport	Particles move from a low concentration to a higher concentration using a carrier protein (pump).
Facilitated diffusion	Particles move from a high concentration to a low concentration through an ion pore or carrier protein.	Endocytosis	Large particles are engulfed by the plasma membrane invaginating and forming a vesicle.
Osmosis	Water molecules move from a high water potential to a lower one.	Exocytosis	Large particles are secreted by a vesicle in the cell merging with the plasma membrane to release the substance.

- The rate at which diffusion across a membrane takes place is influenced by:
  - The **concentration gradient** (**molecular weight** of the substance) – a bigger difference in concentration results in faster diffusion than a smaller gradient.
  - The **thickness of the membrane (permeability)** – as all plasma membranes are the same thickness, this is not really an issue when considering diffusion into and out of cells, but for other situations where particles must cross some kind of barrier, a shorter distance results in faster diffusion.
  - The **surface area of the membrane** – clearly if there is more membrane where diffusion can take place, diffusion will happen faster.
  - **Distance** through which diffusion must take place

- The **rate of diffusion** is also influenced by **temperature**.
  - Diffusion occurs **faster at higher temperatures** because the particles have more kinetic energy and so move faster.
- **Facilitated diffusion**:
  - It is the same process as simple diffusion, in that it depends on a concentration gradient to allow particles to cross the membrane.
  - It differs in that the particles must be helped to diffuse across the membrane (their diffusion must be 'facilitated') by a **carrier protein or a channel protein** with an ion pore.
- **Osmosis:**
  - It is the process by which water moves across a partially permeable membrane.
  - It is, effectively, the **diffusion of water**.
  - However, we do not refer to the concentration of water molecules, but to **water potential**.
  - **Water potential** is the concentration of water molecules.
- **Osmosis** is the movement of water from a **system with a high (less negative) water potential** to one with a **lower (more negative) water potential**, across a partially permeable membrane.

- When comparing the water potential of a solution to that of a cell, we could describe it as:
  - ***Isotonic*** – having the same water potential as the cell.
  - ***Hypertonic*** – having a lower (more negative) water potential than the cell.
  - ***Hypotonic*** – having a higher (less negative) water potential than the cell.

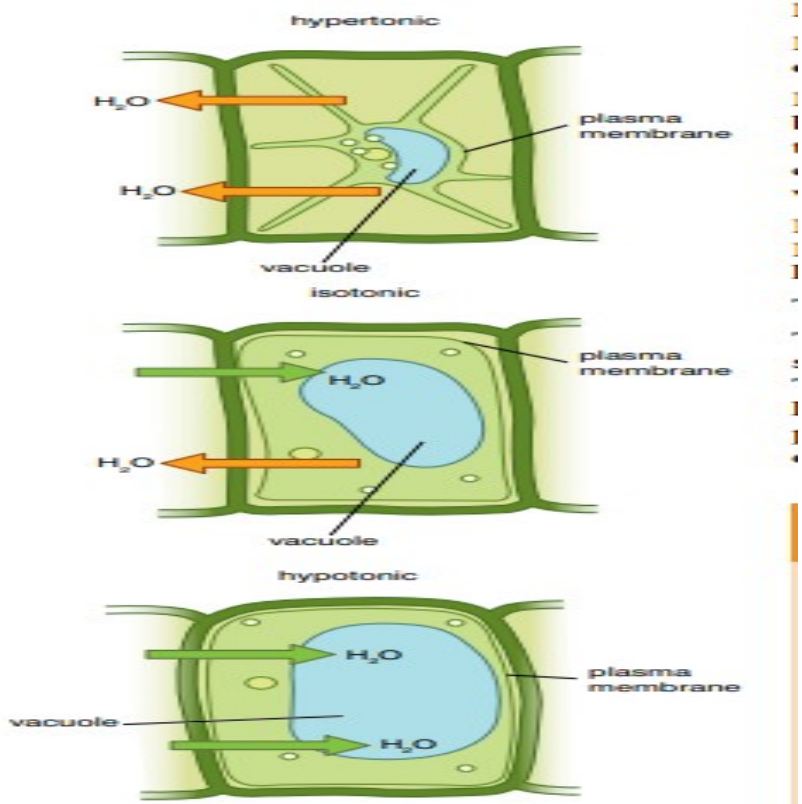


Figure 4.29 The effect of different solutions on plant cells

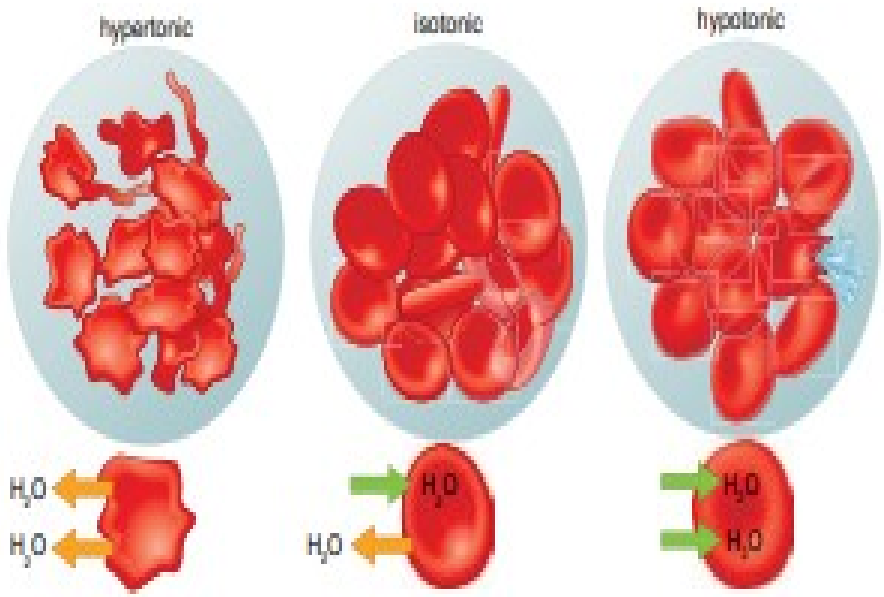


Figure 4.28 The effect of different solutions on red blood cells

- **Active transport:** sometimes, substances must be moved against a concentration gradient – from **a low concentration to a higher one.**
  - This cannot happen by **diffusion**, since it would tend to concentrate particles rather than spread them out.
  - It can only happen if **metabolic energy** is used to drive the process.
  - In living organisms, this energy is released from the ATP produced in **respiration**.
  - The energy is released from **ATP** and broken down into ADP and Pi (inorganic phosphate).
  - The **proteins** used to actively transport substances across plasma membranes are called pumps.

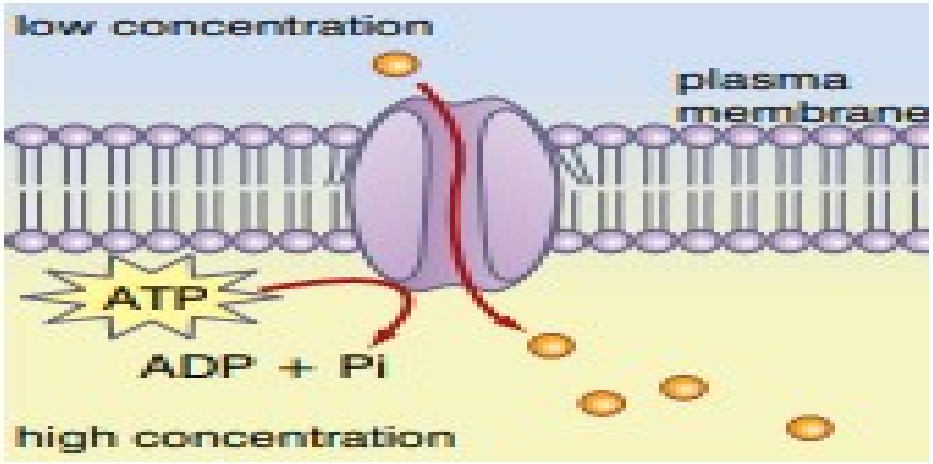
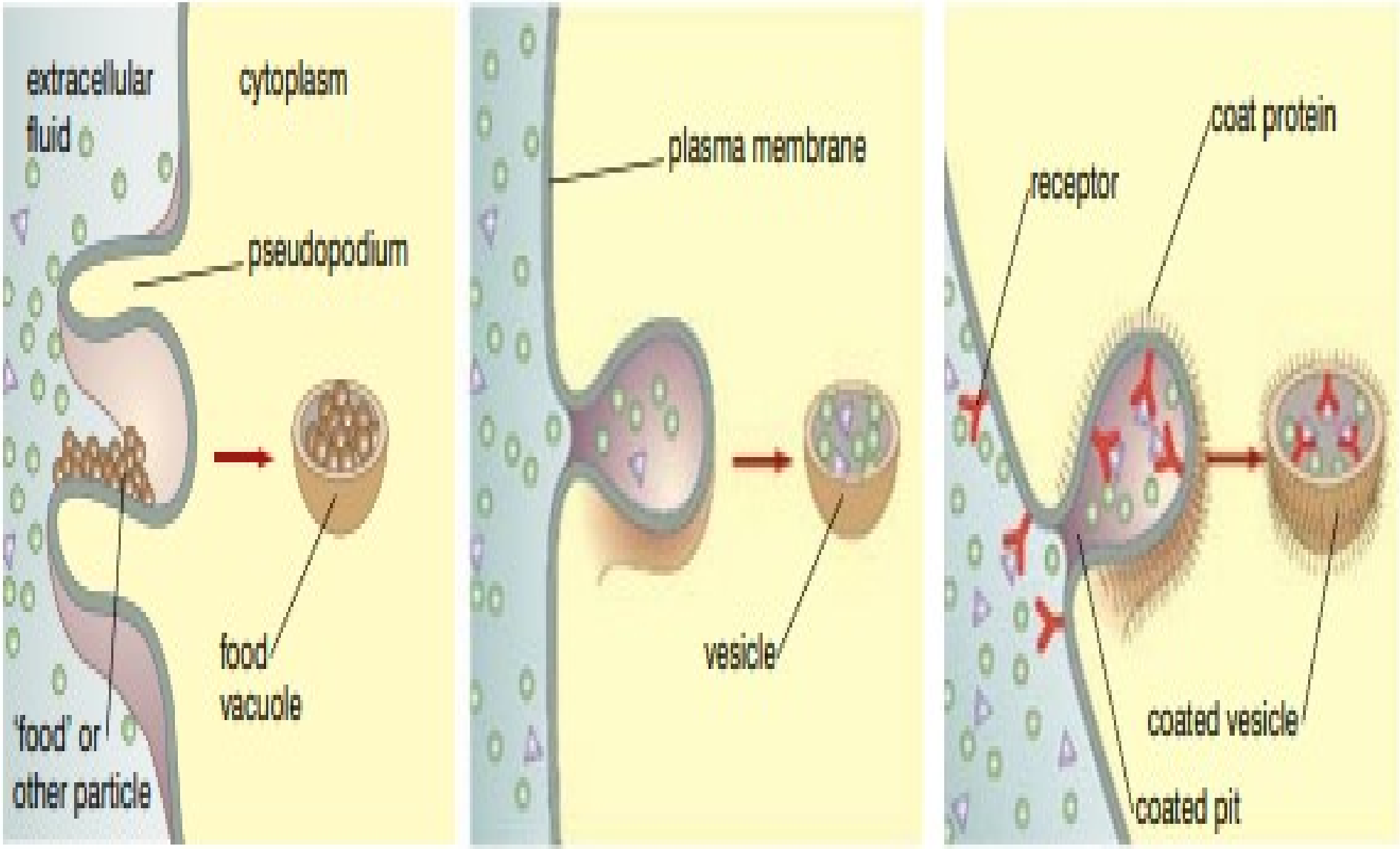


Figure 4.32 Active transport

- **Endocytosis**: in this process, **large particles are engulfed by a cell**.
- There are several ways in which it can happen, but, essentially, part of the plasma membrane surrounds the particles to form a vesicle which is then processed by the cell.
- All of them require **ATP** to move the membrane around the particles to form the vesicle.
  - **Phagocytosis** – involves the creation of pseudopodia (extensions of the plasma membrane) to enclose large particles or even whole organisms outside the cell.
  - Once enclosed by the pseudopodia, they form an internal vesicle which is then moved further inside the cell.
  - **Pinocytosis** – involves the ingestion of liquid particles (but particles that are still too large to cross the membrane by other methods) and does not require the formation of large pseudopodia to engulf the particles.
  - **Receptor-mediated endocytosis** – the membrane enfolds to form vesicles only in regions where particles have bound to specific receptors. The binding stimulates the enfolding.



A phagocytosis

B pinocytosis

C receptor-mediated endocytosis

- **<u>Exocytosis</u>**: in this process, substances are moved from the **inside to the outside** of the cell in what is, effectively, the reverse of endocytosis.
- It is the process by which **enzymes** and **hormones** are secreted.
- Again, **ATP** is used to alter the **configuration** of the membrane.

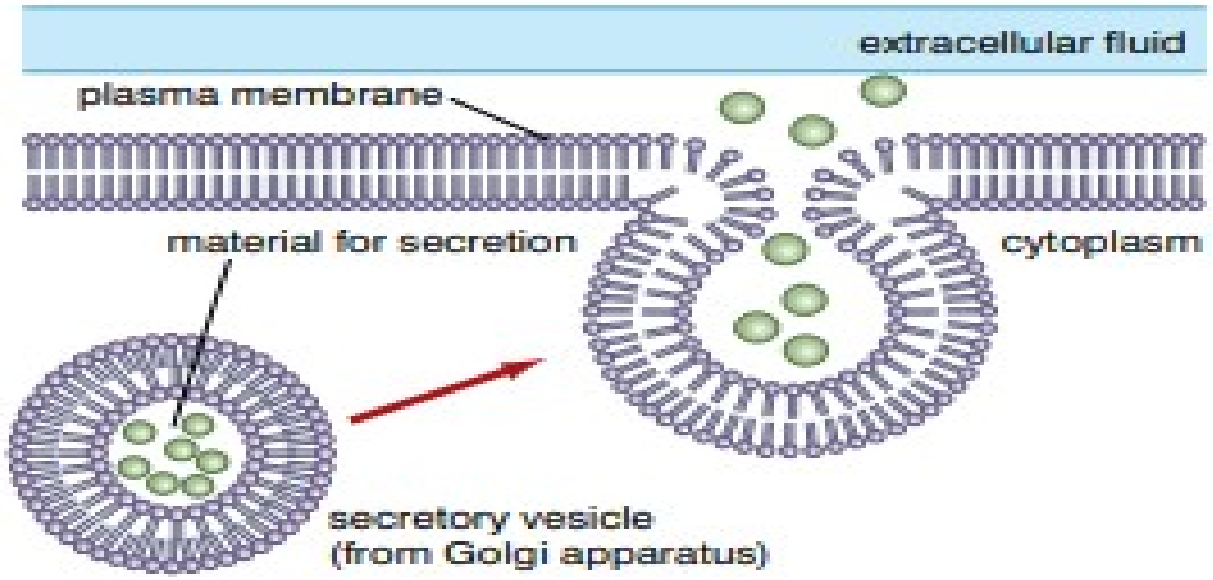


Figure 4.34 Exocytosis

Table 4.5 The transport processes compared

Process	Influence of concentration	Requirement for ATP?	Type of particles moved	Transport proteins needed?
Simple diffusion	Occurs from high to low	No	Lipid-soluble, small, non-polar	No
Facilitated diffusion	Occurs from high to low	No	Ions and medium-sized particles	No
Osmosis	Occurs from high to low (water potential)	No	Water molecules	No
Active transport	Occurs from low to high	Yes	Ions and medium-sized, non-lipid-soluble particles	Yes
Endocytosis	Can occur either way	Yes	Very large particles	Yes
Exocytosis	Can occur either way	Yes	Very large particles	Yes

3.5 Cellular respiration

- **Cellular respiration** is a series of chemical reactions that break down glucose to produce **ATP**, which may be used as energy to power many reactions throughout the body.
- The full name for ATP is ***Adenosine Tri-Phosphate***.
- All **nucleotides** contain:
  - a nitrogenous base (ATP contains adenine)
  - a pentose sugar
  - a phosphate group

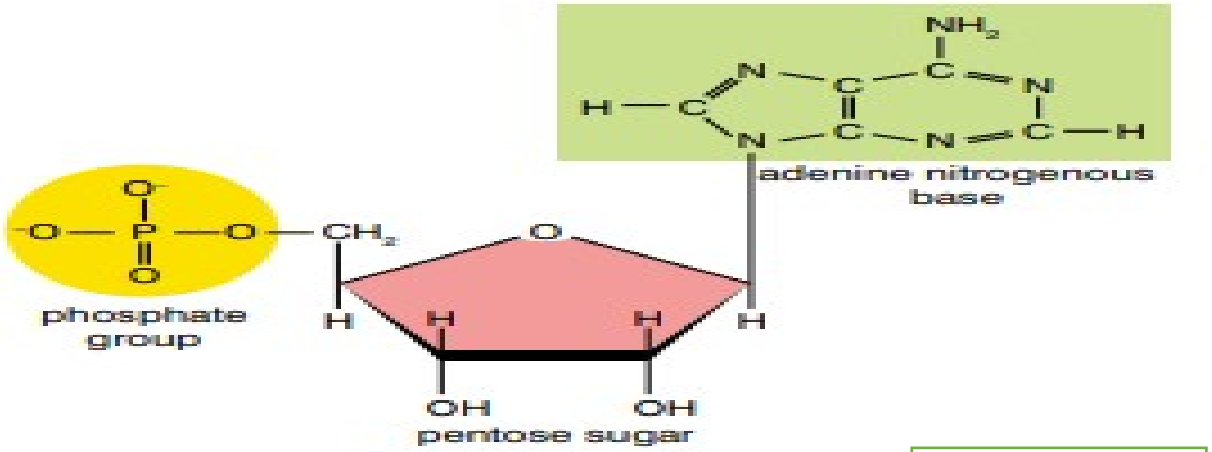


Figure 5.1 A nucleotide containing the nitrogenous base adenine

- The ATP molecule is based on this nucleotide.
- It is sometimes described as a **phosphorylated nucleotide**.
- ATP is essentially the adenine **nucleotide with two extra phosphate groups added** on – making three in all.
- Adding the extra phosphates requires energy, particularly when the third phosphate is added and as a result, energy is **stored in the ATP molecule**.
- When the bonds that hold this third phosphate in place are broken, **the energy is released again**.

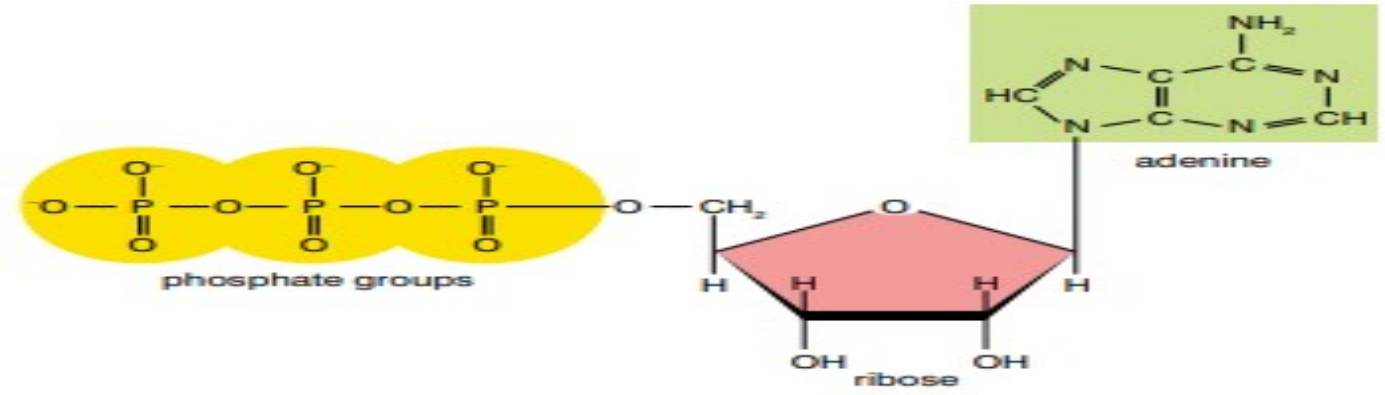


***Figure 5.2** The structure of the ATP molecule*

How is ATP adapted to its role as an energy transfer molecule in cells?

- ATP is adapted to energy transfer because of it:
  - **releases energy** in relatively **small amounts** that are closely matched to the **amounts of energy required** in many biological processes occurring **inside cells.**
  - **releases energy** in **a single-step hydrolysis** reaction, so the energy can be **released quickly.**
  - is **able to move** around the **cell easily,** but **cannot escape** from the cell.
- Examples of processes that require energy from ATP include:
  - the **synthesis of macromolecules –** such as proteins
  - **active transport** across a plasma membrane
  - **muscle contraction**
  - **conduction of nerve impulses**
  - **the initial reactions of respiration** (the later reactions release energy from glucose to form more ATP)

How is ATP produced in a cell?

- The formation of ATP involves an enzyme called **ATP synthase**.
- ATP synthase is found in both the membranes of a **mitochondrion** and a membrane in a **chloroplast.**
- In both **photosynthesis** and **cellular respiration**, many of the reactions generate the **hydrogen ions** that will pass through the ATP synthase to **produce ATP**.

How is ATP produced in respiration?

- There are **two** main pathways by which respiration can produce ATP:
  - The **aerobic pathway** (**aerobic respiration**) – this requires the presence of **oxygen;**
  - The **anaerobic pathway** (**anaerobic respiration and fermentation**) – this can take place in the **absence of oxygen**.

How is ATP produced in aerobic respiration?

- A small amount of **ATP** is produced in a way that **does not** involve the ATP synthase molecule by a method called **substrate-level phosphorylation**.
- In this process, another molecule such as **phosphoenol pyruvate (the substrate)** is able to transfer a phosphate group directly to ADP.
- It is catalyzed by other enzymes than ATP synthase.
- This process only produces a relatively small amount of the ATP (**it produces about 10% of the total ATP produced**).
- About **90% of the ATP produced** in aerobic respiration that is catalyzed by ATP synthase.

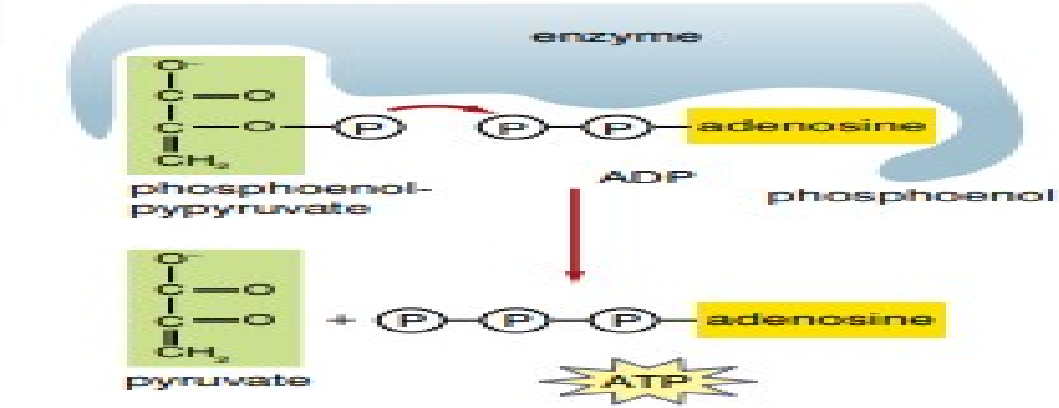


Figure 5.6 Substrate level phosphorylation

- Many different organic molecules can be respired – they are called **respiratory substrates**.
- But, **glucose** is the most commonly **respired substrate.**

How are hydrogen ions transferred from glucose to ATP synthase?

- **Two** molecules are important in this transfer process:
  - Nicotinamide Adenine Dinucleotide (NAD)
  - Flavine Adenine Dinucleotide (FAD)
- Both are **coenzymes** are capable of **accepting hydrogen ions**.
- In this case, these molecules have been reduced.
- The reduced forms of the molecules as **NADH** and **FADH** or called as ***NAD(reduced)*** and ***FAD(reduced)***.
- These molecules can release their hydrogen ions and become oxidized again and be written as **NAD** and **FAD**.
- The hydrogen ions can then be used to turn the rotor of ATP synthase.

What are the stages of cellular respiration of glucose?

- There are **four stages** in the cellular respiration of glucose:
  - Glycolysis (anaerobic respiration)
    - Preparatory phase
    - Energy payoff phase
  - The link reaction (Pyruvate oxidation)
  - Krebs cycle
  - Electron transport and chemiosmosis

1. **Glycolysis** (literally, it means glucose splitting process).
   - Occurs without oxygen
   - Takes place in the cytoplasm
   - Converts **glucose (6-C)** into an intermediate called **2pyruvate (3-C)**
   - Used 2ATP molecules to split glucose
   - Produces 4ATP (4-2) = 2 net ATP + 2 NADH

- The molecules of **pyruvate** pass into the **mitochondria** through **carrier molecules** in the mitochondrial membrane.

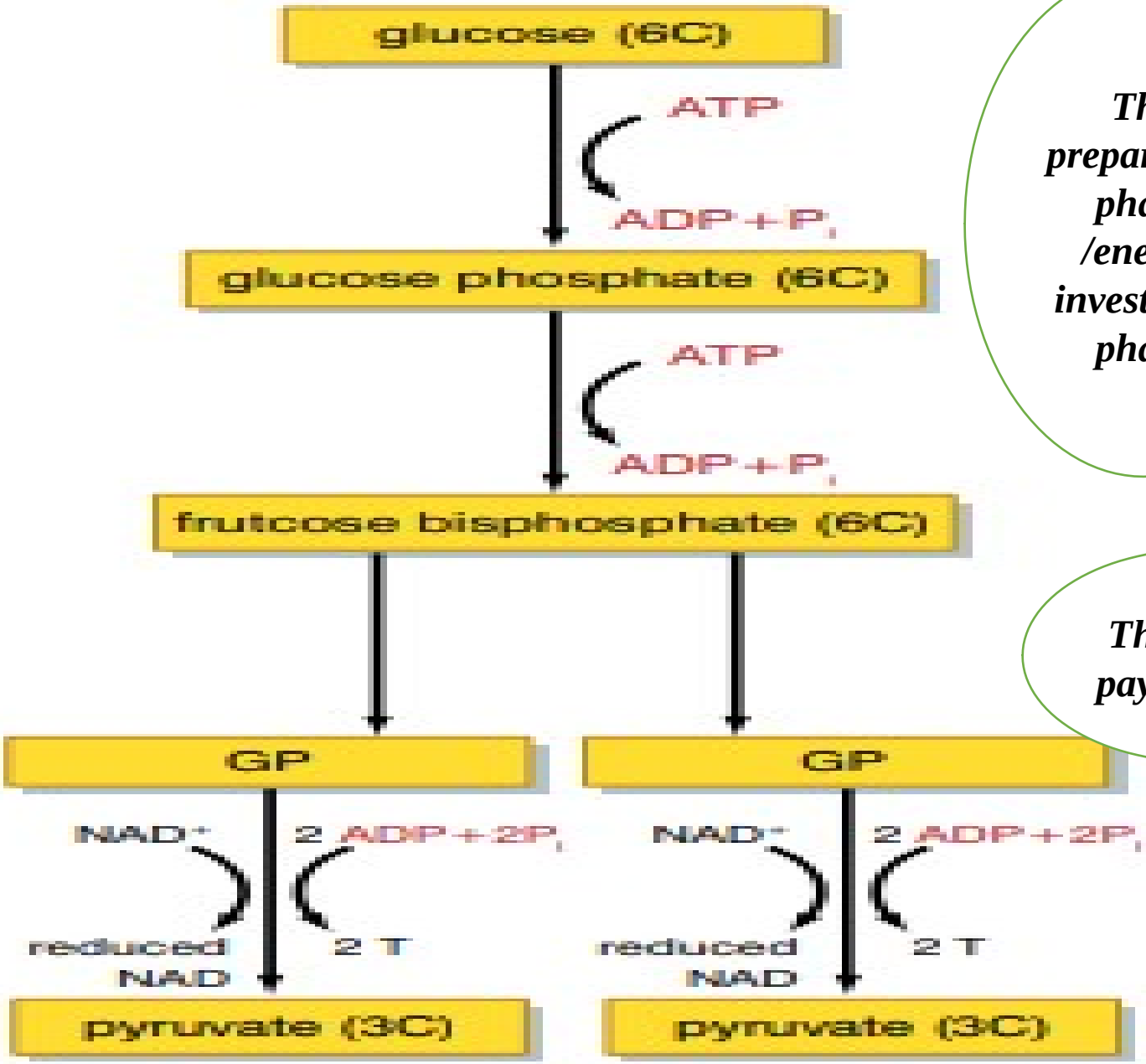


Figure 5.9 *The main stages of glycolysis*

The preparatory phase /energy investment phase

The energy payoff phase

2. The link reaction: a molecule of pyruvate reacts with a molecule of **coenzyme A (CoA)** to form a molecule of **acetyl coenzyme A (acetyl CoA)**.

- In the reaction:
  - Hydrogen is lost and reduced NAD is formed (**NADH**); removing hydrogen from a molecule is **dehydrogenation.**
  - A carbon atom is lost to form **carbon dioxide**; removing carbon from a molecule is **decarboxylation**.
  - The **acetyl coenzyme A** then reacts with **oxaloacetate** (a 4C molecule).
- In the reaction, acetyl CoA breaks down into:
  - A **two-carbon 'acetyl' group**, which reacts with the oxaloacetate to form a **6C compound (citrate),** and
  - The original **coenzyme A molecule** is reused in further reactions with other molecules of pyruvate.
  - This is the first reaction of the **Krebs cycle**.

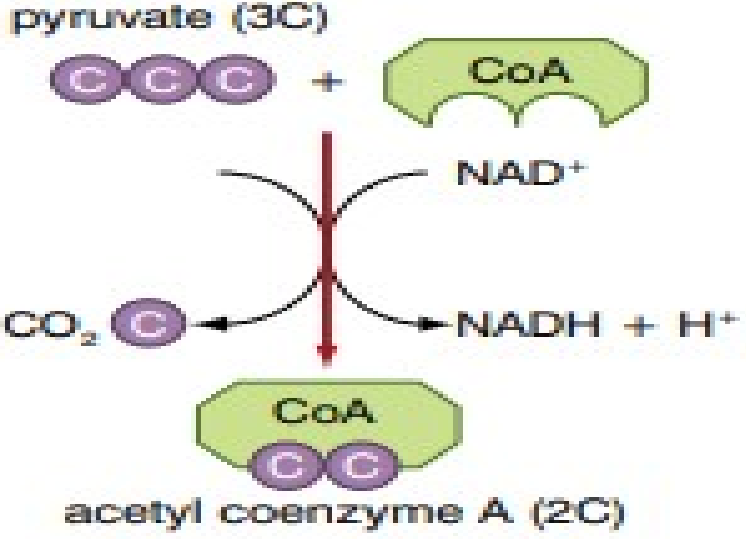


Figure 5.10 *The link reaction*

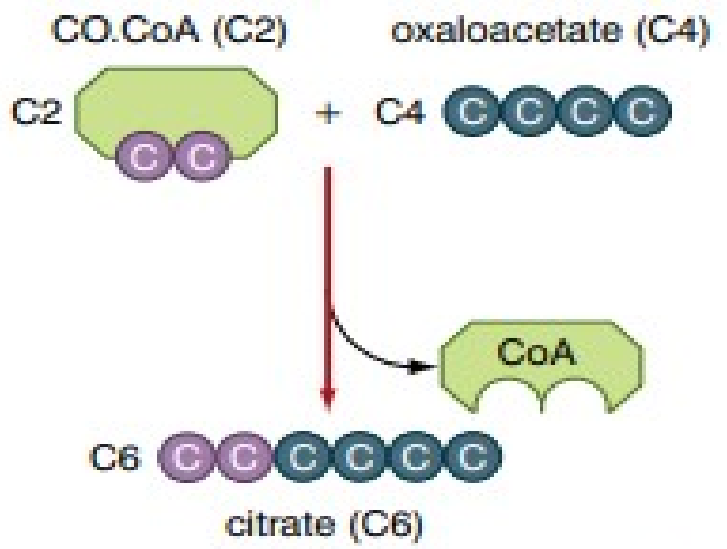


Figure 5.11 *The first reaction of the Krebs cycle*

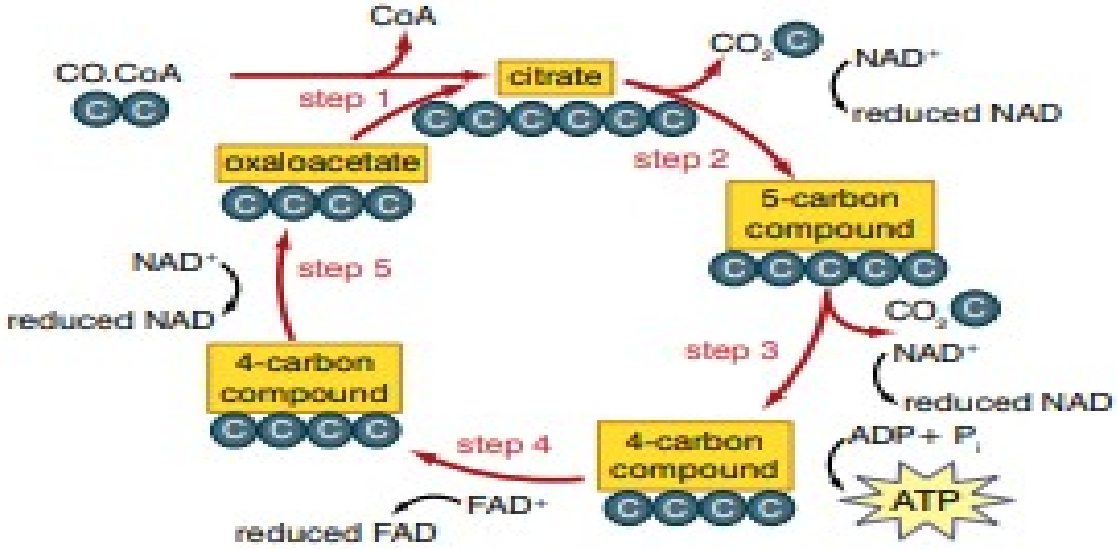


Figure 5.12 *The main stages of the Krebs cycle*

A summary of the overall reaction of the Krebs cycle:

$$CH_3CO.CoA + 3NAD + FAD + C_4H_2O_5^{2-} \rightarrow 2CO_2 + 3NAD \text{ reduced} + FAD \text{ reduced} + CoA + C_4H_2O_5^{2-}$$

The electron transport chain and chemiosmosis

- The **electron transport chain** and **chemiosmosis** together make up the process of **oxidative phosphorylation**.
- The **link reaction** and **Krebs cycle** take place in the **fluid matrix of the mitochondrion**,
- The **electron transport chain** and **chemiosmosis** take place on the **inner mitochondrial membrane**.

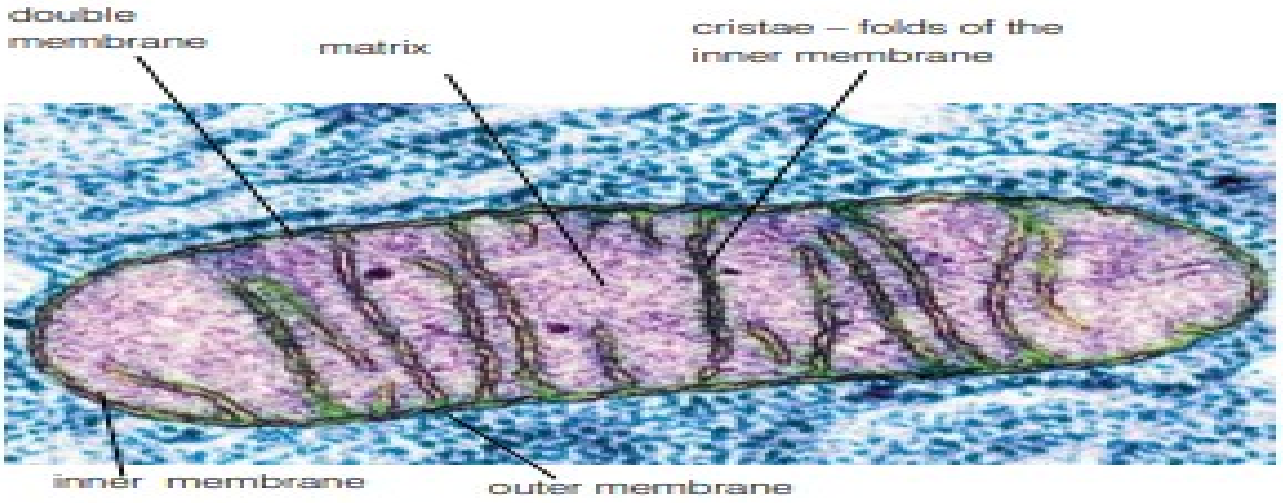


Figure 5.13 An electron-micrograph of a mitochondrion

❖ On the cristae, the following events take place:

- The hydrogen atoms carried by reduced NAD and reduced FAD are released and split into **protons (hydrogen ions)** and **electrons**
- The **electrons** pass along a **series of electron carriers** that form the transport chain; they lose energy as they pass from one carrier to the next.
- Three of the **electron carriers** are **proton pumps** that move protons from the matrix of the mitochondrion to the **inter-membrane space.**
- As the **electrons** are transferred through these **three proton pumps**, the energy they lose powers the pumps which move the protons into the **inter-membrane space**
- **Electrons** from reduced **NAD** make this happen at **all three pumps.**

❖ The molecules that act as electron carriers in the electron transport chain are:

- reduced **NAD dehydrogenase** (also a proton pump)
- **Ubiquinone** (also a proton pump), and
- A number of carriers called **cytochromes** (these are proteins that contain iron);
- two of them form a complex that acts as the **third proton pump**.

- At the end of the electron transport chain, the electrons combine with protons and with oxygen to form **molecules of water**.
- Because of this, **oxygen** is known as the ***terminal electron acceptor***.

A summary of the overall reaction of the electron transport system:

6 reduced NAD (from Krebs' cycle) + 2 reduced NAD (from glycolysis) + 2 reduced FAD (from Krebs' cycle) + 30 ADP + 30 Pi – 2ATP (used in proton pumps) → 36 ATP + 8 NAD + 2FAD

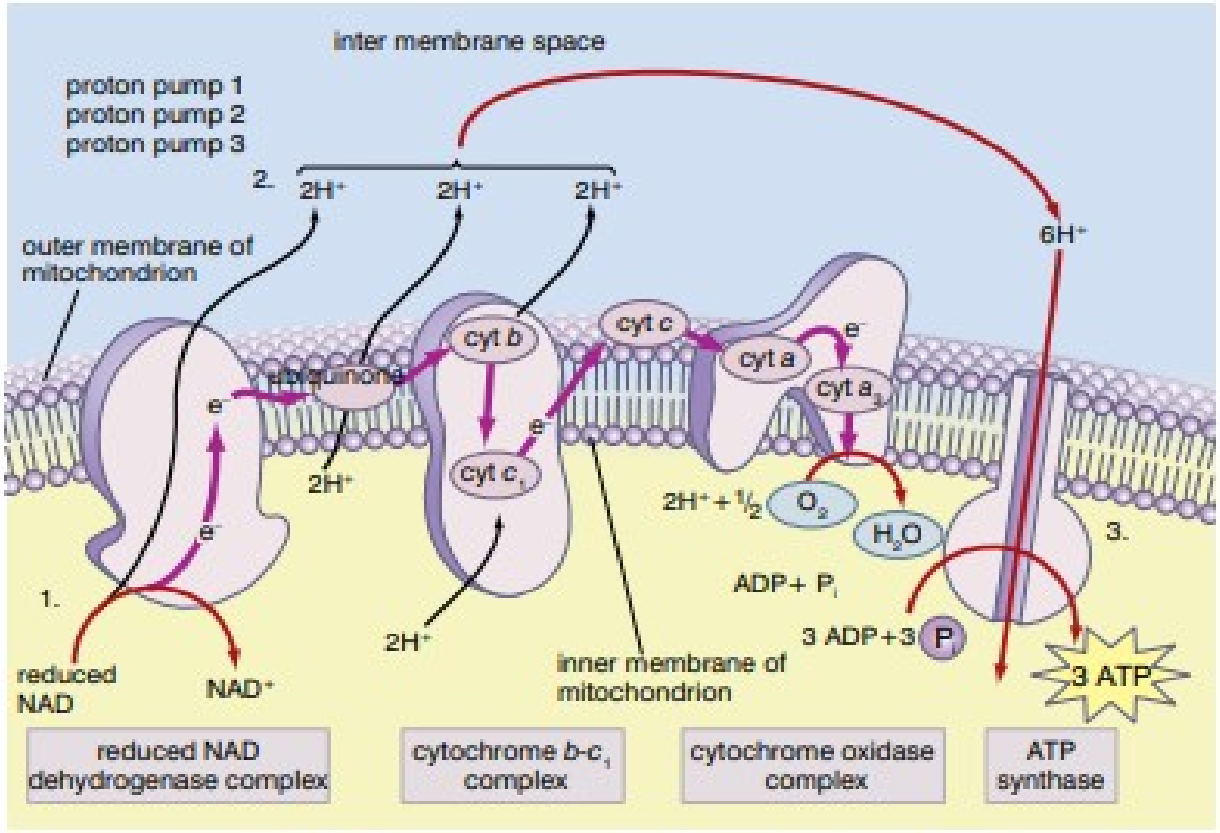


Figure 5.14 *The carrier molecules in the electron transport chain on the inner membrane of a mitochondrion*

What happens in the anaerobic pathway?

- If there is **no oxygen present**, the final reaction of oxidative phosphorylation, where electrons and protons react with oxygen to form water, **cannot take place**.
- As a result, the **electron transport chain** comes to a **halt**.
- **No protons** are pumped and the action of **ATP synthase** also **stops**.
- If the electron transport chain **does not function**, NAD is **not regenerated** from reduced NAD, and FAD is not regenerated from **reduced FAD**.
- The **Krebs cycle** and the **link reaction** come to a halt as both NAD and FAD are required in their oxidized forms for the **Krebs cycle to function.**

- However, **glycolysis** can continue even though it also **requires NAD**.
- This is because the **reduced NAD** formed during glycolysis can be regenerated under anaerobic conditions by converting the **pyruvate into another product** in a reduction reaction.
- **Reduced NAD** supplies the hydrogen for this reduction and becomes oxidized itself.
- It is therefore **regenerated** and can be used **again in glycolysis**.

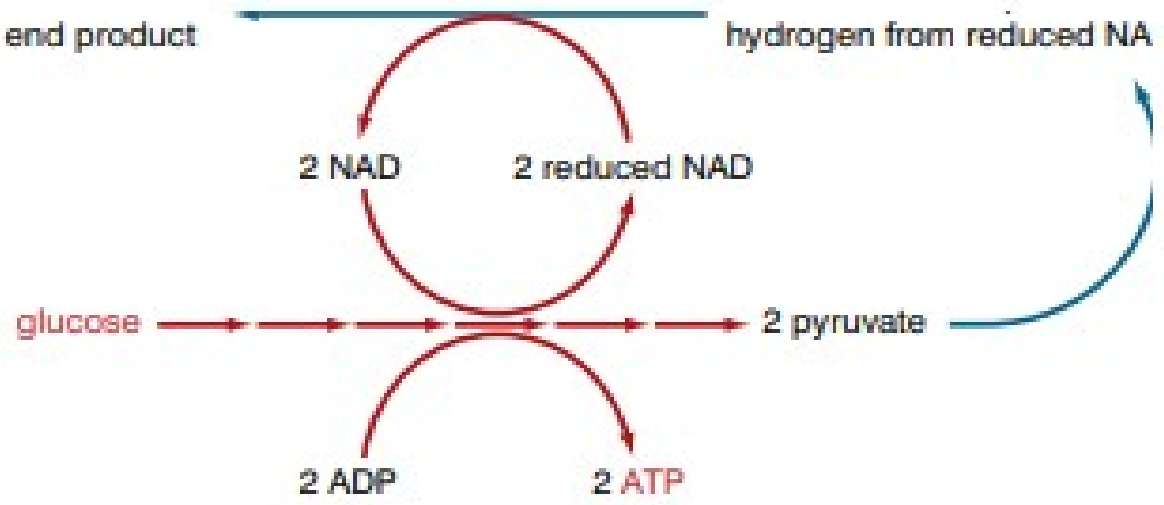


Figure 5.21 How NAD is regenerated in fermentation

- Different organisms produce different fermentation end products:
  - Animal cells produce **lactate (lactic acid)** when they ferment glucose.
  - Yeast cells produce **ethanol (ethyl alcohol).**
  - But both only produce two molecules of **ATP per molecule of glucose**.

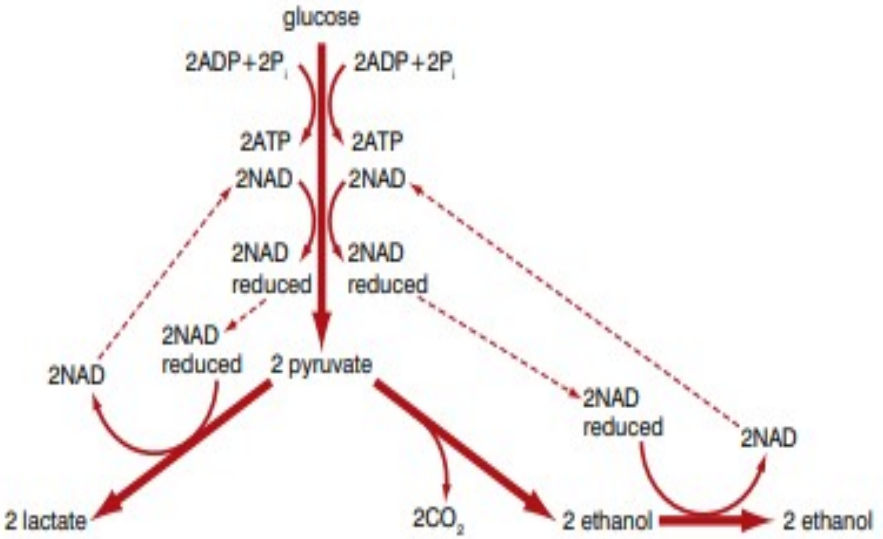


Figure 5.22 *The fermentation processes in animal cells and yeast*

A summary of anaerobic respiration in yeast cells

$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 + 2ATP$

Glucose — Ethanol (alcohol) — carbon dioxide

A summary of anaerobic respiration in animal cells

$C_6H_{12}O_6 \longrightarrow 2C_3H_6O_3 + 2ATP$

Glucose — Lactate (lactic acid)

What substances can be used as energy sources?

- In addition to the **respiration** and **fermentation** of glucose, **lipids,** and **proteins** can also be used as **respiratory substrates**.
- **Lipids** and **proteins** are converted into substances that can enter the **aerobic respiration** pathway at some point.
- The **metabolism** of **proteins**, **lipids**, and **carbohydrates** '***meets***' on the **Krebs cycle**.