NOTEBOOK

NOTEBOOK contains a miscellaneous collection of items all designed to aid your study of biology. Whether dealing with creatures or concepts, evolution or exams, NOTEBOOK will help, inform and remind you of things that you should find useful.

Why life chose carbon

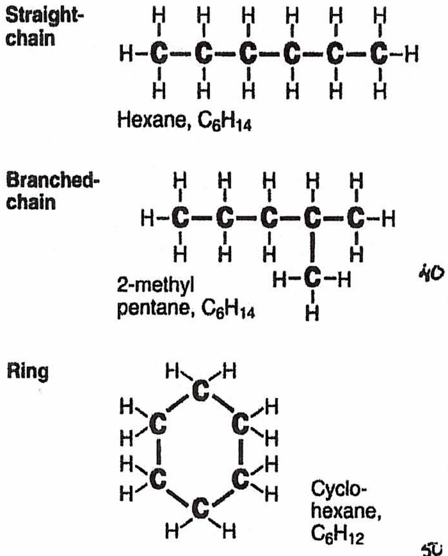

Figure 1 **Carbon chains and rings. Hydrocarbons (alkanes) containing six covalently linked atoms can form three types of structure: straight-chain, branched-chain and ring. Notice that each carbon atom has four other atoms attached to it. Three further branched-chain structures are possible; can you work out what they are?**

Carbon is one of the most widely used elements in the living world. It is the second most abundant element in the human body — about 18% of the wet weight (the most abundant element is oxygen, which makes up 65 percent). Molecules based on carbon — known as **organic molecules** because of their occurrence in living (i.e. **organic**) matter — constitute the majority of molecules found in living organisms, from plants to people. How does one element lead to the diversity found in living matter?

The functioning of a living cell depends on the interactions of many molecules (see Box 1), all of which have specific parts to play. Some are structural components, some are catalysts which help to build these components, some provide fuel for these reactions, and others control the metabolic processes by which energy is released from food.

CARBON'S UNIQUE NATURE

The chemical properties that give a molecule its function are directly related to its chemical structure. Carbon has four special features that have led to its inclusion in so many vital molecules. The first special feature is that carbon atoms are able to bond with each other to form extended **chains** (see Figure 1). They do this by sharing pairs of electrons with neighbouring carbon atoms to form stable **covalent** carbon–carbon bonds. Other elements do not readily link together in this way. Silicon is the only other element that can combine with itself to form chains of covalently linked silicon atoms, but it can form only a few different structures, unlike carbon. And Si–Si bonds, unlike C–C bonds, are readily oxidised in the presence of oxygen to form silicates and insoluble polymers of silicon dioxide (such as quartz).

As well as extended **straight-chains**, carbon can also form **branched-chains** and **rings** (see Figure 1). These chain and ring structures provide the skeletons of organic molecules. The **number** of carbon atoms in the chain is important, since it influences the size and shape of the molecule. However, the examples illustrated in Figure 1 have the same number of C atoms, yet their shapes are totally different. They also have significantly different boiling points, densities and other physical properties. While the versatility of the carbon chain can contribute to the variety of molecules produced, a bare carbon skeleton can have little biological function. The second special feature of carbon is that it can form covalent bonds with other atoms — such as O, H, N, S — so that a large number of functional groups can be introduced into organic molecules (see Figure 2). Functional groups give specific chemical properties to the molecules that contain them. For example, a molecule as complex as DNA (see Figure 3) maintains its structure by the interaction of functional groups, but it is still based on a carbon skeleton. The sugars that, together with phosphate, form the backbone of DNA are based on carbon.

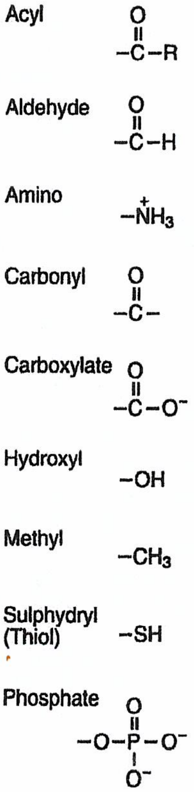

Figure 2 **Functional groups found in biologically important molecules. Each group is shown in the form that predominates in the near-neutral pH of most cells. Under these conditions, the amino group carries a positive charge while the carboxyl and phosphate groups carry negative charges. The structure/function relationship arises because these groups confer characteristic chemical properties on the molecules that contain them.**

BOX 1 EXAMPLES OF IMPORTANT ORGANIC MOLECULES FOUND IN LIVING ORGANISMS

Sugars	Fuel molecules (such as glucose). Structural molecules (such as cellulose). Cell recognition (such as small branched sugar chains on the surfaces of red blood cells).
Amino acids	Components of polypeptides and proteins.
Fatty acids	Components of triacylglycerols (fuel stores), phospholipids (cell membranes) and glycolipids (cell recognition).
Nucleotides	Contain sugar, base and phosphate. Components of nucleic acids (RNA, DNA — the genetic material). Also involved in energy transduction (ATP) and signal transduction (cyclic AMP).
Cholesterol	A sterol, precursor of steroid hormones (male and female sex hormones, hormones involved in glucose and sodium regulation) and bile acids. Component of cell membranes.
Porphyrins	Complex ring structures found in haemoglobin, chlorophyll and cytochromes.

So are the nucleotide bases which, attached to the backbone, form the basis of the genetic code.

CARBON IN 3-D

The third special feature of carbon — a feature that enables it to give rise to even greater diversity — is that carbon compounds have definite 3-D structures.

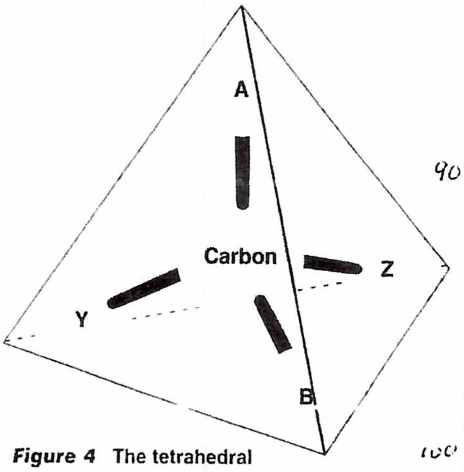

Figure 4 The tetrahedral carbon atom. The outer shell (valency) electrons of carbon are arranged in such a way that its four covalent bonds point to the corners of a regular tetrahedron.

This is because the carbon atom is **tetrahedral** — its four covalent bonds point to the four corners of a regular tetrahedron. A tetrahedron is a pyramid with a triangular base — imagine C at the centre and each of its four bonds pointing to a corner see Figure 4).

Carbon atoms with four different atoms or groups attached are said to be **asymmetric** or **chiral** (from the Greek word for hand). There are two different ways of arranging four different groups around a tetrahedral carbon atom, hence two forms — right-handed and left-handed — exist. The simplest examples are the amino acids (see Figure 5). This 'handedness' arises because of the tetrahedral nature of the carbon atom.

The 3-D structures for which carbon provides the outline are fundamental to the **specific** nature of biological molecules. It is essential that molecules in the cell fit together correctly. For example, **coenzyme** A is an important catalyst in the cell. It contains a sulphhydryl (–SH) functional group which allows it to react in a certain way. Other compounds containing a sulphhydryl group are able to mimic the chemical reactions of coenzyme A, but in the living cell they cannot act as a catalyst. This is because only coenzyme A has the 3-D shape required to attach, to a particular enzyme and prevents other molecules from fitting into the appropriate site on the enzyme (see Figure 6). So the molecule may be given specific properties by a certain functional group but, as far as biology is concerned, a specific skeleton is also needed to fit these properties into the right part of a system.

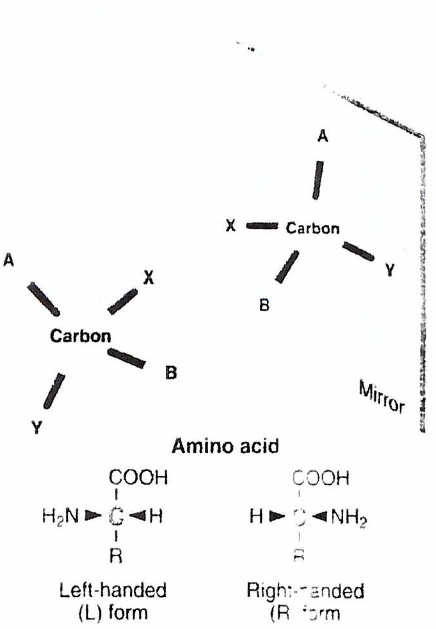

Figure 5 Chiral carbon atoms and mirror-image isomers. When four different atoms or groups are attached to a carbon atom, two mirror image forms of the resulting structures can exist. Amino acids, for example, exist in left-handed (L, *laevo*) and right-handed (D, *dextro*) forms. Proteins in living organisms are constructed entirely of the L forms. Sugars also exist in D and L forms; the D form predominates in living organisms.

Bond	length/ nm	Bond energy/ kJ mol^{-1}
C–C	0.154	346
C=C	0.133	615
C≡C	0.120	812

Stability of bonds is expressed as bond energy, the amount of energy (in kJ) needed to break one mole (6×10^{23}) of such bonds.

Table 1 **Properties of carbon–carbon bonds**

MULTIPLE BONDS

The fourth special feature of carbon is the ability of two carbon atoms to form more than one bond with each other. By sharing two or three electron pairs, double and triple bonds can form between the atoms. These **multiple bonds** are shorter and stronger than single bonds (see Table 1), and provide an additional way of introducing variety into the chemistry of organic molecules. Covalent bonds are strong, their bond energies (the energy needed to break a bond) are measured in hundreds of kJ mol^{-1}. Most biologically important non-covalent bonds (hydrogen bonds for example) have bond energies 10–100 times smaller than this, while the energy of thermal vibration is even lower — about 2.5 kJ mol^{-1}.

The suitability of the C–C bond for building the molecules of life can be seen by comparing its bond energy with the energy contained within sunlight. The visible spectrum extends from red (wavelength about 700 nm) to violet (wavelength about 400 nm). The energies in this spectrum range from 170–270 kJ per mol of photons, insufficient to break C–C bonds. If this were not so, light would break carbon compounds spontaneously so that life as we know it could not exist. Ultraviolet light, on the other hand, contains more energy and is therefore dangerous to life. UV light of wavelength 300 nm has energy of 400 kJ per mol of photons, which is enough to break C–C bonds (see BIOLOGICAL SCIENCES REVIEW, Vol. 10, No. 1, pp. 7–9).

So, the relevance of the chemistry of carbon to life is immense. The special features of this one element determine the bewildering variety and complexity of compounds found in living organisms — compounds responsible for the colour and scent of flowers, the taste and texture of food, the growth and activities of 'all creatures great and small'. Indeed, of all of life on earth. This is why it is important for biologists to have some understanding of basic chemistry — however irrelevant or inconvenient it might seem at first! The structure and the function of biological compounds are not just directly connected — they are inseparable.

FURTHER READING

Atkins, P.W. (1987) *Molecules*, W.H. Freeman & Co.

Rose, S. (1991) *The Chemistry of Life*, Penguin.

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