

Cell structure

Unity and diversity—Cells

Standard level and higher level: 4 hours

Additional higher level: 1 hour

Guiding questions

- What are the features common to all cells and the features that differ?
- How is microscopy used to investigate cell structure?

SL and HL

A2.2.1—Cells as the basic structural unit of all living organisms

NOS: Students should be aware that deductive reason can be used to generate predictions from theories. Based on cell theory, a newly discovered organism can be predicted to consist of one or more cells.

The **cell theory** states that:

1. All living organisms are composed of cells
2. Cells are the basic structural unit of all living organisms
3. All cells arise from pre-existing cells

The cell theory was developed by **inductive reasoning** (several specific observations of cells making up the living tissue of organisms were used to form a general conclusion that all life is cellular) but is applied in a **deductive** manner (the general conclusion that all life is cellular is used to predict that all living organisms are composed of cells).

A2.2.2—Microscopy skills

Application of skills: Students should have experience of making temporary mounts of cells and tissues, staining, measuring sizes using an eyepiece graticule, focusing with coarse and fine adjustments, calculating actual size and magnification, producing a scale bar and taking photographs.

Coarse and fine knobs:

1. Course knobs move the stage a great distance (rough focusing)
2. Fine knobs move the stage a short distance (detailed focusing)

Mounting and staining tissues:

1. Place a very thin layer of tissue on a slide
2. Add a drop of water or stain (for observing transparent samples) on the tissue
3. Carefully lower a cover slip onto the stained tissue
4. Gently squeeze the cover slip to remove any excess water or stain

Eyepiece graticule:

- The **eyepiece graticule** is a lens inserted into the microscope's eyepiece that contains an engraved ruler (0 to 100) which can be observed through the eyepiece to measure specimens
- The **stage micrometer** is a slide that is mounted onto the stage to calibrate the eyepiece graticule

Magnification calculations:

$$I \text{ AM} \rightarrow \text{Image size} = \text{Actual image size} \times \text{Magnification}$$

A2.2.3—Developments in microscopy

Include the advantages of electron microscopy, freeze fracture, cryogenic electron microscopy, and the use of fluorescent stains and immunofluorescence in light microscopy.

Technique	Microscopy type	Resolution	Method	Advantages
Freeze Fracture	Electron	Nanometers	<ol style="list-style-type: none"> 1. Rapid freezing of specimen using a liquid coolant 2. Fracturing the specimen using a nitrogen-cooled blade (tissue breaks at weakest point) 3. Etching; the removal of ice from the surface of the fractured specimen 4. Making a replica of the fractured frozen surface by evaporating a layer of platinum-carbon onto it 5. Cleaning the replica and examining under an electron microscope 	Visualizes the internal 3D membrane structure of cells, including the protein structure and distribution.
Cryogenic	Electron	Angstroms	Rapid freezing of specimen (usually protein) by liquid nitrogen or ethane followed by observation under an electron microscope.	Cryogenic (low) temperatures enable scientists to irradiate samples with more electrons to improve resolution whilst also reducing radiation damage.
Scanning	Electron	Nanometers	The entire surface of the specimen is covered with metal and irradiated with a beam of electrons that are reflected off the surface to generate an image.	3D image of the specimen's surface.
Transmission	Electron	Angstroms	The specimen is thinned , then a beam of electrons is passed <i>through</i> it to generate an image.	2D image of the specimen's crystal structure.
Fluorescence	Light	Micrometers	Fluorophores (like GFP) are molecules that absorb and emit light when exposed to a specific wavelength of light. They are inserted into the cell's genome as tags to a protein of interest, and then a filter is added to the light microscope's lens to observe the fluorescence.	Enables visualization of live cells to track dynamic processes.
Immuno-fluorescence	Light	Micrometers	A type of fluorescence microscopy where the fluorescent stain is bound to a primary or secondary antibody.	Enables localization of a specific protein.

A2.2.4—Structures common to cells in all living organisms

Typical cells have DNA as genetic material and a cytoplasm composed mainly of water, which is enclosed by a plasma membrane composed of lipids. Students should understand the reasons for these structures.

All cells share some common structures:

1. **DNA:** the genetic information needed by living organisms to carry out all functions of life. The location of DNA differs between organisms.
2. **Cytoplasm:** includes all organelles except the nucleus within the **cytosol** (a mixture of substances dissolved in water).
3. **Plasma membrane:** composed of a phospholipid bilayer, it encloses the cell and controls entry of substances in/out of the cell.

A2.2.5—Prokaryote cell structure

Include these cell components: cell wall, plasma membrane, cytoplasm, naked DNA in a loop and 70S ribosomes. The type of prokaryotic cell structure required is that of Gram-positive eubacteria such as *Bacillus* and *Staphylococcus*. Students should appreciate that prokaryote cell structure varies. However, students are not required to know details of the variations such as the lack of cell walls in phytoplasmas and mycoplasmas.

1. **Cell wall:** a thick and strong layer composed of carbohydrates and proteins that encloses the plasma membrane to provide protection and maintain the cell's shape.
2. **Nucleoid:** a non-compartmentalized region within the cytoplasm that contains **continuous circular DNA** (not associated with histones).
3. **70S ribosomes:** responsible for protein synthesis and are smaller than eukaryotic ribosomes.
4. **Pili:** short hair-like structures on the outer side of the cell wall used for attachment to other surfaces.
5. **Flagella:** long hair-like structures on the outer side of the cell wall used for locomotion.
6. **Cytoplasm:** composed of the cytosol but lacks compartmentalization due to the absence of any membrane-bound organelles in prokaryotes.
7. **Plasma membrane:** the arrangement of the plasma membrane with the cell wall varies between prokaryotes, like in Gram-positive and Gram-negative bacteria.
 - **Gram-positive bacteria:** a single lipid bilayer of plasma membrane is covered by an outer cell wall. When stained, appear **purple** under light microscopy. *Bacillus* and *Staphylococcus* are examples of Gram-positive bacteria.
 - **Gram-negative bacteria:** the cell wall lies between two lipid bilayers. When stained, appear **pink** under light microscopy.

A2.2.6—Eukaryote cell structure

Students should be familiar with features common to eukaryote cells: a plasma membrane enclosing a compartmentalized cytoplasm with 80S ribosomes; a nucleus with chromosomes made of DNA bound to histones, contained in a double membrane with pores; membrane-bound cytoplasmic organelles including mitochondria, endoplasmic reticulum, Golgi apparatus and a variety of vesicles or vacuoles including lysosomes; and a cytoskeleton of microtubules and microfilaments.

- 1. Endoplasmic reticulum (ER):** extensive network of branching tubules and flattened sacs that extend from the nucleus to the plasma membrane.
 - **Smooth ER:** does not contain bound ribosomes and is involved in lipid biosynthesis.
 - **Rough ER:** closer to the nucleus and contains bound ribosomes for protein biosynthesis.
- 2. Nucleus:** encloses DNA for storage by the **nuclear envelope** (a porous double-membrane). Eukaryotic DNA is found as multiple linear strands (**chromosomes**) and is associated with **histone** proteins that form **nucleosomes**, which are involved in gene expression.
- 3. 80S ribosomes:** responsible for protein synthesis and are larger than prokaryotic ribosomes. They can either be bound to the ER or free within the cytoplasm.
- 4. Golgi apparatus:** collection of fused **cisternae** (flattened sacs that are less tubule-like than the ER) that form two major networks; the **Cis Golgi network** (first cisternal structure facing the nucleus) and the **Trans Golgi network** (final cisternal structure facing the cell plasma membrane). Golgi cisternae are not contiguous and their widths are not uniform. The Golgi apparatus is involved in packaging, modification, and sorting of proteins and lipids within the cell.
- 5. Vesicles:** spherical sacs of composed a single lipid bilayer that function in storage and transport of substances within the cytoplasm. They are transient, small, highly mobile, and fuse with other membrane-bound organelles.
- 6. Lysosomes:** round organelles composed of single lipid bilayers that contain hydrolytic enzymes for digesting biomolecules in low pH conditions.
- 7. Peroxisomes:** round organelles composed of single lipid bilayers that contain oxidative enzymes for the metabolism of lipids and hydrogen peroxide.
- 8. Vacuoles:** spherical sacs of composed a single lipid bilayer that function in storage of water and other molecules in (mostly) plants. They are permanent, large, relatively stationary, and do not fuse with other membrane-bound organelles.
- 9. Mitochondria:** oval-shaped double-membranous organelles with their own circular DNA and ribosomes. They are primarily responsible for ATP synthesis in aerobic respiration.
- 10. Chloroplasts:** double-membranous organelles with their own DNA and ribosomes that carry out photosynthesis in plants. They contained fluid-filled sacs (**thylakoids**) that are stacked and interconnected within **grana** to increase surface area for photosynthesis.
- 11. Centrosomes:** composed of a pair of **centrioles** that aid in organizing microtubules within the cell.
- 12. Cytoskeleton:** network of **actin filaments**, **intermediate filaments**, and **microtubules**, that aid in cell movement, reinforcement of cell shape, cell division, and organelle movement/anchoring.
- 13. Cytoplasm:** compartmentalized cytosol with membrane-bound organelles.
- 14. Plasma membrane:** encloses the compartmentalized cytoplasm.

A2.2.7—Processes of life in unicellular organisms

Include these functions: homeostasis, metabolism, nutrition, movement, excretion, growth, response to stimuli and reproduction.

All organisms carry out the following functions that are necessary to their life:

1. **Homeostasis:** the ability to maintain constant internal conditions.
2. **Metabolism:** the ability to carry out chemical reactions.
3. **Nutrition:** the ability to obtain energy needed to sustain metabolism.
4. **Movement:** the ability to move.
5. **Excretion:** the ability to release waste or toxic materials into the environment.
6. **Growth:** the ability to develop in size or complexity.
7. **Sensitivity (response to stimuli):** ability to perceive stimuli and respond appropriately to them.
8. **Reproduction:** the ability to produce offspring sexually or asexually.

Unicellular (single-celled) organisms perform all of these functions within their single-cell structure.

Multicellular (composed of multiple cells) organisms rely on division of labor between specialized cells to perform the functions of life.

A2.2.8—Differences in eukaryotic cell structure between animals, fungi and plants

Include presence and composition of cell walls, differences in size and function of vacuoles, presence of chloroplasts and other plastids, and presence of centrioles, cilia and flagella.

	Animals	Plants	Fungi
Plastids	Absent	Present	Absent
Cell wall	Absent	Present (made of cellulose)	Present (made of chitin)
Vacuoles	Present (very small and transient)	Present (large and permanent)	
Centrioles	Present	Absent	Absent
Cilia & Flagella	Present	Absent	Absent

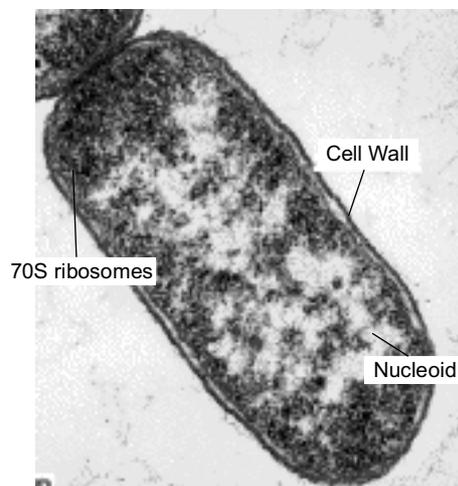
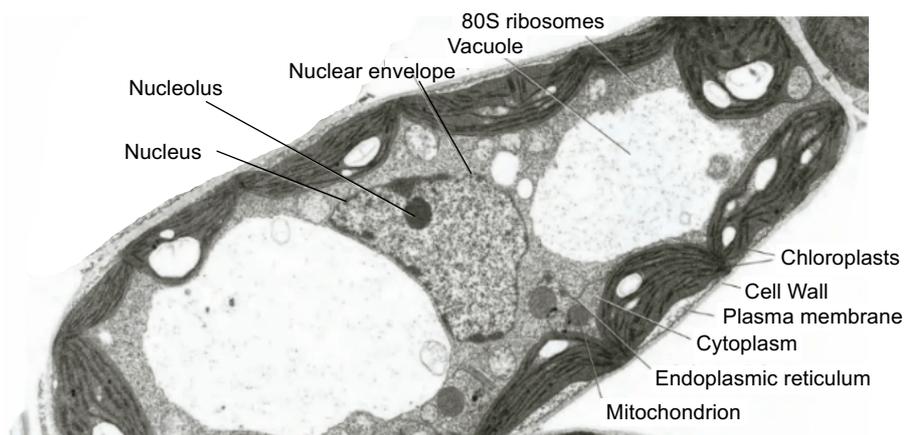
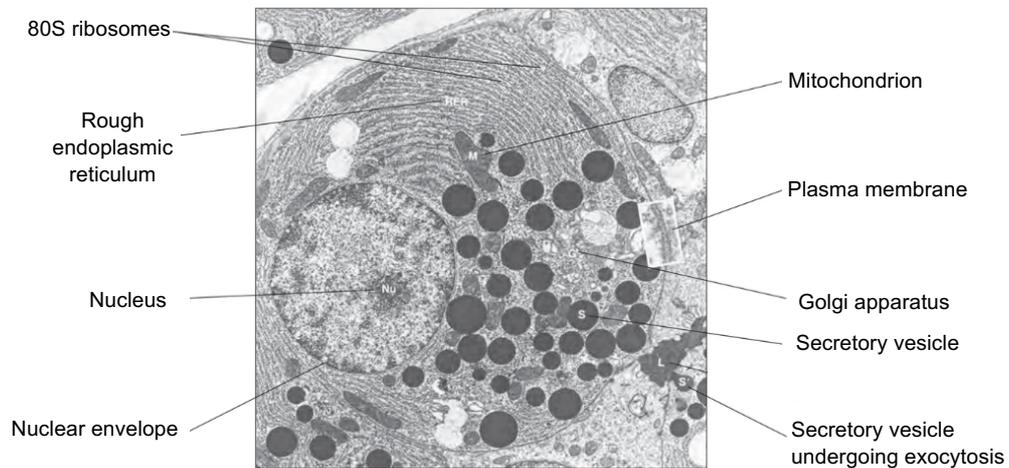
A2.2.9—Atypical cell structure in eukaryotes

Use numbers of nuclei to illustrate one type of atypical cell structure in aseptate fungal hyphae, skeletal muscle, red blood cells and phloem sieve tube elements.

- **Aseptate fungal hyphae:** lack **septa** (internal cell walls), creating a continuous multinucleate cytoplasm.
- **Skeletal muscle:** muscle fibers are composed of columns of cells that have fused together to produce multinucleate structures.
- **Red blood cells (RBCs):** mature RBCs lack a nucleus, so they cannot produce more proteins or repair themselves.
- **Phloem sieve tube elements:** contain pores within their walls and minimal organelles, depending on **companion cells** for staying alive as they are specialized for transport in plants.

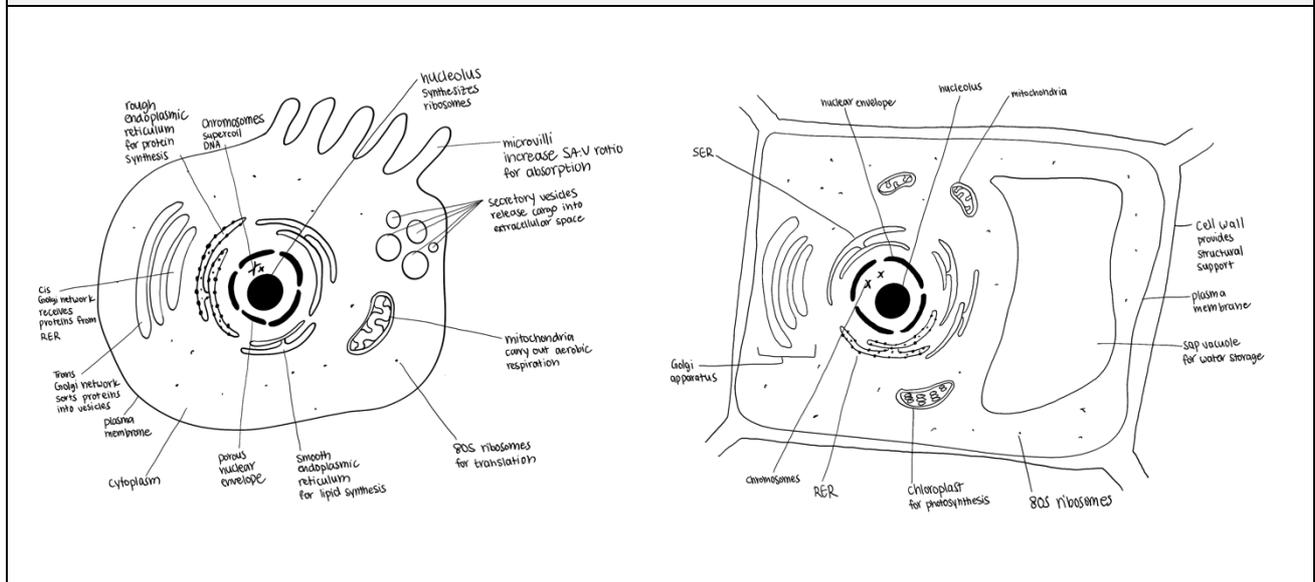
A2.2.10—Cell types and cell structures viewed in light and electron micrographs

Application of skills: Students should be able to identify cells in light and electron micrographs as prokaryote, plant or animal. In electron micrographs, students should be able to identify these structures: nucleoid region, prokaryotic cell wall, nucleus, mitochondrion, chloroplast, sap vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum, chromosomes, ribosomes, cell wall, plasma membrane and microvilli.



A2.2.11—Drawing and annotation based on electron micrographs

Application of skills: Students should be able to draw and annotate diagrams of organelles (nucleus, mitochondria, chloroplasts, sap vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum and chromosomes) as well as other cell structures (cell wall, plasma membrane, secretory vesicles and microvilli) shown in electron micrographs. Students are required to include the functions in their annotations.



Additional higher level

A2.2.12—Origin of eukaryotic cells by endosymbiosis

Evidence suggests that all eukaryotes evolved from a common unicellular ancestor that had a nucleus and reproduced sexually. Mitochondria then evolved by endosymbiosis. In some eukaryotes, chloroplasts subsequently also had an endosymbiotic origin. Evidence should include the presence in mitochondria and chloroplasts of 70S ribosomes, naked circular DNA and the ability to replicate.

The **endosymbiotic theory** states that some eukaryotic organelles were derived from prokaryotic cells and proposes a mechanism for such a process:

1. Engulfment of an **aerobic prokaryote** (mitochondrion precursor) by an **archaeal anaerobic cell**
2. **Invaginations** of the archaean's plasma membrane eventually led to the development of intracellular membrane-bound compartments
3. After mitochondrial engulfment, some archaeans may have also engulfed a **cyanobacterium** (chloroplast precursor) that is capable of photosynthesis

There are several pieces of evidence from mitochondria and chloroplasts supporting the endosymbiotic theory:

1. They have their own DNA
2. They have 70S ribosomes
3. They have double membranes, which makes sense if they were prokaryotes with single lipid bilayers that got engulfed by endocytosis (thus acquiring a second membrane layer)
4. They are only produced by binary fission of pre-existing mitochondria/chloroplasts
5. They are susceptible to antibiotics

A2.2.13—Cell differentiation as the process for developing specialized tissues in multicellular organisms

Students should be aware that the basis for differentiation is different patterns of gene expression often triggered by changes in the environment.

Multicellular organisms divide the functions of life amongst different cell types that are specialized (differentiated) for particular roles. **Cell differentiation** is the process by which an unspecialized cell develops into a cell type with a specific form and function.

Since all cells in a multicellular organism contain the same DNA, differences in their functions are a result of expressing different genes, often triggered by changes in the environment during development.

NOS: Students should appreciate that measurement using instruments is a form of quantitative observation.

Using instruments, like rulers or thermometers, enables the measurement of observation in a quantitative (numerical) manner, which enhances precision and allows for statistical analyses.

A2.2.14—Evolution of multicellularity

Students should be aware that multicellularity has evolved repeatedly. Many fungi and eukaryotic algae and all plants and animals are multicellular. Multicellularity has the advantages of allowing larger body size and cell specialization.

Multicellular organisms have evolved repeatedly due to several advantages:

1. Larger **body sizes** can be achieved whilst still obeying SA:V ratios
2. **Complex functions** can be achieved through cell specialization
3. **Longer lifespans** since they can live even if one of their cells die (unlike unicellular organisms)

NOS: Students should recognize that the strength of a theory comes from the observations the theory explains and the predictions it supports. A wide range of observations are accounted for by the theory of endosymbiosis.

A strong theory, like endosymbiosis, is supported by a wide range of observations from independent lines of evidence.

Linking questions

- What explains the use of certain molecular building blocks in all living cells?
- What are the features of a compelling theory?

Review questions

SL and HL

- Distinguish, using examples, between deductive and inductive reasoning. [2]
- Outline the advantages of different types of electron microscopy. [5]
- Compare and contrast vesicles and vacuoles. [5]
- Describe the structure of prokaryotic cells. [7]
- Outline the differences in eukaryotic cell structure between animals, fungi and plants. [7]
- Describe the similarities and differences between single-layer membrane-bound organelles. [8]
- Describe the structures and functions of **four** eukaryotic organelles present in both animals and plants. [8]
- Explain how different microscopy techniques can be used to investigate cell structures. [8]

Additional Higher Level

- Describe the endosymbiotic theory. [3]
- Outline the advantages of multicellularity. [3]
- Explain how eukaryotic cells with the same DNA perform different functions. [3]
- Describe the evidence for the endosymbiotic theory. [4]
- Discuss why endosymbiosis is a compelling theory. [7]

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Electron Microscopy | TEM vs SEM | Thermo Fisher Scientific - CA. <https://www.thermofisher.com/ca/en/home/materials-science/learning-center/applications/sem-tem-difference.html>.