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More information

Chapter 1: Cell structure

Learning outcomes

You should be able to:

- describe and compare the structure of animal, plant and bacterial cells, and discuss the noncellular nature of viruses
- describe the use of light microscopes and electron microscopes to study cells
- draw and measure cell structures
- discuss the variety of cell structures and their functions
- describe the organisation of cells into tissues and organs
- outline the role of ATP in cells

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Thinking outside the box

Progress in science often depends on people thinking 'outside the box' - original thinkers who are often ignored or even ridiculed when they first put forward their radical new ideas. One such individual, who battled constantly throughout her career to get her ideas accepted, was the American biologist Lynn Margulis (born 1938, died 2011: Figure 1.1). Her greatest achievement was to use evidence from microbiology to help firmly establish an idea that had been around since the mid-19th century – that new organisms can be created from combinations of existing organisms which are not necessarily closely related. The organisms form a symbiotic partnership, typically by one engulfing the other - a process known as endosymbiosis. Dramatic evolutionary changes result.

The classic examples, now confirmed by later work, were the suggestions that mitochondria and chloroplasts were originally free-living bacteria (prokaryotes) which invaded the ancestors of modern eukaryotic cells (cells with nuclei). Margulis saw such symbiotic unions as a major driving cause of

In the early days of microscopy an English scientist, Robert Hooke, decided to examine thin slices of plant material. He chose cork as one of his examples. Looking down the microscope, he was struck by the regular appearance of the structure, and in 1665 he wrote a book containing the diagram shown in Figure 1.2.

If you examine the diagram you will see the 'porelike' regular structures that Hooke called 'cells'. Each cell appeared to be an empty box surrounded by a wall. Hooke had discovered and described, without realising it, the fundamental unit of all living things.

Although we now know that the cells of cork are dead, further observations of cells in living materials were made by Hooke and other scientists. However, it was not until almost 200 years later that a general cell theory emerged from the work of two German scientists. In 1838 Schleiden, a botanist, suggested that all plants are made of cells, and a year later Schwann, a zoologist, suggested the same for animals. The **cell theory** states that the basic unit of structure and function of all living organisms is the cell. Now, over 170 years later, this idea is one of the most familiar and important theories in biology. To it has been added Virchow's theory of 1855 that all cells arise from pre-existing cells by cell division. evolutionary change. She continued to challenge the Darwinian view that evolution occurs mainly as a result of competition between species.



Figure 1.1 Lynn Margulis: 'My work more than didn't fit in. It crossed the boundaries that people had spent their lives building up. It hits some 30 sub-fields of biology, even geology.'

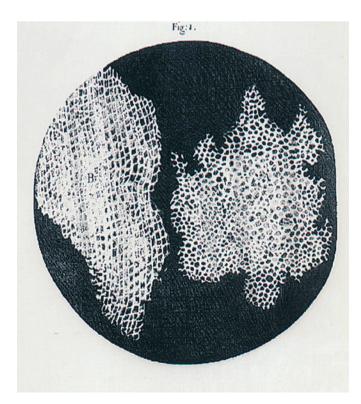


Figure 1.2 Drawing of cork cells published by Robert Hooke in 1665.

Why cells?

A cell can be thought of as a bag in which the chemistry of life is allowed to occur, partially separated from the environment outside the cell. The thin membrane which surrounds all cells is essential in controlling exchange between the cell and its environment. It is a very effective barrier, but also allows a controlled traffic of materials across it in both directions. The membrane is therefore described as **partially permeable**. If it were **freely permeable**, life could not exist, because the chemicals of the cell would simply mix with the surrounding chemicals by diffusion.

Cell biology and microscopy

The study of cells has given rise to an important branch of biology known as **cell biology**. Cells can now be studied by many different methods, but scientists began simply by looking at them, using various types of microscope.

There are two fundamentally different types of microscope now in use: the light microscope and the electron microscope. Both use a form of radiation in order to create an image of the specimen being examined. The light microscope uses light as a source of radiation, while the electron microscope uses electrons, for reasons which are discussed later.

Light microscopy

The 'golden age' of light microscopy could be said to be the 19th century. Microscopes had been available since the beginning of the 17th century but, when dramatic improvements were made in the quality of glass lenses in the early 19th century, interest among scientists became widespread. The fascination of the microscopic world that opened up in biology inspired rapid progress both in microscope design and, equally importantly, in preparing material for examination with microscopes. This branch of biology is known as **cytology**. Figure 1.3 shows how the light microscope works.

By 1900, all the structures shown in Figures 1.4 and 1.5 had been discovered. Figure 1.4 shows the structure of a generalised animal cell and Figure 1.5 the structure of a generalised plant cell as seen with a light microscope. (A generalised cell shows **all** the structures that are typically found in a cell.) Figure 1.6 shows some **actual** human cells and Figure 1.7 shows an actual plant cell taken from a leaf.

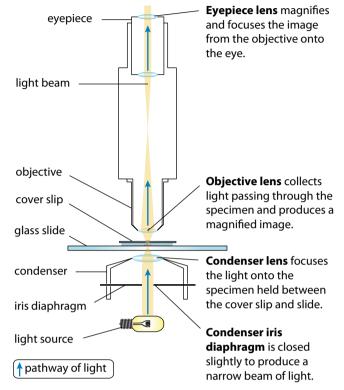


Figure 1.3 How the light microscope works.

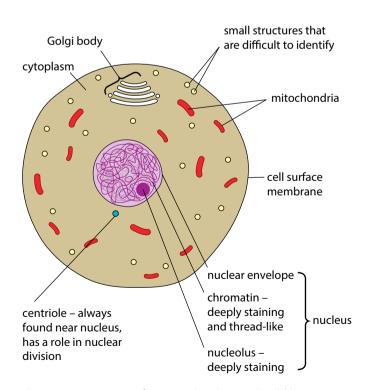


Figure 1.4 Structure of a generalised animal cell (diameter about 20µm) as seen with a very high quality light microscope.

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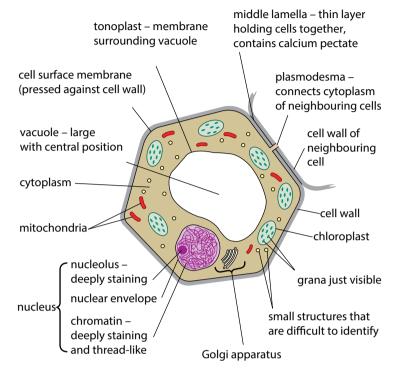


Figure 1.5 Structure of a generalised plant cell (diameter about 40 µm) as seen with a very high quality light microscope.

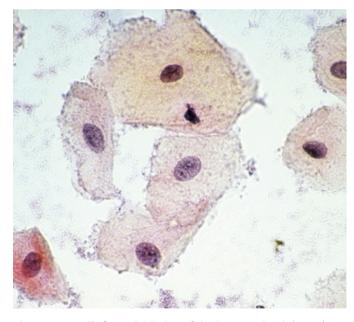


Figure 1.6 Cells from the lining of the human cheek (×400), each showing a centrally placed nucleus, which is a typical animal cell characteristic. The cells are part of a tissue known as squamous (flattened) epithelium.

QUESTION

1.1 Using Figures 1.4 and 1.5, name the structures that animal and plant cells have in common, those found in only plant cells, and those found only in animal cells.

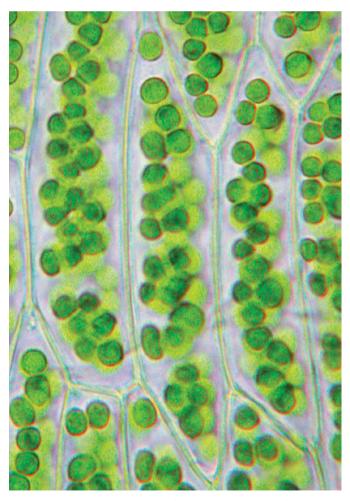


Figure 1.7 Photomicrograph of a cells in a moss leaf (×400).

Animal and plant cells have features in common

In animals and plants each cell is surrounded by a very thin cell surface membrane. This is also sometimes referred to as the plasma membrane.

Many of the cell contents are colourless and transparent so they need to be stained to be seen. Each cell has a **nucleus**, which is a relatively large structure that stains intensely and is therefore very conspicuous. The deeply staining material in the nucleus is called **chromatin** and is a mass of loosely coiled threads. This material collects together to form visible separate chromosomes during nuclear division (page 98). It contains **DNA** (deoxyribonucleic acid), a molecule which contains the instructions that control the activities of the cell (see Chapter 6). Within the nucleus an even more deeply staining area is visible, the **nucleolus**, which is made of loops of DNA from several chromosomes. The number of nucleoli is variable, one to five being common in mammals.

The material between the nucleus and the cell surface membrane is known as cytoplasm. Cytoplasm is an aqueous (watery) material, varying from a fluid to a jelly-like consistency. Many small structures can be seen within it. These have been likened to small organs and hence are known as organelles. An organelle can be defined as a functionally and structurally distinct part of a cell. Organelles themselves are often surrounded by membranes so that their activities can be separated from the surrounding cytoplasm. This is described as compartmentalisation. Having separate compartments is essential for a structure as complex as an animal or plant cell to work efficiently. Since each type of organelle has its own function, the cell is said to show division of labour, a sharing of the work between different specialised organelles.

The most numerous organelles seen with the light microscope are usually **mitochondria** (singular: **mitochondrion**). Mitochondria are only just visible, but films of living cells, taken with the aid of a light microscope, have shown that they can move about, change shape and divide. They are specialised to carry out aerobic respiration.

The use of special stains containing silver enabled the **Golgi apparatus** to be detected for the first time in 1898 by Camillo Golgi. The Golgi apparatus is part of a complex internal sorting and distribution system within the cell (page 15). It is also sometimes called the **Golgi body** or **Golgi complex**.

Differences between animal and plant cells

The only structure commonly found in animal cells which is absent from plant cells is the centriole. Plant cells also differ from animal cells in possessing cell walls, large permanent vacuoles and chloroplasts.

Centrioles

Under the light microscope the **centriole** appears as a small structure close to the nucleus (Figure 1.4, page 3). Centrioles are discussed on page 18.

Cell walls and plasmodesmata

With a light microscope, individual plant cells are more easily seen than animal cells, because they are usually larger and, unlike animal cells, surrounded by a **cell wall** outside the cell surface membrane. This is relatively rigid because it contains fibres of cellulose, a polysaccharide which strengthens the wall. The cell wall gives the cell a definite shape. It prevents the cell from bursting when water enters by osmosis, allowing large pressures to develop inside the cell (page 84). Cell walls may also be reinforced with extra cellulose or with a hard material called lignin for extra strength (page 141). Cell walls are freely permeable, allowing free movement of molecules and ions through to the cell surface membrane.

Plant cells are linked to neighbouring cells by means of fine strands of cytoplasm called **plasmodesmata** (singular: **plasmodesma**), which pass through pore-like structures in their walls. Movement through the pores is thought to be controlled by the structure of the pores.

Vacuoles

Although animal cells may possess small vacuoles such as phagocytic vacuoles (page 87), which are temporary structures, mature plant cells often possess a large, permanent, central vacuole. The plant vacuole is surrounded by a membrane, the tonoplast, which controls exchange between the vacuole and the cytoplasm. The fluid in the vacuole is a solution of pigments, enzymes, sugars and other organic compounds (including some waste products), mineral salts, oxygen and carbon dioxide.

Vacuoles help to regulate the osmotic properties of cells (the flow of water inwards and outwards) as well as having a wide range of other functions. For example, the pigments which colour the petals of certain flowers and parts of some vegetables, such as the red pigment of beetroots, may be located in vacuoles.

Chloroplasts

Chloroplasts are found in the green parts of the plant, mainly in the leaves. They are relatively large organelles and so are easily seen with a light microscope. It is even possible to see tiny 'grains' or **grana** (singular: **granum**) inside the chloroplasts using a light microscope. These are the parts of the chloroplast that contain **chlorophyll**, the green pigment which absorbs light during the process of photosynthesis, the main function of chloroplasts. Chloroplasts are discussed further on page 19.

Points to note

- You can think of a plant cell as being very similar to an animal cell, but with extra structures.
- Plant cells are often larger than animal cells, although cell size varies enormously.
- Do not confuse the cell wall with the cell surface membrane. Cell walls are relatively thick and physically strong, whereas cell surface membranes are very thin. Cell walls are freely permeable, whereas cell surface membranes are partially permeable. All cells have a cell surface membrane.
- Vacuoles are not confined to plant cells; animal cells may have small vacuoles, such as phagocytic vacuoles, although these are not usually permanent structures.

We return to the differences between animal and plant cells as seen using the **electron microscope** on page 13.

Units of measurement

In order to measure objects in the microscopic world, we need to use very small units of measurement, which are unfamiliar to most people. According to international agreement, the International System of Units (SI units) should be used. In this system, the basic unit of length is the **metre** (symbol, **m**). Additional units can be created in multiples of a thousand times larger or smaller, using standard prefixes. For example, the prefix **kilo** means **1000** times. Thus 1 kilometre = 1000 metres. The units of length relevant to cell studies are shown in Table 1.1. It is difficult to imagine how small these units are, but, when looking down a microscope and seeing cells clearly, we should not forget how amazingly small the cells actually are. The smallest structure visible with the human eye is about $50-100 \,\mu\text{m}$ in diameter. Your body contains about $60 \,\text{million}$ million cells, varying in size from about $5 \,\mu\text{m}$ to $40 \,\mu\text{m}$. Try to imagine structures like mitochondria, which have an average diameter of $1 \,\mu\text{m}$. The smallest cell organelles we deal with in this book, ribosomes, are only about $25 \,\text{nm}$ in diameter! You could line up about $20\,000$ ribosomes across the full stop at the end of this sentence.

Electron microscopy

As we said on page 3, by 1900 almost all the structures shown in Figures 1.4 and 1.5 (pages 3 and 4) had been discovered. There followed a time of frustration for microscopists, because they realised that no matter how much the design of light microscopes improved, there was a limit to how much could ever be seen using light.

In order to understand why this is, it is necessary to know something about the nature of light itself and to understand the difference between **magnification** and **resolution**.

Magnification

Magnification is the number of times larger an image is, than the real size of the object.

	magnification = $\frac{\text{observed size of the image}}{\text{actual size}}$
	actual size
or	$M = \frac{I}{A}$

Here I = observed size of the image (that is, what you can measure with a ruler) and A = actual size (that is, the real size – for example, the size of a cell before it is magnified).

If you know two of these values, you can work out the third one. For example, if the observed size of the image and the magnification are known, you can work out the

actual size: $A = \frac{I}{M}$. If you write the formula in a triangle

Fraction of a metre	Unit	Symbol
one thousandth = $0.001 = 1/1000 = 10^{-3}$	millimetre	mm
one millionth = $0.000001 = 1/1000000 = 10^{-6}$	micrometre	μm
one thousand millionth = $0.000000001 = 1/1000000000 = 10^{-9}$	nanometre	nm

Table 1.1 Units of measurement relevant to cell studies: μ is the Greek letter mu; 1 micrometre is a thousandth of a millimetre; 1 nanometre is a thousandth of a micrometre.

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as shown on the right and cover up the value you want to find, it should be obvious how to do the right calculation. Some worked examples are now provided. I M × A

WORKED EXAMPLE 1

Measuring cells

Cells and organelles can be measured with a microscope by means of an **eyepiece graticule**. This is a transparent scale. It usually has 100 divisions (see Figure 1.8a). The eyepiece graticule is placed in the microscope eyepiece so that it can be seen at the same time as the object to be measured, as shown in Figure 1.8b. Figure 1.8b shows the scale over a human cheek epithelial cell. The cell lies between 40 and 60 on the scale. We therefore say it measures 20 eyepiece units in diameter (the difference between 60 and 40). We will not know the actual size of the eyepiece units until the eyepiece graticule scale is calibrated.

To calibrate the eyepiece graticule scale, a miniature transparent ruler called a **stage micrometer** scale is placed on the microscope stage and is brought into focus. This scale may be etched onto a glass slide or printed on a transparent film. It commonly has subdivisions of 0.1 and 0.01 mm. The images of the two scales can then be superimposed as shown in Figure 1.8c.

In the eyepiece graticule shown in the figure, 100 units measure 0.25 mm. Hence, the value of each eyepiece unit is:

$$\frac{0.25}{100} = 0.0025 \,\mathrm{mm}$$

Or, converting mm to µm:

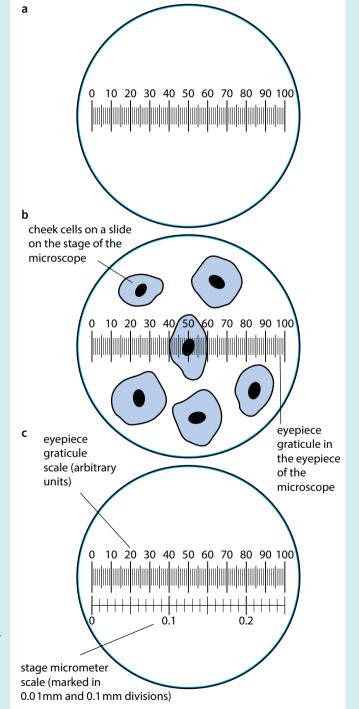
$$\frac{0.25 \times 1000}{100} = 2.5 \mu m$$

The diameter of the cell shown superimposed on the scale in Figure 1.8b measures 20 eyepiece units and so its actual diameter is:

$$20 \times 2.5 \,\mu m = 50 \,\mu m$$

This diameter is greater than that of many human cells because the cell is a flattened epithelial cell.

Figure 1.8 Microscopical measurement. Three fields of view seen using a high-power (×40) objective lens. **a** An eyepiece graticule scale. **b** Superimposed images of human cheek epithelial cells and the eyepiece graticule scale. **c** Superimposed images of the eyepiece graticule scale and the stage micrometer scale.



WORKED EXAMPLE 2

Calculating the magnification of a photograph or image

To calculate *M*, the magnification of a photograph or an object, we can use the following method.

Figure 1.9 shows two photographs of a section through the same plant cells. The magnifications of the two photographs are the same. Suppose we want to know the magnification of the plant cell labelled P in Figure 1.9b. If we know its actual (real) length we can calculate its magnification using the formula

$M = \frac{I}{A}$

The real length of the cell is $80\,\mu$ m. **Step 1** Measure the length in mm of the cell in the photograph using a ruler. You should find that it is about 60 mm.

Step 2 Convert mm to μ m. (It is easier if we first convert all measurements to the same units – in this case micrometres, μ m.)

	$1mm = 1000\mu m$
so	$60\text{mm} = 60 \times 1000\mu\text{m}$
	=60000µm
Step 3	Use the equation to calculat

Step 3 Use the equation to calculate the magnification.

magnification, $M = \frac{\text{image size, }I}{\text{actual size, }A}$ = $\frac{60\,000\,\mu\text{m}}{80\,\mu\text{m}}$ = $\times 750$

The multiplication sign in front of the number 750 means 'times'. We say that the magnification is 'times 750'.

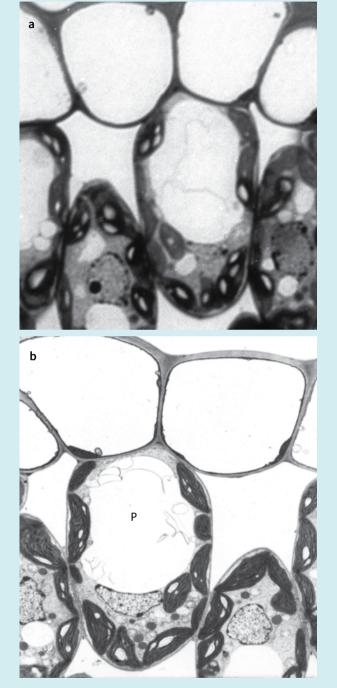


Figure 1.9 Photographs of the same types of plant cells seen **a** with a light microscope, **b** with an electron microscope, both shown at a magnification of about ×750.

QUESTION

- **1.2 a** Calculate the magnification of the drawing of the animal cell in Figure 1.4 on page 3.
 - **b** Calculate the actual (real) length of the chloroplast labelled **X** in Figure 1.29 on page 21.

WORKED EXAMPLE 3

Calculating magnification from a scale bar Figure 1.10 shows a lymphocyte.

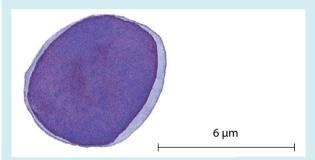


Figure 1.10 A lymphocyte.

We can calculate the magnification of the lymphocyte by simply using the scale bar. All you need to do is measure the length of the scale bar and then substitute this and the length it represents into the equation.

- **Step 1** Measure the scale bar. Here, it is 36 mm.
- **Step 2** Convert mm to µm:
 - $36\,\text{mm} = 36 \times 1000\,\mu\text{m} = 36\,000\,\mu\text{m}$
- **Step 3** Use the equation to calculate the magnification:

magnification, $M = \frac{\text{image size, }I}{\text{actual size, }A}$ = $\frac{36\,000\,\mu\text{m}}{6\,\mu\text{m}}$ = ×6000

WORKED EXAMPLE 4

Calculating the real size of an object from its magnification

To calculate A, the real or actual size of an object, we can use the following method.

Figure 1.27 on page 19 shows parts of three plant cells magnified ×5600. One of the chloroplasts is labelled 'chloroplast' in the figure. Suppose we want to know the actual length of this chloroplast.

Step 1 Measure the observed length of the image of the chloroplast (I), in mm, using a ruler. The maximum length is 40 mm.

 $\textbf{Step 2} \ \ \text{Convert} \ mm \ to \ \mum:$

 $40 \text{ mm} = 40 \times 1000 \mu \text{m} = 40000 \mu \text{m}$ Step 3 Use the equation to calculate the actual length:

> actual size, $A = \frac{\text{image size, } I}{\text{magnification, } M}$ = $\frac{40\,000\,\mu\text{m}}{5600}$ = 7.1 μ m (to one decimal place)

BOX 1.1: Making temporary slides

Background information

Biological material may be examined live or in a preserved state. Prepared slides contain material that has been killed and preserved in a life-like condition. This material is often cut into thin sections to enable light to pass through the structures for viewing with a light microscope. The sections are typically stained and 'mounted' on a glass slide, forming a permanent preparation.

Temporary preparations of fresh material have the advantage that they can be made rapidly and are useful for quick preliminary investigations. Sectioning and staining may still be carried out if required. Sometimes macerated (chopped up) material can be used, as when examining the structure of wood (xylem). A number of temporary stains are commonly used. For example, iodine in potassium iodide solution is useful for plant specimens. It stains starch blueblack and will also colour nuclei and cell walls a pale yellow. A dilute solution of methylene blue can be used to stain animal cells such as cheek cells.

Viewing specimens yourself with a microscope will help you to understand and remember structures more fully. This can be reinforced by making a pencil drawing on good quality plain paper, using the guidance given later in Chapter 7 (Box 7.1, page 129). Remember always to draw what you see, and not what you think you should see.

Procedure

The material is placed on a clean glass slide and one or two drops of stain added. A cover slip is carefully lowered over the specimen to protect the microscope lens and to help prevent the specimen from drying out. A drop of glycerine mixed with the stain can also help prevent drying out.

Suitable animal material: human cheek cells Suitable plant material: onion epidermal cells, lettuce epidermal cells, *Chlorella* cells, moss leaves

Resolution

Look again at Figure 1.9 (page 8). Figure 1.9a is a **light micrograph** (a photograph taken with a light microscope, also known as a **photomicrograph**). Figure 1.9b is an **electron micrograph** of the same specimen taken at the same magnification (an electron micrograph is a picture taken with an electron microscope). You can see that Figure 1.9b, the electron micrograph, is much clearer. This is because it has greater resolution. **Resolution** can be defined as the ability to distinguish between two separate points. If the two points cannot be **resolved**, they will be seen as one point. In practice, resolution is the amount of detail that can be seen – the greater the resolution, the greater the detail.

The maximum resolution of a light microscope is 200 nm. This means that if two points or objects are closer together than 200 nm they cannot be distinguished as separate.

It is possible to take a photograph such as Figure 1.9a and to magnify (enlarge) it, but we see no more detail; in other words, we do not improve resolution, even though we often enlarge photographs because they are easier to see when larger. With a microscope, magnification up to the limit of resolution can reveal further detail, but any further magnification increases blurring as well as the size of the image.

Resolution is the ability to distinguish between two objects very close together; the higher the resolution of an image, the greater the detail that can be seen.

Magnification is the number of times greater that an image is than the actual object;

magnification = image size ÷ actual (real) size of the object.

The electromagnetic spectrum

How is resolution linked with the nature of light? One of the properties of light is that it travels in waves. The length of the waves of visible light varies, ranging from about 400 nm (violet light) to about 700 nm (red light). The human eye can distinguish between these different wavelengths, and in the brain the differences are converted to colour differences. (Colour is an invention of the brain!)

The whole range of different wavelengths is called the **electromagnetic spectrum**. Visible light is only one part of this spectrum. Figure 1.11 shows some of the parts of the electromagnetic spectrum. The longer the waves, the lower their frequency (all the waves travel at the same speed, so imagine them passing a post: shorter waves pass at higher frequency). In theory, there is no limit to how short or how long the waves can be. Wavelength changes with energy: the greater the energy, the shorter the wavelength.

Now look at Figure 1.12, which shows a mitochondrion, some very small cell organelles called ribosomes (page 15) and light of 400 nm wavelength, the shortest visible wavelength. The mitochondrion is large enough to interfere with the light waves. However, the ribosomes are far too small to have any effect on the light waves. The general rule is that the limit of resolution is about one half the wavelength of the radiation used to view the specimen. In other words, if an object is any smaller than half the wavelength of the radiation used to view it, it cannot be seen separately from nearby objects. This means that the best resolution that can be obtained using a microscope that uses visible light (a light microscope) is 200 nm, since the shortest wavelength of visible light is 400 nm (violet light). In practice, this corresponds to a maximum useful magnification of about 1500 times. Ribosomes are approximately 25 nm in diameter and can therefore never be seen using light.

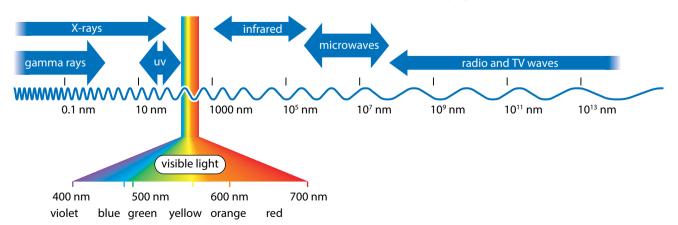


Figure 1.11 Diagram of the electromagnetic spectrum (the waves are not drawn to scale). The numbers indicate the wavelengths of the different types of electromagnetic radiation. Visible light is a form of electromagnetic radiation. The arrow labelled uv is ultraviolet light.