Preface

Life in the Solar System and beyond is a subject that includes the study of life on Earth, but particularly the possibility of life elsewhere. It is of enormous interest and widespread significance, not least because of the progress that has been made in recent decades in our understanding of life on Earth, and of the potential for life existing elsewhere. At present, with no firm evidence as yet for extraterrestrial life, the study of life beyond the Earth is concerned with the location and study of possible habits, not only within the Solar System but outside it too. It is a wide-ranging subject, embracing aspects of all the core areas of science – astronomy, planetary science, chemistry, biology, and physics. This breadth is a challenge for authors and readers alike. Another challenge is the rapid pace of development of the subject, and it is hoped that the websites included in Resources at the end of the book will help us all keep up to date.

I have written a broad introduction to 'life in the Universe', a subject that is variously known as bioastronomy and astrobiology, though increasingly as the latter. The text is aimed at people with some background in science, though not much, given the breadth of science that astrobiology draws on. The readership could include science undergraduates, graduates with little previous knowledge of the field, and the interested non-specialist, including the amateur astronomer. A basic knowledge of atoms and the chemical elements will help, as will familiarity with graphs and with simple algebraic expressions and equations.

In studying the book it will benefit you to absorb the summaries at the end of each chapter – these are intended to encapsulate the main points to carry forward. There are also a few end of chapter questions. These are not comprehensive in their coverage, but are intended to illustrate how various topics can be progressed – they require more than recall. Full answers are given at the back of the book to all the questions set.

The chapters are arranged as follows. Chapter 1 is a broad introduction to the cosmos, with an emphasis on where we might find life out there. In Chapters 2 and 3 we discuss life on Earth, the one place we know to be inhabited, which provides us with an essential guide in our search. Chapter 4 is a brief tour of the Solar System, leading us in Chapters 5 and 6 to two promising potential habitats, Mars and Europa. Each of these worlds, and their exploration for life now or in the past, has separate chapters devoted to them. In Chapter 7 we meet the fate of life in the Solar System, which gives us extra reason to consider life further afield. Chapter 8 focuses on the types of stars that might host habitable planets, and where in the Galaxy these might be concentrated. Chapters 9 and 10 describe the instruments and techniques being employed to discover planets of other stars (exoplanetary systems), and those that will be employed in the near future. In Chapter 11 a summary is given of the known exoplanetary systems, and an outline of the sort of systems we expect to discover soon, particularly those containing habitable planets. Chapter 12 describes how we will attempt to find life on these planets, and Chapter 13, the final chapter, brings us to the search for extraterrestrial intelligence, to where we wonder whether we are alone.

2

Life on Earth

The Earth is the only place where we know that life exists. We must use terrestrial organisms as an indicator of what it is we are looking for. This will guide us towards the extraterrestrial locations that have the greatest chance of being inhabited. In this chapter we look at life on Earth today. In the next chapter we consider how it has evolved from the earliest organisms, and how these earliest organisms originated. But first we look briefly at the Earth itself.

2.1 THE EARTH

2.1.1 The Earth's interior

The interior of the Earth is better known than that of any other planetary body. This is because of the wealth of gravitational, seismic, and other data. Figure 2.1 shows a segment of the Earth reaching down to its centre, where the temperature is about 4000°C. The main compositional division is between the iron-rich core and the silicate-rich mantle and crust. The core extends a little over half way to the Earth's surface, but accounts for only one-sixth of the volume. It is divided into an inner core that is solid, and an outer core that is liquid. The outer core is actually slightly cooler than the inner core, so it might surprise you that it, and not the inner core is liquid. This is partly because of the increase in pressure with depth, and partly because of a slight compositional difference – whereas the inner core is almost entirely made up of iron plus a few percent nickel, the outer core contains a few percent of additional constituents, perhaps iron sulphide (FeS) or even iron hydrides (FeH_x). The melting point of the outer core is lower for both reasons. The outer core is the source of the Earth's magnetic field. This is because it is an electrical conductor, a liquid, and in motion due to a combination of heat from the inner core plus the Earth's rotation.

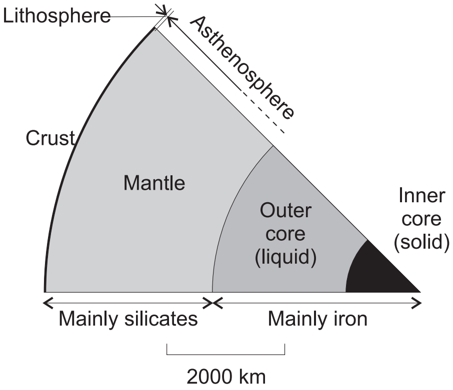


Figure 2.1 A model of the Earth's interior, showing the main divisions by chemical composition.

The Earth's interior was originally heated and partially melted by the gravitational energy released as planetesimals and embryos came together, and by the decay of short-lived radioisotopes, notably one of aluminium, ^{26}Al, perhaps provided by a supernova in the region of the Solar System's birth. Any downward separation (differentiation) of the iron core would have provided further heating. Subsequently, and in addition to residual primordial heat, long-lived radioisotopes, particularly of uranium (^{235}U, ^{238}U), potassium (^{40}K), and thorium (^{232}Th), have sustained the high internal temperatures. A source of heat that could be crucial to keeping the outer core moving, is the growth of the inner core at the expense of the outer core. Without this, the Earth might have no magnetic field. This would make the Earth's surface less habitable – the magnetic field deflects energetic charged particles from space.

Outside the core silicates predominate (compounds of one or more metallic elements with the abundant elements silicon and oxygen). The mantle reaches from the core almost to the Earth's surface, and is fairly homogeneous in composition. The upper mantle consists almost entirely of pyroxene ($(\mathrm{Ca,Fe,Mg})_2\mathrm{Si}_2\mathrm{O}_6$) and olivine ($(\mathrm{Mg,Fe})_2\mathrm{SiO}_4$), and though in the lower mantle the crystalline form is different, the chemical mix is much the same. At a typical depth of about 10 km the crust is encountered, also dominated by silicates, but substantially different from those in the mantle. In particular, the crustal silicates are richer in calcium and aluminium, and poorer in iron and magnesium. The crust has been derived from the mantle by partial melting, and is less dense than the mantle.

2.1.2 The Earth's crust, lithosphere, and plate tectonics

The crust itself has a compositional division into oceanic and continental forms (Figure 2.2). As these names imply, they are predominantly found respectively under the oceans and making up the continents. However, it is only a coincidence that the volume of the oceans raises sea level approximately to where the division occurs. The mix of silicates that makes up oceanic crust is loosely referred to as

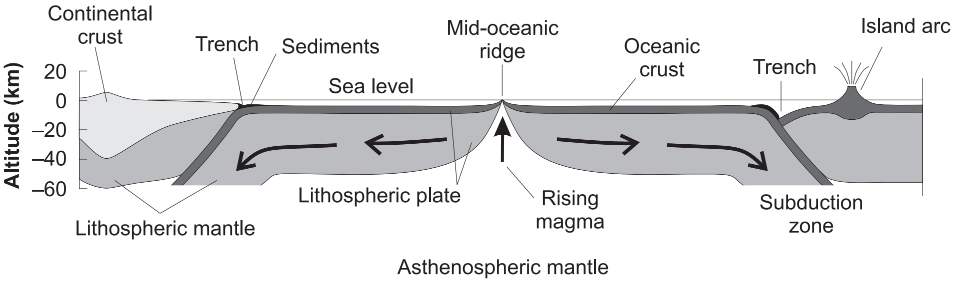


Figure 2.2 A section through the Earth's crust and upper mantle, showing the main features associated with plate tectonics.

basalt, or of basaltic composition. Overall, these silicates are richer in magnesium and iron than those that constitute continental crust, though they are still short of the proportions found in the mantle.

The partial melting that produces the crust and that promotes the creation of the two crustal types is driven by *plate tectonics*, briefly outlined in Section 1.1.3. The crust is fairly rigid, and so too is the upper few tens of kilometres of the mantle. Together, these constitute the lithosphere (Figure 2.2). The lithosphere is underlain by a much less rigid layer, extending from about 50 km downwards, perhaps to the core, called the asthenosphere. The lithosphere is divided into a few dozen plates, of various sizes, and these move over the asthenosphere. At some plate boundaries the plates are moving apart, with fresh oceanic crust appearing from partial melting of the mantle. At others they are just sliding sideways, and at others the plates push together, with one of them being reincorporated into the mantle, at what is called a subduction zone. If one of the plates at a subduction zone carries continental crust then the partial melting will create more continental crust. There are thus great cycles of plate motion, on timescales of tens of millions of years, where the continental crust is trundled around the globe, deforming, assembling, breaking up, and growing in volume. Volcanism, and other forms of geological activity, are thus maintained at a high level.

The immediate cause of plate motion is convection in the mantle. Most of the mantle is solid, so this is solid-state convection, facilitated by the high pressures and temperatures in the mantle, and by the plasticity of a partially molten zone at the top of the asthenosphere. Convection is sustained today by the heat from long-lived radioisotopes plus residual primordial heat. For the plates to move in response to convection it is essential that the continental crust is flexible, otherwise the plates would jam. It might also be necessary for water to be present in the crust – compounded in rocks, it lowers their melting points.

2.1.3 Atmosphere, oceans, and biosphere

The Earth's atmosphere has the composition shown in Table 2.1, where the number fraction of each component is given – this is the fraction of all the molecules in the

Table 2.1. The main constituents of the Earth's atmosphere.

	N_2	O_2	H_2O	Ar	CO_2
Number fraction	0.78	0.21	0.01 (mean)	0.0093	0.000 345
Partial pressure (Pa)	0.79×10^5	0.21×10^5	10^3	940	34.9

atmosphere contributed by the component. The mean pressure at sea level is 1.013×10^5 pascal (Pa), which is 1013 millibars, or 1.013 bars. This is the sum of the partial pressures of each component, also given in Table 2.1. The partial pressure is proportional to the number fraction. For example, the partial pressure of O_2 at sea level is $0.21 \times 1.013 \times 10^5\,\text{Pa} = 0.21 \times 10^5\,\text{Pa}$. Atmospheric pressure declines rapidly with altitude, so that at the modest altitude of 2 km it is already as low as 7.95×10^4 Pa, and at 20 km it is only 5.5×10^3 Pa – for all its importance to life the atmosphere is just a thin veneer. The oceans are intimately coupled with the atmosphere, chemically and physically, and account for most of the water above the base of the crust. There are traces in the mantle, that, because of the mantle's huge volume, could exceed the quantity in the oceans.

The global mean surface temperature (GMST) is 15°C, and most of the time in most places it is between 0°C and 35°C. The GMST is the outcome of the balance between the energy gains by the surface of a planet, and its energy losses. If you imagine the energy gains being switched on then the temperature of the surface rises until the losses balance the gains. The losses consist of infrared radiation emitted by the surface by virtue of its temperature, plus the heat convected away through the atmosphere. The gains consist of the absorbed fraction of solar radiation (the fraction not reflected back to space by the surface, clouds, and atmosphere), plus the absorbed fraction of the infrared radiation emitted by the atmosphere. The GMST would be lower but for the *greenhouse effect*. This is the name given to the phenomenon whereby the surface temperature of a planet is raised because the atmosphere absorbs some of the infrared radiation emitted by the surface and reradiates a proportion back to the surface. Water vapour and CO_2 are responsible for nearly all of the Earth's greenhouse effect, without which the GMST would be −18°C, and much or all of the surface would be uninhabitable.

The atmosphere also shields life on Earth from damaging ultraviolet (UV) radiation from the Sun. This it does through the presence of a trace of ozone (O_3) high in the atmosphere. The ozone is derived from O_2 by the action of UV radiation.

Life on Earth constitutes the *biosphere*, the assemblage of all things living and their remains. Plate 14 shows a typical scene of life on Earth. It is neither herds on the African plains, nor a rain forest, nor an ocean teeming with fish, but single celled creatures, unicellular creatures, 1–100 μm (10^{-6}–10^{-4} m) across. The *cell* is the basic unit of life, an enclosed environment within which the processes of life are conducted. The membrane that encloses the cell regulates the exchange of substances between the cell and its environment. There is a great variety of unicellular creatures, with bacteria as a very large group. One type of bacterium is shown in Plate 14, which also shows a group of non-bacterial single cells. There are also multicellular creatures – plants, and animals being particularly familiar. The human body contains about 10^{13} cells, aggregated into various organs – heart, liver, and so on.

Although there are different types of cell, all contain the same sorts of chemical compounds. We shall first outline what sort of compounds these are, then go on to consider how they are organised within cells, and then we shall look at the fundamental processes of life.

2.2 THE CHEMICALS OF LIFE

Table 2.2 shows the composition of a typical mammalian cell in terms of the broad types of chemical compounds it contains. Though cells differ somewhat in the proportions of their different compounds, Table 2.2 gives the correct impression that any living cell consists mainly of water, with proteins as another prominent component. Except for water and inorganic ions, the cell is made up of organic compounds. These are carbon compounds containing hydrogen. They were originally named because of their association with life, though many organic compounds are abiological. Life on Earth is characterised by a special selection of organic compounds, mostly with large complex molecules, and by water. Moreover, the water has to be liquid over at least part of the cell's life cycle, and therefore *carbon–liquid water life* is an apt name for life on Earth. Water is needed as a solvent, a transport medium, and as a participant in biochemical reactions.

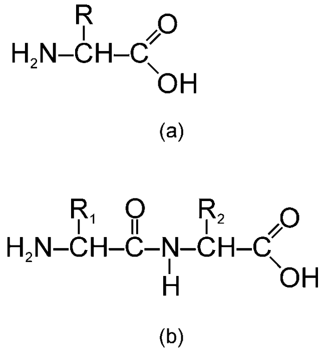
In terms of chemical elements, life is dominated by C, H, O, and N. In an organism the number fractions have representative values 63% H, 28% O, 7% C, and 2% N. At significant fractions of a percent are calcium and phosphorus, and as traces there are many other elements.

2.2.1 Proteins and nucleic acids

Proteins are large, complex organic compounds. About 100 000 different proteins have been identified in terrestrial organisms, and between them they fulfil a wide range of functions – structural, transport, storage, and catalysis of biochemical reactions. They are made up of many units, where each unit is one of about 20 amino acids. Figure 2.3(a) shows the general molecular plan of an *amino acid*. They differ in the nature of 'R'. The simplest is glycine, in which 'R' is a hydrogen atom H. Figure 2.3(b) illustrates the joining of just two amino acids. In

Table 2.2. Chemical composition of a typical mammalian cell.

	Water	Proteins	Lipids	Polysaccharides	Nucleic acids	Small organic molecules	Inorganic ions
Mass (% of total)	70	18	5	2	1	3	1



$$H_2N{-}\overset{R}{\overset{|}{C}}H{-}C(=O){-}OH$$

(a)

$$H_2N{-}\overset{R_1}{\overset{|}{C}}H{-}\overset{O}{\overset{\|}{C}}{-}\underset{\underset{H}{|}}{N}{-}\overset{R_2}{\overset{|}{C}}H{-}C(=O){-}OH$$

(b)

Figure 2.3 (a) Amino acids, the building blocks of proteins. They differ in the nature of 'R'. (b) Two amino acids joined together.

the joining, a molecule of water would have been liberated. (Note that models like that in Figure 2.3 label the locations of the constituent atoms, and show which atoms are bonded together. The actual atoms are large enough to touch each other, and the bond directions are not necessarily all in the same plane.) A *protein* consists of about 50–1000 amino acids joined together in a string. In some proteins several strings are intertwined but they remain string-like; these are called fibrous proteins, and their function is structural. In other proteins a single string is wound to form a roughly spherical shape. Many of these catalyse biochemical reactions. Such catalysts are called *enzymes*, and without them biochemical reactions would occur far too slowly to sustain life, or would not outpace abiological reaction rates sufficiently to allow life to find a niche. Nearly all enzymes are proteins. The precise geometrical shape of an enzyme determines which biochemical reactions it catalyses. This shape in turn depends on the particular sequence of amino acids that make up the protein. Note that with an 'alphabet' of about 20 letters and a 'word' that is 50–1000 'letters' long, the 100 000 different biological proteins are a *very* small fraction of those that could in principle exist.

The *nucleic acids* are also large, complex organic compounds, and comprise *ribonucleic acid* (*RNA*), and *deoxyribonucleic acid* (*DNA*). These are at the heart of protein synthesis, and are central to the processes by which organisms reproduce themselves. The basic unit of RNA is called a *nucleotide*, and there are four types. Each consists of a molecule of a sugar (ribose), a phosphate group (which contains the element phosphorus), and one of four different organic molecules called bases, as shown in Figure 2.4(a). The base labels A, C, G, and U stand for adenine, cytosine, guanine, and uracyl. Each base is a compound of C, H, and N, and, in some cases, O. To make RNA the units can be joined in any order, as illustrated in Figure 2.4(b). RNA consists of hundreds to tens of thousands of nucleotides in a string, and so a huge variety of RNA sequences is possible. The string might also be folded.

DNA also consists of four nucleotides. These are the same as in RNA except

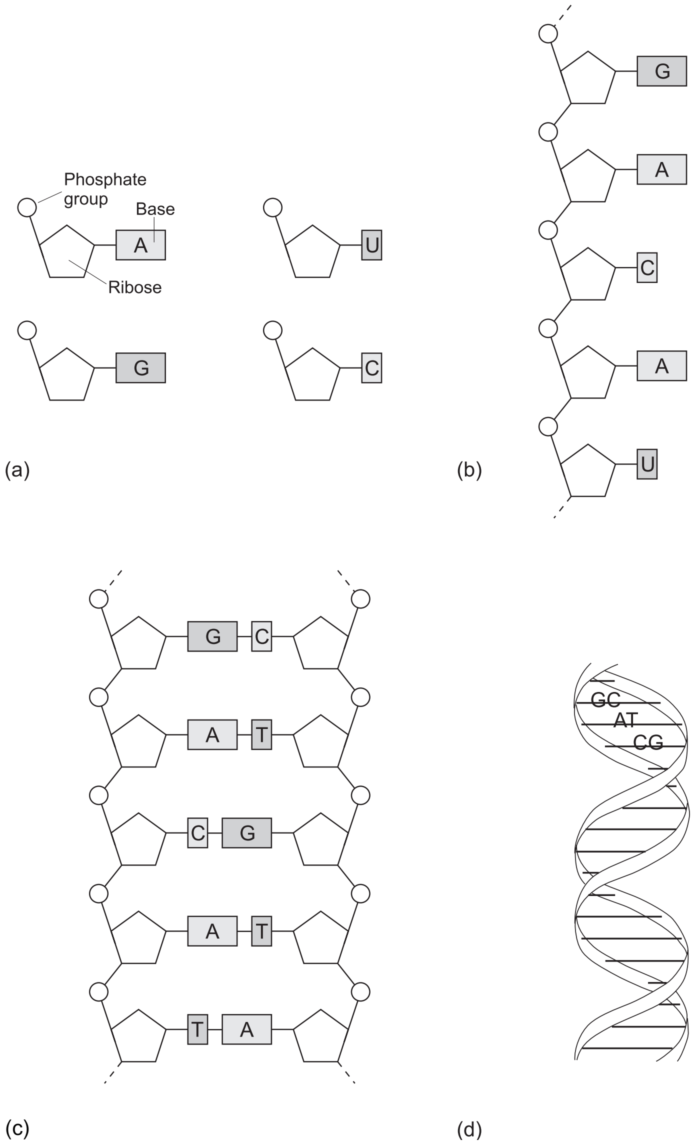


Figure 2.4 The four basic units (nucleotides) of RNA. (b) A short RNA sequence. (c) A short segment of a DNA molecule. (d) The double helix of DNA.

that uracyl is substituted by another base, called thymine (T). Another difference is that in the spine the sugar is deoxyribose rather than ribose. A third difference is illustrated in Figure 2.4(c). There are two strands joined by the bases to form a 'ladder' with 'rungs'. Each rung is either A–T (or T–A), or C–G (or G–C). The rungs can occur in any order, and so, with thousands of rungs, there is a huge number of possible base-pair sequences in a molecule of DNA. The ladder is twisted to form the famous double helix structure of DNA (Figure 2.4(d)). The double helix is not straight but curled up, to give a complex three dimensional structure.

2.2.2 Polysaccharides, lipids, and small molecules

Though polysaccharides are another class of large molecules, they are somewhat simpler than proteins and nucleic acids in that each molecule consists either of hundreds of identical units, or hundreds of just a few different units. Polysaccharide means ‘many sugars’, because each unit is a sugar molecule. There are various sugars, but all of them contain C, H, and O, with common structural features in the molecules that distinguish them from other C, H, and O compounds. Some sugars also contain other elements, such as N, P, and S. The simplest sugar is glucose, with the chemical formula $C_6H_{12}O_6$. Other well known sugars are fructose and sucrose. The term carbohydrate is in common use – this term embraces sugars and polysaccharides. Sugars are far more soluble in water than are most polysaccharides.

In joining sugars together to form a polysaccharide (with the ejection of a water molecule per pair of sugars joined), a great variety of outcomes is possible because of the variety of sugars and the various ways of linking them together. Cellulose, the rigid supporting framework of the cell walls in all plants, is a single string of glucose molecules, whereas starch, the major energy store of plants, though again consisting only of glucose units, is branched in most of its forms.

Unlike proteins, nucleic acids, and polysaccharides, a lipid is not a polymer but a relatively small molecule. For example, the lipid glyceril tristearate has the semistructural formula $(C_{17}H_{35}\text{–}COOCH_2)\text{–}(C_{17}H_{35}COOCH)\text{–}(C_{17}H_{35}\text{–}COOCH_2)$, small by biological standards! The simplest lipids are the fats and oils, the distinction being that oils are liquid at room temperatures whereas fats are solid. Care has to be taken to distinguish the lipids from mineral oils. The latter include compounds of hydrogen and carbon (hydrocarbons), such as paraffin oil, and are not found in cells. Lipids and mineral oils share the property of insolubility in water.

The small organic molecules (Table 2.2) include *adenosine triphosphate* (*ATP*) and *adenosine diphosphate* (*ADP*), where P represents a phosphate group. ATP and ADP play a central role in energy storage and transfer in the cell. There are also many other organic molecules present in small quantities, some of them occurring only in certain types of cell.

Our inventory of chemical compounds in the cell is completed by inorganic ions. Simple inorganic ions result when common salt is dissolved in water. A proportion of the NaCl molecules dissociate to give the positive ion Na^+ and the negative ion Cl^-. There are many other types of ion present.

2.3 THE CELL

The chemicals of life are contained within cells. All life forms on Earth consist of one or more cells. The cell is bounded by a membrane that divides the environment

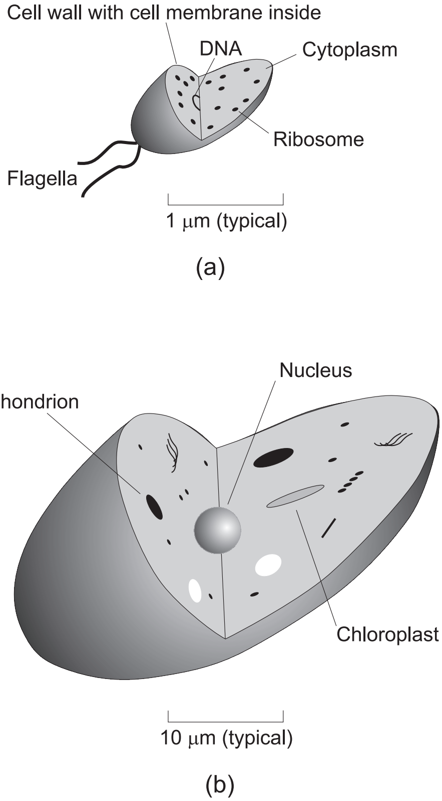


Figure 2.5 The essential components of (a) a prokaryotic cell (b) a eukaryotic cell.

Adapted from Figure 12.4 in *Earth: evolution of a habitable world* by J. I. Lunine, CUP, 1999.

within the cell from the environment outside it, and regulates the transfer of substances between the two. There are two basic types of cell, the prokaryotic cell and the eukaryotic cell. In unicellular organisms the cell can be of either type, whereas almost all multicellular organisms consist of eukaryotic cells. Few prokaryotes are multicellular.

Figure 2.5(a) shows the essential components of the *prokaryotic cell*. The membrane consists of proteins and a class of lipids called phospholipids, and little else. Outside the membrane the great majority of prokaryotes have a cell wall that provides a measure of rigidity. This wall consists of strings of 20–40 amino acids (too short to be classified as proteins) and polysaccharides. The membrane encloses cytosol, a saltwater medium containing proteins. Floating in the cytosol is DNA and small particles called ribosomes that contain RNA. Most prokaryotic cells can move by means of protein strands attached outside the cell wall – these are called flagella.

Figure 2.5(b) shows the essential components of a *eukaryotic cell*. It is typically much larger than the prokaryotic cell, 10–100 μm instead of about 1 μm. It is also much more complex. Of particular note are the various structures inside the cell called organelles. One such is the nucleus, where much (but not all) of the cell's DNA is housed. Another is the mitochondrion, inside which cell respiration occurs (Section 2.4.2). In green plants there are chloroplasts, which are the sites of photosynthesis (Section 2.4.2). Mitochondria and chloroplasts also contain DNA. There are various other organelles and other structures that will not concern us.

In multicellular creatures different cells take on different functions. For example, in animals a nerve cell carries out a different function from a muscle cell or a liver cell. This specialisation comes about during the growth of the organism from a single cell. Most plants cells have a rigid cell wall made of cellulose fibres held together by a glue. By contrast cells in animals have no wall and generally change shape readily.

2.4 THE FUNDAMENTAL PROCESSES OF LIFE

Any living organism on Earth is involved in three processes. First, biosynthesis, in which small organic molecules are constructed, and then combined to form the complex molecules that make up the cell. Second, reproduction, in which cells make copies of themselves, so that life is sustained from one generation to the next. Third, catabolism, in which molecules are broken down into smaller ones.

Each of these processes requires energy transfer. In this respect life is like every other process in the Universe – nothing can happen unless energy is transferred from one place to another, often changing from one form to another. Life also requires the availability of the chemical elements that constitute the various compounds in Table 2.2, but it is energy that reorganises these elements.

2.4.1 Chemical energy

Organisms utilise chemical energy. This is energy that is either stored or released when the configuration of electrons in atoms or molecules is changed. Such changes occur in chemical reactions. A simple chemical reaction is:

$$\mathrm{O} + \mathrm{H} \rightarrow \mathrm{OH} \tag{2.1}$$

In this reaction the electron in the hydrogen atom on the left becomes shared between the two atoms in OH. Overall, the hydrogen has lost sole possession of its electron and the oxygen has gained. The hydrogen is an electron donor, and the oxygen is an electron acceptor. This is an example of a *redox reaction*. These reactions are particularly important because they involve a lot of energy. In Reaction (2.1), the electron transfer lowers the energy of the electron and this energy is released in the form of kinetic energy (energy of motion) of the OH and infrared radiation. A reaction such as this with a net release of energy is called exothermic. Note that a third body needs to be involved in the reaction, to carry away some of the vibrational energy of the newly formed OH, or it will at once dissociate. The reverse reaction:

$$\mathrm{OH} \rightarrow \mathrm{O} + \mathrm{H} \tag{2.2}$$

requires energy to be given to the OH to raise the electron energy in the products O and H. A reaction such as this that results in an increase in the energy stored is called endothermic.

The name 'redox' is a contraction of 'reduction–oxidation'. If an atom or molecule gains electrons it is said to be reduced, with the process of gaining an electron called reduction. If it loses electrons it is said to be oxidised, and the process of loss is called oxidation. Thus, in a chemical reaction involving electron transfer, reduction and oxidation both occur, and hence it is called a redox reaction. In Reaction (2.1) the hydrogen is oxidised and the oxygen is reduced. For the substances involved in redox reactions the following terms are equivalent: electron donor = reducing agent = fuel; electron acceptor = oxidising agent = oxidant.

The terms oxidation and reduction arose many years ago to denote, respectively, the addition of oxygen and the removal of oxygen, but the terms have now been broadened and expressed in terms of electron transfer. There is certainly no need for oxygen to be involved. Thus the reaction:

$$\mathrm{Na} + \mathrm{Cl} \rightarrow \mathrm{NaCl} \tag{2.3}$$

is a redox reaction in which sodium shares an electron with chlorine to form a molecule of common salt.

2.4.2 Energy for the cell

Energy stores and energy release

There is a large variety of ways in which organisms store and release energy, some more widespread than others. First consider how energy is released from its store in the cell. Energy is stored in the form of sugars, polysaccharides, certain lipids, and, rarely, proteins. Energy is derived from these molecules when they are converted to smaller molecules (catabolism). Central to the supply of a cell's energy is ATP (Section 2.2.2). An ATP molecule gives up energy when it is converted to the closely related molecule ADP. Conversely, when energy is given to ADP it turns into ATP. Note that ATP is only a temporary store of energy – it acts as a molecular link between energy released by the breakdown of molecules in a store, and energy required for some process. The energy required to convert one molecule of ADP to ATP – 5.1×10^{-20} joules (J) – is a useful unit of energy currency in a cell, and this can be expressed as the number of molecules of ATP produced.

In almost every organism catabolism happens through a process called respiration. Aerobic respiration uses oxygen, the second most abundant component of the Earth's atmosphere, and also present in the Earth's rivers, lakes, and oceans. Most eukaryotes use oxygen in a chemical reaction that converts the organic materials in the energy store to water and carbon dioxide, releasing energy that forms ATP from ADP. In the case of a store of glucose, a large series of chemical reactions can be summarised as:

$$\mathrm{C_6H_{12}O_6} + 6\mathrm{O_2} \rightarrow 6\mathrm{CO_2} + 6\mathrm{H_2O} \tag{2.4}$$

This is a redox reaction in which the fuel is glucose and the oxidant is oxygen.

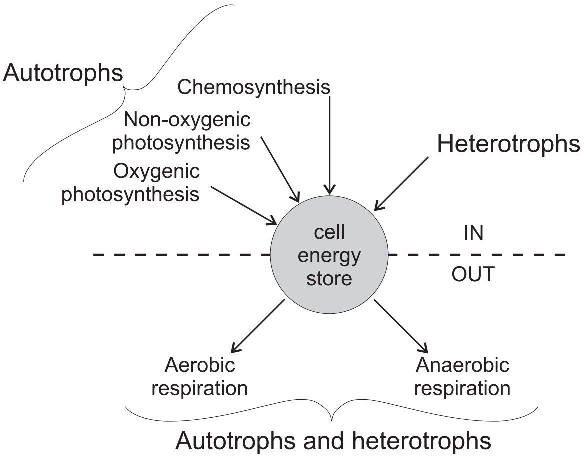


Figure 2.6 Methods of energy storage and release in cells.

There is an alternative to aerobic respiration, and it is essential for organisms intolerant of oxygen. This is called (naturally) anaerobic respiration and it is carried out today in various ways by a variety of unicellular organisms. A familiar example is the fermentation that produces alcohol through the activity of yeasts, which are colonies of unicellular eukaryotes belonging to the kingdom of fungi. Fermentation results in the formation of ATP from ADP through the energy released in the conversion of glucose into ethanol (‘alcohol’) and carbon dioxide. The overall effect of a number of stages is:

$$C_6H_{12}O_6 \rightarrow 2CO_2 + 2C_2H_5OH \qquad (2.5)$$

However, per molecule of glucose, only 2 ATP molecules are produced, whereas with aerobic respiration 36 ATP molecules are produced.

Organisms that require oxygen in some way are called aerobes. The rest are anaerobes, and they divide into those for which oxygen is toxic and those that will use aerobic respiration when oxygen is available. Figure 2.6 displays these two forms of respiration. This Figure also summarises various ways in which energy stores in cells are created, to which we now turn.

Creating energy stores

Where do the sugars, polysaccharides, lipids, and, rarely, proteins, that constitute energy stores, come from? For some unicellular organisms, and many multicellular organisms including animals, the answer is ‘food’ (i.e. organic materials from other organisms, ingested or absorbed, though there might be some processing preceding storage). Humans are particularly omnivorous, obtaining organic matter from a great variety of sources. Organisms that rely on such ready-made organic material are called heterotrophs (‘other-feeders’). Others synthesise them from inorganic compounds. These are the autotrophs (‘self-feeders’) and they lie at the base of the food chains.

Green plants are autotrophs that manufacture organic compounds through the process of *photosynthesis*, in which CO_2 and water are used to make glucose. The CO_2 is the source of carbon. Though the process is complicated, involving several stages, the overall effect in green plants can be summarised as:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \tag{2.6}$$

where the CO_2 has been reduced to form glucose, the electrons coming from H_2O which is oxidised to form oxygen. Oxygen is a by-product, so this is called *oxygenic photosynthesis*. The products (on the right-hand side of the reaction) have more energy than the reactants (on the left-hand side), and therefore some energy source is needed to promote this reaction. This is solar radiation.

Solar radiation, or any other form of electromagnetic radiation, travels through space like a wave, with a wavelength λ and a frequency f, linked by the equation $c = f\lambda$, where c is the speed of the wave, in this case the speed of light. But when electromagnetic radiation interacts with matter, it does so as if it is a stream of particles called *photons*. The energy e of a photon is proportional to the frequency of the wave, and so:

$$e = hf = h\frac{c}{\lambda} \tag{2.7}$$

where h is a universal constant called Planck's constant (see physics texts in Resources). In green plants a molecule called chlorophyll absorbs two photons in the wavelength range 0.4–0.7 μm, and this initiates a complex sequence of events. An important intermediate stage is the conversion of ADP to ATP and the production of a substance called $NADPH_2$ (details of which will not concern us). These two substances are then used to produce glucose and thus build up the energy store. Other substances are produced too, such as amino acids.

Some unicellular organisms also photosynthesise broadly in the above manner. Some prokaryotes do it differently. They perform photosynthesis without generating oxygen by using molecules such as hydrogen sulphide (H_2S) as the electron donor in place of H_2O. This particular example can be summarised schematically as follows:

$$2H_2S + CO_2 + (C) \rightarrow 2\text{`}CH_2O\text{'} + 2S \tag{2.8}$$

CH_2O is the simplest carbohydrate, and is shown in quotes because the actual carbohydrates produced are more complicated. This is less efficient than oxygenic photosynthesis in that it captures a smaller proportion of the energy of the available solar radiation, though it can be utilised by organisms that are intolerant of oxygen. Nevertheless, biosynthesis and respiration benefited greatly from the appearance of oxygen in the Earth's atmosphere, because it made more energy available.

Some autotrophic prokaryotes create energy stores using chemical reactions that do not involve photosynthesis. This is called *chemosynthesis*. In chemosynthesis the organism takes advantage of substances in its environment that can be made to react exothermically within the cell. The energy released is used to make ATP, etc. Even in clear water, at depths greater than only about 100 m, there is insufficient sunlight for photosynthesis and therefore only chemosynthesis is possible. The same is true in underground caves and crevices. Of particular importance, because of their energy yield, are redox reactions. One example among many is the pair of dissolved gases CO_2 and H_2 that emerge from volcanic vents on the ocean floor. At temperatures of about 400°C these gases remain intact, but at lower temperatures they react as follows:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{2.9}$$

However, the reaction rate is extremely low, and so they still persist, allowing certain cells the opportunity to absorb them. Inside the cell the reaction is greatly speeded by the action of enzymes (Section 2.2.1). The overall effect is the production of a carbohydrate energy store 'CH_2O', again using CO_2 as the carbon source:

$$2CO_2 + 6H_2 \rightarrow\text{'}CH_2O\text{'} + CH_4 + 3H_2O \tag{2.10}$$

The appearance of CH_4 in this process gives it the name *methanogenesis*, and the organisms that perform it are called methanogens.

Figure 2.6 summarises these various ways in which energy stores are created in cells. Let's now consider the main processes for which this energy is required.

2.4.3 Protein synthesis

After water, and excluding cell walls in some organisms, proteins make the largest contribution to the mass of a cell (Table 2.2). They also dominate in the breadth of their functions, though only a very few protein molecules can make copies of themselves. Therefore, to form a protein something else is almost invariably needed, and that is the DNA that is found in a cell. The DNA contains the instructions for making all the cell proteins, and is therefore a 'blueprint' of the cell – it is where all the genetic information resides. Protein synthesis, in most cells, consumes more energy than any other biosynthetic process.

Consider the typical prokaryotic cell. There are two main steps in protein synthesis. First, part of the DNA molecule is disrupted by an enzyme that breaks the weak bonds between the base pairs that constitute the rungs on the ladder. A particular enzyme will break the bonds from a particular start site to a particular stop site. The sequence of bases between these extremities constitutes a *gene*. The enzyme builds RNA on just one of the two strands of disrupted DNA, as shown in Figure 2.7(a), using RNA bases floating in the cell. Note that a particular form of RNA is produced in which the base sequence mirrors that on the DNA strand in accord with the rules that A(DNA) pairs with U(RNA), C(DNA) with G(RNA), G(RNA) with C(RNA), and T(DNA) with A(RNA) (Figure 2.7(b)). When this assembly is complete the enzyme and the RNA leave the DNA, which reassembles. The RNA so formed is called messenger RNA (mRNA).

The second step is the assembly of a particular set of amino acids – a particular protein – corresponding to the particular mRNA base sequence. This assembly takes place within the ribosomes (Figure 2.7(a) and (b)). The bases strung out along the mRNA, taken three at a time, specify the sequence of amino acids in the protein, and thus specify the type of protein. Each triplet of bases is called a codon, and it will correspond to just one of the 20 or so different amino acids. A form of RNA called

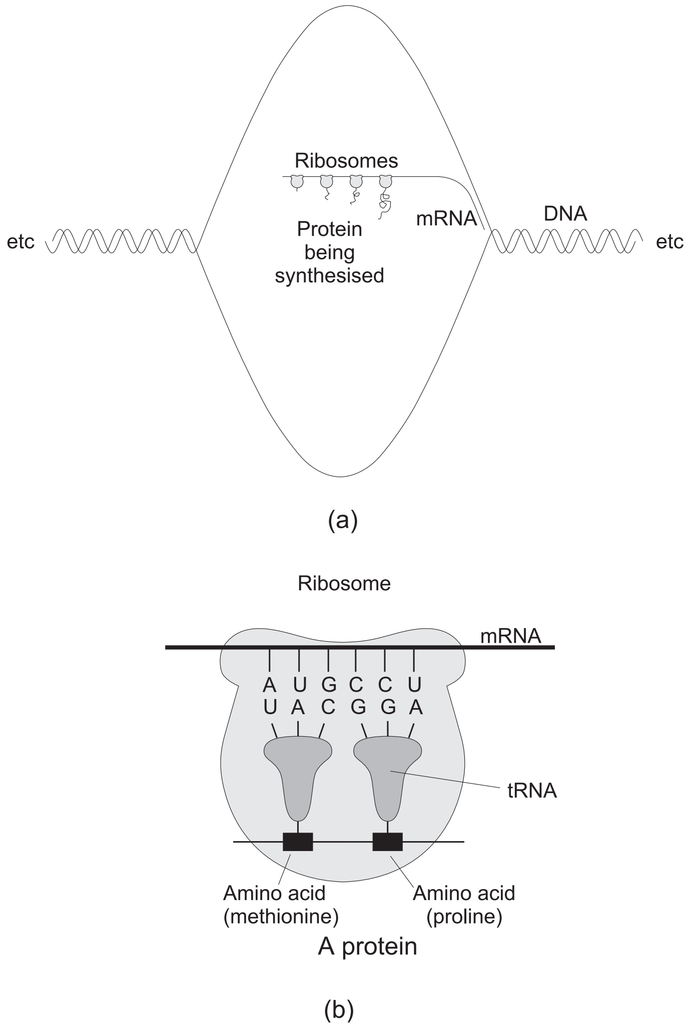


Figure 2.7 (a) A protein being formed by ribosomes, acting on instructions from mRNA that is derived from DNA. (b) A close-up of the action of a ribosome.

transfer RNA (tRNA) mediates between a codon on mRNA and an amino acid. There is one form of tRNA for each amino acid. During protein synthesis a ribosome contains a segment of the mRNA and up to two tRNA molecules that it has temporarily incorporated from the cytosol to match the mRNA segment currently inside it. The process starts with a tRNA molecule attaching itself to the mRNA at its first codon, and this tRNA attracts the corresponding amino acid floating in the cell. Another tRNA molecule then attaches to the mRNA at the next codon – a different form of tRNA unless the codon is the same as the first one. The corresponding amino acid is then attached to the first one. The first tRNA molecule then departs, a third arrives, and so on until the whole protein is synthesised.

The ribosomes act on the mRNA until the protein is complete. This whole process is repeated for other genes, until all the necessary proteins have been synthesised. A ribosome itself consists of proteins, and molecules of a third form of RNA called ribosomal RNA (rRNA). It might be the rRNA that catalyses the assembly, not the ribosomal proteins.

In eukaryotic cells the basic biochemical processes of protein synthesis involving DNA and RNA are broadly the same as in the prokaryotic cell, if rather more complicated. In heterotrophs, whether prokaryotes or eukaryotes, most of the amino acids have to come from food that traverses the cell membrane, though animals can make some of them (within the mitochondria – Section 2.3). In autotrophs they are synthesised within the cell.

2.4.4 Reproduction and evolution

All organisms have limited lifespans. It is therefore essential for the survival of a particular type of organism that it reproduces itself. In all organisms today the information for making each of its many and varied proteins is contained entirely within its DNA. Therefore, the information for making a copy of itself is also contained within the DNA. It is thus not surprising that the persistence of an organism from one generation to the next requires the passing on of DNA.

Figure 2.8 shows the main stages in prokaryotic cell division, in a highly simplified way. In stage 1 the DNA replicates in a manner to be outlined shortly. The cell then has two identical DNA molecules. Each DNA molecule migrates to

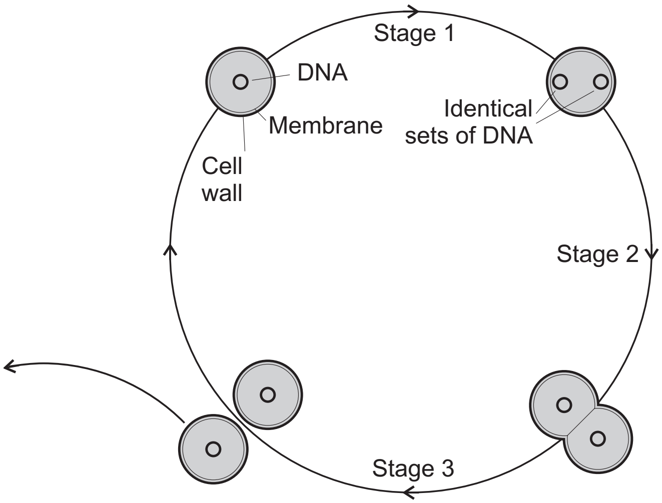


Figure 2.8 A simple view of cell division in prokaryotes.

opposite ends of the cell. Stage 2 is when the cell develops a 'waist' traversed by a new membrane, dividing the cell into halves. In the final stage the compound cell separates at the waist to yield two (nominally) identical cells. Each of these new cells can undergo further doubling.

DNA replication is triggered in ways that are beyond the scope of this book. The outcome is that certain enzymes gradually separate the DNA molecule into its two strands, as shown in Figure 2.9. This leaves two sets of exposed, unpaired bases. Each exposed base attracts its complementary nucleotides from the free nucleotides that are present in abundance in the cell. These free nucleotides will have been manufactured through enzyme action. To link them to form new DNA another enzyme is required. One complete DNA molecule thus builds up from each of the single strands of the original molecule. The base sequence is identical in both molecules.

The whole process of DNA copying is driven by enzymes, so we have enzymes causing DNA to be made, and the enzymes, being proteins, require DNA for their synthesis. When it comes to considering the origin of life in Chapter 3 we shall have to consider carefully this chicken and egg situation.

In cell division the copying of the DNA is not always perfect. The 'children' are therefore not identical to the 'parent'. If the 'children' are viable this will lead to an increase in variety. This can also result from a prokaryotic cell transferring some of its DNA to another prokaryotic cell, possibly of a substantially different type, with incorporation of the DNA into the recipient's DNA. This transfer occurs in a number of ways. Another source of variation is damage to the DNA caused by certain chemicals in the environment, by solar UV radiation, and by energetic charged particles and gamma radiation from radioactive materials on Earth and from space. Yet another cause is processes internal to the cell that cause segments of DNA to be moved from one location to another. We can group these DNA changes together as *mutations*.

Cell division also occurs in eukaryotic cells, though by different processes from that in prokaryotes. One process (called mitosis) enables unicellular eukaryotes to reproduce asexually, and enables multicellular organisms to grow and replace dysfunctional or lost cells. However, the process of reproducing a new organism can be different. In plants and animals this is usually by sexual reproduction, in which half the DNA for the new organism comes from special cells in the female, and the other half from special cells in the male (in animals, egg and sperm respectively). This means that the DNA in the offspring is not identical to that in either parent, though it is sufficiently similar that we recognise the offspring as belonging to the same type of organism as its parents – to the same species. The cell division that results in this mixing of DNA from two parents in eukaryotes is called meiosis. Sexual reproduction clearly promotes variation in the DNA of the offspring. Further variation in eukaryotes arises from DNA mutations.

Thus, in eukaryotes as well as in prokaryotes, DNA in any type of organism is not an invariable entity passed on from one generation to the next. In the great majority of cases the outcome of DNA changes has either no discernible effect, no important effect, or a damaging effect. But some descendents will be more suited to

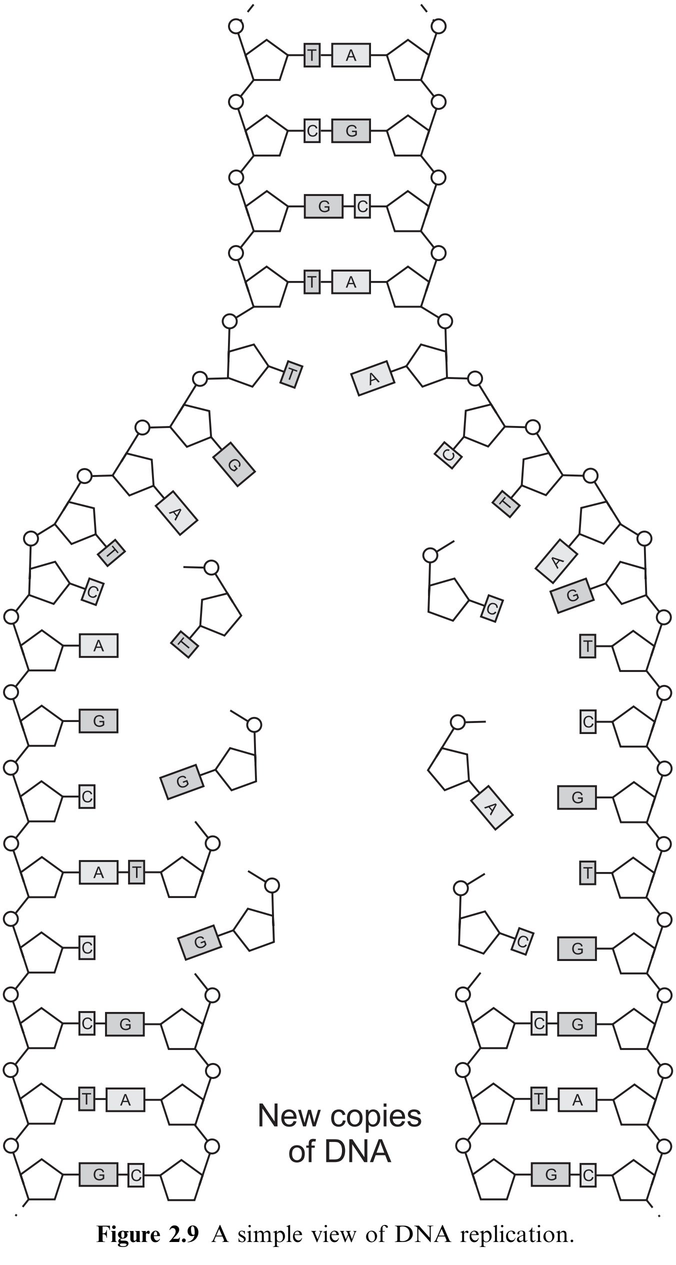


Figure 2.9 A simple view of DNA replication.

the environment than others, and it is these that will have a better chance of survival and reproduction. It is this that has enabled life to evolve from its earliest forms. It has driven evolution in a direction that has benefited the survival of species and the emergence of new, viable species. Evolution occurs because there is variety in the offspring. The inherited characteristics that promote survival to reproduce will therefore spread. This is the basis of Darwin's theory of *evolution by natural selection*, and it leads to a variety of species each adapted to its own environment.

2.5 DIVERSITY OF HABITATS

Life is ubiquitous on the Earth's surface and in the Earth's oceans. It is also present in the crust of the Earth, not just in underground caves and sediments but inside the rocks themselves. Life thus inhabits a wide diversity of habitats, though the most extreme of these are occupied mainly by prokaryotes. But in spite of this diversity, liquid water is common to all habitats. In order to survive, an organism requires access to water and to conditions under which this water can be liquid within its cells. No organism can survive without liquid water during at least part of its life cycle. For the great majority of organisms the water has to be available externally as liquid, rather than as ice or vapour. Consider non-extreme habitats first.

2.5.1 Non-extreme habitats

The most familiar non-extreme habitat is of course the Earth's surface, exposed to the Earth's oxygen-rich atmosphere (Table 2.1), where the mean pressure at sea level is 1.013×10^5 Pa and the global mean surface temperature is 15°C (most of the time, in most places, it is between 0°C and 35°C).

You or I, unprotected by clothing or dwelling places, could only survive under a very narrow range of conditions. Even if there were an ample supply of food and liquid water, we would die if exposed for a few days at any temperature outside the approximate range 5–45°C. Few animals or plants can live at sustained temperatures outside the range 0–45°C, and none at all outside the approximate range −20°C to 50°C. Other conditions to be met for survival by some organisms is the partial pressure of O_2 in the local atmosphere. For humans, a partial pressure of about 0.04×10^5 Pa is the lower limit for survival – about one-fifth that at sea level, and encountered at about 12 km altitudes. However, there are many habitats that have no oxygen, such as lake sediments, where we find anaerobes (Section 2.4.2). Indeed, early in the history of life on Earth there were only anaerobes – there was too little oxygen to sustain aerobes, as you will see in Section 3.2.3. Therefore, we will not regard the absence of oxygen as an extreme environment.

The salinity, and the alkalinity–acidity of the environment also impose constraints. If you are not familiar with the pH ('pea–aitch') measure of alkalinity–acidity, you need only note that $\mathrm{pH} = 7.0$ is neutral, like pure water, that greater values are alkaline, and smaller values are acidic. Thus, washing soda solution, as normally used, is a weak alkali with a pH of about 10.5, and vinegar, as bought from the supermarket, is a weak acid with a pH of 2–3. In the vast majority of cells the internal pH is 7.7, very mildly alkaline, and this has to be sustained whatever the pH of the environment. Likewise, the salinity inside the cell has to be sustained at about one-third that of sea water. Salinity is normally measured in terms of NaCl content, though other salts are present in smaller, well-defined proportions. In the cell the proportion is roughly 0.85% NaCl by mass. Also, for all life, exposure to UV and ionising radiation must be below some limits, otherwise too much damage occurs to DNA and other molecules.

2.5.2 Extreme habitats

Table 2.3 shows the extreme environmental conditions under which various terrestrial organisms live – survival in some dormant state occurs under even wider conditions. A particular organism will not necessarily survive across the whole of a range. Instead, each range tends to be occupied only by certain organisms. At most of the extreme values only unicellular organisms are found, and most of these are prokaryotes. These do far better than plants and animals in surviving extreme environments, partly because plants and animals consist of many different types of cell, with specialised functions, and many types of organs and large-scale structures. Keeping this working is possible in most cases only under moderate conditions. Organisms living at the extremes are called *extremophiles*, 'lovers of extremes', though this is a chauvinistic term, because we regard the conditions under which we live as non-extreme.

The extremes in Table 2.3 are striking. If water freezes or boils then the cell is disrupted, so how can some organisms survive at −18°C and others at 123°C? The answer is that the familiar freezing and boiling points, 0°C and 100°C, apply to pure water at a pressure of 1.013×10^5 Pa. Figure 2.10 shows the ranges of temperature and pressure over which pure water exists in stable form as a liquid, solid, and gas. At pressures greater than 1.013×10^5 Pa the boiling point is raised. It is indeed the case that the hyperthermophiles ('lovers of extreme heat') are found at the high pressures deep in the oceans. Given sufficient pressure, the upper limit for carbon–liquid water life could in principle be as high as 160°C, the temperature at which essential carbon compounds cannot avoid being broken down.

Table 2.3. Some extreme environmental conditions under which terrestrial organisms live. Most are prokaryotes.

Parameter	Limit(s)	Type of organism
Temperature	−18°C to 15°C	Psychrophiles
	60–80°C	Thermophiles
	80–123°C	Hyperthermophiles
Pressure	610 Pa to $> 10^5$ Pa	(No special name)
	up to 1.3×10^8 Pa	Piezophiles (barophiles)
Salinity	15–37.5% NaCl	Halophiles
pH	0.7–4	Acidophiles
	8–12.5	Alkalophiles

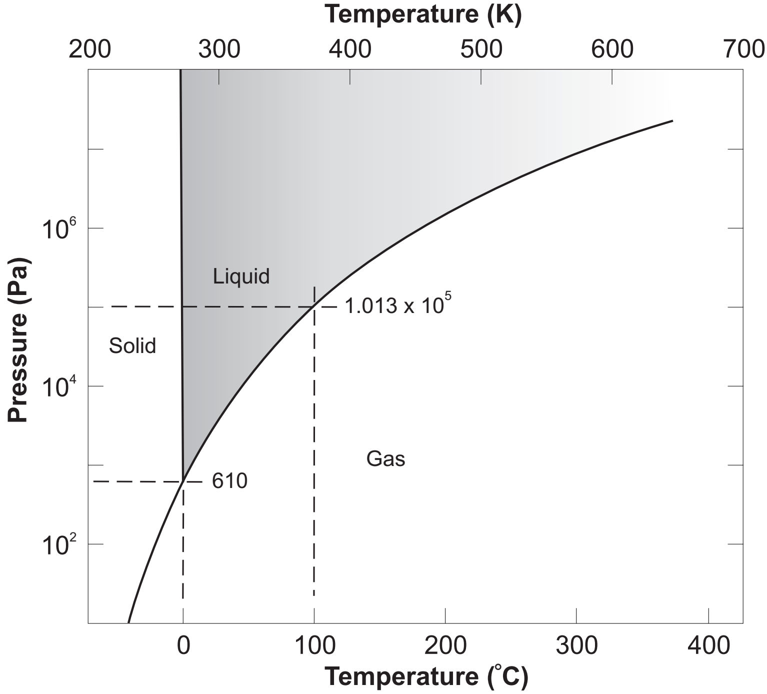


Figure 2.10 The phase diagram of pure water, showing the ranges of temperature and pressure over which pure water exists in stable form as a liquid, solid, and gas.

At the other extreme of temperature, psychrophiles ('lovers of cold') must avoid three threats. Most obviously, the water in the cell must not freeze. Pressure does not help – Figure 2.10 shows that it hardly affects the freezing point. But if substances are dissolved in water then the freezing point can be significantly lowered (and the boiling point is again raised). Certain proteins lower the freezing point of water in the cells of psychrophiles. Second, the rates of biochemical reactions must not become too low. These decline exponentially as temperature falls, and in non-psychrophiles are extremely slow below about 10°C. Psychrophiles avoid this problem via special enzymes, not found in other cells, that promote reactions at low temperatures. Finally, the cell membrane must not become too rigid to function as a regulator of what substances pass through it. This is avoided by the incorporation of special lipids into the membrane that keep it flexible.

The lower end of the pressure range in Table 2.3, 610 Pa, is determined by the requirement to have liquid water. The minimum pressure for pure water is 610 Pa – at lower pressures water can only exist as a solid or a gas (Figure 2.10). The upper end of the pressure range is the hydrostatic pressure in the deepest ocean where life has so far been found (the Mariana Trench, Western Pacific Ocean). For unicellular creatures the true limit could be far higher. Unicellular organisms living at great depths do not die when brought up to the surface, nor do those living at the surface when taken down. Multicellular creatures perish, particularly if the transition is rapid.

The range of salinities in Table 2.3 is to be measured against the 2.95% average for seawater. The pH range extends from strongly acidic to strongly alkaline. An extreme not listed in Table 2.3 is exposure to radiation, in particular UV radiation, energetic charged particles, and gamma radiation. These cause damage to DNA (Section 2.4.4). Some prokaryotes can stand levels of radiation that would quickly be lethal to us, such as those inside nuclear reactors!

Extreme conditions are found in extreme habitats. Let's look at two habitats of particular interest to the search for extraterrestrial life.

Hydrothermal vents

Hydrothermal vents, also called black smokers, are found in regions where new oceanic crust is being created at plate boundaries (Section 2.1.2). The vents are protuberances typically a metre across and a few metres tall, pouring out water at temperatures up to 400°C, much of it is recycled oceanic water that has percolated into the crustal rocks. The water contains dissolved gases, including CO_2, H_2, CH_4, and H_2S. Where the hot water meets the cool oxygenated water of the oceans there are chemical reactions in which solid sulphides form, colouring the water black and building the protuberances. Figure 2.11 shows a vent and Figure 2.12 shows some of the organisms that are found in their vicinities.

Figure 2.11 A hydrothermal vent (black smoker) about 1 m tall, pouring out water at temperatures up to 400°C, and containing dissolved gases, including CO_2, H_2, CH_4, and H_2S.

D. Foster, © Woods Hole Oceanographic Institution.

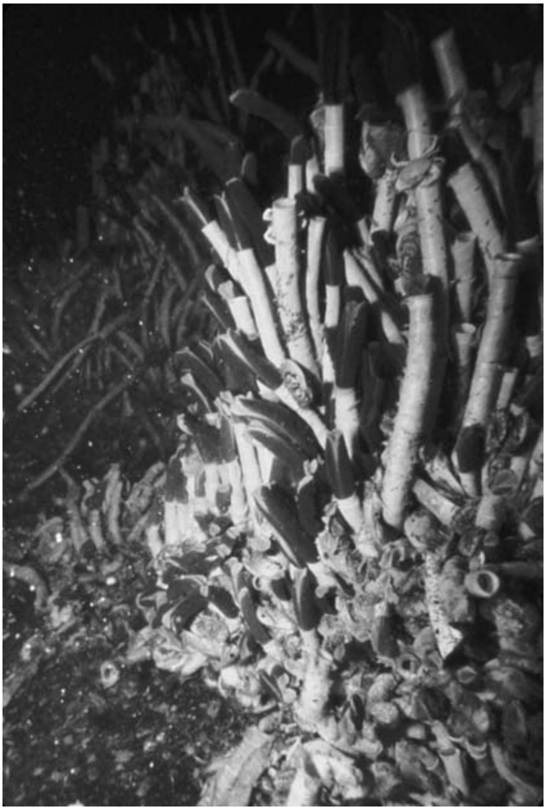


Figure 2.12 Life near a hydrothermal vent. Tubeworms, spider crabs, clams, shrimps, and unicellular creatures are among the organisms found at such vents.

F. Grassle, © Woods Hole Oceanographic Institution.

The organisms seen in Figure 2.12 are tubeworms and spider crabs. Animals such as mussels and worms can also be found along with unicellular creatures. At such depths all these creatures are piezophiles. Near the vent there are hyperthermophiles. These are prokaryotes, many of which are also anaerobes, the vent water being almost devoid of oxygen. Further from the vent the temperature drops to about 3°C, and psychrophiles live there. Thus, over distances of a few tens of metres we pass from the domain of organisms adapted to hot conditions to those adapted to cold conditions.

A food supply for heterotrophs here (and elsewhere in the deep oceans) is detritus sinking from surface waters, but there is a supplementary base to the food chain, provided by autotrophic prokaryotes, which can end up as food. No sunlight penetrates to these depths and so they do not photosynthesise. Instead, they perform chemosynthesis. However, it is not clear that these chemosynthesisers are truly independent of photosynthesis. For example, there are methanogens that use the

CO_2 and H_2 dissolved in the vent water (Reaction 2.9). The CO_2 comes partly from the break-up of carbonates that have been taken down into the Earth's interior, and partly from the oxidation of crust and mantle carbon. Much of the carbonate comes from the shells of sea creatures that have relied partly on photosynthesising organisms for food. Moreover, the oxidation of carbon could rely in part on the oxygen in the oceans, itself the result of oxygenic photosynthesis (Reaction 2.6). There might also be a biological component to the H_2, even though much of this could be produced abiologically, for example through the oxidation by water of iron in new crustal rocks. If the chemosynthesisers at hydrothermal vents are not independent of the rest of the biosphere, where might we find some that are? One possibility is in the crustal rocks.

Crustal rocks

Perhaps the most surprising type of habitat on Earth is within solid bodies – within ice or rock. In the cold deserts of Antarctica, such as the Dry Valleys of Victoria Land, there are rocky outcrops of sandstones and quartzites within which there are colonies of unicellular organisms of great variety. These are all within a centimetre or so of the surface, a depth to which sunlight can penetrate and so photosynthesis can occur. Water is also present, despite the dry environment, trapped in pores in the sandstone. Moreover, even though the surrounding air temperatures are usually below 0°C, the temperature a few millimetres into the rocks can reach 10°C. We thus have life living under not very extreme conditions; the surprise is that such conditions can be found in rocks within a much more extreme environment.

Even more surprising is the presence of dormant unicellular organisms in ice recovered from depths up to 2.5 km in Antarctica. Most astonishing of all is the discovery of unicellular creatures up to several kilometres deep in the Earth's crustal rocks. Much of the biosphere today, perhaps most of it by mass, is in unicellular form, mostly prokaryotic, well below the surface of the Earth. Water-filled pore spaces and cracks in rocks are plenty big enough for single cells. The pores are not isolated and so the crust is rather like a sponge through which unicellular life and its watery environment can pass. The water contains chemical reactants, and a variety of chemosynthetic autotrophic processes occur, including methanogenesis. Enzymes promote redox reactions that provide the basic energy source for life. It is important that such enzymes are necessary, otherwise the available chemical energy would be liberated spontaneously and rapidly by abiological processes, and there would soon be none for organisms. The abiological processes would dominate only at temperatures too high for life. In some locations where life is found deep in the crust it is possible that chemosynthetic autotrophs are the sole base of the food chain, and that the reactants they use to store energy are independent of the rest of the biosphere.

Truly, life on Earth seems to occupy everywhere that it is possible for carbon–liquid water life to exist – everywhere between the temperature range -18°C to 123°C where liquid water is available and there is a suitable energy source.

2.6 THE TREE OF LIFE

The bewildering variety of organisms on Earth has long been classified into a hierarchy with many different levels. Among plants and animals the lowest level that will concern us is the species. Two plants or two animals are said to belong to different species if a fully developed male of one species and a fully developed female of the other cannot produce fully fertile offspring under natural conditions, or if production of a fertile hybrid is extremely rare. In practice it is often difficult to put this to the test, and impossible with fossils. Therefore most organisms have been classified on the basis of their appearance and their behaviour. Species are grouped into families, and the further aggregations are called order, class, phylum, and kingdom. For example, the domestic cat (all varieties) is classified as follows: species, Catus (domestic cat); genus, Felis (wild and domestic cats); family, Felidae (all cats); order, Carnivora; class, Mammalia; phylum, Chordata; kingdom, Animalia. The phylum specifies a characteristic body plan. Chordata have backbones, and so include fish, frogs and humans, but not spiders. There are 24 phyla in the animal kingdom.

Since the 1970s it has become possible to measure the biological dissimilarity (distance) between species by comparing their RNA and DNA. This also tells us something about evolution. For example, two species A and B that differ only slightly in their nucleic acids probably diverged from a common ancestor more recently that species A and C that exhibit greater differences. With the advent of this technique some rather fundamental revisions were made to the classification of life with the outcome shown in Figure 2.13. This is commonly called the tree of life. The top level of the hierarchy is the domain. Figure 2.13 shows the three domains Bacteria, Archaea, and Eukarya, plus some of the subdivisions into kingdoms and phyla. The tip of a branch could represent a kingdom/phylum alive today, or one that has become extinct and led nowhere. Away from the tips are ancestors of the

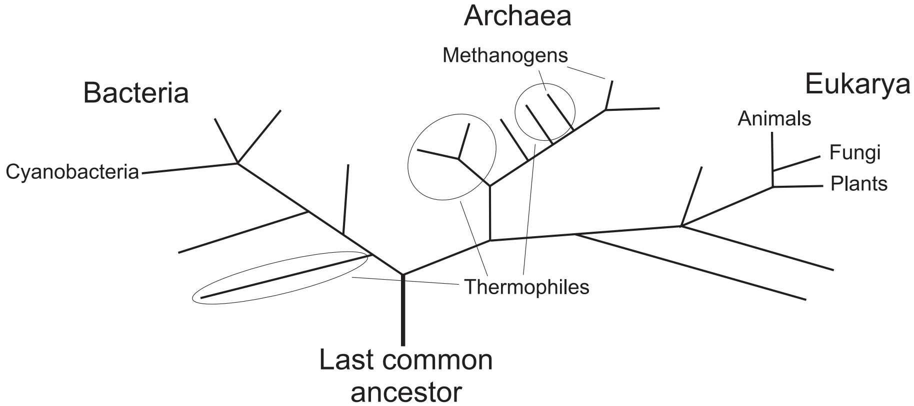


Figure 2.13 The tree of life, showing the three domains, Bacteria, Archaea, and Eukarya, into which all life on Earth is classified. For clarity, some branches have been omitted from the tree.

organisms at the tips, now extinct. At a branch point lies the common ancestor of all the organisms on the branches that diverge from that point. The distances along the branches represent evolutionary distances, as measured by differences and similarities in the nucleic acids in different organisms. Thus, animals and plants are much more closely related than either of these is to methanogens. Within each domain there are autotrophs and heterotrophs.

The Eukarya comprise all the organisms with eukaryotic cells. This domain is divided at the next level in the hierarchy into four kingdoms, and you will be familiar with members of the Animalia (animals), Plantae (plants), and Fungi kingdoms (e.g., yeast and mushrooms). Nearly all of the members of these three kingdoms are multicellular, though some fungi are unicellular. The fourth kingdom, Protoctista, consists mostly of unicellular organisms, though seaweeds are a familiar multicellular example. Protoctista comprise a very wide variety of forms so to think of it as just a quarter of the Eukarya is misleading. It might one day be split into several kingdoms.

The other two domains comprise the prokaryotes, for which the great majority of organisms are unicellular. The division between the Archaea and the Bacteria followed differences discovered in the late 1970s by the molecular biologist Carl Woese. He showed that a certain type of RNA is different in the cells of what he later named Archaea, from the RNA that performs the same functions in cells of Bacteria. The Archaea include many thermophiles, as shown in Figure 2.13, and this has led some scientists to regard them as the most similar among living organisms to the very earliest forms of carbon–liquid water life on Earth, as discussed in the next chapter. This view is supported to some extent by the early divergence of some of these types of Archaea branch from the trunk. The base of the tree trunk represents some unknown common ancestor of all life on Earth.

That we can place all known organisms on Earth on a tree reaching back to a common ancestor shows that all present life on Earth had a common origin. This view is supported by the great similarity at a fundamental biochemical level of all organisms alive on Earth today. Quite what this origin was is one of the main subjects of the next chapter.

2.7 SUMMARY

- The Earth has an iron-rich core, the outer part of which is liquid, and is the source of the magnetic field. The rest of the Earth is rich in silicates, with compositional divisions that define the mantle and the crust. The surface of the Earth is shaped by plate tectonics. The biosphere is confined to the crust and the surface, beneath an atmosphere rich in oxygen and in nitrogen.
- The basic unit of life is the cell. There are two broad types, the prokaryotic cell and the more complex eukaryotic cell.
- Cells consist largely of water and organic compounds, with proteins accounting for much of the latter. Proteins fulfil a wide range of functions – structural, transport, storage, and catalysis of chemical reactions (enzymes).

- Chemical energy is a fundamental requirement for life, particularly redox reactions. Energy is liberated from stores in the cell through respiration, aerobic or anaerobic.
- Energy stores in the cell (sugars, polysaccharides, and lipids) are constructed from food by heterotrophs, and by autotrophs either by photosynthesis or by chemosynthesis.
- Proteins are synthesised using the information contained in the base sequences of the nucleic acid DNA, mediated by mRNA and tRNA.
- DNA (rarely RNA) contains the genetic information that enables repair and reproduction. Imperfect reproduction or mutation is essential for evolution.
- Organisms occupy a wide range of habitats, including the hyperthermophiles that live at temperatures up to 123°C, many of which are anaerobes. Life on Earth seems to be everywhere that it is possible for carbon–liquid water life to exist (e.g. everywhere within the temperature range -18°C to 123°C) provided that liquid water and a suitable energy source are available. This includes hydrothermal vents deep in the oceans, and pores and crevices deep in crustal rocks.
- Organisms are divided into three domains – the Eukarya, Bacteria, and Archaea. The Eukarya are made of eukaryotic cells, and the other two of prokaryotic cells. The Archaea are thought to include organisms most similar among living species to the very earliest carbon–liquid water life on Earth.

2.8 QUESTIONS

Answers are given at the back of the book.

Question 2.1

An article in a popular science magazine contains the following statement: 'Life on Earth requires only very few of the 100-odd chemical elements. These are hydrogen, oxygen, and carbon. The hydrogen and oxygen make water – all life needs a continuous supply of liquid water. The carbon is needed to make hydrocarbons.' List the mistakes in this extract, citing evidence to support your conclusions.

Question 2.2

What kind(s) of autotrophs would most likely be found in the following types of environment:

(i) An oxygen-poor hot spring in a volcanic region, beneath an opaque surface-slime.
(ii) On the sea floor, an average of 10 m below the ocean surface.
(iii) At a depth of 3.5 km in a South African gold mine – the organisms were there before the mine was sunk.

Question 2.3

A biologist claims to have discovered a hyperthermophile near a hydrothermal vent. It consists of a colony of single cells, and on close examination he discovers that each cell contains a nucleus and several mitochondria. Discuss where you would place this organism in the tree of life.

Question 2.4

Place the common ancestors of the following pairs of types of organism in a time sequence stretching back from the present: Archaea–Eukarya, Animalia–Fungi, Bacteria–Archaea. Justify your sequence.