1 Introduction to cell biology

Key features of cells

- All organisms are composed of cells, which can only arise from the division of pre-existing cells.
- Differences in the structures of cells and their molecules allow all organisms to be classified into one of three domains: the Archaea, Bacteria, or the Eucarya.
- The Archaea and Eucarya are the most closely related of all three domains.
- Eucarya possess nuclei, mitochondria, and chloroplasts that are thought to have evolved from bacterial ancestors.
- The fabric of all cells is similar; they contain, for example, carbohydrates, nucleic acid, proteins, and lipids.

1.1 THE DISCOVERY OF CELLS

Living cells (Figure 1.1) were first observed by the Dutch linen merchant Leeuwenhoek who observed unicellular organisms in pond water, and later blood cells, oral bacteria, and spermatozoa.

- His remarkable observations were made using self-made microscopes with almost spherical lenses only about 1 mm in diameter but capable of magnifications of 300–500× (Figure 1.2).
The discovery of cells

Figure 1.1 Human cervical adenocarcinoma (HeLa) cells viewed by confocal microscopy. Courtesy of Olympus Corporation, UK.

• Leeuwenhoek reported his initial findings to the Royal Society of London in 1674; the term cell had been used in 1665 by the Society’s curator, Hooke, to describe the empty cell walls of cork (Figure 1.3), and this name became an established term.

• Progress in cell biology was initially slow because of the poor resolution of microscopes, lack of technical equipment, and a suitable paradigm in which new findings could be incorporated.

• In 1831, Brown, using an improved type of microscope, observed the nucleus, which controls the activities and development and is the largest structure in many cells.

• In 1838 and 1839, Schleiden and Schwann working independently proposed that all organisms are composed of cells.

• In 1858, Virchow, using the findings and conclusions of Remak, stated that ‘all cells arise from other cells’ and firmly established the cell theory.

Figure 1.2 A Leeuwenhoek microscope.
Hence by the beginning of the twentieth century, biologists had established the importance of cells to biological studies.

In 1937, Chatton used the terms *eukaryotique* to describe those cells with nuclei and *prokaryotique* for those without nuclei, such as bacteria.

The cell theory, Darwin’s theory of evolution by natural selection, and the elucidation of the structure and role of deoxyribonucleic acid (DNA) by Crick and Watson, form the three great unifying ideas of modern biology.

Developments in technical equipment, particularly since the 1950s, have allowed cell biology to progress to its present high state of knowledge, although much remains to be discovered.

### 1.2 CLASSIFICATION OF ORGANISMS

Despite cells being the basic structural and functional unit of all organisms, differences between them are sufficient to classify organisms into different groups.

Woese and co-workers, for example, examined the sequences of a ribosomal ribonucleic acid (RNA) (the 16 S RNA; see Chapters 5 and 6) from different organisms and concluded they comprised three phylogenetic domains:

1. Archaea
2. Eucarya
3. Bacteria.

Subsequently, the determination of the sequences of nucleic acids from many species has produced a vast amount of data that has been essential in determining the evolutionary relationships between these groups.

These data suggest that the Bacteria and Eucarya domains are distinct groups that diverged from a last universal common ancestor (LUCA) and that domain Archaea is more closely related to domain Eucarya and separate from the Bacteria domain (Figure 1.4).

![Classification of organisms](image)
Archaea

The domain Archaea consists of prokaryotic organisms.

- Prokaryotic cells are surrounded by a surface membrane and are encased in a cell wall, while the interior is generally undifferentiated cytoplasm containing the genetic material as a single, freely suspended chromosome (Figure 1.5).

Figure 1.4 Phylogenetic tree showing evolutionary relationships between representative members of the three domains.

• Archaea can be distinguished from bacteria, which are also prokaryotic, because of differences in their cell walls and membranes (Chapter 3), and because their molecular biology is more like that of eukaryotes than bacteria (Chapter 5).
• Archaea were originally found occupying ecological niches characterized by extremes: for example, high temperatures (the extreme thermophilic organism), high concentrations of salts (halophiles), or an environment that is extremely chemically reducing in nature (methanogens).
• Archaea consist of two groups:
  1. Crenarchaeota, which contains the extreme thermophiles.
  2. Euryarchaeota, which contains the halophiles and methanogens.
• Archaea are now thought to also occur in more ‘normal’ conditions.

**Eucarya**

Eucarya are composed of eukaryotic cells that possess a **nucleus**.

• Their cells are surrounded by a plasma membrane and most types are encased in a cell wall.
• The cytoplasm of eukaryotic cells contains an **endomembrane system** (Chapters 8 and 9) and discrete structures limited by membranes called **organelles** that have specific function(s); cytoplasm surrounding the endomembrane system and organelles is called the **cytosol** (Figure 1.6).
• Eucarya include many of the commonly seen groups of organisms, for example, plants, animals, seaweeds, and fungi as well as diverse groups of microorganisms such as protozoa (Figure 1.4).

**Bacteria**

Bacteria consist of prokaryotic organisms that superficially appear similar to archaea (Figure 1.7) but are distinguishable from them by differences in their membranes, biochemistry, and molecular biology (Chapters 4 and 5).

• In some cases, the cytoplasm of bacterial cells is divided into microcompartments by infoldings of the surface membrane or shells of proteins.
• Bacteria comprise at least 23 distinct groups of microorganisms that vary in their metabolisms and the ecological niches they occupy.
• Individual species of bacteria were initially classified on the basis of differences in the shapes of their cell, for example, bacilli are rod-shaped, cocci spherical, and spirochetes helical. However, bacterial cells share many common features (Chapter 4).

**Major differences between archaea, eucarya, and bacteria**

Visually, archaenal and bacterial cells appear similar because both types are composed of prokaryotic cells and are of similar sizes.
Thrive in Cell Biology

- Archaeal and bacterial cells differ from eukaryotic cells in generally being smaller and not having a nucleus or other organelles, although this is no longer regarded as a strong taxonomic character, and the two groups are thought to be widely different in their evolutionary lineages (Figure 1.4).

- In terms of their biochemistry and molecular biology, archaia and eucarya are the more closely related groups, although bacterial and eukaryotic cells also share a number of features (Table 1.1).

Classification of organisms

![Classification of organisms diagram](image)

Figure 1.6 (A) Schematic illustrations of a typical eukaryotic (i) animal and (ii) plant cell. (B) Electron micrograph of a human monocyte (a type of lymphocyte). Note the numerous intracellular compartments compared with Figures 1.5 and 1.7. Courtesy of Dr A. Curry, Public Health Laboratory, Withington Hospital, Manchester, UK.
**Classification of organisms**

*Figure 1.7* Electron micrograph of rod-shaped bacterial cells. Courtesy of Dr I.D.J. Burnett, National Institute for Medical Research, London, UK. Compare with Figures 1.5 and 1.6, and Figure 4.1 in Chapter 4.

### Table 1.1 Major differences between archaeal, eukaryotic, and bacterial cells

Differences and similarities between archaea, bacteria, and eukaryotes are highlighted in Chapters 3–7.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Archaea</th>
<th>Eucarya</th>
<th>Bacteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleus</td>
<td>Not present</td>
<td>Present (Chapter 6)</td>
<td>Not present</td>
</tr>
<tr>
<td>Organelles</td>
<td>Not present</td>
<td>Present</td>
<td>Not present</td>
</tr>
<tr>
<td>Cell diameter (μm)</td>
<td>1–10</td>
<td>10–100</td>
<td>1–10</td>
</tr>
<tr>
<td>Chromosomes</td>
<td>Circular and associated with histone-like proteins (Chapter 4)</td>
<td>Linear chromosomes associated with histones (Chapter 6)</td>
<td>Circular chromosome associated with bacterial proteins (Chapter 4)</td>
</tr>
<tr>
<td>Reproduction</td>
<td>Binary division (Chapter 5)</td>
<td>Mitosis and meiosis (Chapter 16)</td>
<td>Binary division (Chapter 5)</td>
</tr>
<tr>
<td>RNA polymerase</td>
<td>Single enzyme with 8–12 subunits (Chapter 5)</td>
<td>Three specific eukaryotic enzymes with 12–14 subunits (Chapter 6)</td>
<td>Single, specific bacterial enzyme with 4 subunits (Chapter 5)</td>
</tr>
<tr>
<td>Post-transcriptional activities</td>
<td>Moderate (Chapter 5)</td>
<td>Extensive (Chapter 6)</td>
<td>Some (Chapter 5)</td>
</tr>
<tr>
<td>Ribosomes</td>
<td>70 S (Chapter 5)</td>
<td>80 S (Chapter 7)</td>
<td>70 S (Chapter 5)</td>
</tr>
<tr>
<td>Translation initiated by</td>
<td>Methionine (Chapter 5)</td>
<td>Methionine (Chapter 7)</td>
<td>Formylmethionine (Chapter 5)</td>
</tr>
<tr>
<td>Translation requires</td>
<td>Multiple initiation and elongation factors</td>
<td>Multiple initiation and elongation factors</td>
<td>Two initiation and three elongation factors</td>
</tr>
<tr>
<td>Cytoskeleton</td>
<td>Actin- and tubulin-type proteins present</td>
<td>Actin, intermediate filaments, and tubulin proteins present (Chapter 7)</td>
<td>Actin- and tubulin-type proteins present (Chapter 4)</td>
</tr>
<tr>
<td>Membrane lipids (Chapter 3)</td>
<td>Branched polyprenyl glycerol esters</td>
<td>Phosphoacylglycerols Sphingomyelins Glycolipids Sterols</td>
<td>Phosphoacylglycerols</td>
</tr>
<tr>
<td>Flagella and cilia</td>
<td>Archaeal types (Chapter 4)</td>
<td>Eukaryotic 9 + 2 types (Chapter 7)</td>
<td>Bacterial types (Chapter 4)</td>
</tr>
</tbody>
</table>

Chapter 1 Introduction to cell biology
Evolution of cells

1.3 EVOLUTION OF CELLS

The earth was formed about 4.5 billion years ago; conditions compatible with life are thought to have occurred within 200 to 300 million years.

- The initial atmosphere was reducing in nature, containing large quantities of dinitrogen (N₂), methane (CH₄), dihydrogen (H₂), and carbon dioxide.
- Various types of energy, such as lightning, ultraviolet solar radiation, or volcanic heat could have caused components of the atmosphere to react and form a variety of organic compounds now associated with organisms.
- It is thought that life began with a group(s) of molecules that were capable of catalysing their self-replication.
- Given that RNA molecules can store genetic information and catalyse a number of biological reactions, it has been suggested that these earliest self-replicating systems consisted of RNA molecules: a so-called RNA world.
- Self-replicating RNA molecules could have recruited amino acids and peptides, which would have improved their catalytic powers and been selected for, leading to the present protein-rich biosphere.
- Fossil evidence shows microbial life was present 3.5 billion years ago and had possibly evolved much earlier, with LUCA first appearing approximately 4 billion years ago. This cell is generally thought to have lacked a nucleus and organelles.
- A number of hypotheses have been proposed to explain the origin of eukaryotic cells including the fusion of two or three different types of prokaryotic cells.
- Eukaryotes possess a number of unique characteristics but also some archaeal and bacterial ones.

Check your understanding

1.1 Which of the following statements is/are true and which is/are false?
   a. Leeuwenhoek was the first to observe and use the term cell.
   b. Virchow was the first to realize all cells are derived from pre-existing cells using the phrase ‘all cells arise from other cells’.
   c. Differences in the sequences of nucleic acids suggest that bacteria and archaea are more closely related to each other than are the archaea and eucarya.
   d. Archaea were first discovered in extreme types of environments.
   e. Nuclei are not present in archaea and bacteria.
Composition of cells

- For example, eukaryotic genes are partly of the bacterial type and partly of the archaeal type, implying a mixed ancestry.
- Generally, genes with nuclear functions (informational genes) have archaeal characteristics; those whose products have cytoplasmic metabolic and ‘housekeeping’ functions possess bacterial features.
- One hypothesis to explain this distribution is that the nucleus arose from an archaeon that consumed hydrogen to synthesize methane and which formed an endosymbiotic relationship with a host bacterial cell that produced hydrogen by fermentation. The bacterial genes were eventually transferred into the archaeon, which evolved to become the nucleus.
- Alternatively, the nucleus may have arisen from invaginations of the bacterial surface membrane; to date, no idea has been fully accepted.
- Approximately 2.4 billion years ago, oxygenic photosynthesis began converting the atmosphere from one rich in methane and hydrogen to one containing large amounts of dioxygen ($O_2$).
- Oxygen-using organelles such as mitochondria (Chapter 11) and peroxisomes (Chapter 12) must have been acquired after that date.
- Although the evolutionary origins of the nucleus are debatable, mitochondria and chloroplasts definitely arose from bacteria.
- The ancestor of mitochondria was an aerobic bacterial endosymbiont of an anaerobic host.
- Plants evolved later when a mitochondrial-containing cell (or at least one with a mitochondrial precursor) acquired a cyanobacterium-like endosymbiont that became the ancestor of chloroplasts.
- Hydrogenosomes and mitosomes (Chapter 11) evolved later from mitochondria as secondary adoptions to anaerobic environments.
- Despite differences in structure and evolutionary origins, all cells have extremely similar compositions.

The evolution of different organelles is revised in Chapters 6 and 10–12.

Check your understanding

1.2 The more primitive a biological structure, the earlier it appeared during evolution. With this in mind, which two of the three domains are considered the most primitive?

1.4 COMPOSITION OF CELLS

Cells are largely composed of water and a variety of inorganic minerals and organic constituents.

- Cells are composed of approximately 60–70% water, most of which is not free but associated with macromolecules.
Composition of cells

- The major minerals present are K\(^+\), Mg\(^{2+}\), and phosphate and sulphate ions (P\(_i\) and S\(_i\)).
- In multicellular organisms, the extracellular fluid surrounding cells is rich in Na\(^+\), Cl\(^-\), and HCO\(_3^-\).
- The major organic compounds are:
  - carbohydrates
  - nucleotides and nucleic acids
  - amino acids and proteins
  - lipids.
- Some carbohydrates, nucleic acids, and proteins are macromolecules: these have a relative molecular mass, \(M_r\), in excess of approximately 5000.
- Biological macromolecules are polymers, which are constructed by covalently linking much smaller units together in condensation reactions (Figure 1.8).
- Polymeric carbohydrates are formed by linking simple sugars together; nucleic acids are polymers of nucleotides, and proteins are polymers of amino acids.

\[
\begin{align*}
R - \text{OH} & + \text{HO} - R' \\
\text{H}_2\text{O} & \text{H}_2\text{O} \\
R - O = R' & (\text{Ether link}) \\
\text{R} - C = O & + \text{HO} - R' \\
\text{H}_2\text{O} & \text{H}_2\text{O} \\
R - C - O = R' & (\text{Ester link}) \\
\text{R} - C = O & + \text{H}^+ + \text{H}^- \text{N} - R' \\
\text{H}_2\text{O} & \text{H}_2\text{O} \\
R - C - N - R' & (\text{Amide link})
\end{align*}
\]

*Figure 1.8* Examples of condensation reactions used in forming biological macromolecules.
Composition of cells

- The units within the polymer are called residues; linking two together gives a dimer, three a trimer, and so on to eventually form a polymer that may contain hundreds or thousands of residues.
- Lipids are not macromolecules but in aqueous environments can aggregate to form large structures such as droplets or lipid bilayers (Figure 3.3).

Revision tip
Explore the structures of macromolecules with the easy to use Jmol molecular modelling program at the Protein Data Base: http://www.rcsb.org/pdb/home/home.do

- Details of the structures and functions of some of these biological molecules can be obtained from the companion volumes of this series and in the ‘Further reading’ listed on the dedicated website.

See the companion volumes Thrive in Biochemistry and Molecular Biology and Thrive in Genetics for a detailed revision of biological molecules.

Revision tip
Do browse through the further reading references given for this chapter online. Go to http://www.oxfordtextbooks.co.uk/orc/thrive/

Check your understanding
1.3 Which of the following statements is/are true and which is/are false?
   a. Archaea and bacteria can be distinguished by differences in their cell walls, ribosomes, and biochemistry.
   b. All present-day organisms are thought to have evolved from self-replicating molecules.
   c. Mitochondria are thought to have evolved from the domain Bacteria.
   d. Within the Eucarya, genes with nuclear functions generally have bacterial characteristics but the products of those with archael features normally have cytoplasmic metabolic and ‘housekeeping’ functions.
   e. The major intracellular cations are Na$^+$ and Mg$^{2+}$, and the major one in the extracellular fluid of multicellular organisms is K$^+$. 

Chapter 1 Introduction to cell biology 11