A1 Prokaryotic cells

Key Notes

The origin and evolution of cells	All organisms on Earth evolved from a common ancestor. In the prebiotic era, simple organic molecules formed and spontaneously polymerized into macromolecules. These macromolecules then acquired the ability to self-replicate and catalyze other reactions, before being enclosed within a membrane to form the first cell. Present-day cells are divided into three main groups: bacteria, archaea and eukaryotes.
Prokaryotes	Prokaryotes are the most abundant organisms on Earth and fall into two distinct groups, the bacteria (or eubacteria) and the archaea (or archaebacteria). A prokaryotic cell does not contain a membrane-bound nucleus.
Prokaryote cell structure	Each prokaryotic cell is surrounded by a plasma membrane. The cell has no subcellular organelles. The deoxyribonucleic acid (DNA) is condensed within the cytosol to form the nucleoid.
Bacterial cell walls	The peptidoglycan (protein and oligosaccharide) cell wall protects the prokaryotic cell from mechanical and osmotic pressure. Some antibiotics, such as penicillin, target enzymes involved in the synthesis of the cell wall. Gram-positive bacteria have a thick cell wall surrounding the plasma membrane, whereas Gram-negative bacteria have a thinner cell wall and an outer membrane, between which is the periplasmic space.
Bacterial flagella	Some prokaryotes have tail-like flagella. By rotation of their flagella, bacteria can move through their surrounding media in response to chemicals (chemotaxis). Bacterial flagella are made of the protein flagellin that forms a long filament whose rotation is driven by a flow of protons through the flagellar motor proteins.
Related topics	(A2) Eukaryotic cells (B1) Amino acid structure (B5) Molecular motors (E1) Membrane lipids (E2) Membrane structure (F2) Genes and chromosomes (L2) Electron transport and oxidative phosphorylation

The origin and evolution of cells

Despite the huge variety of living systems, all organisms on Earth are remarkably uniform at the molecular level, indicating that they have evolved from a **common ancestor**. Life first emerged at least 3.8 billion years ago, although how life originated and how the first cell came into existence are matters of speculation. Experiments have shown that simple organic molecules can form and spontaneously polymerize into macromolecules under the conditions thought to exist in primitive Earth's atmosphere, the so-called **prebiotic era.** The next critical step was the ability of the macromolecules to **self-replicate,** as seen with the present-day nucleic acids, and to catalyze other reactions, as demonstrated for ribonucleic acid (**RNA**) (Section G1). The first cell is presumed to have arisen by the enclosure of the self-replicating RNA in a **membrane** composed of **phospholipids** (Section E1), thus separating the interior of the cell from its external environment. The encapsulated macromolecules would thus have been maintained as a unit, capable of self-reproduction and further evolution to give rise to the variety of life forms found on Earth today. The analysis of the deoxyribonucleic acid (**DNA**) sequences (Section F1) of organisms has allowed a possible evolutionary path from a common ancestral cell to the present-day cells and organisms to be deduced (Figure 1).

The living world therefore has three major divisions or domains: **bacteria**, **archaea**, and **eukaryotes** (Section A2). The bacteria are the commonly encountered prokaryotes in soil, water and living in or on larger organisms, and include *Escherichia coli* (*E. coli*) and the *Bacillus* species, as well as the cyanobacteria (photosynthetic blue-green algae). The archaea mainly inhabit unusual environments such as salt brines, hot acid springs, and the ocean depths, and include the sulfur bacteria and the methanogens, although some are found in less hostile environments.

Prokaryotes

Prokaryotes are the most numerous and widespread organisms on Earth, and are so classified because they have no defined membrane-bound nucleus. Prokaryotes comprise two separate but related groups: the bacteria (or eubacteria) and the archaea (or archaebacteria). These two distinct groups of prokaryotes diverged early in the history of life on Earth (Figure 1).

Prokaryote cell structure

Prokaryotes generally range in size from 0.1 to 10 μm, and have one of three basic shapes: spherical (cocci), rod-like (bacilli) or helically coiled (spirilla). Like all cells, a prokaryotic

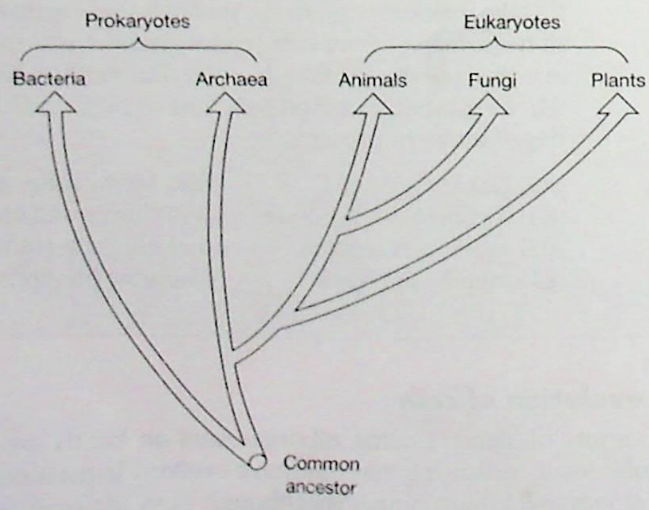

Figure 1. Evolution of cells.

cell is bounded by a **plasma membrane** that completely encloses the cytosol and separates the cell from the external environment (Figure 2). The plasma membrane, which is about 8 nm thick, consists of a lipid bilayer containing proteins (Sections E1 and E2). Prokaryotes lack the membranous subcellular organelles characteristic of eukaryotes (Section A2). The aqueous cytosol contains the macromolecules [enzymes, messenger ribonucleic acid (mRNA), transfer RNA (tRNA) and ribosomes], organic compounds and ions needed for cellular metabolism. Also within the cytosol is the prokaryotic 'chromosome' consisting of a single circular molecule of DNA, which is condensed to form a body known as the **nucleoid** (Figure 2) (Section F2).

Bacterial cell walls

To protect the cell from mechanical injury and osmotic pressure, most prokaryotes are surrounded by a rigid 3–25 nm-thick **cell wall** (Figure 2). The cell wall is composed of **peptidoglycan**, a complex of **oligosaccharides** and **proteins**. The oligosaccharide component consists of linear chains of alternating *N*-acetylglucosamine (GlcNAc) and *N*-acetylmuramic acid (NAM) linked β1–4 (Section J1). Attached via an amide bond to the lactic acid group on NAM is a **D-amino acid**-containing tetrapeptide. Adjacent parallel peptidoglycan chains are covalently cross-linked through the tetrapeptide side-chains by other short peptides. The extensive cross-linking in the peptidoglycan cell wall gives it its strength and rigidity. The presence of D-amino acids in the peptidoglycan renders the cell wall resistant to the action of **proteases**, which act on the more commonly occurring L-amino acids (Section B1), but provides a unique target for the action of certain **antibiotics** such as **penicillin**. Penicillin acts by inhibiting the enzyme that forms the covalent cross-links in the peptidoglycan, thereby weakening the cell wall. The β1–4 glycosidic linkage between NAM and GlcNAc is susceptible to hydrolysis by the enzyme **lysozyme**, which is present in tears, mucus and other body secretions.

Bacteria can be classified as either **Gram-positive** or **Gram-negative** depending on whether they take up the **Gram stain**. Gram-positive bacteria (e.g. *Bacillus polymyxa*) have a thick (25 nm) cell wall surrounding their plasma membrane, whereas Gram-negative bacteria (e.g. *E. coli*) have a thinner (3 nm) cell wall and a second **outer membrane** (Figure 3). In contrast with the plasma membrane, this outer membrane is very

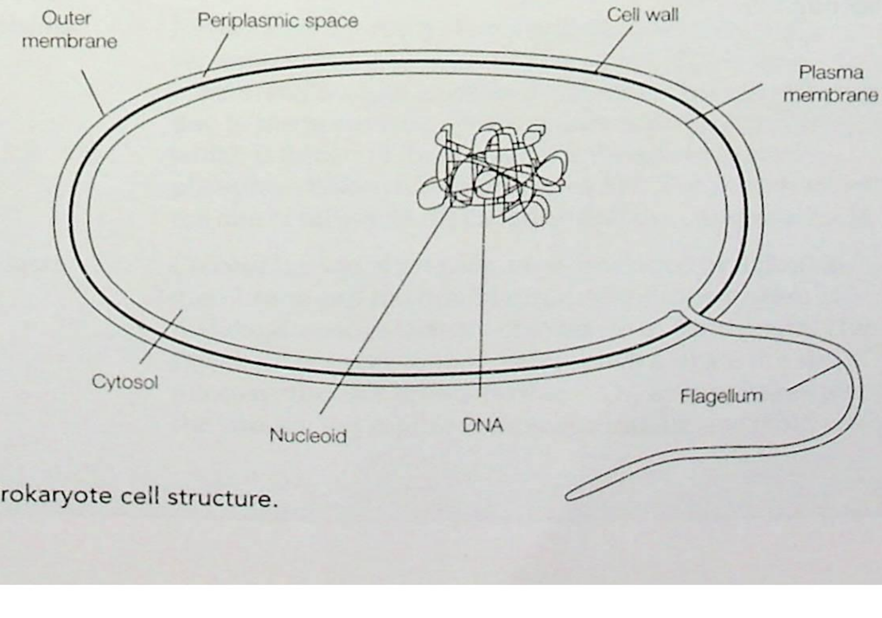

Figure 2. Prokaryote cell structure.

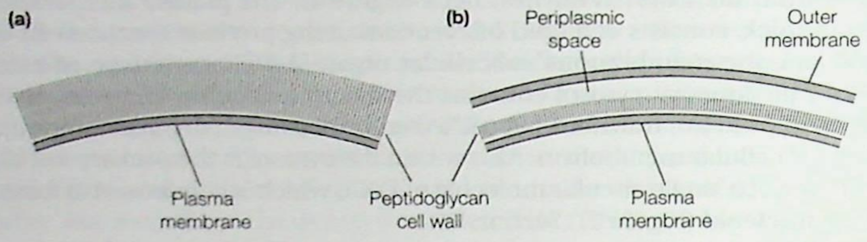

Figure 3. Cell wall structure of (a) Gram-positive and (b) Gram-negative bacteria.

permeable to the passage of relatively large molecules (molecular weight >1000 Da) due to **porin proteins**, which form pores in the lipid bilayer (Section E3). Between the outer membrane and the cell wall is the **periplasm**, a space occupied by proteins secreted from the cell.

Bacterial flagella

Many bacterial cells have one or more tail-like appendages known as **flagella**. By **rotating** their flagella, bacteria can move through the extracellular medium towards attractants and away from repellents, so called **chemotaxis**. Bacterial flagella are different from eukaryotic cilia and flagella in two ways: 1. each bacterial flagellum is made of the protein **flagellin** (53 kDa subunit) as opposed to tubulin (Section B5); and 2. it **rotates** rather than bends. An *E. coli* bacterium has about six flagella that emerge from random positions on the surface of the cell. Flagella are thin helical filaments, 15 nm in diameter and 10 μm long. Electron microscopy has revealed that the **flagellar filament** contains 11 subunits in two helical turns, which, when viewed end-on, has the appearance of an 11-bladed propeller with a hollow central core. Flagella grow by the addition of new flagellin subunits to the end away from the cell, with the new subunits diffusing through the central core. At its base, situated in the plasma membrane, is the **flagellar motor**, an intricate assembly of 40 or so proteins. The rotation of the flagella is driven by a flow of protons through certain proteins of the flagellar motor. A similar proton-driven motor is found in the F_0F_1-adenosine triphosphatase (ATPase) that synthesizes adenosine triphosphate (ATP) (Section L2).

A2 Eukaryotic cells

Key Notes

Eukaryotes	Eukaryotic cells have a membrane-bound nucleus and a number of other membrane-bound subcellular (internal) organelles, each of which has a specific function.
Plasma membrane	The plasma membrane surrounds the cell, separating it from the external environment. The plasma membrane is a selectively permeable barrier due to the presence of specific transport proteins and has receptor proteins that bind specific ligands. It is also involved in the processes of exocytosis and endocytosis.
Nucleus	The nucleus stores the cell's genetic information as DNA in chromosomes. It is bounded by a double membrane but pores in this membrane allow molecules to move in and out of the nucleus. The nucleolus within the nucleus is the site of ribosomal RNA synthesis.
Endoplasmic reticulum	This interconnected network of membrane vesicles is divided into two distinct parts. The rough endoplasmic reticulum (RER), which is studded with ribosomes, is the site of membrane and secretory protein biosynthesis and their post-translational modification. The smooth endoplasmic reticulum (SER) is involved in phospholipid biosynthesis and in the detoxification of toxic compounds.
Golgi apparatus	The Golgi apparatus is a system of flattened membrane-bound sacs. It receives membrane vesicles from the RER, further modifies the proteins within them, and then packages the modified proteins in other vesicles, which eventually fuse with the plasma membrane or other subcellular organelles.
Mitochondria	Mitochondria have an inner and an outer membrane separated by the intermembrane space. The outer membrane is more permeable than the inner membrane due to the presence of porin proteins. The inner membrane, which is folded to form cristae, is the site of oxidative phosphorylation, which produces ATP. The central matrix is the site of fatty acid degradation and the citric acid cycle.
Chloroplasts	Chloroplasts in plant cells are surrounded by a double membrane and have an internal membrane system of thylakoid vesicles that are stacked up to form grana. The thylakoid vesicles contain chlorophyll and are the site of photosynthesis. Carbon dioxide (CO_2) fixation takes place in the stroma, the soluble matter around the thylakoid vesicles.

Lysosomes	Lysosomes in animal cells are bounded by a single membrane. They have an acidic internal pH (pH 4–5), maintained by proteins in the membrane that pump in H^+ ions. Within the lysosomes are acid hydrolases – enzymes involved in the degradation of macromolecules, including those internalized by endocytosis.
Peroxisomes	Peroxisomes contain enzymes involved in the breakdown of amino acids and fatty acids, a byproduct of which is hydrogen peroxide. This toxic compound is rapidly degraded by the enzyme catalase, also found within the peroxisomes.
Cytosol	The cytosol is the soluble part of the cytoplasm where a large number of metabolic reactions take place, e.g. glycolysis, gluconeogenesis, fatty acid synthesis. Within the cytosol is the cytoskeleton.
Cytoskeleton	The cytoskeleton is an internal scaffold that controls the shape and movement of the cell and the organelles within it. The cytoskeleton consists of microfilaments, intermediate filaments and microtubules. Microfilaments are 5–9 nm diameter helical polymers of the protein actin that have a mechanically supportive function in the cell. Intermediate filaments are 7–11 nm diameter rope-like fibers made from a family of intermediate filament proteins that provide mechanical strength and resistance to shear stress. Microtubules are hollow cylinders of 25 nm diameter made of the protein tubulin. The mitotic spindle involved in separating the chromosomes during cell division is made of microtubules. Colchicine and vinblastine inhibit microtubule formation, whereas taxol stabilizes microtubules. Through interfering with mitosis, some of these compounds are used as anticancer drugs.
Plant cell wall	The cell wall surrounding a plant cell is made up of the polysaccharide cellulose. In wood, the phenolic polymer called lignin gives the cell wall additional strength and rigidity.
Plant cell vacuole	The membrane-bound vacuole is used to store nutrients and waste products, has an acidic pH and, due to the influx of water, creates turgor pressure inside the cell as it pushes out against the cell wall.
Related topics	(A1) Prokaryotic cells (E4) Membrane transport: macromolecules (F2) Genes and chromosomes (H4) Protein targeting

Eukaryotes

Eukaryotes include species as diverse as animals, plants, fungi and slime molds. In all eukaryotes the cell is surrounded by a **plasma membrane**, has a **membrane-bound nucleus** and contains a number of other distinct **subcellular organelles** (Figure 1). These organelles are membrane-bounded structures, each having a unique role and each containing a specific complement of proteins and other molecules. The key differences between eukaryotic and prokaryotic cells (Section A1) are listed in Table 1. Animal and plant cells have the same basic structure, although some organelles and structures are found in one and not the other (e.g. chloroplasts, vacuoles and cell wall in plant cells, lysosomes in animal cells).

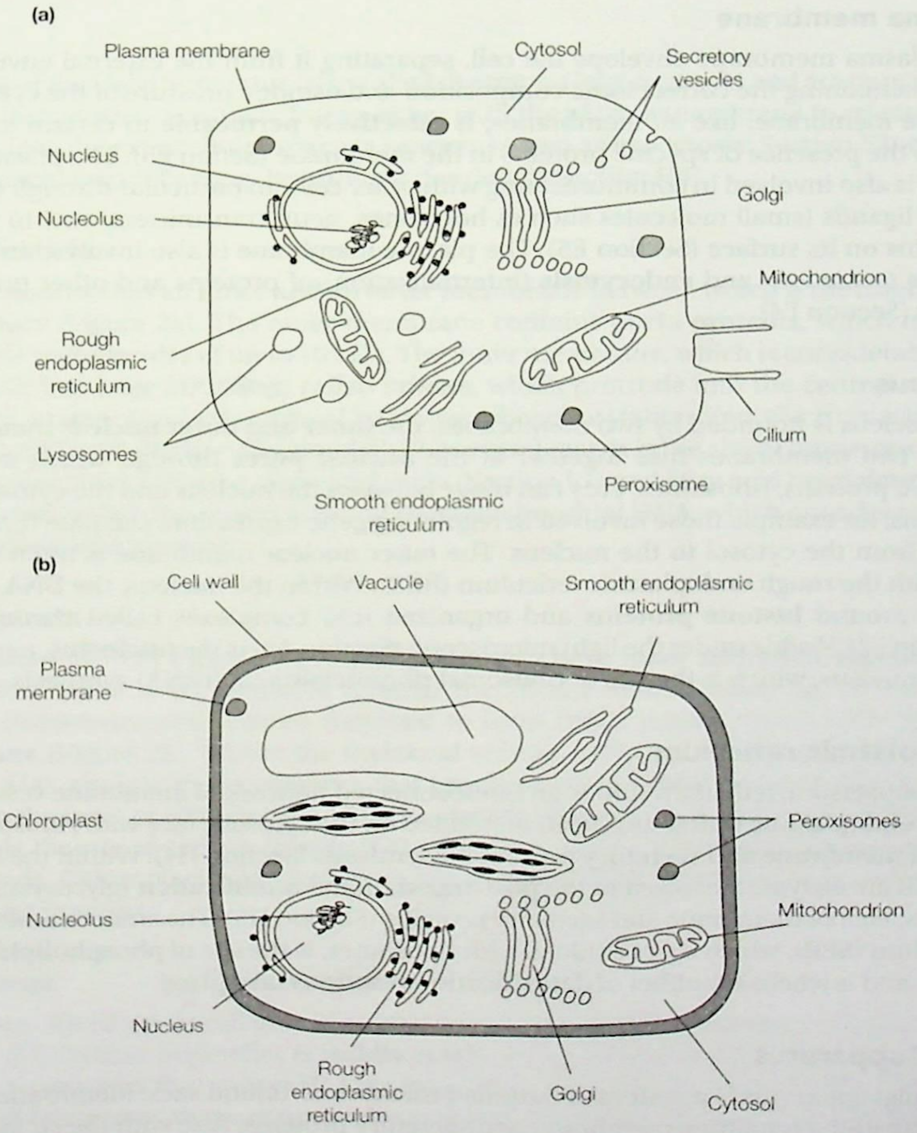

Figure 1. Eukaryote cell structure: (a) structure of a typical animal cell; (b) structure of a typical plant cell.

Table 1. The key differences between eukaryotic and prokaryotic cells

Characteristic	Prokaryote	Eukaryote
Diameter	Approx. 1 μm	10–100 μm
Nucleus	Absent	Present
Cytoplasmic organelles	Absent	Present
DNA content (base pairs)	1×10^6 to 5×10^6	1.5×10^7 to 5×10^9
Chromosomes	Single circular DNA molecule	Multiple linear DNA molecules

Plasma membrane

The plasma membrane envelops the cell, separating it from the external environment and maintaining the correct ionic composition and osmotic pressure of the cytosol. The plasma membrane, like all membranes, is **selectively permeable** to certain molecules due to the presence of specific proteins in the membrane (Setion E3). The plasma membrane is also involved in communicating with other cells, in particular through the binding of ligands (small molecules such as hormones, neurotransmitters, etc.) to **receptor proteins** on its surface (Section E5). The plasma membrane is also involved in the **exocytosis** (secretion) and **endocytosis** (internalization) of proteins and other macromolecules (Section E4).

Nucleus

The nucleus is bounded by two membranes, the **inner and outer nuclear membranes**. These two membranes fuse together at the **nuclear pores** through which molecules (mRNA, proteins, ribosomes, etc.) can move between the nucleus and the cytosol. Other proteins, for example those involved in regulating gene expression, can pass through the pores from the cytosol to the nucleus. The outer nuclear membrane is often continuous with the rough endoplasmic reticulum (RER). Within the nucleus, the **DNA** is tightly coiled around **histone proteins** and organized into complexes called **chromosomes** (Section F2). Visible under the light microscope (Section A4) is the **nucleolus**, a subregion of the nucleus, which is the site of ribosomal ribonucleic acid (rRNA) synthesis.

Endoplasmic reticulum

The endoplasmic reticulum (ER) is an interconnected network of membrane vesicles. The **rough endoplasmic reticulum** (RER) is studded on the cytosolic face with **ribosomes**, the sites of **membrane and secretory protein biosynthesis** (Section H4). Within the lumen of the RER are enzymes involved in the **post-translational modification** (glycosylation, proteolysis, etc.) of membrane and secretory proteins (Section H5). The **smooth endoplasmic reticulum** (SER), which is not studded with ribosomes, is the site of **phospholipid biosynthesis**, and is where a number of **detoxification reactions** take place.

Golgi apparatus

The Golgi apparatus is a system of flattened membrane-bound sacs. Membrane vesicles from the RER, containing membrane and secretory proteins, fuse with the *cis* face of the Golgi apparatus and release their contents into it. On transit through the Golgi apparatus, further **post-translational modifications** to these proteins take place and they are then sorted and packaged into different vesicles (Section H5). These vesicles bud off from the

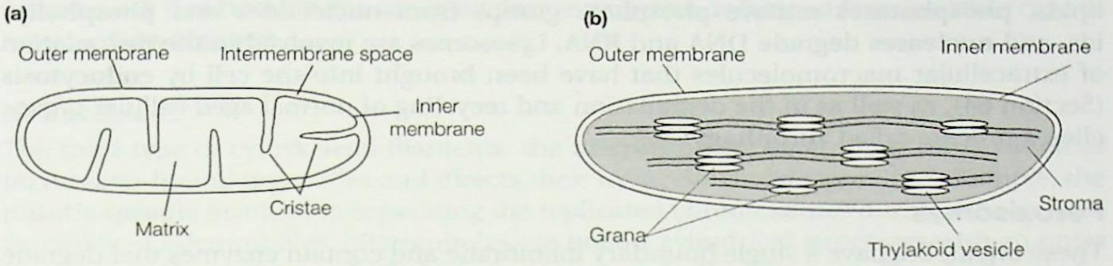

Figure 2. Structure of (a) a mitochondrion and (b) a chloroplast.

trans face of the Golgi apparatus (also called the trans-Golgi network) and are transported through the cytosol, eventually fusing either with the plasma membrane to release their contents into the extracellular space (a process known as **exocytosis**; Section E4) or with other internal organelles (e.g. lysosomes) (for details Section H4).

Mitochondria

A mitochondrion has an **inner and an outer membrane** between which is the **intermembrane space** (Figure 2a). The outer membrane contains **porin proteins**, which make it permeable to molecules of up to 10 kDa. The inner membrane, which is considerably less permeable, has large infoldings called **cristae**, which protrude into the **central matrix**. The inner membrane is the site of oxidative phosphorylation and electron transport involved in ATP production (Section L2). The central matrix is the site of numerous metabolic reactions including the citric acid cycle (Section L1) and fatty acid breakdown (Section K2). Also within the matrix is found the mitochondrial DNA, which encodes some of the mitochondrial proteins.

Chloroplasts

Chloroplasts, present exclusively in plant cells, also have **inner and outer membranes**. In addition, there is an extensive internal membrane system made up of **thylakoid vesicles** (interconnected vesicles flattened to form disks) stacked upon each other to form **grana** (Figure 2b). Within the thylakoid vesicles is the green pigment **chlorophyll** (Section M4), along with the enzymes that trap light energy and convert it into chemical energy in the form of ATP (Section L3). The **stroma**, the space surrounding the thylakoid vesicles, is the site of carbon dioxide (CO_2) fixation – the conversion of CO_2 into organic compounds. Chloroplasts, like mitochondria, contain DNA, which encodes some of the chloroplast proteins.

Lysosomes

Lysosomes, which are found only in animal cells, have a single boundary membrane. The internal pH of these organelles is **mildly acidic** (pH 4–5), and is maintained by integral membrane proteins that pump H^+ ions into them (Section E3). The lysosomes contain a range of hydrolases that are optimally active at this acidic pH (and hence are termed **acid hydrolases**) but which are inactive at the neutral pH of the cytosol and extracellular fluid. These enzymes are involved in the degradation of host and foreign macromolecules into their monomeric subunits; **proteases** degrade proteins, **lipases** degrade