

SYMMETRY: SCIENCE & CULTURE

**SYMMETRY AND STRUCTURE IN BIOLOGY:
FROM MOLECULES TO MAN**

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INTRODUCTION

William T. Astbury, FRS, one-time professor of Biomolecular Structure at the University of Leeds, and coiner of the term 'Molecular Biology', once remarked at the start of a lecture to a gathering of eminent textile physicists that it was very important to capture an audience at the outset with a *telling* first sentence (Astbury, 1953).

Astbury then confessed that he didn't have such a first sentence for that particular occasion: the 1952 Mather Lecture. Instead he showed a lantern slide of a silk purse made from a sow's ear. This illustration was from a little brochure put out in 1921 by Arthur D. Little, Inc., of Massachusetts in the USA, to show that it was no longer true chemically to say that you cannot make a silk purse from a sow's ear. The 'silk' in question was reconstituted collagen fibres from the dermis of the animal's ear.

I do not have a mind-arresting first sentence, so I am also going to show a slide (Fig. 1). Each year, I show this micrograph to the students in my first year class in Cell Biology and Biochemistry as an exercise in interpreting images. I suggest to them that it is an aerial view of Suva harbour taken just after an off-shore earthquake had sucked most of the water out of the passage through the reef and left cruise liners and Russian trawlers stranded at right angles to the wharf. Maybe I have an honest face, or perhaps "it's the way I tell 'em", but I can guarantee that about half the class believes me!

Figure 1 is, in fact, an optical micrograph of a section through the silk secreting gland of a bumble-bee larva (Kenchington, 1965). The cigar-shaped objects are highly regular assemblies of rod-shaped protein molecules which have been secreted from the cytoplasm of the cells forming the wall of the gland. Such three-dimensional formations are known as 'tactoids'. They are particularly pleasing

examples (aesthetically so) of symmetry in biological structure. I shall come back to these tactoids later in this talk.

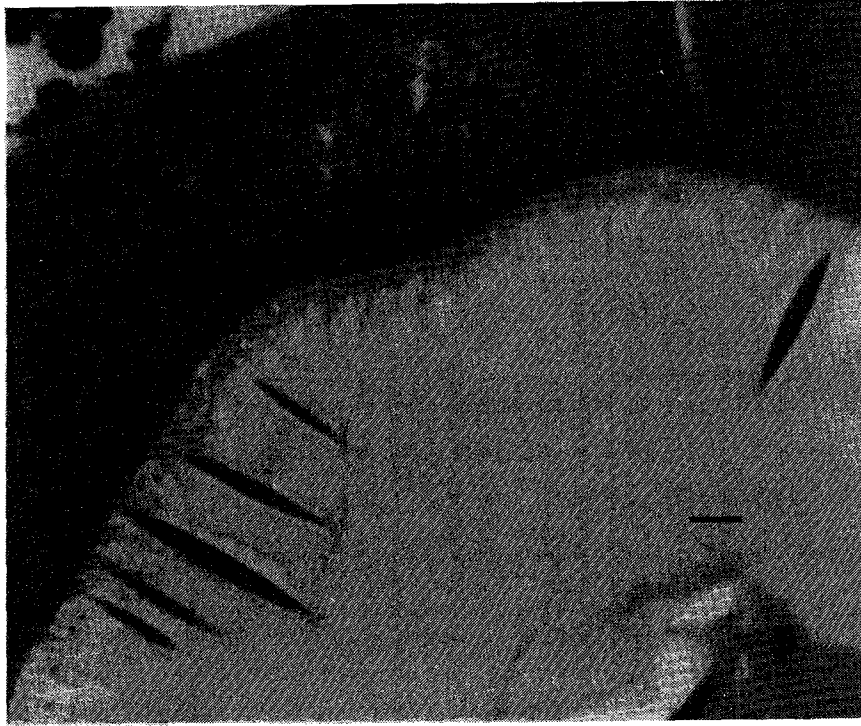


Figure 1: Transverse section through the anterior cubical cell region in the silk gland of *Bombus lucorum* showing a group of silk tactoids at the periphery of the lumen. Stained with Heidenhain's iron haematoxylin. Scale bar = 10 μm . (From Kenchington, 1965).

As a matter of fact, in relation to my introductory remarks, I *do* have some telling first sentences, but they are not mine; they belong to more eminent men. The first is by the late Heinz Pagels, Professor of Physics at Rockefeller University: "The universe begins in a very hot state of utmost simplicity and symmetry and as it expands and cools its perfect symmetry is broken, giving rise to the complexity we see today." (Pagels, 1985).

The second offering is by the poet Paul Valéry, who lived from 1871 to 1945: "The universe is built on a plan the profound symmetry of which is somehow present in the inner structure of our intellect." And the third example is that famous opening stanza, curious for its peculiar spelling and rhyme, by William Blake:

"Tyger! Tyger! burning bright
In the forests of the night,
What immortal hand or eye
Could frame thy fearful symmetry?"

MOLECULAR SYMMETRY

To deal adequately with biological phenomena, at the levels which I am going to discuss, necessitates looking at the molecules from which the structures are made. Indeed, I will have to admit at the outset that, at the molecular level at least, most of biological structure is *asymmetric*. Let me begin with the carbon atom, for that is the fundamental building brick, as it were, of all living matter. The model that I am demonstrating shows a tetrahedral carbon atom fitted with four white straws representing the four co-valent bonds which could be formed with other atoms or groups of atoms.

It is impossible to say whether the α -carbon atom itself is symmetrical or not. As Heisenberg's Uncertainty Principle explains, it is not possible to predict at any one instant the positions of the orbiting electrons. However, if I start to attach atoms, or groups of atoms, to this tetrahedral carbon atom, patterns of symmetry may or may not emerge.

For example, if I attach four chlorine atoms, represented here by the green model units, I get a representation of carbon tetrachloride, CCl_4 , the now infamous cleaning fluid which is rightly banned in most countries because of its carcinogenic properties. CCl_4 , as can be seen from the model, is a symmetrical molecule with three planes of symmetry.

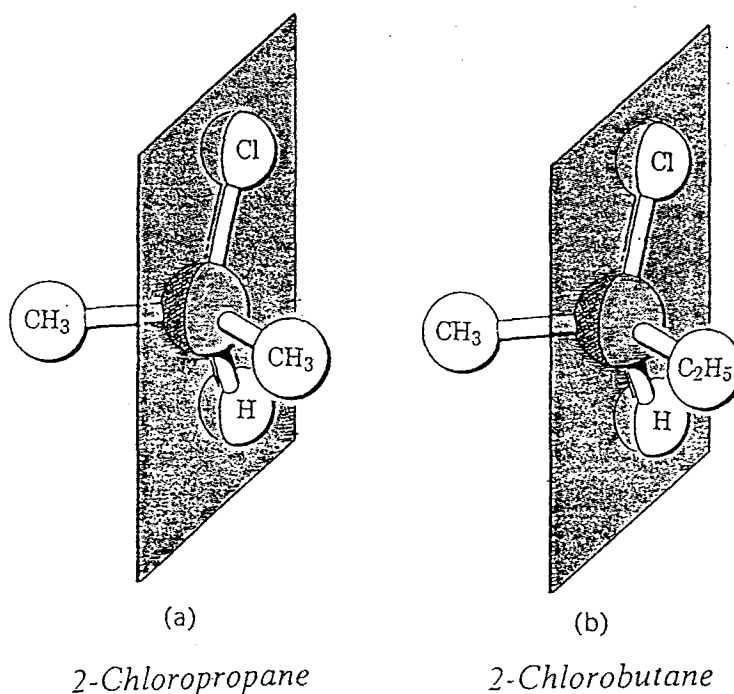


Figure 2: Symmetry and asymmetry in organic molecules. (a) 2-chloropropane shows planar symmetry with respect to the Cl-H 'axis'. (b) 2-chlorobutane shows planar asymmetry because of the C_2H_5 .

Figure 2 shows two other simple organic molecules: one is symmetrical while the other is asymmetric. The tetrahedral carbon atom combines with three different groups in the case of 2-chloropropane. This molecule is therefore symmetrical. 2-chlorobutane, with four different groups attached to the tetrahedral carbon atom, is asymmetric.

The tetrahedral carbon atom has a prominent role in all biomolecules – not least, the amino acids. As shown in Figure 3, the stereoscopic pairs of diagrams represent the arrangement of the four different groups on the central tetrahedral carbon atom: the carboxyl group (C), the amino group (N), the side chain (R) and the lone hydrogen atom (H). Thus, the amino acids are asymmetric molecules (apart from the simplest, glycine, in which the side chain is also a hydrogen atom) which occur in two optically different forms, or enantiomers. The dextro (or D-) form is the mirror image of the laevo (or L-) form. Only the L-form, shown at the top of the diagram, is found in naturally occurring proteins. The D-form does exist in some small molecules such as amino sugars, but never in naturally occurring proteins. Members of another important class of biomolecular building blocks, the sugars, are also asymmetric, and exist as enantiomers. But this time it is the D-forms which polymerise to form the naturally occurring macromolecules: the polysaccharides.

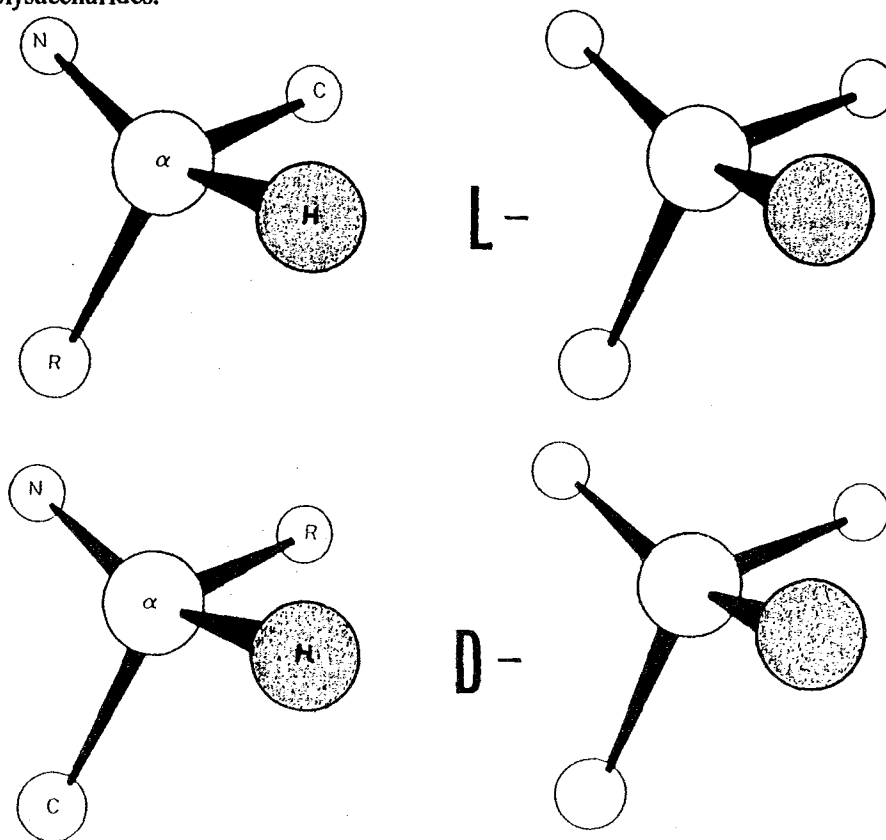


Figure 3: Stereoscopic pairs representing L- and D- amino acid conformations.

So, if you feed a cell-free (*in vitro*) synthesising system with mixtures of D- and L- amino acids, and D- and L- sugars, it will select only the L- amino acids, and the D- sugars, and build them into proteins and polysaccharides respectively. This is important evidence to support the widely held belief that all existing life has descended from a single, self-reproducing entity which incorporated only L- amino acids and D- sugars. A sort of molecular 'Eve', if you like.

How does symmetry in biopolymers arise from asymmetric monomers? A.C. Neville, in his monograph "Animal Asymmetry", argues that it does not (Neville, 1976). I quote: "All living systems are characteristically made of non-racemic mixtures of asymmetrical molecules"; and again: "Since biological helices have the same sense on both sides of the body, they too represent a type of structural asymmetry".

In my opinion, Neville is considering planes of symmetry only. Consider the models of the α -helix and the small length of DNA that I have brought along. They are, indeed, asymmetric in the sense that they are made up of linear arrays of asymmetric monomers, but they also demonstrate a special type of symmetry: that is, *screw*, or *helical*, symmetry. These molecules, and others such as keratin, actin, myosin, starch and collagen – all of them important structural and metabolic biopolymers – have an axis of symmetry.

This brings me back to the silk tactoids that I showed earlier. Tactoids are shaped like cigars. Or, perhaps like minute 'skylons'. Some of you may have visited the 1951 Festival of Britain Exhibition site on the South Bank of the Thames in London, and seen the 'skylon' which was a functionless, rather inconsequential but nevertheless aesthetically pleasing piece of engineering extravaganza.

Whereas the skylon was constructed from a complex framework of metal rods, etc., welded together at all sorts of different angles, these tactoids are simply linear assemblies of rod-shaped protein molecules. When tactoids are dispersed in weak salt solutions, the individual subunits (called fibrils) can be seen at high magnification under the electron microscope. These fibrils are about 10 nm in diameter and consist of assemblies of multi-stranded 'coiled-coil' helices. Atkins (1967) considered that the individual molecules were four-stranded coiled-coils on the basis of X-ray diffraction analysis.

SYMMETRY IN ORGANELLES

I now turn to a slightly higher level of biological organisation: the organelle. This term describes the various sub-cellular structures such as the nucleus, mitochondria, chloroplasts, Golgi bodies and so on. Most of these are anything but symmetrical, but there are some exceptions. One of the most notable, and important, is the mitotic spindle. This remarkable piece of 'cellular apparatus' forms at the onset of cell division. It is an array of 'fibres', which are actually microtubules, which grow from pole to pole and also radiate from the centrioles to form the so-called asters. The chromosomes become attached to this spindle after they have duplicated themselves and, by a mechanism that is still not fully clear, the

replicates are pulled to opposite poles. Actual division of the cell follows to produce two 'daughter' cells which are genetically identical to the 'parent' cell.

There is a certain degree of structural symmetry present in the spindle. However, it is the *functional* symmetry that I wish to stress. That is, the mechanism that enables two identical sets of chromosomes to be re-packaged into two almost identical cells. Or, in the case of the single-celled Protista, two identical organisms.

SYMMETRY IN ORGANISMS

My first examples cannot really be classified as organisms proper because they are not independently reproducing entities, nor do they possess many of the characteristics which are diagnostic of living things. I refer to the viruses. Many viruses are little more than crystalline assemblies of protein molecules surrounding a core of DNA or RNA.

I shall have to limit myself to only a few from a very large number of examples of symmetry in organisms. And it should be stressed at the outset that symmetry is invariably confined to the external form: the degree of symmetry to be found within animals and plants is usually limited.

At the simplest level, organisms such as bacteria exhibit symmetry: cocci are spherical, bacilli are rod-shaped and some (including the infamous spirochaetes) are helical. Some spectacular examples of symmetry are to be found amongst the Protozoa, particularly in the group known as the Sarcodina. This large group of organisms includes many types which have intricate skeletons composed of siliceous plates, spines and spicules. Good examples are found in the class Radiolaria. As their name suggests, these organisms have radially disposed spines.

Turning to multicellular organisms, the Cnidaria (jellyfish, sea anemones, etc.) are characterised by radial symmetry, as are the Echinodermata (sea stars, sea urchins, etc.). It is this latter phylum that I want to consider in more detail because they are unique in their development of symmetry. Embryologically, they start off as more or less bilaterally symmetrical larvae. Four of the six classes (the sea stars, the basket stars, the sea lilies and the sea daisies) then develop into radially symmetrical adults. A fifth class, the sea urchins, shows some secondary bilateral symmetry superimposed on a basic radially symmetrical plan, while the sixth class, the sea cucumbers, are bilaterally symmetrical with vestiges of the radial symmetry characterising the phylum as a whole. Interestingly, the most primitive echinoderms, similar to the Crinoidea (sea lilies) living today, showed no trace of radial symmetry.

Sea stars basically have a pentamerous radial symmetry, but there are variations on this theme: the sunstar has 13 arms, while the Crown of Thorns has up to 23. The holothurians (sea cucumbers, or beche-de-mer) are the aberrant members of the phylum from the point of view of their symmetry. Whereas the starfish, sea urchins and the brittle stars sit on their heads, so to speak, in the sense that they crawl around with the mouth next to the substrate and the anus directed up, the sea cucumbers have become reorientated so that the oral-aboral axis lies parallel to the substrate. They have a definite head end and tail end. The remnants of radial

symmetry are evident if one considers a cross-section of the body, but superimposed on the pentamerous arrangement is a bilateral symmetry generated by the reorientation of the body.

The phylum Cnidaria, together with the Ctenophora (sea gooseberries), constitute a major division of the animal kingdom called the Radiata in recognition of the predominantly radial symmetry that exists. The other division is the Bilateria. As the name implies, the predominant symmetry present is bilateral. It is generally accepted by biologists that as animals evolved they became more motile (some rapidly so) and therefore more independent of their environment. Obviously this is a generalisation: there are many exceptions. Bilateral symmetry allows the development of a streamlined body shape which enhances motility, allows the development of fins, legs, wings etc. However, as Neville has pointed out, this bilateral symmetry is confined to the external form; the internal organs are asymmetrical for the most part (Neville, 1976).

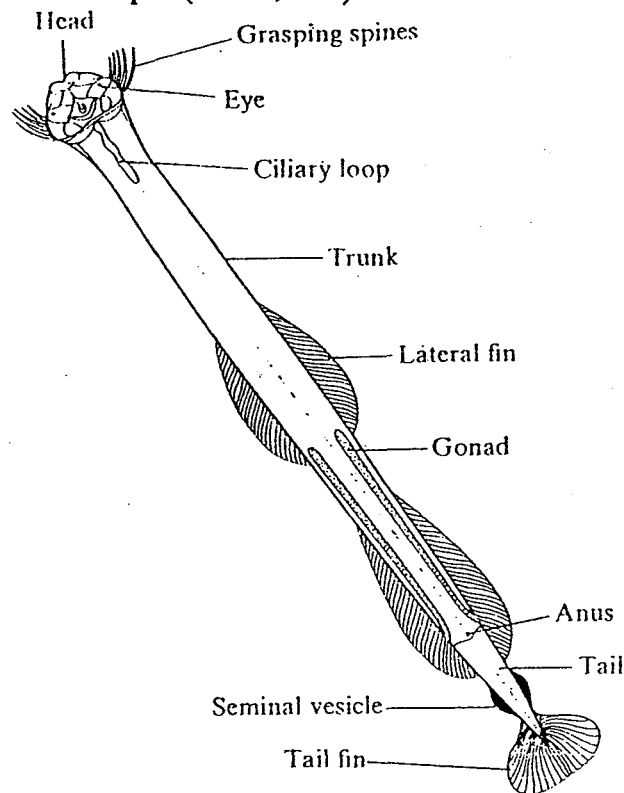


Figure 4: The arrow worm, *Sagitta elegans*, X 2.

The only example that I want to give of the huge numbers available is the arrow worm, *Sagitta* (Fig. 4). Not only is it a particularly elegant example (indeed, its specific name is *elegans*!) but it is an animal on which I have done some research in the past (described in Rudall, 1976). You will note the grasping spines around the

mouth. The animal uses these to catch its prey. The spines are made of the polysaccharide chitin which, in this situation, is in an unusually highly crystalline form as shown by its electron diffraction pattern. Both electron and X-ray diffraction patterns are beautifully symmetrical. Alas, this is only coincidental: asymmetrical structures would also yield symmetrical diffraction patterns.

So far, I have confined my attention to the animal kingdom. Widespread symmetry occurs in the plant kingdom — mainly involving flowers and fruits. But there is some degree of symmetry in the structure of the plants themselves.

THE ORIGIN OF SYMMETRY IN ANIMALS

How does symmetry arise in multicellular organisms? Undoubtedly it must be determined genetically to a greater or lesser extent. Embryologically, all multicellular animals develop from a fertilised ovum (the zygote) by way of a series of cell divisions which are initially symmetrical. These cleavages follow two patterns: radial and indeterminate, or spiral and determinate.

Radial cleavage occurs in all the Deuterostomia (which includes the echinoderms, tunicates and vertebrates). The rest of the multicellular animals (classified as Protostomia) develop through spiral cleavage which is also symmetrical in the early stages of development. The different patterns result from the orientation of the spindle with respect to the axes of the original zygote. In radial cleavage, the spindle is oriented parallel, or at right angles, to the polar axis. In spiral cleavage, it is oriented at an angle of about 45° to the polar axis.

SYMMETRY AND MAN

Man, like most other chordates, has an external shape which is basically bilaterally symmetrical, as is so elegantly illustrated in the famous sketch by Leonardo da Vinci: *del Canone delle proporzioni del corpo umano* in the Gallerie dell'Accademia, Venice. Da Vinci was one of the first to appreciate that mathematics and geometry were closely linked to man's artistic and cultural endeavours. He warned: "Do not read me if you are no mathematician" in a treatise on painting. I will return to this theme later.

Neville (1976) highlights certain asymmetric features, for example the face. Using a photographic 'trick', he demonstrates that the two sides of the face are different enough so that, when 'twinned', two demonstrably different looking people emerge. He suggests that such reconstructions make it difficult to identify the individual in question, and that this is a fault common to many police 'Identikit' pictures.

However, I am more interested in another aspect of man's symmetry: that of the mind. Let me reiterate the quotation from Paul Valéry:

"The universe is built on a plan the profound symmetry of which is somehow present in the inner structure of our intellect."

This is evident in two of man's creative endeavours: art and science. Sometimes the two are intuitively combined. In the nineteenth century, for example, crystallographers worked out the thirty-two different types of symmetry in crystals. A crystallographer who visited the thirteenth century Moorish palace, the Alhambra, in Spain found that the mosaics on the walls and floors displayed all the known varieties of crystal symmetry. As Judson (1980) points out, the artist had taken a theme and worked out all the variations and had exhausted the geometry of symmetry.

Symmetrical design has played an important part in artefacts all over the world through the millenia. Some have claimed that the symmetrical pyramids confer magical properties of preservation, and that dead matter, for instance, which is placed in precisely located spots inside scale models, will never decompose. Or that used razor blades similarly positioned will sharpen themselves overnight. I once tested this latter claim. The fact that I have a beard is not at all related to the failure of that experiment!

The symmetrical Stonehenge in Wiltshire, England, and similar structures elsewhere, were undoubtedly designed with a specific and practical purpose in mind: to predict astronomic events and seasons of the year. The custodians of such knowledge must surely have held powerful positions in their society.

And finally, what of evolution itself? That genius of design Maurits Escher has cleverly represented the evolution of vertebrate forms, and the migration from water to land, in his 'Verbum'. At first glance, there seems to be an overall symmetry in the scheme, but it is essentially an asymmetrical situation, both in the design itself and the theme which it expounds. Biological evolution is anything but symmetrical as a glance at any evolutionary tree will confirm.

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