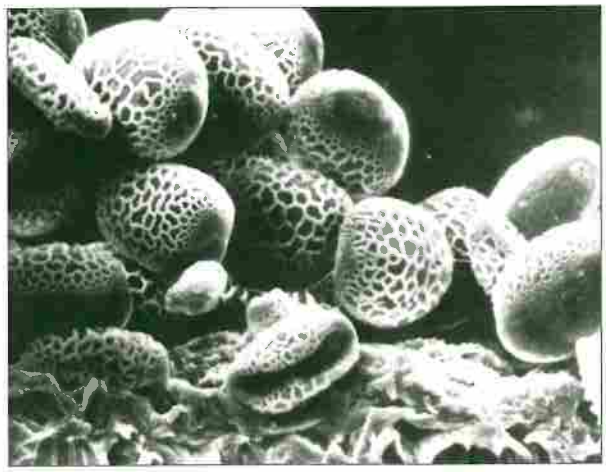
instruments and stained to provide appropriate contrast between the structures being viewed or photographed. The degree of preparation involved can sometimes produce 'artefacts' or changes in the image.

There are two types of electron microscope, the transmission electron microscope and the scanning electron microscope.

The transmission electron microscope (TEM) involves electrons passing through a very thin specimen. It produces images with a very high resolution and consequently can be used for very high magnifications (see pages 51 and 52 for examples).

The scanning electron microscope (SEM) involves electrons reflecting off the surface of the image as opposed to going through it. Resolution and magnification are not as high but it is useful for giving a 3-D image of surface features as can be seen in the SEM electron micrograph of pollen grains opposite.



SEM image of pollen grains

Image courtesy of Dr Gerard Brennan, School of Biological Sciences, Queen's University, Belfast

Cell ultrastructure

Understanding the eukaryotic cell

The typical eukaryotic cell (a cell with a nucleus) consists of a cell-surface membrane (we will revisit the cell-surface membrane later) and cytoplasm, within which a nucleus and a host of membrane systems and organelles are embedded.

The detail of a cell when viewed through an electron microscope is known as its **ultrastructure**.

Eukaryotic cells are found in **animals, plants** and **fungi**. The organelles and membrane systems covered in the next section are not all found in animals, plants and fungi; some are specific to certain group(s) only.

Membrane systems and organelles of animal cells

The nucleus

The nucleus is the largest and most obvious organelle in most cells. It is usually between about 10–25 μm in diameter. The nucleus contains DNA in chromosomes. When cells are not dividing the chromosomes are not visible but are more diffusely organised in a form called **chromatin**. In parts of the nucleus, the chromatin is more densely packed (**heterochromatin**), appearing dark when viewed by the electron microscope. In other parts it is less densely packed (**euchromatin**), and therefore appears lighter when viewed.

The nucleus often contains one or more **nucleoli** (1–3 μm). When viewed under the electron microscope, a nucleolus appears even darker than the densely packed heterochromatin and is a more discrete structure than the more diffuse heterochromatin, which is often concentrated close to the nuclear membrane. A nucleolus synthesises ribosomal RNA (rRNA) makes ribosomes, which are components essential in the process of protein synthesis.

In general, the nucleus is the control centre of the cell, as the DNA in the chromosomes codes for the synthesis of proteins in the cytoplasm. By isolating the chromosomes (and DNA) from the rest of the cytoplasm and the reactions that take place there, the DNA is protected from damage. However, the 'DNA code' for protein synthesis needs to be taken from the safety of the nucleus to the cytoplasm, where protein synthesis takes place and other molecules (for example, enzymes involved in making DNA) need to enter the nucleus from the cytoplasm. This is achieved by the presence of **nuclear pores** in the **nuclear envelope** (membrane). The nuclear envelope is in fact a double membrane, with a very narrow space between each membrane.

Endoplasmic reticulum (ER)

The ER is a membrane system that extends throughout the cytoplasm – it is very common and will be evident in virtually all electron micrographs of cytoplasm. Its three-dimensional membrane system encloses sacs called **cisternae**. Some of the ER has ribosome organelles dotted along the outside (cytoplasmic side) of the membranes. This is **rough endoplasmic reticulum (RER)**. Other parts of the ER do not have ribosomes attached. This is **smooth endoplasmic reticulum (SER).**

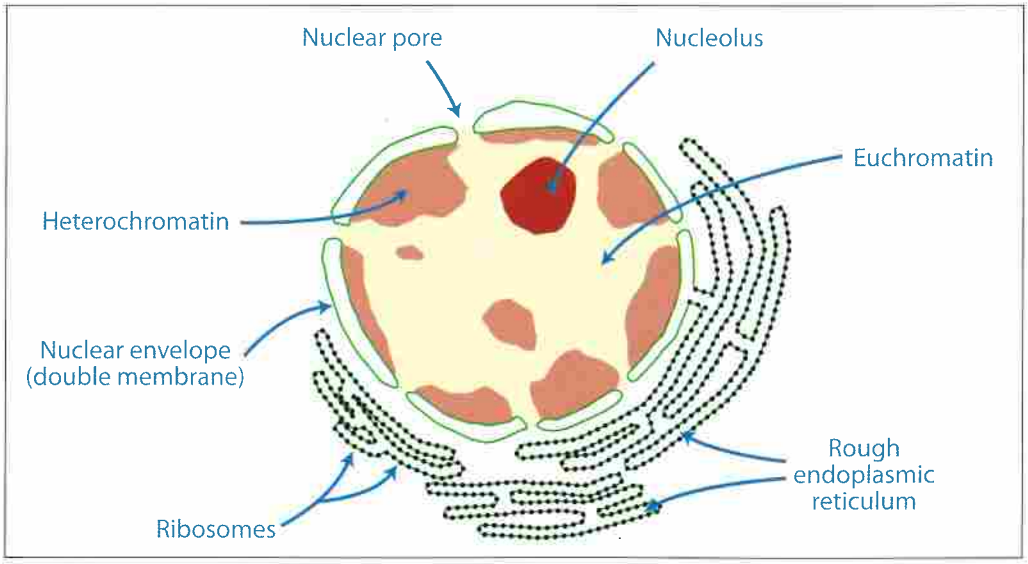
The RER provides the 'scaffolding' for the ribosomes to make protein and the ER then operates as a distribution network for the proteins. The ER is joined with the nuclear envelope, facilitating the transport of the RNA (which carries the DNA code) from the nucleus to the ribosomes (the sites of protein synthesis). Not surprisingly, RER is particularly common in cells whose function is to secrete protein.

The SER has many roles involving the metabolism of lipids, including the synthesis of cholesterol.

Ribosomes

These very small organelles (up to about 30 nm in diameter) are visible as small black dots in EM micrographs. They are found either free in the cytoplasm or attached to the outer surface of the ER as described above.

Each ribosome is formed of a large and a small sub-unit, and is made of protein and ribosomal RNA (rRNA). They frequently occur in groups called **polyribosomes**, creating 'hot spots' of protein synthesis.



The nucleus and surrounding rough endoplasmic reticulum (RER) containing ribosomes

Golgi apparatus

The Golgi apparatus (body) can be described as a series of curved flattened sacs (**cisternae**). They characteristically have a number of small **vesicles** both entering and leaving the system. Vesicles containing newly synthesised protein pinch off from the RER and coalesce with the 'forming' (convex) edge of the system (usually the edge closest to the nucleus). Within the main body of the Golgi, the proteins are modified, for example, they may have carbohydrate added to form glycoprotein. Once the protein is modified, vesicles containing the 'finished' protein are pinched off from the 'maturing' (concave) face (usually the side furthest away from the nucleus). These vesicles transport the protein either within the cell or fuse with the cell-surface membrane to release their contents outside the cell.

The organelles and membrane systems discussed so far (nucleus, ER, ribosomes and Golgi apparatus) are all intricately linked in function – they play important roles in protein synthesis and the subsequent modification and transport of the protein produced.

Lysosomes

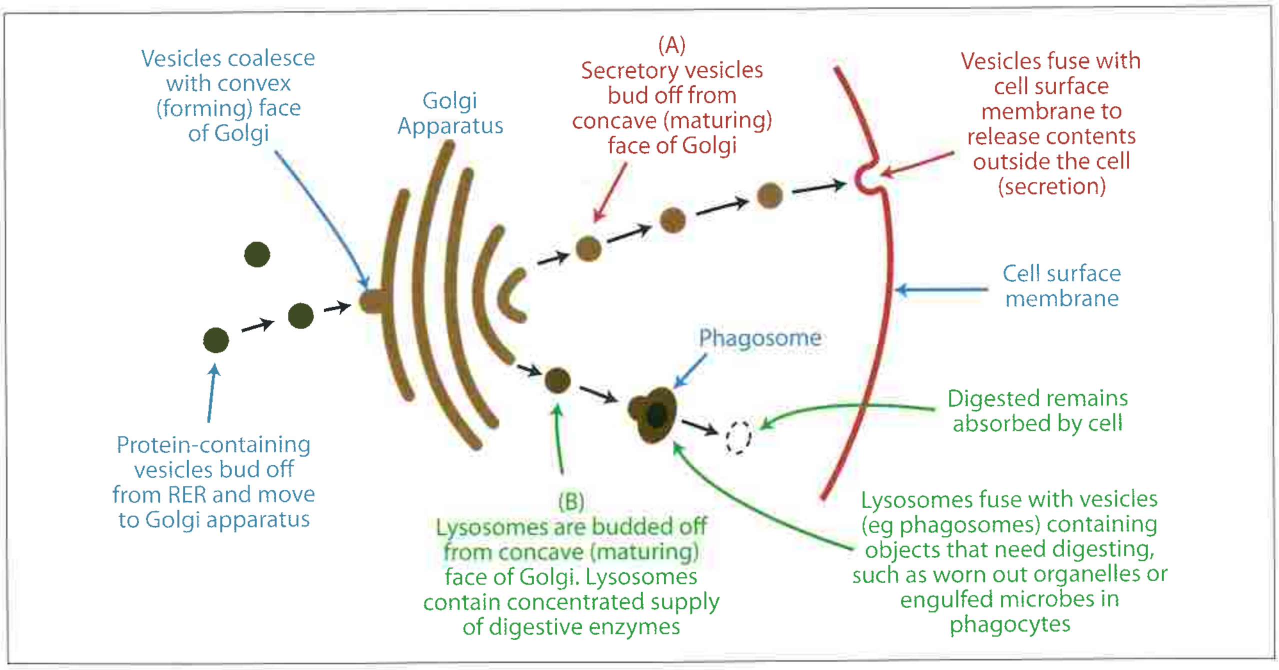
Lysosomes are tiny vesicles usually about 0.5 μm in size. They are formed by the Golgi apparatus and they contain **hydrolytic enzymes** for internal use. They fuse with other vesicles in the cell that contain something that has to be destroyed or digested (for example, worn out cell organelles or other cell debris). When they fuse they form secondary lysosomes. They have an important role in **phagocytes**, where they digest engulfed bacteria enclosed in a phagosome (membrane bound vesicle in the phagocyte). Lysosomes have relatively thick membranes (compared with other internal organelles), as obviously it is important that the hydrolytic enzymes are not accidentally released inside the cell.

Note: vesicles are not restricted to association with the Golgi apparatus – they can be used for the storage and transport of substances throughout the cell.

Mitochondria

Mitochondria are present in almost all types of animal cell. They are relatively large

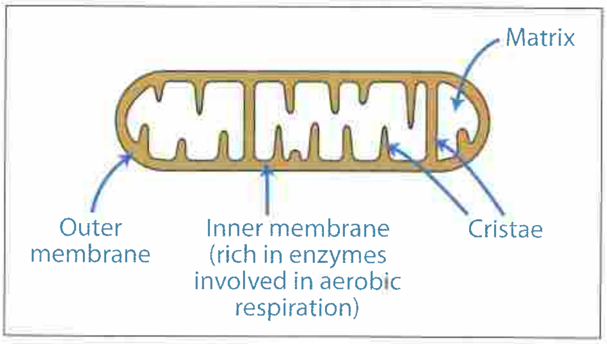
Golgi apparatus producing (A) secretory vesicles and (B) lysosomes



organelles (up to 10 μm in length). They are typically 'sausage shaped' but can be very variable in shape. Mitochondria are enclosed within a **double membrane**, separated by an inter-membrane space. The inner membrane is folded to form **cristae** that extend into the **matrix** of the mitochondria. This infolding gives the inner mitochondrial membrane a greater surface area, therefore increasing the number of enzymes that can be embedded within the membrane.

The mitochondrion is the 'powerhouse' of the cell. It is the site of **ATP synthesis** during **aerobic respiration**. Mitochondria are particularly common in cells that have high energy requirements, such as muscle cells. Additionally, as many of the enzymes involved in ATP synthesis are located within the inner mitochondrial membrane, the cristae tend to be more numerous and more deeply infolded in highly active cells.

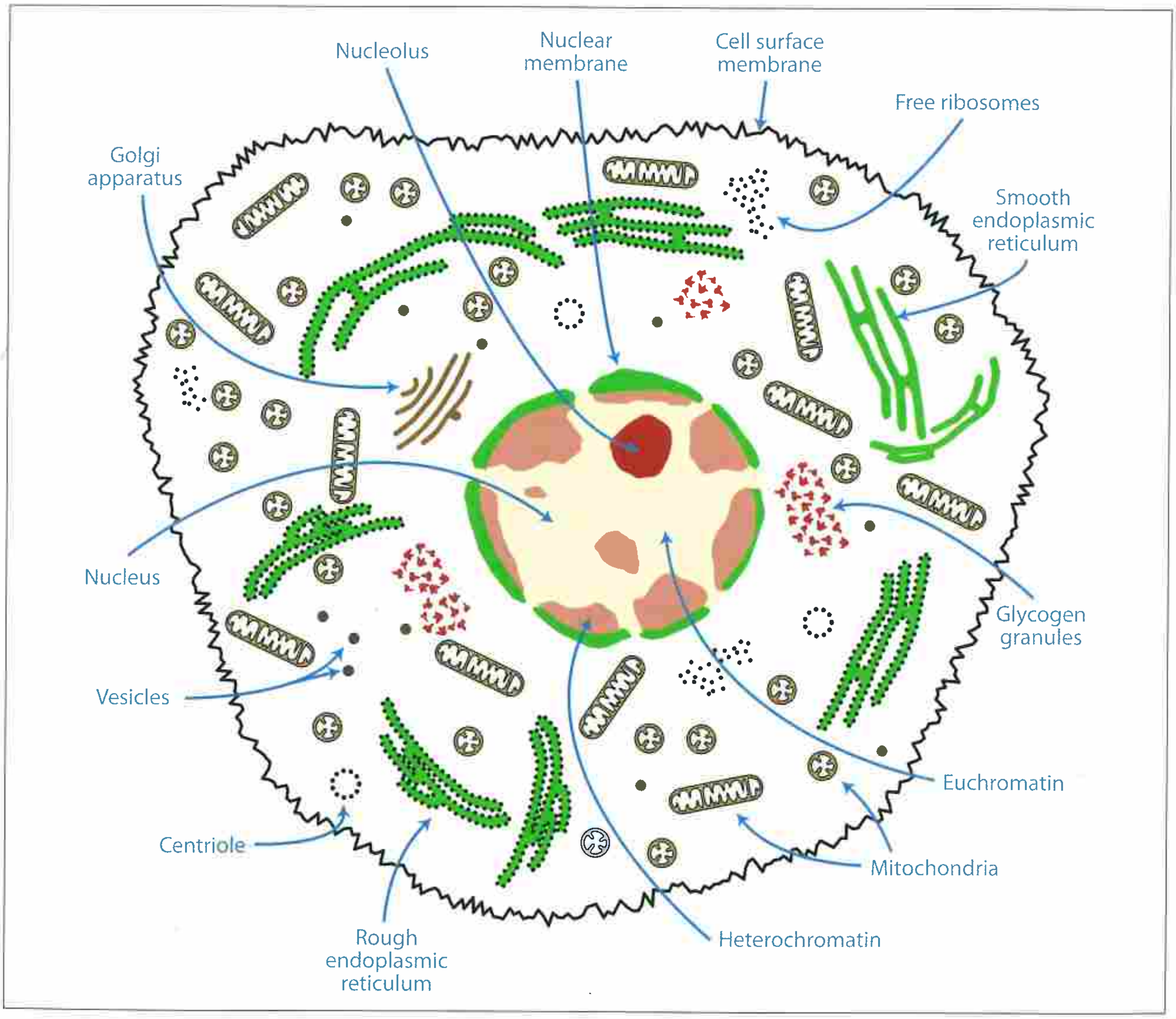
A mitochondrion



Microtubules

Microtubules are hollow cylinders formed from the protein tubulin. They are about 25 nm in diameter and up to 10 μm in length.

Ultrastructure of a generalised animal cell



Although found throughout the cytoplasm they tend to be concentrated in specific areas and for specific functions. They occur within the centrioles that form the spindle fibres essential in nuclear division. In the centriole they form nine triplets of microtubules arranged in a circular formation. They also are found in cilia and flagella. As part of the cytoskeleton of the cell they help direct the movement of cell organelles.

Membrane systems and organelles of plant cells

Similar to animal cells, plant cells have a nucleus, ER, ribosomes and Golgi apparatus. They differ from animal cells in **not** having **lysosomes** or **centrioles**. However, the major difference is that they possess some organelles and membrane systems that are not present in animal cells.

These include:

Plant cell wall – All plant cells are surrounded by a cell wall that lies immediately outside the cell-surface membrane. Cell walls are around 1 μm thick. The main component in plant cell walls is the polysaccharide **cellulose**. The cellulose is laid down as **microfibrils**. Each microfibril consists of many cellulose molecules cross-linked to each other. The **primary cell wall** is made up of many microfibrils orientated in different and random directions. The relatively loose arrangement of microfibrils allows the cell wall to expand as the cell grows.

Secondary cell wall – When the cell reaches full size, additional layers of cellulose can be deposited to form the secondary cell wall. In the secondary cell wall, each layer of cellulose has the microfibrils orientated in the same direction. However, additional layers are orientated in different directions to other layers. This lattice type arrangement gives the great strength necessary in cell wall function.

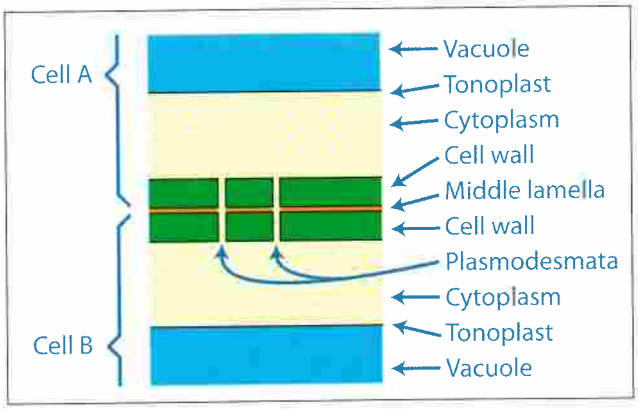
Middle lamella – Cell walls of adjacent cells are linked by the middle lamella. The middle lamella is largely made of polysaccharides called **pectin. Calcium pectate** forms a gel or 'cement' that acts as an adhesive and holds neighbouring cells together.

The function of plant cell walls is to provide support. As they form fairly rigid structures they can support the cells directly, but are also very important in turgor. They restrict the outward expansion of the cell contents (**protoplast**) as the cell takes in water, thus providing the supporting force associated with turgor pressure. Unlike the cell-surface membrane, which is selectively or differentially permeable, the cell wall is fully permeable and plays no part in determining which substances can enter and leave cells.

Plasmodesmata

Plasmodesmata are strands of cytoplasm that extend between neighbouring plant cells. Plasmodesmata provide 'gaps' in the cell walls of adjacent cells that enable different kinds of molecules to pass through. As the cell membranes of the adjacent cells pass through the pores, the neighbouring cells are joined, physically and metabolically.

Plant cell wall with plasmodesmata



Chloroplasts

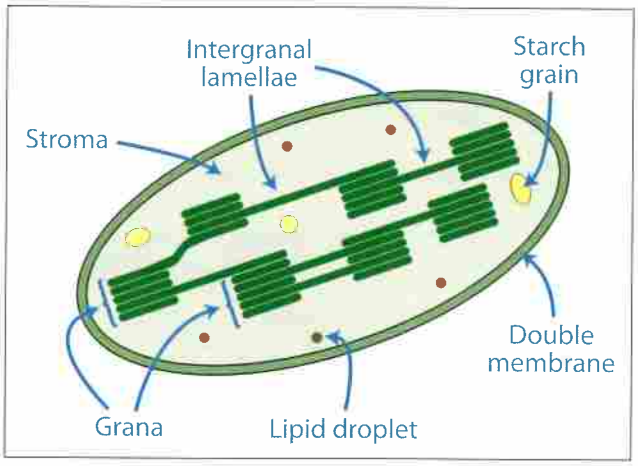
Chloroplasts are large organelles and are usually intermediate in size between the nucleus and mitochondria. They are bounded by a **double membrane** or **envelope**, which encloses the **stroma**. Within the stroma is a system of membranes, called thylakoids. At intervals, the **thylakoids** are arranged in stacks called **grana**. Between grana the membranes are less concentrated and are referred to as **inter-grana**.

The thylakoids contain chlorophyll, which is most densely concentrated in the grana.

Chloroplasts usually have one or more **starch grains** and smaller **lipid** droplets produced through photosynthesis.

Chloroplasts are the sites of **photosynthesis** and are located in photosynthesising cells, in particular cells in the palisade layer of leaves. Not surprisingly, most actively photosynthesising cells tend to have many chloroplasts that have many-layered grana, with many grana being present in each chloroplast.

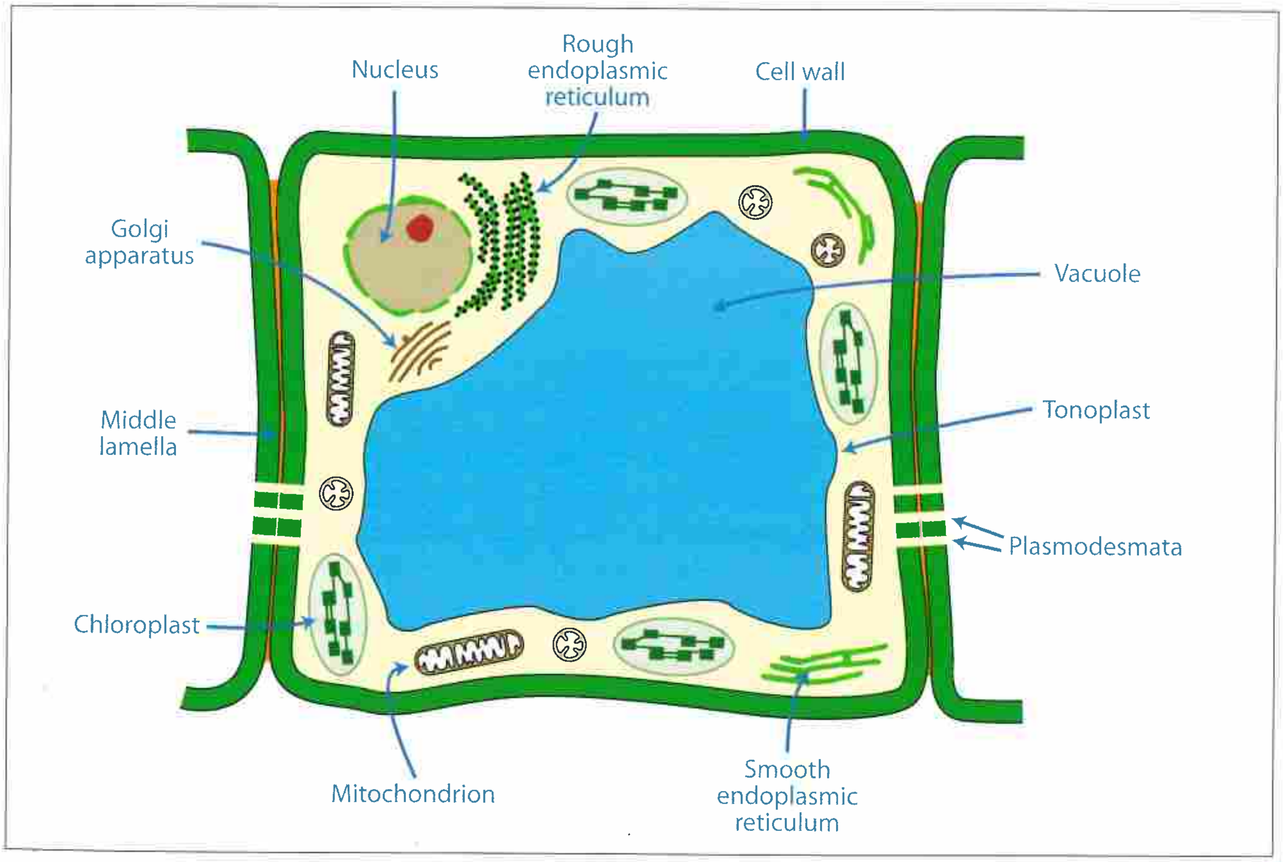
A chloroplast



Large vacuole

Plant cells have a large vacuole within the cytoplasm. The vacuole is important in the storage of ions and water, and plays an important part in the development of turgor for support.

Ultrastructure of a generalised plant cell



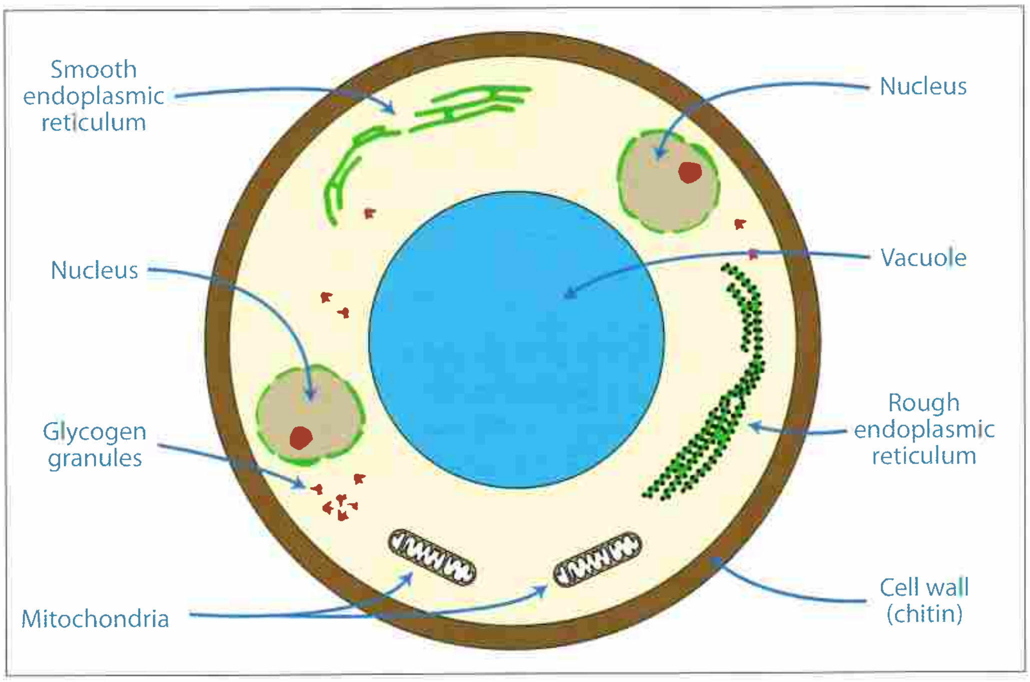
Fungal cells

Fungi (like animals and plants) are eukaryotic organisms and therefore they have eukaryotic cells.

Fungal cells have cell walls, but unlike plants their cell walls are made of the glycoprotein **chitin**, not cellulose. They have other plant-like features such as the presence of a **vacuole**.

They are significantly different to plants in that they do not photosynthesise, and therefore do not have chloroplasts. They are more similar to animal cells in having **glycogen** as the carbohydrate store and also through the presence of **lysosomes.**

Fungi do possess nuclei but the cells of many species are **multinucleate**.



A typical fungal cell

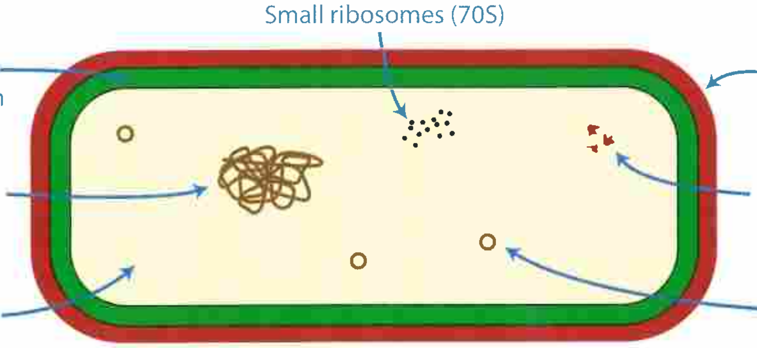
The diagram above shows a transverse section through a fungal cell. Many fungi are in the form of long, elongated threads of hyphae that spread through the substrate. The cells are often elongated and multinucleate.

Prokaryotes and Eukaryotes

There are two distinct categories of cell in the living world, **prokaryotic** and **eukaryotic** cells. Prokaryotic cells are generally simpler. They do not have a nucleus and the membrane-bound organelles more typical of more complex cells. Bacteria have prokaryotic cells and they are described as **prokaryotes**.

We have already looked at eukaryotic cells in detail. They are the cells found in animals, plants and fungi. They have a membrane-bound nucleus, chromosomes and a range of complex organelles that have specific roles within the cell.

The table opposite summarises the main differences between eukaryotic and prokaryotic cells.



A generalised prokaryote cell

	Prokaryotic cell	Eukaryotic cell
Size	Usually < 5 µm	10–200 µm
Site of DNA	DNA free in cytoplasm	DNA inside membrane-bound nucleus
DNA organisation	Circular and without associated protein	DNA linear and in chromosomes. Chromosomes contain both helically arranged DNA and packaging protein (histones)
Ribosomes	Small – 20 nm (70S)	Large – 25 nm (80S)
Internal structure	No complex organelles	Complex membrane-bound organelles including nucleus, mitochondria and Golgi apparatus
Cell walls	Complex – made of peptidoglycan (glycoprotein)	Cellulose cell walls in plants Chitin cell walls in fungi
Plasmids	Usually present	Not present
Microtubules	Not present	Present as centrioles in animal and some fungal groups

The cell-surface membrane

The cell-surface (plasma) membrane is a critical component of cells. It is the boundary or interface with the outside world, whether that is the environment (in unicellular organisms), other cells or internal cavities, such as the gut, in multicellular organisms.

The cell-surface membrane consists of two basic components, a **phospholipid bilayer** and **protein**. It is the phospholipid bilayer that forms the 'skeleton' of the membrane and this is largely due to the properties of the phospholipid molecules.

As noted in Chapter 1 on molecules, phospholipids consist of **hydrophilic** (water loving) 'heads' that can mix with water but not lipid and two **hydrophobic** (water hating) 'tails' that will mix with lipid but not water.

Note: the terms 'water loving' and 'water hating' have been used here for explanatory purposes. In examinations you should use the scientific terms hydrophilic and hydrophobic.