Lecture 4: Biological Basics

Aims of Lecture

(1) Briefly to introduce the main types of organic molecule;

(2) To discuss the genetic code and the roles of RNA and DNA;

(3) To introduce the nomenclature and structure of simple cells; and

(4) Briefly to introduce the top-level taxonomic classifications of living species

Contents of Lecture

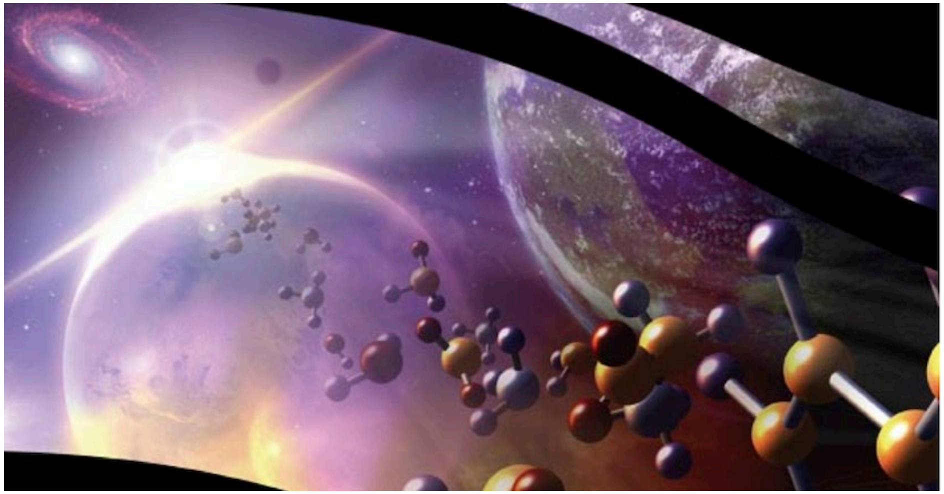

Fig. 1. NASA artwork showing organic molecules in space. A basic understanding of molecular biology is essential for understanding astrobiology (NASA).

1. Introduction

In order to set the scene for future lectures on the origin and the metabolic requirements of life, it is necessary to revise the basic chemistry of life, and to introduce some key biological concepts and nomenclature. This is the aim of the present lecture.

2. The importance of carbon

Apart from silicon, carbon is unique as a common chemical element in being able to form four chemical bonds with other atoms. This gives it great chemical versatility and enables it to form a very wide variety of molecules (Fig. 2)

3. A note on silicon

Silicon is the only other relatively common element that is also able to form four chemical bonds, and there has been much speculation in the science fiction literature about silicon-based life. Although we don't know that silicon-based life is impossible, and it is important to keep an open mind, there are several reasons for believing that silicon is a much less suitable basis for biology than carbon:

- Silicon is actually only about as tenth as abundant as carbon, and easily bound up with the much more abundant oxygen atoms to form chemically quite inert silicate minerals.
- The bonds formed by silicon are weaker than those formed by carbon, which makes the resulting molecules less robust. They are also not very stable in water which may be a disadvantage;
- Silicon tends only to form single bonds, which makes it much less versatile than carbon, much of the versatility of which results from its being able to alternate single and double bonds.

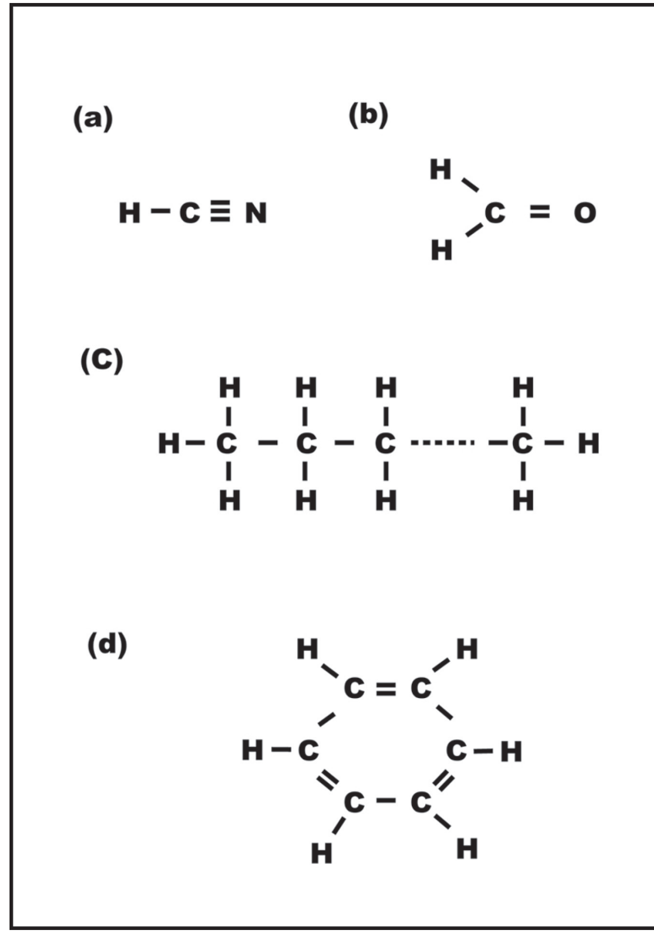

Fig. 2. Examples of organic molecules, illustrating the versatility of carbon atoms. (a) a three-atom molecule: hydrogen cyanide; (b) a four atom molecule: formaldehyde; (c) a linear hydrocarbon chain; (d) a hydrocarbon ring (benzene in this case). The thick lines joining the letters represent the molecular bonds. Note, in chains and rings one or more of the hydrogen atoms is often replaced by some other atom, greatly increasing the number of possible molecules.

4. Some key biological molecules

4.1 Proteins

Proteins form key structural components of organisms, but even more importantly, as **enzymes**, they catalyze biochemical reactions without which life would be impossible. They are composed of long, folded chains of simpler molecules called **amino acids**. Their catalytic properties result from an ability to fold into complex shapes, which encourage third-party molecules in contact with them to react. The specific shape, and thus the specific reaction catalysed, depends on the ordering of the amino acids of which they are composed.

4.2 Amino acids

Amino acids are the building blocks of proteins. They all have the same basic structure, as shown in Fig. 3. The side chain is unique for a given amino acid. For glycine, the simplest amino acid, it is a simple hydrogen atom, while for others it is a more complicated set of atoms. Although hundreds of amino acids are possible chemically, life on Earth makes use of just twenty.

The assembly of proteins takes place by the reaction between the amino group of one amino acid and the carboxyl group of another. This reaction releases a water molecule, and leaves the two former amino acid molecules joined by a single chemical bond (a 'peptide bond') as shown in Fig. 4.

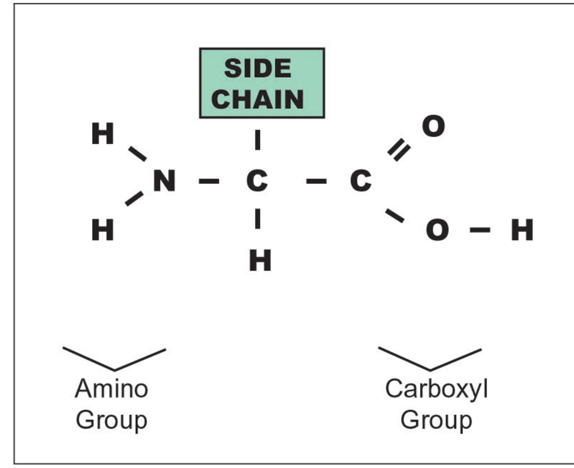

Fig. 3. The general structure of an amino acid molecule. All amino acids consist of a nitrogen-bearing 'amino group' and a carbon and oxygen-bearing carboxyl group, as shown. Different amino acids are distinguished by a unique 'side chain' connected to the central carbon atom.

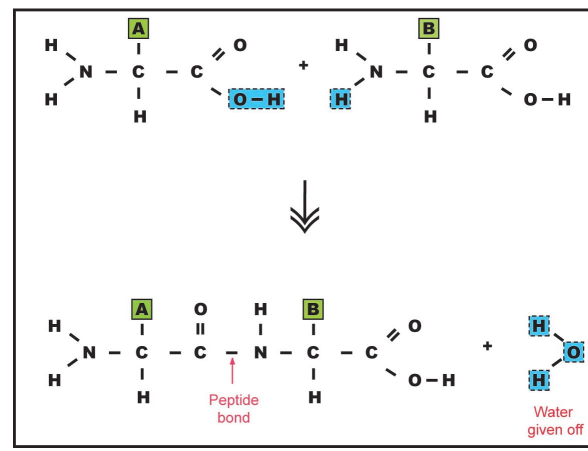

Fig. 4. Joining of two amino acids through the formation of a peptide bond and the release of a water molecule.

4.3 Sugars

Sugars are ring-shaped organic molecules which contain oxygen in addition to carbon and hydrogen (and are thus a class of carbohydrates). Examples are glucose ($C_6H_{12}O_6$), sucrose ($C_{12}H_{22}O_{11}$), ribose ($C_5H_{10}O_5$) and deoxyribose ($C_5H_{10}O_4$). The structure of ribose, a key component of RNA, is shown in Fig. 5. Deoxyribose, a key component of DNA, is identical except that it lacks one oxygen atom, as indicated.

4.4 Lipids

Lipids are the key components of cell membranes, and thus play a crucial role in isolating the internal processes of living cells from a generally hostile external environment. There are many types of lipids, and a full discussion of their structure is beyond the scope of this lecture. Their principal components are 'fatty acids': long hydrocarbon chains with a carboxyl group at one end, as shown in Fig. 6.

Of particular importance in cell membranes are the **phospholipids**, which consist of two fatty acid 'tails' joined by a 'head' containing a phosphate group (i.e. a phosphorous atom surrounded by four oxygen atoms) and a nitrogen-containing molecule (Fig. 7).

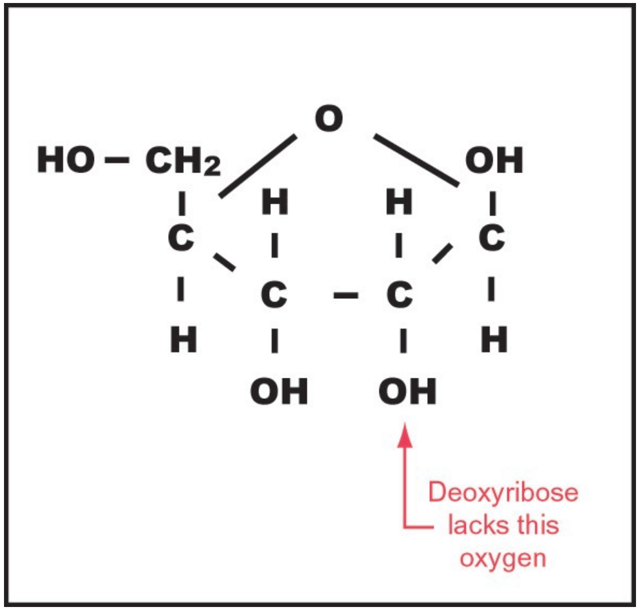

Fig. 5. Ribose, an example of a sugar, and a key constituent of RNA. Deoxyribose, the sugar of DNA, lacks the oxygen atom indicated but is otherwise identical.

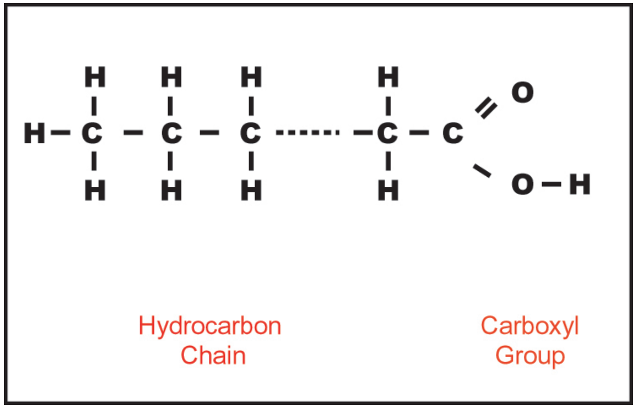

Fig. 6. An example of a fatty acid, consisting of a carboxyl group connected to a hydrocarbon chain.

Phospholipids have the property that their heads are hydrophilic ('loving water' – a consequence of the electric charges shown in Fig. 7), while their tails are hydrophobic ('hating water'). As a consequence, if placed in an aqueous medium they have a tendency to form membranes composed of two layers ('phospholipid bilayers') which enclose a volume within which biochemical reactions may take place (Fig. 8). While modern cell membranes are much more complicated than this (being buttressed with various proteins, and having all sorts of molecular 'gates' to allow substances in and out), the phospholipids bilayer remains central to their design, and the earliest cells may well have been enclosed by structures similar to that sketched in Fig. 8.

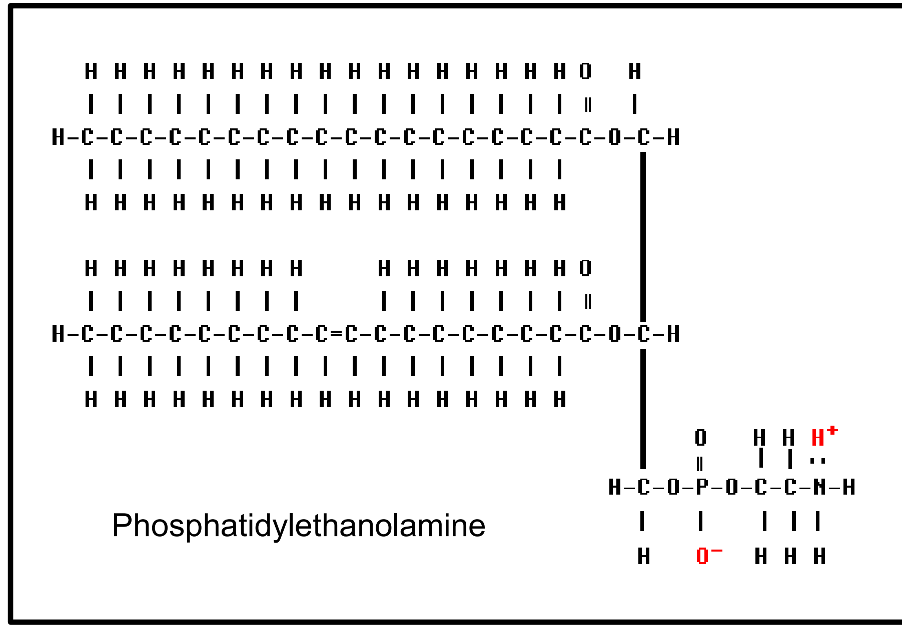

Fig. 7. An example of a phospholipid, consisting of two fatty acid chains linked by a 'head' containing a phosphate and amino group. The charges in the latter (marked in red) this end of the molecule hydrophilic (see text for details).

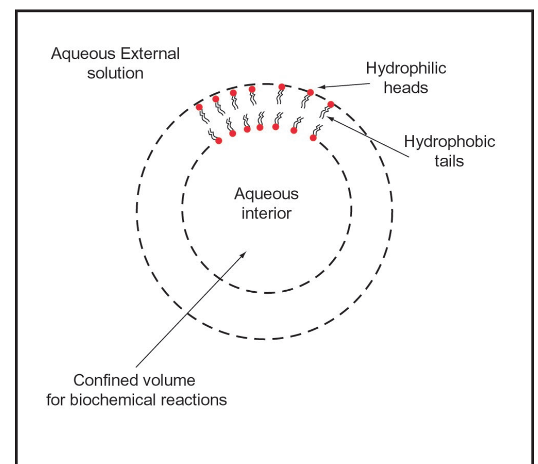

Fig.8. Schematic illustration of a membrane formed from a phospholipid bilayer. The hydrophobic tails orientate themselves in such a way as to enclose a volume containing an aqueous solution, within which biochemical reactions can be confined.

4.5 Nucleic acids

The most important nucleic acids (so-called because they are found in the nuclei of living cells) are ribose nucleic acid (RNA) and deoxyribose nucleic acid (DNA). They consist of long strands of repeating units (‘nucleotides’), each consisting of a sugar (ribose or deoxyribose for RNA and DNA, respectively), a phosphate group and a base. The basic structure of RNA is shown schematically in Fig. 9.

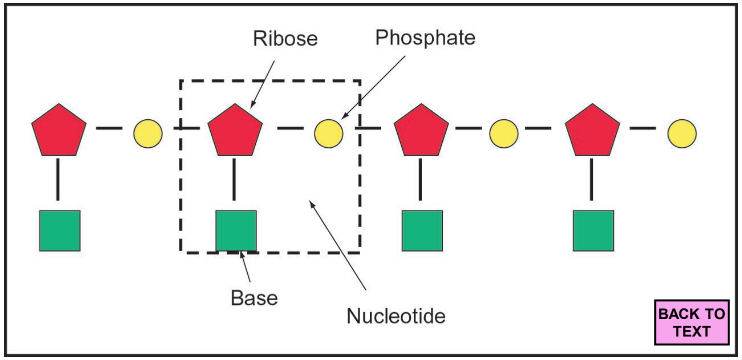

Fig. 9 (above). Schematic illustration of the basic structure of RNA.

Fig. 10 shows the structure of DNA in more detail, including the four DNA bases: Adenine (A), Thymine (T), Guanine (G), and Cytosine (C). Note that:

- Ribose in RNA is replaced by deoxyribose in DNA
- RNA doesn’t use Thymine as a base, but instead uses a very similar molecule called Uracil
- DNA consists of two strands, wound around each other in a spiral (the famous ‘double helix’) such that opposing bases join together (like rungs of a ladder). The bases always pair such that A joins to T, and G joins to C.

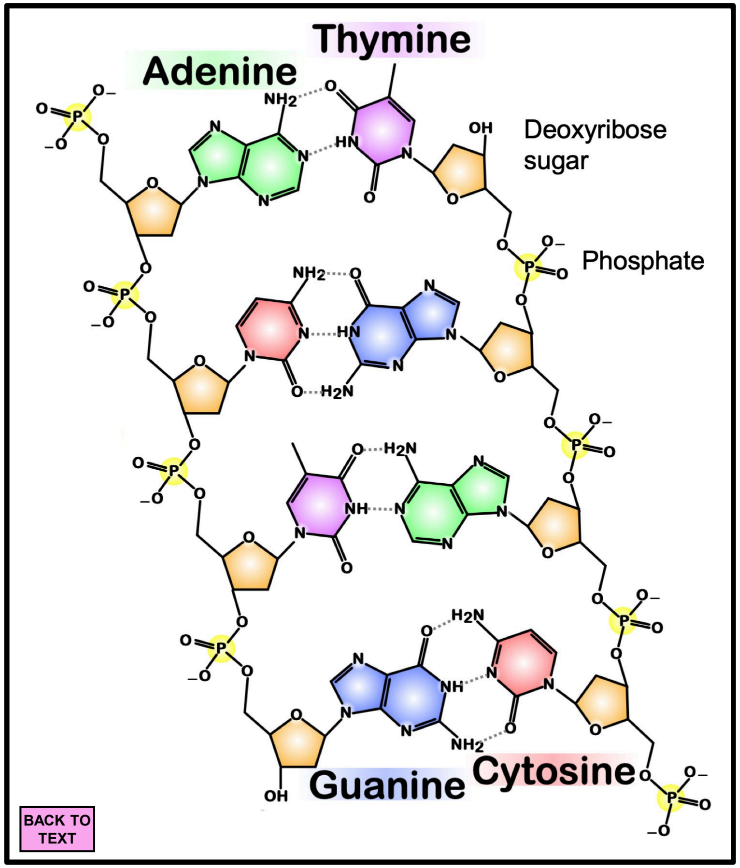

Fig.10 (right). The structure of DNA. The components are colour coded as shown (C atoms are implied at bond junctions unless otherwise indicated; most H atoms are omitted for clarity). Dashed lines represent hydrogen bonds. (Diagram by Madeleine Price Ball/Wikimedia Commons/CC-BY-SA 3.0).

4.6 ATP

All cells use the same molecule, adenosine triphosphate (ATP) to store energy and carry it around the cell to where it is needed. The structure of ATP is sketched in Fig. 11, and consists of the base adenine, a ribose sugar, and three phosphate groups. It is thus essentially a free adenine nucleotide, but with three phosphates rather than one.

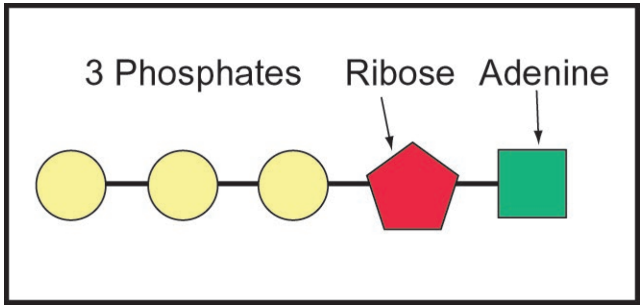

Fig. 11 (above). Schematic illustration of the structure of ATP (see text for details).

By removing a phosphate (to make adenosine diphosphate, ADP) energy is given up to a chemical reaction which requires it. ADP is recharged (i.e. converted back to ATP) using energy that may be derived ultimately from a number of external sources (e.g. sunlight, chemical energy, or aerobic respiration). Note that a common energy carrier, like a common genetic code (discussed below), argues powerfully for a single origin of life on Earth.

As an example of the complexity of biological processes, we note that ADP is converted to ATP by the enzyme ATP synthase, which is built from ~5000 amino acid molecules (~10^5 atoms) and acts as a molecular motor powered by hydrogen ions (Fig. 12).

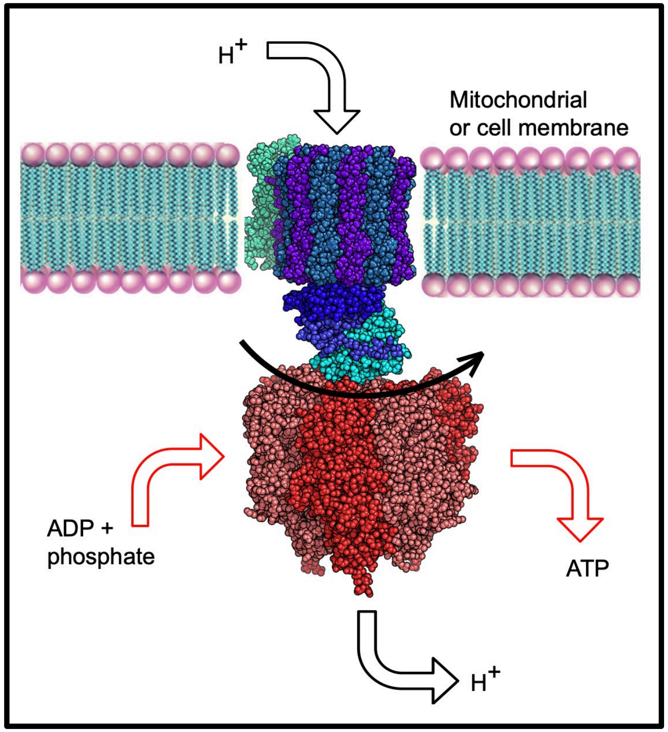

Fig. 12 (right). Illustration of the functioning of ATP synthase. H^+ ions passing through the molecule from one side of a cell membrane to the other cause the lower section to rotate, causing shape changes that facilitate the reaction of ADP and a phosphate group to form ATP. (Background image from Wikimedia Commons/Alex X./CC-BY-SA 3.0; lettering by IAC).

5. The genetic code

Information for the assembly of proteins is contained in the sequence of DNA bases. Life uses 20 amino acids, but there are only four bases. To solve this problem the genetic code is a triplet code, where three consecutive bases stand for one amino acid (with some duplication); the set of three bases which code for a specific amino acid is known as a ‘codon’.

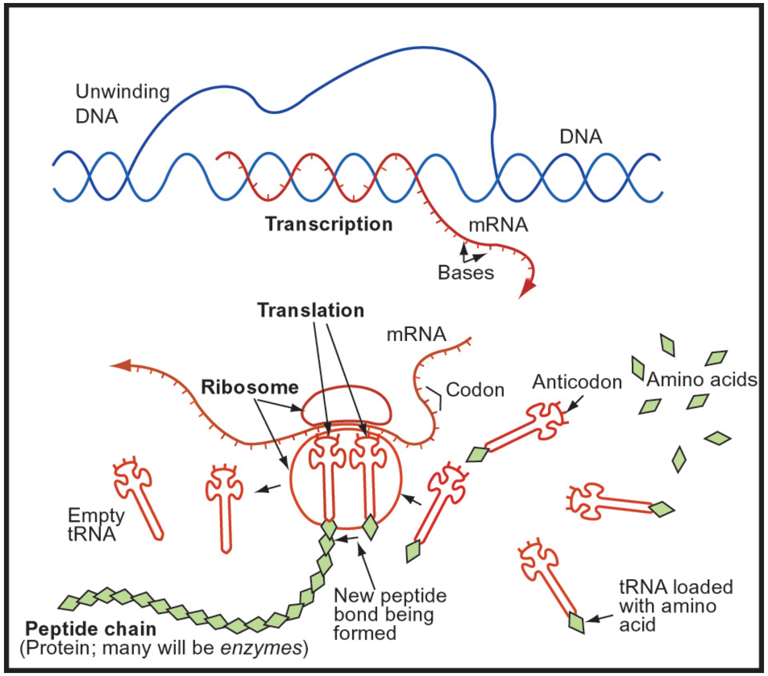

Fig. 13. Schematic illustration of information transfer from DNA (blue), via RNA (red), to the ribosomes, where amino acids (green) are strung together in the correct order to make proteins. All the components drawn in red are based on RNA. (After G.S. Kutter, *The Universe and Life*; Fig. 6.8).

The process is shown schematically in Fig. 13. With the help of specialised enzymes, part of the DNA strand unwinds and a complementary strand of RNA forms, using the DNA strand as a template. This RNA molecule is known as messenger RNA (mRNA) as it carries the genetic instructions to the sites of protein synthesis (**ribosomes**). Elsewhere in the cell other specialized RNA molecules (transfer RNA; tRNA), attach themselves to amino acid molecules, each bearing the complementary triplet code (‘anticodon’) which will match the codon for that particular amino acid on the mRNA strand. In the ribosome (which itself incorporates yet more specialised RNA molecules – ribosomal RNA; rRNA) codon and anticodon are matched up and the amino acids strung together in the order specified by the original strand of DNA. Two points should be noted immediately:

(1)The complexity of the process, implying that it must have evolved from simpler beginnings;

(2) The central, multiple, roles played by RNA, which suggests that RNA was central to whatever simpler system preceded that sketched in Fig. 13 (we will return to this point in Lecture 5).

6. Cell types

All life on Earth is based on cells. There are two main types:

6.1 Prokaryotic cells

These are the simplest cells. They lack nuclei, and the genetic material consists of a single strand of DNA floating within the cytoplasm (the interior fluid of the cell). They possess ribosomes, without which they would be unable to synthesise proteins, but otherwise have relatively simple internal structures. The structure of a prokaryotic cell is shown schematically in Fig. 14. Prokaryotic organisms are generally unicellular, although some form multi-cellular filaments. Typically, the cells are between 1 and 10 μm across. Given their relative simplicity, it seems likely that the first cells to evolve would have been prokaryotes.

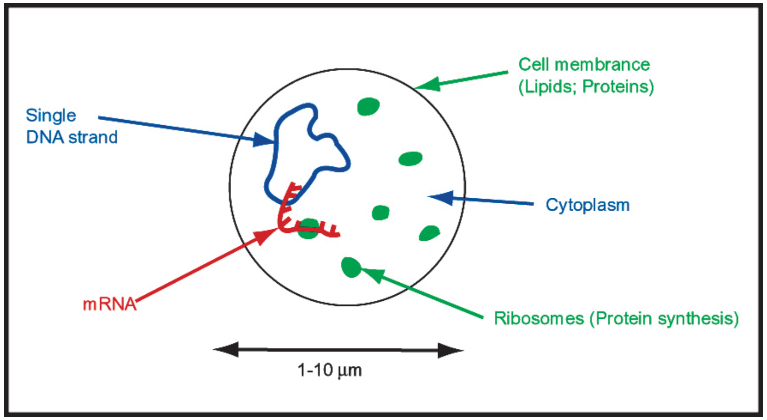

Fig. 14. Schematic illustration of the internal structure of a prokaryotic cell.

6.2 Eukaryotic cells

In today's world, while the bacteria and archaea are prokaryotes, all other, 'higher', forms of life are based on larger, vastly more complicated, eukaryotic cells. Fig. 15 is a schematic illustration of the interior structure of a eukaryotic cell; Fig. 16 shows a real example. NB. although only ~ten times larger than prokaryotic cells in linear dimension, this corresponds to a thousand times the volume.

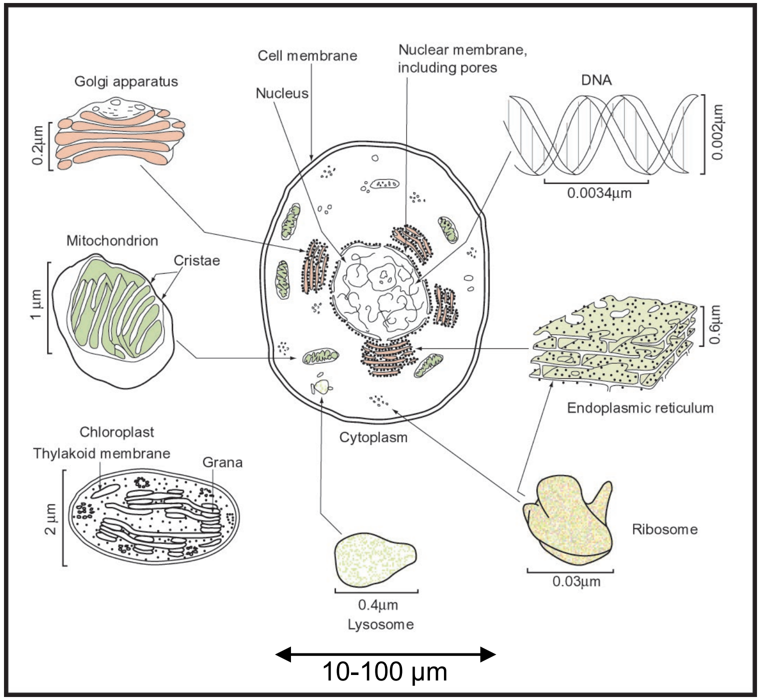

Fig. 15. Schematic illustration of the structure of a eukaryotic cell, with particular organelles indicated (after G.S. Kutter, *The Universe and Life,* Fig. 11.5).

The principal characteristics of eukaryotic cells are:

1. The DNA is enclosed by an internal membrane, forming a discrete nucleus. Moreover, the DNA is generally packaged into several chromosomes rather than forming a single strand.

2. The cell contains various specialised components (organelles – 'little organs'). Two important examples of organelles, that we will discuss in Lecture 6, are:

   • **Mitochondria** (Fig. 17): the sites where energy is released through the oxidation of carbohydrates, and ATP is generated via ATP synthase, in cells which rely on aerobic respiration.

   • **Chloroplasts** (Fig. 16): the sites where photosynthesis occurs in the cells of plants.

   As discussed in Lecture 6, both mitochondria and chloroplasts are derived from once free-living bacteria that have formed a symbiotic relationship with eukaryotic cells.

3. The cytoskeleton: an internal network of protein filaments, which gives structural support, controls the external shape, and plays a crucial role in cell division (although note that cytoskeleton-like structures have now been found in some prokaryotes as well).

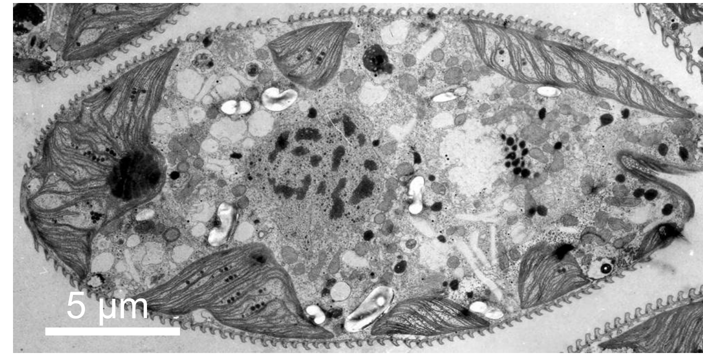

Fig. 16. Example of a eukaryotic cell: TEM image of the unicellular alga Euglena. The stringy objects are chloroplasts; numerous mitochondria (grey circular blobs) are visible, especially around the nucleus (centre); dark blob to the left is a pyrenoid where CO_2 is concentrated. Image courtesy of Mark A. Farmer, University of Georgia, USA, and Nick Lane, UCL; used with permission).

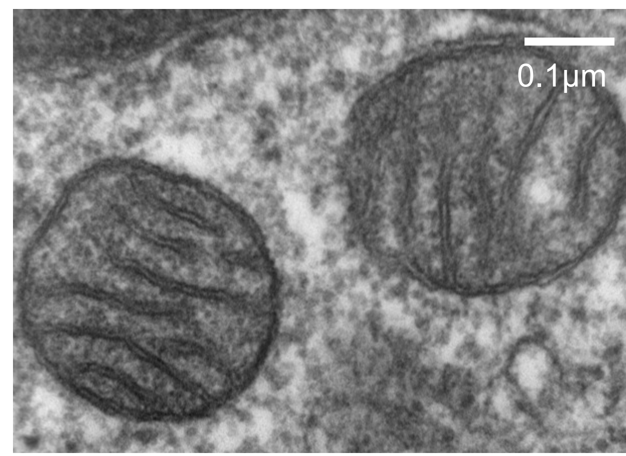

Fig. 17. Transmission electron microscope image of mitochondria in cells of mammalian lung tissue. ATP generation occurs via ATP synthase on the internal membranes. (Louisa Howard//Wikimedia Commons/Public domain; scale added).

7. Top-level taxonomic classifications

There are several ways in which living things may be classified. In order to introduce nomenclature which will be used in subsequent lectures, it is necessary here to outline the top-level classifications which are in use.

7.1 Five kingdoms

In 1959, a ‘five kingdom’ classification was agreed upon for the description of life on Earth, as follows:

Plants	Multi-cellular eukaryotes
Animals	
Fungi	
Protists	Single-celled eukaryotes
Monera (bacteria)	Prokaryotes

Below the level of Kingdom, lower taxonomic levels are recognized as follows: Phylum (characterised by basic body plans), Class, Order, Family, Genus, and, finally, Species.

For example, humans belong to the kingdom of animals, the phylum of chordates (essentially the vertebrates), the class of mammals, the order of primates, the family of hominids (man-like), the genus Homo (man), and the species sapiens (‘wise’).

7.2 Three domains

By 1977, molecular biology had discovered that there exist three great ‘domains’ of life, defined by molecular criteria (e.g. rRNA structure), membrane structure, and other differences. Organisms within a particular domain are more closely related to each other than to those in other domains. The three domains are:

Eukarya	Eukaryotes
Bacteria	Prokaryotes
Archaea	Prokaryotes

Many of the extremophiles of interest to astrobiology (discussed in Lecture 7) are archaea. The evolutionary relationships between the three domains of life will be discussed in Lecture 6.

Just as an interesting astrobiological aside – this crucial discovery about the nature of life on Earth was made *after* the Viking biology experiments had been designed and launched to search for life on Mars in 1976....