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Lucretius: Atoms and Opinions*

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ABSTRACT: It is argued that the scientific program most clearly articulated by Lucretius is still appropriate today, although it continues to represent a minority view of the world. In *De rerum natura* Lucretius formulated the goals of explaining, without religious or supernatural assumptions, the properties of all living and nonliving things in terms of the emergent properties of atoms. We examine five topics: atoms—structure underlies function; group theory and the breakdown of exact equivalence; the emergence of complex properties from simple units; the parallel between letters (of the alphabet) and atoms in the building of complex structures; and the coming coalescence of the mental and physical worlds.

Nothing exists except atoms and empty space; all else is opinion.
Democritos

INTRODUCTION: ATOMS

I am delighted to have this first and last opportunity of presenting my views as a kind of *apologia pro vita sua* to my colleagues, but must begin with the disclaimer that since science is a numerically small and somewhat persecuted international sect, my opinions are widely but not densely shared. Scientists are necessary to their societies, but they are treated like the smiths of classical times (Hephaistos was the mythical archetype), who were social outcasts but were lamed to prevent them from running away, since their skills were needed but not understood. Daedalus, the first technician, was also the first technician to emigrate [1,2]. Crystallography is an apparently harmless branch of science concerned with the internal and external structure of crystals, that is, with the arrangement of atoms to make up the various beautiful shapes observed since the earliest times. The word "crystal" comes from the Greek *krystallos,* which signified ice or rock-crystal, and indicated the very reasonable theory that quartz was just ice that had become petrified by extreme cold. Words and meanings evolve together like DNA and proteins, and Grimm's law in linguistics has its molecular parallels.

I mention etymology because now, since the discovery of the genetic code, we have an example of a natural language in which words, and the things to which they refer, are seen to be closely connected in a joint system. The meaning of the word "crystallography" and the subject itself have evolved together. After the genetic code, the understanding of mental processes is the most exciting enterprise of modern science. Language and meaning have reentered the vocabulary of the hard sciences, and Max Müller's claim [3] for a science of language is in prospect of realization.

My earliest introduction to language structure and to educational technology was provided by Latin lessons, which were conducted in a manner that would have been entirely familiar to the ancient Romans, since they invented it to educate the obdurate inhabitants of these islands. The schoolmaster wrote on the board the paradigm of the declension of the Latin adjective: bonus, bona, bonum, boni, bonae, boni, . . . and said: "The first boy to learn it gets sixpence and the last boy gets beaten." This method has not been improved on over the millennia, except that it is now called positive reinforcement. I still bear the mental scars of such an education, since we were also more passively exposed to the liturgies of the Church of England. It produced a superficial conformity and a tendency to go on thinking one's own thoughts underneath it.

Thus, crystallography is, I think, more a kind of nonconformist movement than a subject in the academic sense. Crystallographers like to find out for themselves. Typically, they have identified problems to the solution of which they think they can contribute perhaps half, but have persisted in learning much of the other half, which enables them to keep control of the topic. Knowledge is power and, like people at the time of the Reformation, crystallographers want to have direct access to the supreme power without having to go through the established priesthood—for

 Inaugural lecture as professor of crystallography, November 15, 1988.

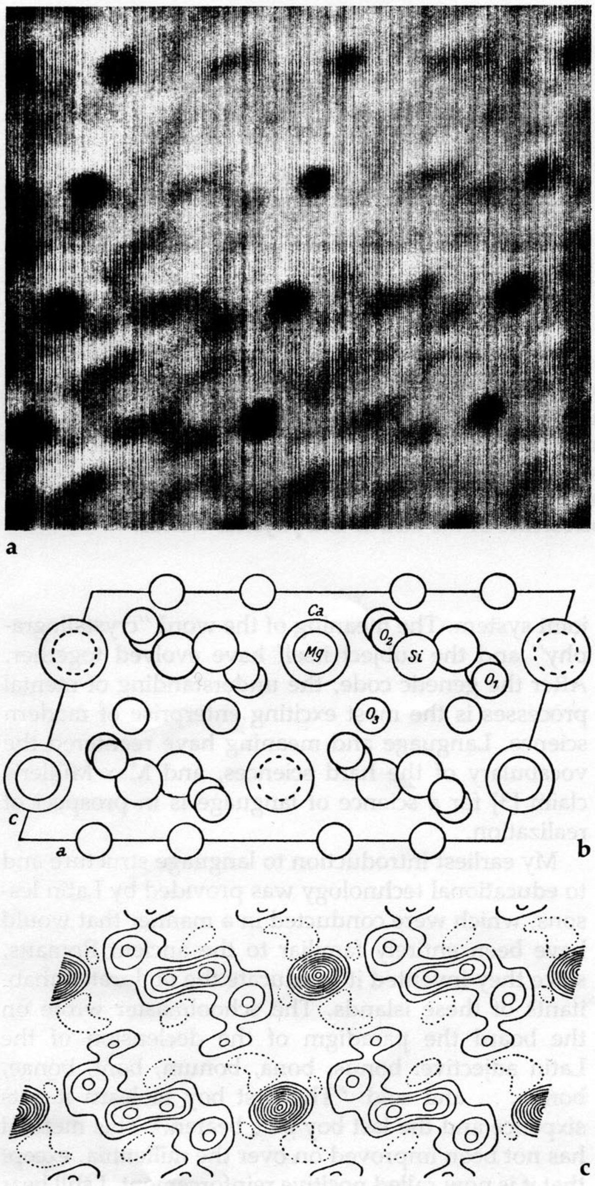

FIGURE 1. Diopside. (a) The first X-ray "picture" of a crystal structure. (b) Atomic positions. (c) Fourier map. (Reproduced from Reference 4.)

example, to use the computer without having to go to the window of the confessional box, prove that you are a registered communicant, and log in with the magic password. Thus, they have not become mere custodians of a technique to which others with real problems turn for assistance. They like to do their own physics, chemistry, biochemistry, and computing, and at times have even fancied that they could contribute to the political and social sciences.

In its modern form the subject of crystallography exploits the occurrence of materials as crystals to make possible a process that can be seen to be a form of microscopy, to make visible the way in which the component atoms are arranged in space. Crystallography appeals directly to the visual cortex and uses many models and pictures for thinking. The skills our simian ancestors used for swinging through the trees—and one of the most important facts of history is that there were many more trees then—can be seen any day if you watch crystallographers at work on the computer graphics, swinging through the creepers of protein molecules. Eyes provide a direct, hard-wired, stereo interface to the brain. Words tend to take second place, and their processing is less direct.

This versatility has been continually demonstrated since our founding fathers William Bragg and his son Lawrence Bragg first demonstrated in 1913 that X-ray diffraction could enable us to see the positions of the atoms in crystals [4]. The first crystal structure they solved was that of sodium chloride. Although not unexpected, the structure showed that there were no molecules of NaCl and that the equality in the numbers of sodium and chlorine atoms was due to the structure, the three-dimensional chessboard pattern. This rather shook a few of the more orthodox chemists of the time. The first actual picture of atoms in a crystal (Figure 1) they produced was one of diopside, a magnesium silicate.

The Braggs' work had many admirable features characteristic of the British empirical scientific tradition. It was visual, and the investigators took great pains to present their results and methods in terms of models and pictures. Sir William Bragg himself produced a book using Lucretius' title "On the Nature of Things" and lectured at the Royal Institution on "Old Trades and New Knowledge," explaining how the traditional trades of the sailor, smith, weaver, dyer, potter, and miner depend on the properties of materials, which are to be understood in terms of the arrangement of their constituent atoms in space. Relevance to industrial needs is not something new.

We leave to our physicist friends the more difficult job of working out what atoms are made of. There are several layers of structure below atoms, but we are concerned with the Nature of Things as materials and are, in fact, following the program of Lucretius laid out in his poem *De rerum natura* [5] written in the first century B.C.

Crystallographers have always been concerned with the real world. Since 1913, more and more complicated molecules have been explored and their modes of operation considered. About 80,000 organic molecules, 25,000 metallic and inorganic structures, and 300 proteins have been studied by the methods of crystallography. It is necessary first to see how X-ray diffraction acts as a kind of microscope (Figure 2) because, besides being the basis of X-ray crystallography, it affords an important philosophical demonstration.

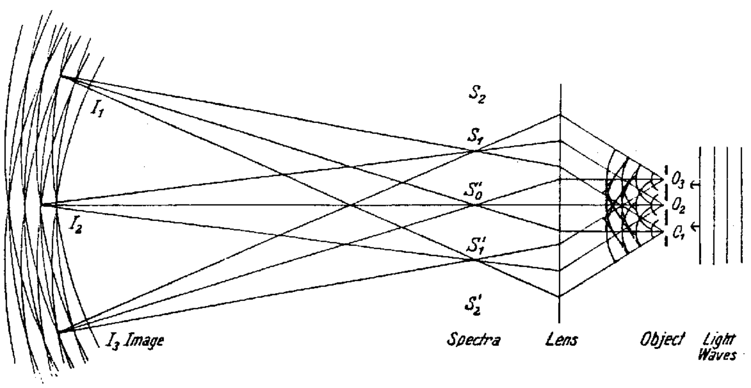

FIGURE 2. The Abbe theory of the microscope. (Reproduced from Reference 4.)

The formation of an image takes place in two stages. In the first stage a diffraction pattern is formed. In the second, this is again transformed and gives the final image. The function of the lens is to bring the diverging beams together again so that they interact to form the image. Because there are no lenses for X-rays, this second stage has to be done by computer. Moreover, in recording the diffraction pattern, more than half of the information is lost, so that the reconstruction is in principle impossible unless we can supply other knowledge.

Many processes can be represented in this way. For example, in representing some situation as a language, the situation in real space is projected into the transform (symbolic) space. Only certain features are projected and the rest are lost, so that the operation is irreversible. We can restore the real space situation only by supplying knowledge from some external source. We must immediately be reminded of Plato's analogy of the cave, where we are imagined as seeing only shadows of ideal objects.

The key idea is that here we have a partial representation or model in another "language" with which we can work. We can then transform our model back to the real world and examine the consequential changes.

Crystallography, then, gives pictures of atoms and how they are arranged in space. Understanding the properties of living and nonliving materials depends on knowing these arrangements.

Lucretius was the popularizer and promoter of the ideas of the early Greek atomists, Democritos and Epicurus, whose actual works have survived only in vestigial form [6]. In *De rerum natura* [5], Lucretius sketched out a view of the universe in which the primordial components, the atoms, combined in layers of increasing complexity to give the universe, and all the inorganic materials and the living creatures in it. His guesses were astonishingly good.

1. "Atoms . . . are the 'primary particles' because they come first and everything else is composed of them." (p. 28)
2. "Nothing can ever be created by divine power out of nothing." (p. 31)
3. "Nature resolves everything into its component atoms and never reduces anything to nothing." (p. 33)
4. "There is vacuity in things." (p. 37)
5. "Nothing exists that is different both from body and from vacuity." (quoting Democritos: "There exist only atoms and empty space, all else is opinion.") (p. 40)
6. "Although all the atoms are in motion, their totality appears to stand totally motionless. This is because the atoms all lie far below the range of our senses." (p. 69)
7. "The number of different forms of atoms is finite. (The number of atoms of any one form is infinite.)" (p. 74)
8. "There is no visible object that consists of atoms of one kind only." (p. 77)
9. "It must not be supposed that atoms of every sort can be linked in every variety of combination." (p. 80)
10. "Whatever is seen to be sentient is nevertheless composed of atoms that are insentient." (p. 85)
11. "Mind and spirit are both composed of matter" p. 101)

The behavior of living creatures, including their consciousness and self-consciousness and their emotions, are all seen as consequences of their atomic structures. Richard Feynman, who died in 1988, wrote in his celebrated textbook [7]:

> Everything is made of atoms. That is the key hypothesis. The most important hypothesis in all of biology, for example, is that everything that animals do, atoms do. In other words, there is nothing that living things do that cannot be

> understood from the point of view that they are made of atoms acting according to the law of physics. This was not known from the beginning, it took some experimenting and theorizing to suggest this hypothesis, but now it is accepted, and it is the most useful theory for producing new ideas in the field of biology.

People in this department have contributed very greatly to our understanding of, for example, the hormone molecules which are the material basis of our emotional reactions. I will not try the experiment of insulting you, to demonstrate what adrenaline molecules do and the consequent physical changes produced by a purely symbolic or cultural stimulus. Aldous Huxley was quite right when he wrote in 1931: "Our ductless glands secrete, among other things, our moods, our aspirations, our philosophy of life" [8]. The ways in which atoms are arranged in three-dimensional structures are the primary level.

Present-day crystallography is engaged in working out the program of Lucretius to explain the properties of all kinds of things, from rocks to man himself, including J. D. Bernal's favorite topic, the origin of life on earth, in terms of atoms and their properties in combination.

This program immediately takes us into the political battlefield, since, for example, Mrs Thatcher has affirmed, *ex cathedra,* to the General Assembly of the Church of Scotland that "We were made in God's own image" [9]. The program of crystallography is, I think, gradually revealing that the opposite is, in fact, the case.

Because of this, from the beginning of politics—the way of governing the conduct of large aggregations of people in cities—the views of Lucretius, and those of his forerunners and successors, have been repressed in most civilizations and cultures. It has recently been suggested by Piero Redondi [10] that Galileo's real crime was that of atomism, but that through plea bargaining he was allowed to stand accused of the lesser crime of heliocentrism. The doctrine of the immutability of atoms was clearly dangerous to the central religious doctrine of transubstantiation and was not to be discussed in public.

Our departmental notice for seminar speakers carriers the text: "There exist only atoms and empty space; all else is opinion," which Lucretius quotes from Democritos in the fifth century B.C. This might appear to be a mild exhortation to keep to the point, but you might note that the Vatican Council ruled (in 1870) that "If anyone shall not be ashamed to assert that, except for matter nothing exists; let him be anathema."

Lucretius' book was on the Index of Prohibited Books (which existed until about 1948), but I have not been able to find out for how long.

Science has always had to deal with the civil and military powers that be, and these have different ideas of truth. It is important to know what people in charge of plutonium regard as religious truths. In a modern technological civilization, we increasingly see the conflict between political truth and scientific truth. This was demonstrated recently in the American Challenger rocket disaster, where public relations took precedence over facts of nature. Vacuum systems cannot be dealt with by rhetoric or anathemas, as you quickly find out in experimental physics. The book *Zen and the Art of Motorcycle Maintenance* chronicles the journey of a Platonic philosopher who gradually discovers that "A motorcycle functions entirely in accordance with the laws of reason, and a study of the art of motorcycle maintenance is really a miniature study of the art of rationality itself" [11].

As Leibniz argued, it is not necessary that an agreed ethical system for governing human relationships be founded on myth. He believed (probably quite erroneously) that the Chinese led exceptionally moral lives without supernatural foundations. However, the technology of government usually appealed to supernatural sanction. The Emperor of Japan is still of divine ancestry and people there get into serious trouble if they publicly assert otherwise. As Strabo the Geographer explained [12].

> The poets were not alone in sponsoring myths. Long before them cities and lawmakers had found them a useful expedient. . . . They needed to control the people by superstitious fears, and these cannot be aroused without myths and marvels.

One might argue that a major function of the first research institution in the world, the great Museum of Alexandria [13], was to produce the miracles of technology with which the priests could mystify the populace. This resulted in many steam- and water-driven machines but, since there was plenty of slave power, these were not applied in industry but in the technology of religion. However, as with the space program, much significant research, such as Euclid's Elements, was generated as a by-product. Plato, in *The Republic,* explained exactly how myths should be used by the rulers, who did not themselves have to believe in them but used them purely for manipulation of the ruled.

Lucretius followed the principle, which, I think, should be that of every good scientist, that his outlook on the world should be an uncompartmentalized whole. It is not permissible for a scientist to carry irreconcilable views in the same head—everything has to be fitted in to an overall pattern, which is continually changing and adapting, sometimes radically, as new facts come to light. The scientist must worry about contradictions and cannot have one compartment for his myths and another for his science. This, of course, is the reason for the recent row in *Nature* (the journal) over the curious experimental results that seemed to be anomalous in supporting homeopathy. There appeared to be a serious contradiction between experiments and current theories, which has to be resolved by experiment. The strength of science is that it is one coherent building, although with bits falling down and other bits being added and, some allege, with dry rot in the foundations.

The scientific profession has always been a minority one, with beliefs that are sharply different from those of the majority of the populations in which they have had to exist. I think that the conflict between science and religion [14] was more open and acknowledged in the eighteenth and nineteenth centuries, when Denis Diderot, editor of the *Encyclopaedia*, could propose with gusto: "with the bowels of the last priest let us strangle the last king." Somehow, nowadays it gets hushed up and is mixed with the controversies about ethnicity and equal respect for all cultures and their incompatible myths. In his after-dinner speech at the British Association for the Advancement of Science meeting of 1874, in Belfast of all places, James Clerk Maxwell could venture to recite his own verses:

> In the very beginning of science,
> the parsons who handled things then,
> being handy with hammer and chisel,
> made gods in the likeness of men;
> Till commerce arose and at length
> some men of exceptional power
> supplanted both demons and gods by
> the atoms, which last to this hour.

I doubt whether he could do it now without sectarian protests; indeed at that meeting John Tyndall's presidential address on the same theme, which Maxwell was paraphrasing, excited tremendous opposition.[1] Even the scientific profession does not have monolithic views. The British Association for the Advancement of Science still has a church service (on which we can read Peter Medawar's comments), and A. B. Pippard, formerly the Cavendish professor of physics, quoted exactly the same extract from Feynman in his recent Eddington lecture, before going on to reach a theistic conclusion [15].

GROUP THEORY

Although the early atomists Democritos and Epicurus were Greek, the views of other Greeks predominated, at least in our literary culture.

The Greeks discovered the five regular Platonic solids, or perhaps just heard of them from the Babylonians. They were so fascinated by this that in his book "Timaeus," Plato made them the fundamental units of his ideal universe; or rather, since each of the five solids can be built up of triangles, he took as the two fundamental units the triangles every schoolchild used to have in his geometry set.[2] This was rather abstract and fanciful, especially as we now know that Greek civilization could do much better. Indeed, Plato himself complained [16] of the ludicrously inadequate state of solid geometry in his time. What they actually had was a representation of certain groups of symmetry operations, but this gave the illusion of acquiring absolute knowledge about the world *a priori* from certain axioms without experiments.

We must distinguish between the Platonic models, which were a self-contained ideal system, and experimental models, which were used for thinking about the real world.

The discovery and the recent elucidation [17] of the working of the Anti-Kythera machine, which was a mechanical calculator of stellar positions, has shown that 2000 years ago, they could make a mechanical device as complex as a modern preelectronic clock. However, then as now, engineers were not greatly esteemed by the philosophers and politicians, and their works did not figure in literature. This machine has shown that there were important features of Greek civilization not transmitted by our literary culture.

One of the greatest of the Greek experimentalists, Archytas of Tarentum, who made a model aircraft and other devices, was rebuked by Plato for using physical methods in geometry (that is, thinking with models—the forerunner of computer graphics). Later too, Archimedes himself admitted that he found various pure mathematical results by a mechanical method, but to get them accepted by mathematicians had to prove them in the axiomatic geometrical form.

We now see a sharp split, brought about by the computer, between absolute logic and what is computable by actual machines. Nature itself is seen now to be a computer of limited and not infinite accuracy, at least as regards assemblies of atoms. Nature often settles for the "near enough" solution. The discovery that the square root of 2 could not be expressed as the ratio of two integers worried the logicians, and it is said that the man who found this secret perished in a shipwreck so that the dreadful scandal should not get about. However, we cannot measure root two with infinite accuracy.[3]

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[1] I am grateful to Roy MacLeod for pressing me to read about this BAAS meeting. It is astonishing how little change there has been in 115 years.

[2] George Sarton (*Introduction to the History of Science*, Vol. 1, p. 113) goes so far as to say that the influence of the Timaeus "was largely an evil one."

[3] The Babylonians, who thought numerically rather than geometrically, could calculate the square root of 2 to one in 10 million—a much greater accuracy than that of their measurements. (O. Neugebauer, *The Exact Sciences in Antiquity*, 1957, p. 35.)

Crystallography has recently moved from the absolutist Platonic phase to a more realistic computer phase in which there has been a very similar and equally scandalous discovery (due to Dan Shechtman at the U.S. National Bureau of Standards and published in late 1984) [19] with which we have been closely concerned.

No major theory of science today is so complete and finished as that of crystal symmetry. If you begin with the proposition that in a crystal an infinite number of identical units are situated with identical surroundings, you find that there are only 230 ways of arranging them. This result was due to Fedorov, Schoenflies, and Barlow about 100 years ago—before atoms were properly demonstrated. There is the trifling difficulty that no crystal is actually infinite, but it is accepted that since atoms are so small, most crystals consist of at least a million million atoms and are effectively infinite. A row of 5 million atoms is about a millimeter long.

This classical theory of the space groups of symmetry [19] shows that only axes of symmetry of order 2, 3, 4, and 6 can occur in crystals. Fivefold, sevenfold, and other higher orders are impossible.

It has been most gratifying to find recently that such a well-organized subject can still be broken apart by new ideas, growing like weeds through gaps between the foundation stones.

One of the most interesting weeds has been fivefold symmetry. In fact, this is the symmetry most weeds have.

Crystals are the result of local packing rules (Figure 3). We may imagine the order, heard in the Red Fort in Delhi: "Bombardier Smith! Get this shot stacked!" Laying out a layer of spheres in a square array and then repeating this layer on top so that the sphere in one layer fall over the gaps in the layer below automatically generates a crystal in which each sphere

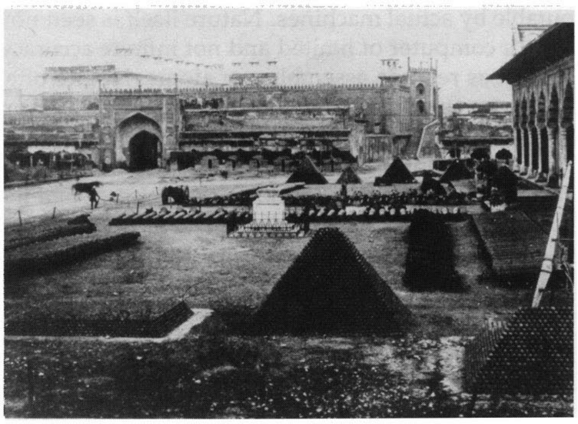


FIGURE 3. "Bombardier Smith, pile up those cannon-balls!" The Red Fort, Delhi.

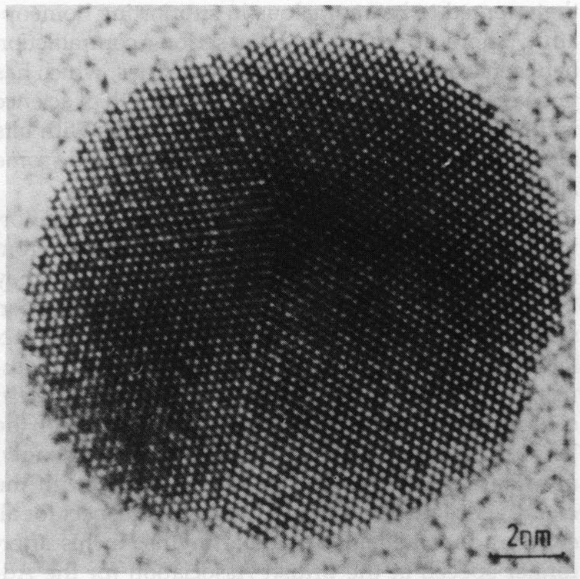


FIGURE 4. Twinned crystal of gold at atomic resolution. (Electron micrograph, Cavendish Laboratory.)

touches 12 others and densely packed plane faces of hexagonally packed spheres result, bounding the pyramid on all four sides. This is the structure of gold. We may compare this with an electron micrograph of gold atoms of atomic resolution (Figure 4), where five segments of perfect crystal are joined by twin boundaries.

Let us take, for the moment, the case of packing in the plane. Here (Figure 5) we have a planar crystal with various symmetry operations. You can see threefold and twofold axes of symmetry, which would result automatically if we were given a pile of identical jigsaw pieces and asked to join them up. We need not know the long-range pattern in advance. The long-range order comes from the local rules of combination.

Regular lattices of points, with identical surroundings, can have only the symmetries 2, 3, 4, or 6 at these points; fivefold axes are impossible. Every textbook of solid-state physics, for example, that by C. Kittel,[4] and every textbook of crystallography[5] tell you this in the first chapter.

A single, nonrepeated, fivefold axis is very common for the finite objects of biology. Indeed N. V. Belov wrote in 1962 [20]:

> The exclusion of a fivefold axis for crystals, as well recognised, results from the impossibility of reconciling it (and axes of order greater than six) with the "lattice state" of

[4] Kittel in fact swithers from one edition to another on this issue.

[5] The writers are unable to prove that the lowest energy configuration of an assembly of identical units must be crystalline, perhaps because it is not true.

> crystalline matter. It would appear, then, that for small organisms the fivefold axis represents a distinctive instrument in their struggle for existence, acting as insurance against petrifaction, against crystallisation, in which the first step would be their "capture" by the lattice.

However, most people who have played with geometrical arrangements have themselves tried to pack pentagons just to see what happens. Kepler and before him Albrecht Dürer, who as a master draftsman also wrote a book on geometry [21], found various solutions. Basically there are three ways of changing the rules so that we can have fivefold axes and can pack pentagons.

1. Curve the plane into the surface of sphere. Twelve pentagons then pack nicely to give the dodecahedron and we get a finite closed space (Figure 6). Dürer was perhaps the first to construct fold-up cardboard figures of this type.

2. In the plane pack six pentagons to give a bigger pentagon; pack six of these to give a still bigger one, and so on hierarchically (Figure 7). Larger and larger gaps appear, but it is found that these can be filled in if our pattern is made out of pieces of two kinds. This yields the Penrose pattern (Figure 8) (found also by Roger Penrose,[6] who was concerned to produce a regular but nonperiodic pattern).

3. Abandon finite atoms and allow an infinite regress, which gives an infinitely fine texture with fivefold symmetry everywhere. The mathematics of this approach, developed by N. D. Mermin and his colleagues, takes one quickly into very deep waters of number theory, and we will not pursue it further, although it is of the greatest interest. We must stay with the idea of atoms.

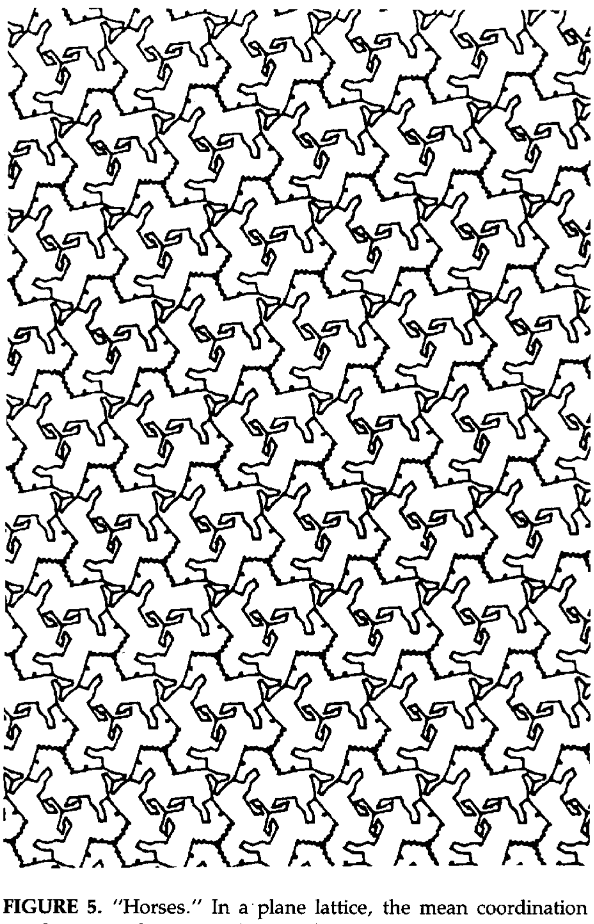


FIGURE 5. "Horses." In a plane lattice, the mean coordination number is 6. (Computer drawing by the author after a motif by Nakamura.)

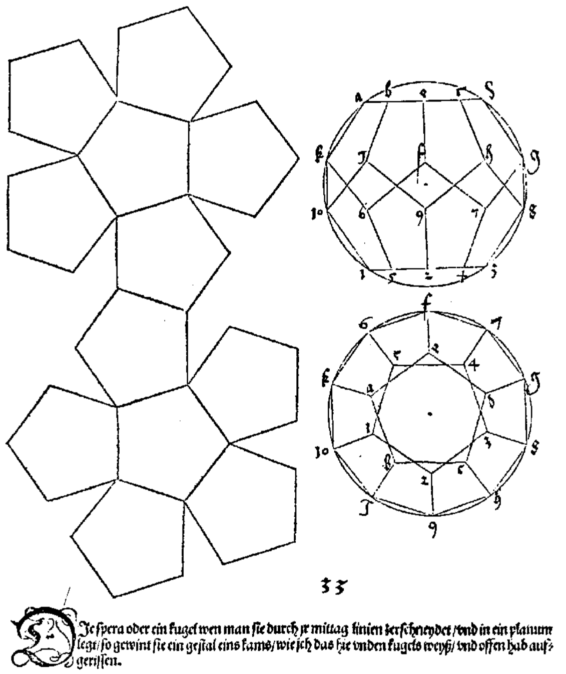


FIGURE 6. Albrecht Dürer tried to pack pentagons; 12 pentagons fold into a dodecahedron.

Case 1 was of great interest when Klug and Franklin were examining the polio virus. They found that 60 asymmetric units formed a finite capsule and that these large units then crystallized normally. The symmetry of this icosahedral unit can be shown by wrapping one of Escher's best known drawings around an icosahedron (Figure 9).

In case 2 if we stop drawing the Penrose pattern in the middle, we see that it has a fractal structure with five-pointed snowflakes (Figure 10).

If we ask whether we can also have sevenfold symmetry in the plane, then the answer is yes. Regular heptagons can be packed together so that all are iden-

[6] Formerly professor of mathematics at Birkbeck—although unfortunately he did not then talk to crystallographers.

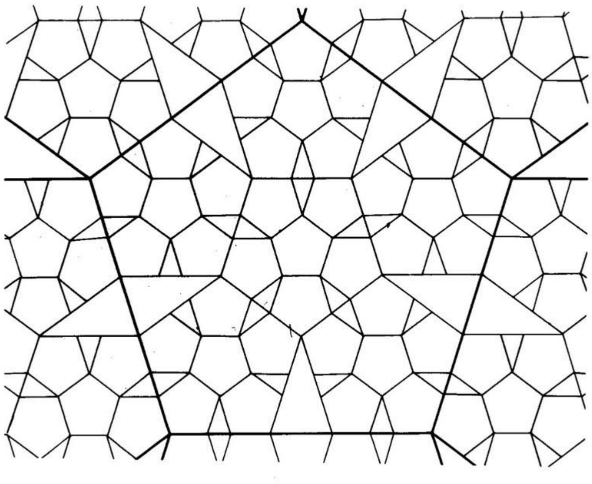


FIGURE 7. If we insist on packing pentagons in a plane, it can be done hierarchically with extra rules for filling in the gaps.

FIGURE 9. Sixty asymmetric objects can be packed into an icosahedron so that each is identically situated, as in poliovirus.

tically situated, but the space then curves in the opposite direction and its radius of curvature becomes imaginary. However, we can still draw a stereographic projection (Figure 11) of this space, which is called the "hyperbolic plane." Only small elements of this space, which are saddle-shaped can be constructed. Saddle-shaped regions can be joined together to give an infinite manifold of nonpositive curvature in which the mean coordination number is greater than it is for the plane.

Such surfaces have also turned out to be of practical importance and are found as the shapes of the surfaces that separate oil and water in lyotropic colloids. Several saddles can be assembled to give a kind of pipe-joint, and these join together to give an infinite crystal (Figure 12). Another such surface is shown in Figure 13.

However, until 1984, all the structures associated with fivefold symmetry were merely recreational mathematics while those involving curved manifolds had already proved useful in many applications.

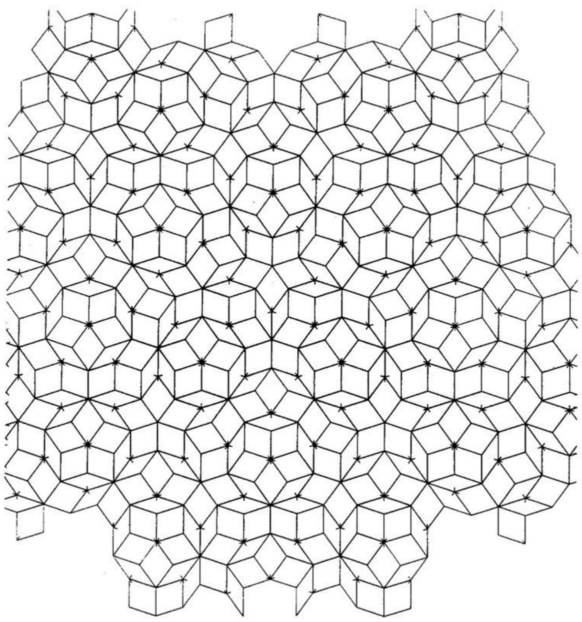


FIGURE 8. The hierarchic packing is equivalent to the Penrose tiling, where tiles of two kinds fill the plane. (Model made by the author.)

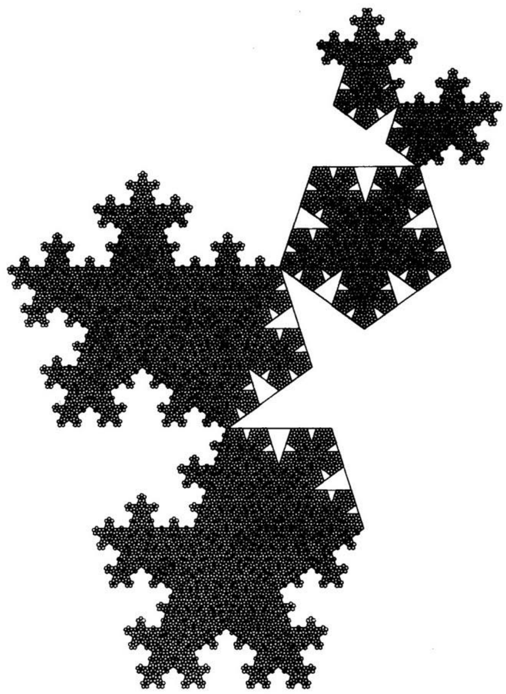


FIGURE 10. The five-pointed snowflake. (Computer drawing by Robert Mackay.)

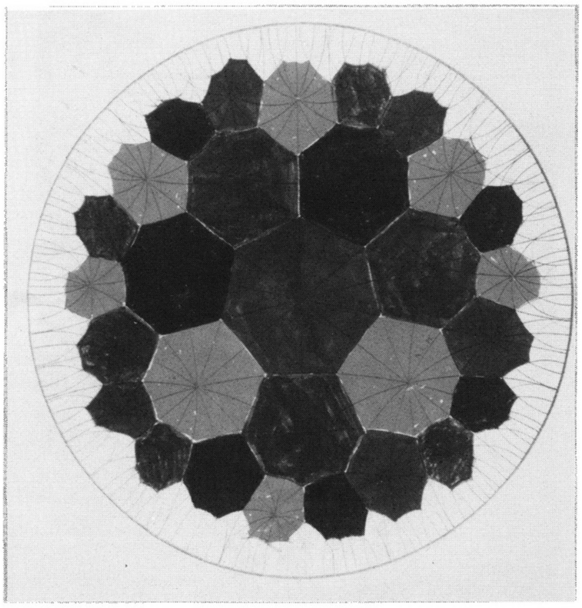


FIGURE 11. If the coordination number is 7, we can get the negatively curved hyperbolic space.

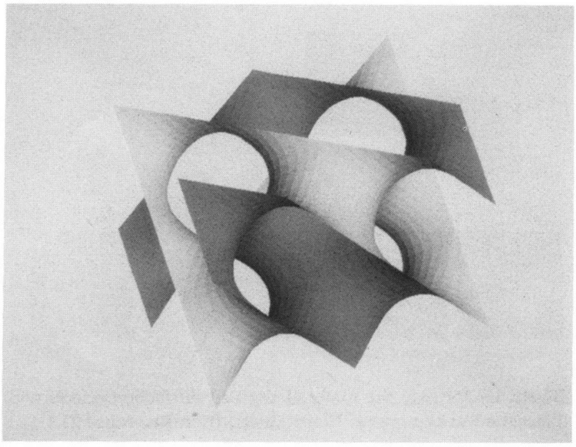


FIGURE 13. Another surface made of saddle-shaped elements.

Then, in 1984, a startling report appeared in *Phys. Rev. Letters* [18] saying that Dan Shechtman at the U.S. National Bureau of Standards had found an extended specimen of an aluminum manganese alloy that showed diffraction patterns with fivefold symmetry. Many workers quickly verified this result. Figure 14 is what we obtained here from a specimen of a similar alloy kindly provided by the group in Varanasi. In fact the diffraction effects (Figure 15) from the material have the full symmetry of the icosahedron. Before very high resolution microscopy had become available, the results would have been attributed to twinning as in Figure 4, but micrographs from Hiraga and Hirabayashi in Sendai (Figure 16) showed that the structure was not twinned but was, in fact, very similar to that of the Penrose pattern. The crystals themselves were rather like the pentagonal snowflake (Figure 17). This new type of ordering has become known as "quasi-crystalline." Since the original report, some 600 papers have been published but, unfortunately, commercial applications for the material have not appeared to be very dramatic and so it has been rapidly overshadowed by warm superconductors. However, the discovery of quasicrystals has caused a great burst of activity, both theoretical and experimental, in crystallography, and all new textbooks will henceforward have to begin differently.

Thus, quasicrystals represent an extremely ingenious natural compromise between the demands of atomic clustering for icosahedral local order and the

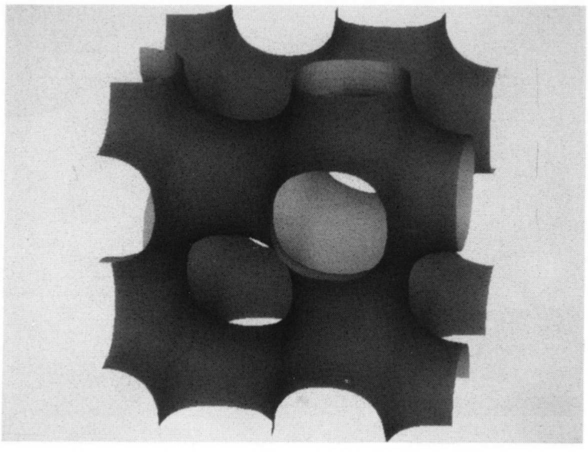


FIGURE 12. *P* surface. (Computer drawing by I. Angell and G. Griffiths.)

FIGURE 14. Electron diffraction pattern by the author of a quasicrystal of $Mg_{32}(Al, Zn)_{49}$.

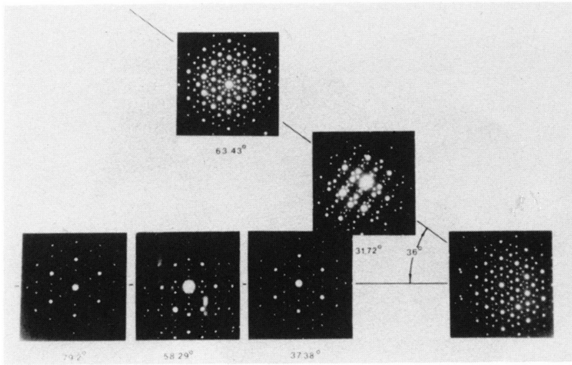


FIGURE 15. Indeed, the material showed diffraction effects with full icosahedral symmetry. (Reproduced from Reference 21.)

inconsistent demands of long-range global order made by the lattice structure of normal crystals (Figure 18).

No actual laws of crystallography as it existed before 1984 have been broken. It has become necessary, however, to distinguish more carefully between the symmetry of the real space structure and that of the diffraction pattern. It seems that physicists had not previously asked a number of simple questions about

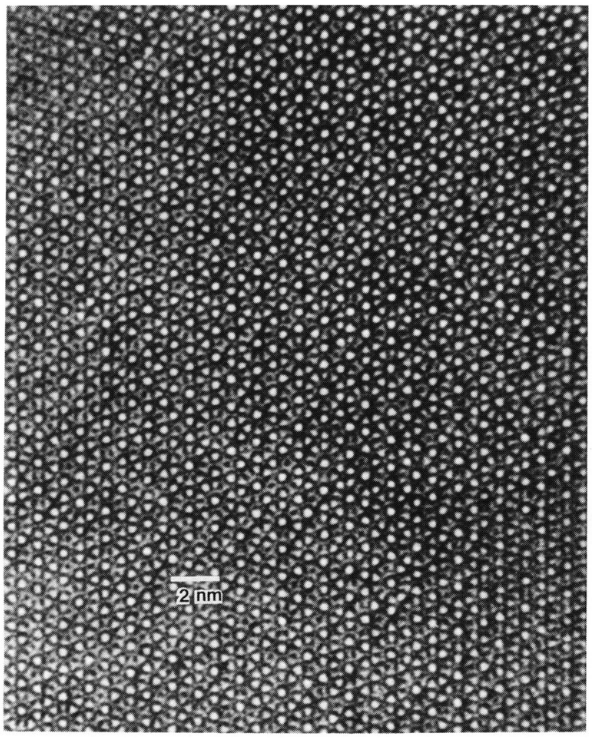


FIGURE 16. High resolution electron microscope image of Al-Mn-Si icosahedral quasicrystal looking along a fivefold axis (Reproduced by courtesy of M. Hirabayashi and K. Hiraga.)

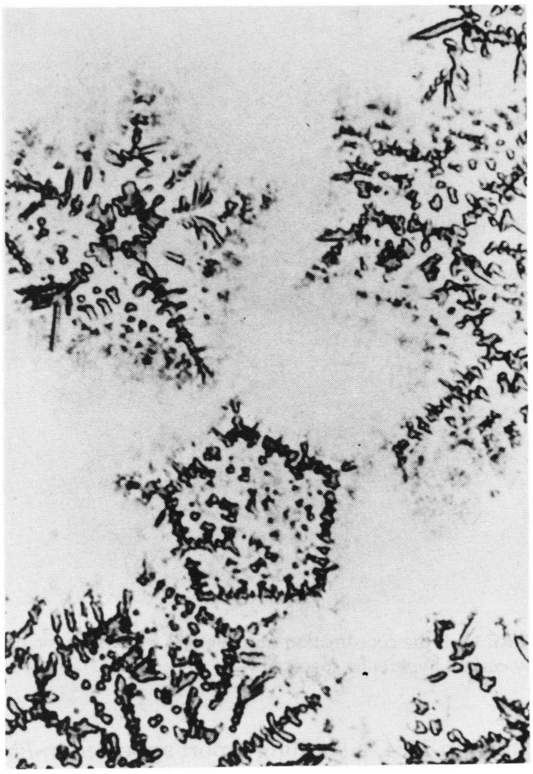


FIGURE 17. Optical micrograph of quasicrystals. (Courtesy of Leo Bendersky, U.S. National Bureau of Standards.)

the diffraction from gratings with "quasi-periodically" spaced lines.

It is thus important, if we are to hope to see new patterns in nature, to have a stock of possible patterns ready to hand to look for.

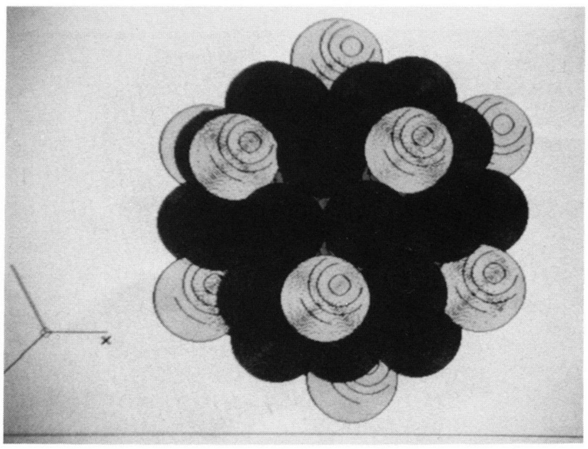


FIGURE 18. The reason for the appearance of quasicrystals is the occurrence of strong icosahedral local clustering, which conflicts with the long-range order necessary for crystals.

COMPLEX PROPERTIES FROM SIMPLE UNITS

In other departments of science there have been recent advances that have answered the objections some people have made "that they themselves are not 'just atoms'" and to the cries of "reductionism." These advances have demonstrated the very complex behavior that can arise from quite simple systems. The conclusions affect the issue as to whether biology is "reducible to chemistry, and chemistry to physics" and bear on the sensations of consciousness and free will.

There have recently been dramatic advances in our realization that even simple systems following the strict laws of Newtonian mechanics can show chaotic and unpredictable behavior, even without indeterminacy and the considerations of quantum mechanics. For example, the position of a simple pendulum, with damping and forced at a particular frequency, cannot be predicted (for certain regimes) with unlimited accuracy. There is no better way of prediction than following its movement instant by instant with whatever computational accuracy we can muster. Its path never exactly retraces itself. The weather and economic systems are now realized to have regimes of behavior of this chaotic type. Kondratiev cycles in economics do not really allow long-range predictions. No doubt some of the behavior of the large molecules of molecular biology is also like this.

An important branch of computer science has developed under the heading of "cellular automata." These are mathematical models of the way in which complex and sometimes unpredictable behavior emerges from relatively simple rules. There is nothing which could not have been done with pencil and paper, given a few years. Newton himself could have found it. The best-known example of a cellular automaton is the Life Game invented by John Conway, which swept the computer world from 1970. Simple rules generate complex patterns, and these can be compared to the spatial patterns that emerge from the coupling of neighboring atoms according to the rules of chemistry.

Stephen Wolfram [22] has divided the phenomena into four types. In the first the outcome is simple and definite and does not depend on the initial conditions; in the second we get a limited pattern, which depends somewhat on the initial conditions; in the third case an infinite fractal-type pattern is obtained (it may be self-similar on a number of scales, but after a while the overall pattern can be seen); the fourth type produces an infinite, completely unpredictable pattern. This pattern, although it is conditioned by a simple set of clear rules, cannot be predicted for a future time in any way more directly than actually carrying out the process for the necessary time. In the social sciences it has also been demonstated, by Robert Axelrod [23], how simple local rules, particularly, the Tit-for-Tat strategy, produce cooperative behavior. He said: "Mutual cooperation can emerge in a world of egoists without central control, by starting with a cluster of individuals who rely on reciprocity." Again, large-scale structure emerges from local relationships.

All this means that complex systems cannot be completely predicted from a knowledge of their components. Regimes of various kinds of behavior, determinate or chaotic, can be mapped out. Thus complex systems have to be studied at all levels of organization simultaneously.

The conclusion is that there are layers upon layers of complexity. While the layer below, in general, conditions the behavior of the layer above, there are critical junction points that cannot be estimated with infinite accuracy. At certain times the role of the individual in history may be critical in nucleating a supersaturated situation. Astonishingly, in the introduction to *War and Peace*, Tolstoy discussed the molecular dynamics approach to history, but the section is too long to quote here. Marx, who wrote his thesis, presented *in absentia* in the University of Jena, on Epicurus and Lucretius [6], was also aware of the metaphor. He said [24]:

> Lucretius is the truly Roman heroic poet; his heroes are the atoms, indestructible, impenetrable, well-armed, lacking all qualities but these, a war of all against all, the stubborn form of eternal substance. Nature without gods, gods without a world.

Laplace's concept of being able to compute the whole future of the universe, if given the positions and velocities of all the atoms, is quite illusory, as he himself must have realized. Even the positions of the balls on a snooker table cannot be predicted indefinitely far ahead, because however many digits we use in the computer, sooner or later we get to a situation where they are not enough to decide whether two balls hit or miss and from then on the whole configuration begins to be indefinite. "Reductionism" is itself reduced to being merely a vague term of philosophical abuse.

LANGUAGES AND ALPHABETS

The most important discovery of this century has been that of the genetic code; here, for the first time, we encounter assemblies of atoms (the DNA molecules) that describe other assemblies of atoms (the protein molecules). We see a naturally evolved symbolic system in action. Both the symbols and the things to which they refer exist and interact under the very strong constraints that they are both built out of atoms and must follow the general constraints of

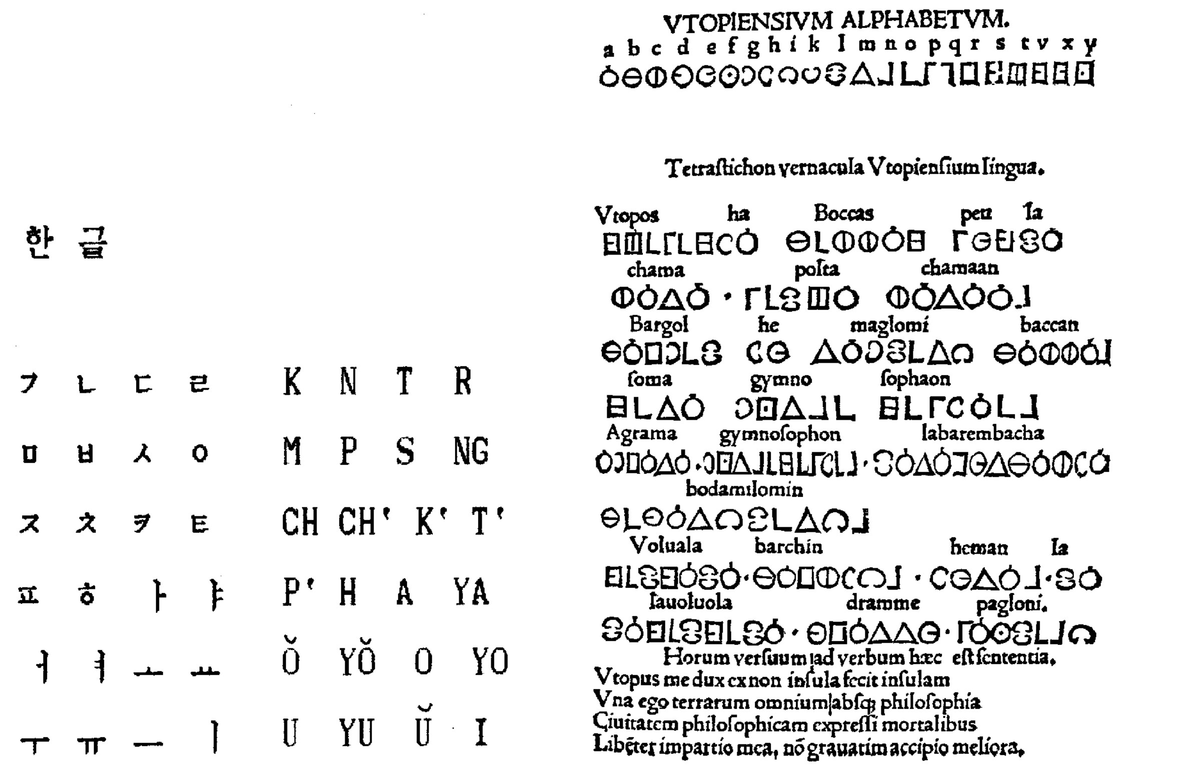


FIGURE 19. (a) The components of the Korean alphabet (promulgated by King Sejoing in 1446). (b) The resemblance of the utopian alphabet appearing in Thomas More's book of 1516 is striking—although we suggest no causal connection beyond the common analytic capacities of the human brain.

physics and chemistry, although new features continually emerge. We have a clear example of a natural language and can see how the hierarchy of levels of complexity may be built up, each layer largely separate but partly conditioned by those above and below as Lucretius suspected. He wrote: "Although all the atoms are in motion, their totality appears to stand totally motionless. This is because the atoms lie far below the range of our senses." It was left to Maxwell and Boltzmann to work out this proposition more fully and quantitatively.

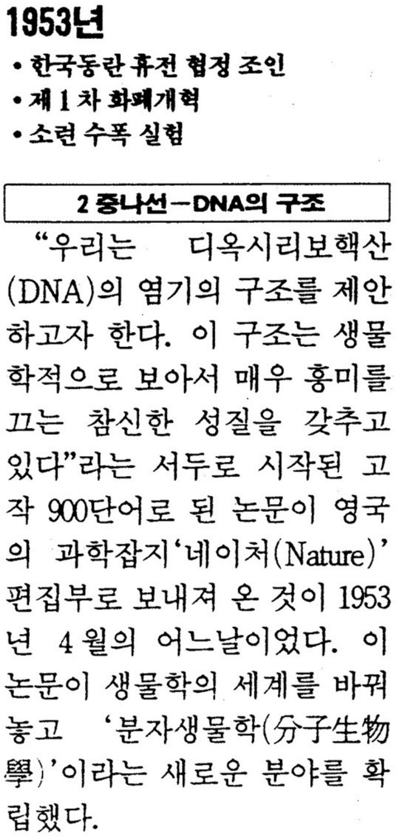
Language and writing are also built out of primordial units, also with layer upon layer of complexity. The parallel between the greatest creation of antiquity, the alphabet, and the idea that materials are made of atoms has been noted since the earliest times. Epicurus himself used the metaphor [25]:

> The atoms come together in different order and position like the letters, which, although they are few, by being placed together in different ways, produce innumerable words.

We might look at an example of the way in which a writing system, for transcribing speech, can be built up (Figure 19). The resemblance to the alphabet invented by Sir Thomas More for use in his *Utopia* is striking. Letters form syllables; syllables make up words; words are combined into sentences (Figure 20); sentences go to give us books and literature.

The parallel between a natural human language and the the natural genetic language can be carried very far.

The significance of the computer in this connection is that we can see how programs are built up hierarchically. The computer begins with 1 plus 1 equals 10, that is, with binary operations in machine language. Then blocks of these primordial operations are used to add two real numbers, these operations are lumped together to give statements, statements are organized into subroutines, subroutines are organized into subprograms, and so on, until eventually we can have a computer that will drive a robot. This robot must have a model of its surroundings and itself in its program. If we have only atoms from which to make the model, logic immediately shows us that it cannot be a complete model and that we cannot have an infinite regress, like the homunculus in the spermatozoon. The model must be an incomplete description in another language. However, the exercise of constructing a robot that is really just a logical system, itself constructed solely of atoms, gives us insights into how atoms can operate in a naturally evolved system such as a colony of ants.


1953년

- 한국동란 휴전 협정 조인
- 제 1 차 화폐개혁
- 소련 수폭 실험

2중나선—DNA의 구조

"우리는 디옥시리보핵산(DNA)의 염기의 구조를 제안하고자 한다. 이 구조는 생물학적으로 보아서 매우 흥미를 끄는 참신한 성질을 갖추고 있다"라는 서두로 시작된 고작 900단어로 된 논문이 영국의 과학잡지'네이처(Nature)' 편집부로 보내져 온 것이 1953년 4월의 어느날이었다. 이 논문이 생물학의 세계를 바꿔놓고 '분자생물학(分子生物學)'이라는 새로운 분야를 확립했다.

FIGURE 20. Korean text.

The great question is how these culturally evolved symbolic systems, which are our models or descriptions of ourselves and our environments, are related to the way the atoms are organized in the brain [26]. Do all human languages operate with the same kinds of neural network? For example, how similar are the neural networks of English and Japanese or Korean speakers (Figure 21)? We are on the verge of finding out.

We can easily believe now that Japanese brains are wired up by education so that "L" and "R" have become indistinguishable and that segments of speech are differently processed.

Formerly we had to be content only with the morbid anatomy of the brain (Figure 22), but static observation does not tell us how the system operates. Only in the past few years have we been able to see atoms thinking. This has been done by positron emission tomography [27] (see also Figure 23), and by nuclear magnetic resonance imaging (Figure 24). Radioactive glucose, the fuel for activity, is automatically directed to where it is needed by thought processes, such as the recognition of written and spoken symbols, and the restricted areas of the brain in which this is done can be seen to light up, like computer chips, as their services are called upon. As Delgado put it: "Mind arises when symbols, by material means, shape the neurones."

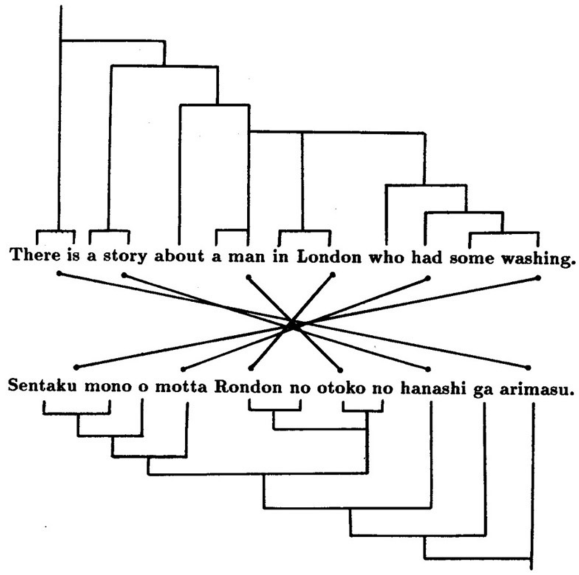


FIGURE 21. English and Japanese sentences are often the inverses of each other.

We may reasonably expect that after language and vision, sensations of consciousness, of self-consciousness, and of free will, may eventually become understood. Crystallographers are in the exciting position that, now the static structures of very many molecules have been found, they must follow these molecules and find out how they work. Crystallography thus has steadily widening concerns.

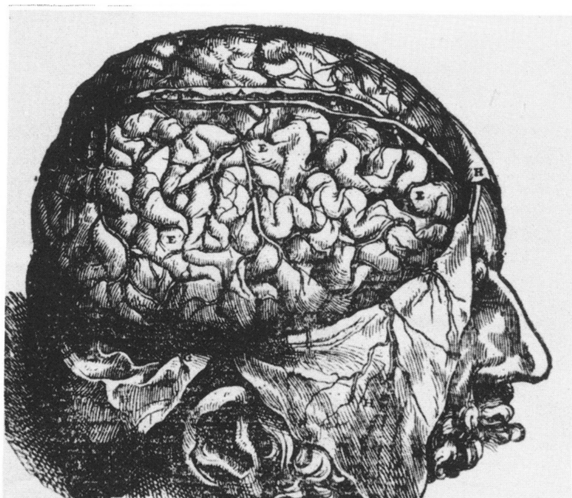


FIGURE 22. Drawing by Vesalius from *De humani corporis fabrica.* Static observation does not tell us how the living brain operates.

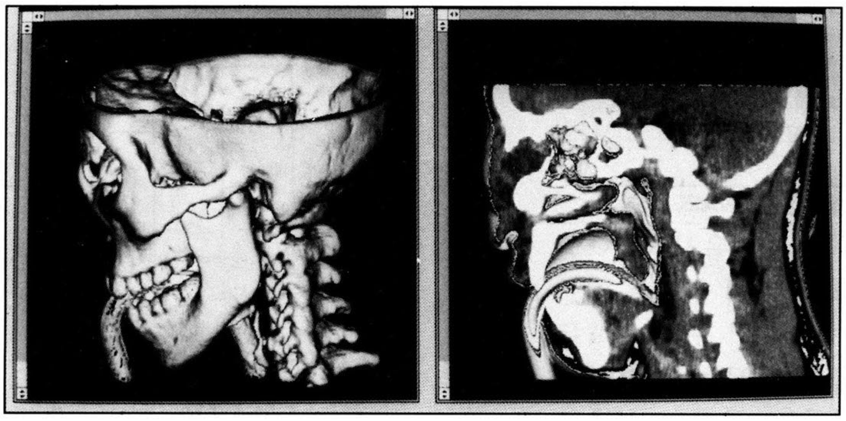


FIGURE 23. The components of the living brain can now be imaged, in this case by X-ray tomography.

CONCLUSION

My claim is that of Lucretius, namely that the intellectual, social, linguistic, economic, and political systems rest on a material basis of science and technology and ultimately on the properties of atoms. Globally we are passing into a new period where the now perennial dangers of ordinary and of nuclear war, of economic chaos, and of population explosion, which are political, are being joined by consequential physical problems of the environment (the climate, radioactive waste, the biosphere, and what we might call the genosphere). We recall the efforts of H. G. Wells [28] in launching "The Open Conspiracy"—surely the forerunner of transnational "Green" politics—to stimulate a world movement in the days of the League of Nations. Like Wells's postulated invasion from Mars, these problems, such as AIDS, might serve as a supranational challenge uniting mankind, although I doubt it. They can be dealt with only by using the best efforts of science and technology; but in Britain the future is being sold to pay for today, and education, science, and technology, which are necessary investments in the future, are all being run down. Too many scientists are forced to compete for too little support in the way that, before decasualization, dock laborers had to fight each other at the dock gates for too few jobs. As a portent of the future Britain we may meet, in Tottenham Court Road, a man, discarded by our monetarist economy, living in

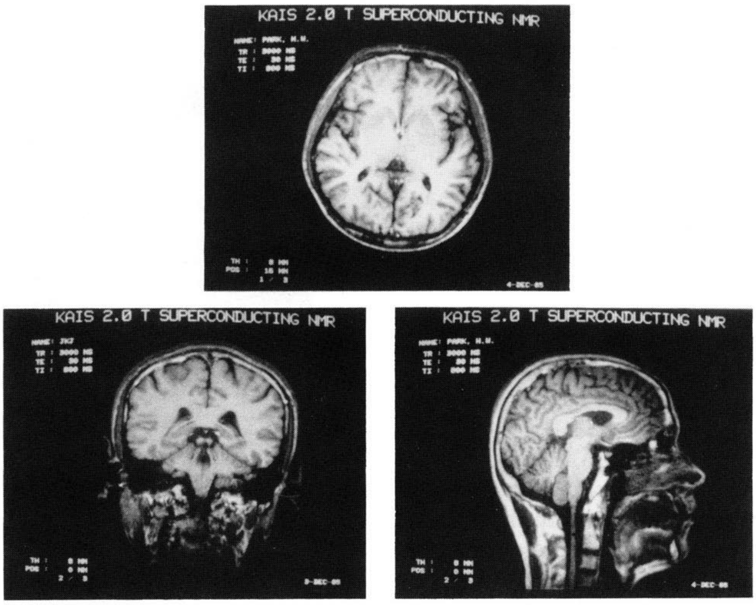


FIGURE 24. NMR picture of the brain.

the cardboard boxes from imported Japanese electronic goods.

When human beings lived in small isolated communities, their mutually inconsistent religions and myths did not matter very much in an essentially infinite world; but now we realize that in many aspects the world is finite. The religious views of Mrs. Thatcher, the astrology of Ronald Reagan [29], the promises by the Ayatollahs of Paradise for those killed in the holy war, the dogmas of the Vatican or of Chairman Mao—the atomic bomb is not in any way a paper tiger—are not the way to deal with the concrete problems of our globe, although they may be effective social engineering. Richard Feynman, in his report on the Challenger disaster warned: "Reality must take precedence over public relations, for nature cannot be fooled."

To understand nature we have to promote science, starting with simple systems and working toward an understanding of ourselves in the "declaration of intent" mapped out by Lucretius, when he said: "I am setting out to unloose the mind from the knots of religion." He began by postulating atoms and guessed that the whole of the living and the nonliving world could be built from their combinations. Now we can readily see atoms at work and have taken very many gigantic strides toward this objective. Very recently the atomists have entered the domains of thought and language, which have hitherto been approachable only through the humanistic culture which we must try to understand. Two two cultures are coalescing through the efforts of science. But, J. Z. Young, in his *Introduction to the Study of Man,* warned [30]:

> The biologist must recognise the fact of the belief of many people in the existence of a transcendent Spirit . . . such beliefs are held and stated as a result of cerebral action. We may therefore hope that better knowledge of the brain will give us still better beliefs, or at least better insight into those that we have.

Perhaps innate religious feelings just represent the default settings, which are made at the switching on of the neonate brain.

In a dispute between a Muslim and a Christian there is no judge, and similarly in disputes between the corresponding theocratic states, each, perhaps, holding nuclear weapons and professing belief in life after death. One myth is as good as another when it comes to building an ideology, or in reinforcing a system of ethics, but in an argument between chemists, or indeed between crystallographers, there is a final appeal to nature for a decision, and this decision can be accepted by all parties. This common basis for agreement between groups accidentally divided by nationality and religion, already demonstrated in the Pugwash movement and in many other international scientific organizations, will become still more important as our concern for the survival of our descendants and their environment increases. I think that it is not a coincidence that crystallographers have taken a significant part in many such organizations and that crystallography is more an intellectual movement than a particular college department. I rest my case.

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