

THE UNIVERSE AND LIFE: DEDUCTIONS FROM THE WEAK ANTHROPIC PRINCIPLE*

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Abstract. The existence of life in the Universe is interpreted in terms of the 'Weak Anthropic Principle'. It is shown that cosmological models are constrained to a class that involves an open timescale and access to infinite quantities of carbonaceous material.

1. Introduction

In the present context we interpret the weak anthropic principle to imply that the universe must be consistent with the existence of life, and in particular with the existence of human life. The surprise is that so much can be deduced, some things predictively, from a seemingly obvious statement. It is, for example, sufficient to break the physicist's concept of 'a typical observer'. If we can only exist in some special place or over some restricted time interval then that is where we must be, even if the chance of a randomly-chosen abstract 'observer' lying in the spacetime volume in question happens to be small. The weak anthropic principle serves to remove otherwise inexplicable cosmic coincidences by the circumstance of our own existence.

One of the present writers was involved in an early application of the weak anthropic principle. Out of the 80 stable elements, 20 or so are necessary for life. There are four with high abundances – hydrogen, carbon, nitrogen and oxygen, nine with intermediate abundances – sodium, magnesium (in chlorophyll), silicon (in diatoms), phosphorus, sulphur, chlorine, potassium, calcium and iron, five trace elements that are present in organisms generally – manganese, cobalt, copper, zinc and molybdenum, and five more said to be present also in trace quantities in particular organisms – boron, vanadium chromium, gallium and tungsten. Of these 23 elements only hydrogen is thought to be primordial. Hence the other 22 have had to be produced in some way. The case of carbon, the element whose complex chemistry forms the basis of life, is particularly interesting in this respect. It was shown in 1952–53 that to understand how carbon and oxygen could be produced in approximately equal abundances, as they are in living systems, it was necessary for the nucleus of ^{12}C to possess an excited state close to 7.65 Mev above ground

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level. No such state was known at the time of this deduction but a state at almost exactly the predicted excitation was found shortly thereafter. So one could say this was an example of using the weak anthropic principle in order to deduce the way the world must be, although the concept of the anthropic principle had not been explicitly formulated at that time.

Besides the need for the 7.65 Mev state in ^{12}C , a positive requirement, there was also a negative requirement. The nucleus of ^{16}O has an excited state at 7.12 Mev above ground level, which is just a little less than the sum of the rest mass energies of ^{12}C and an alpha particle (^4He). If things had been the opposite way, with the excited state in ^{16}O a little above $^{12}\text{C} + \alpha$, there would again have been no carbon in the world, because the nuclear reaction $^{12}\text{C} + \alpha \rightarrow ^{16}\text{O}$ would have taken out the carbon as fast as it was produced, there would have been a resonance as one says for the conversion of carbon to oxygen. So the approximately equal balance of carbon and oxygen in living organisms depended on the nuclei of these elements being rather finely-tuned in two respects, one in ^{12}C the other in ^{16}O .

When one examines the details of the situation more closely than we do here, it is hard to avoid asking a more searching question: Is the favourable fine-tuning, favourable to life, just a matter of chance? Or is the situation in these nuclei somehow connected with the existence of life? If this were the sole grounds for asking this rather fantastic question we might feel inclined to dismiss it, as nowadays we would dismiss the chance coincidence that the angular diameter of the Moon is almost exactly the same as the Sun. But when one looks at other circumstances affecting the existence of life, for example in the details of the chemistry of carbon, and how these details depend on the numerical value of the so-called fine-structure constant, the same question arises repeatedly. The physical properties of matter appear to be adjusted to permit the existence of life. This form of words suggests a teleological (purposive) connection, which being unpopular in science has been replaced by the concept of the strong anthropic principle, according to which our existence somehow forces the physical properties of matter to take a form consistent with our existence. If the 'somehow' here could be satisfactorily explained in scientific terms, all would be well, however. Otherwise many will object, seeing the strong anthropic principle only as a semantic substitute for teleology, which by common consent is disbarred from science, because history shows the admission of teleology leads to fragmentation and disagreement in the way we look at the world.

In our view, the value of a concept to science depends either on the predictability criterion or on the concept serving to tie together in a demonstrable way facts which hitherto had seemed disjoint. We have not seen how the strong anthropic principle can be tested in either of these respects, whereas the weak anthropic principle is indeed open to test, not just in regard to the example mentioned above, but in a far-reaching way in the subject of cosmology, which will be the subject of the present chapter. The discussion will proceed in four stages:

- (i) an attempt to define the nature of life;

- (ii) a determination of what might be called the information content of life;
- (iii) a matching of the information content of life to what various cosmologies might be expected to provide, with the inference that if a particular form of cosmology cannot match the information content of life then it is not the correct cosmology;
- (iv) within a permissible cosmology astrophysical conditions must be arranged in such a manner as to permit the origin and evolution of terrestrial life.

Our discussion of the nature of life is intended to cover only the biochemical hardware of life. The neurological systems of higher animals can be thought of in terms of a computer analogy, with both hardware and software components. To many it seems as if the software component may have an existence independent of the hardware. The software may be considered to manifest itself with the phenomenon of consciousness, which is generally accepted nowadays by physicists to have a critical role to play in the interpretation of quantum mechanics. This adds considerably to the case of those who think there may be more to the software than straightforward evolution involving hardware alone, a case which also touches on the strong anthropic principle.

Fascinating as such speculations may be, they do not form the topic of this paper. Here we are concerned solely with the hardware of life and with what its information content may imply for cosmology.

2. The Nature of Life

The atoms present in living systems are no different from similar atoms in non-living material. An atom of carbon in our bodies has the same individual physical properties as a carbon atom in a flake of soot. Yet the cooperative properties possessed by the arrangements of atoms in living matter are astonishingly different from those in inanimate material. You could store equal quantities of carbon dioxide and free hydrogen in a bell jar in the laboratory for an eternity and that is the way they would stay. But introduce a special kind of bacterium into the bell jar and the gases will go in short order into methane and water. The bacteria in question are of a special kind which in recent years have become known as archaebacteria. They form a special kingdom, apparently without microbiological connections to other bacteria, or to the larger so-called eukaryotic cells of which ordinary plants and animals are built.

Defining the nature of life is one of those questions which becomes harder and harder the more you look into it. Instinct tells us that a snail is radically different from a stone. By why is it different?

Let us start an attempt to answer this question by noticing that the issue of which assembly of molecules is most stable (the proportions of their constituent atoms being specified) depends on the temperature. At laboratory temperature the most stable form for a suitable mixture of hydrogen, oxygen and carbon is methane

and water. But at the temperature of a wood fire the most stable form is carbon dioxide and hydrogen. Add to this that mixtures of atoms do not necessarily reach their most stable forms. At higher temperatures like the log fire they usually do, but at laboratory temperatures they may not. Start from methane and water in the laboratory and heat the mixture. Given adequate time it will go to hydrogen and carbon dioxide. Now cool the mixture. It will not return to methane and water, no matter how slowly you cool it. Unless archaebacteria happen to be present.

The most stable forms for mixtures with atoms of hydrogen, carbon, nitrogen and oxygen, the commonest atoms in living material, behave in exceedingly complex ways at laboratory or lower temperatures. But the most stable forms are generally not attained by inanimate mixtures. They are attained, however, or nearly attained, when living organisms are present. It is this property of being able to reach the stable forms of mixtures at temperatures characteristically found on the Earth (300 Kelvin) that defines the nature of life.

The mixtures on which living systems operate in this way are usually derived from higher temperatures. It is a general property that as mixtures go to their most stable forms with decreasing temperature, energy is released, not absorbed. Thus the ability of life forms to reach equilibrium states with lowering temperature provides them with energy sources. It is on such sources that life in its simplest forms depends.

The nature of science can be defined by the magnitude of energy transitions. The biggest steps are those found in particle physics, running to thousands of millions of electron volts (eV). Accumulating basic information about such steps is difficult and consequently expensive. Most of the basic data on which theories in particle physics are based could be written on three sheets of paper, data which has cost billions of dollars to obtain. In contrast, basic data at energy steps of a few eV, obtained in the 19th century and early years of this century, cost sums measured only in thousands of dollars. This was the data of atomic physics that led in its highest theoretical form to the development of quantum mechanics. Because of its history, the habit of thought in physics is to relate subtlety directly to energy, the larger the energy step the greater the measure of subtlety. Biology challenges this point of view. Biology says, conversely, that the lower the energy step the greater the measure of subtlety. It is perhaps because of this inversion of attitude that physics and biology have become so sharply separated in our educational system.

The chemical bonds between atoms that have to be changed in reactions at low temperatures in order to achieve the most stable states are pretty much the same as in atomic physics, energy steps of a few electron volts. But whereas state changes in atomic physics are achieved by radiation units, quanta, with energies that are the same as those of the changes in question, quanta of a few eV, in biology the state changes are achieved with quanta of much lower energy, typically of about 1/40 of an electron volt. This is done by exceedingly subtle accumulations of energy, by pumping through sequences of metastable states. An analogy might be to surmount a high wall step-by-step up the many rungs of a ladder. Or one might think of

charging an electric battery over a lengthy period and of then discharging it in short order.

In one important respect biology also takes advantage of quanta with energies of about three electron volts, in the process of photosynthesis whereby carbon dioxide and water are reduced to oxygen and sugars, a similar result to the operation of archaebacteria but very different in its detailed operation. The operation is by no means completed through the higher energy quanta. Their absorption serves as an energy source, which gives rise to a train of reactions of the more usual lower energy type.

The substances that control the small energy steps of biology are proteins. Proteins consist characteristically of linked chains of amino acids of which 20 different kinds dominate the situation in biology. Only an exceedingly small fraction of the possible chains of amino acids are biologically relevant – just how small will form the main topic of the next section. Also characteristically, a biologically important protein (enzyme) will have a number of amino acids in its chain ranging from about 100 on the low side to about 1000 on the high side, with 300 as a fair average.

Although it is useful for diagrammatic purposes to think of a protein as a linear chain, enzymes actually take up amazingly complicated shapes in three-dimensions, especially when suspended in water. The primary structure is a helix. Water is repellant to a fraction of the 20 amino acids and these, wherever they are in the chain, form a central region in the presence of water, so as to become shielded from the water by the others. This leads to a hugely complicated shape which is then given stability by chemical linkages, as for instance between the sulphur atoms that are present in just one of the 20, the amino acid methionine. Such linkages are like the spars used in buildings to give strength to a human-made structure. Notice that although these so-called disulphide bonds occur between amino acids that are adjacent in space, such neighbours are not usually neighbours in the original chain. They have been brought together by the manner in which the original chain has been folded by its water-repellant members. The extreme complexity of the situation is illustrated by a particular example in Figure 1. Determining a structure like Figure 1 is a difficult job for the experimentalist. So not unnaturally the experimentalist chooses the relatively simplest cases to study. Thus Figure 1 is towards the simpler end of the class of enzymes.

Enzymes do not have simple surfaces. On the outside they are irregular with one specially important cavity, the so-called active site. The shape of this cavity is crucial to making chemical reactions 'go' that would not 'go' under inanimate conditions, like those reactions which promote the conversion of carbon dioxide and hydrogen to methane and water in the case of the archaebacteria. What happens for a particular reaction is that the chemicals involved fit with startling precision into the cavity of the relevant enzyme, not just as pieces of a jig-saw fit, but in a specially reactive orientation with respect to each other. Moreover, the chemicals are jostled so as to promote the reaction by the amino acids with which they are in contact, the amino acids forming the active site. The jostling is not random.

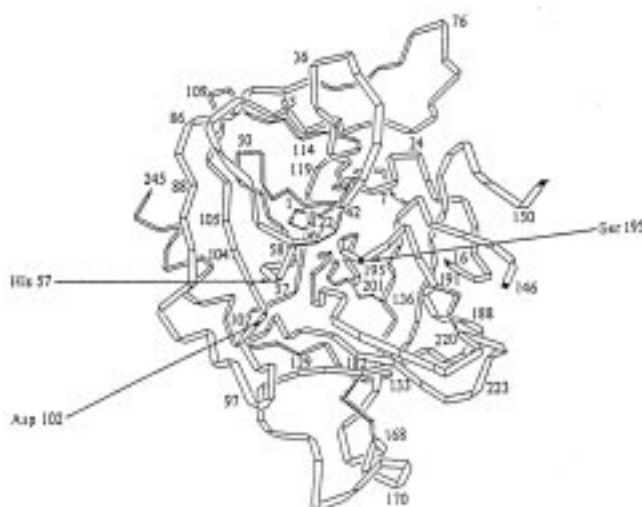


Figure 1. Structure of an enzyme.

It is organised in the sense of the ladder-over-a-wall analogy. When the reaction is completed, with the reacting chemicals having changed their shapes, they no longer fit the enzyme cavity as before. Consequently they break away from the cavity, freeing it to promote the same reaction yet again. And again and again in the manner of a catalyst. A catalyst is defined in chemistry as a substance which promotes a chemical reaction without itself being changed. Enzymes are catalysts analogous to human-made catalysts, but they are millions of times more effective.

A living system has need of many copies of each of its enzymes. A literal accurate copying, amino acid-by-amino acid, of a structure like Figure 1 would be so difficult as to be hardly feasible. Just as we ourselves copy buildings from blueprints rather than by copying brick-by-brick or stone-by-stone, so copies in living systems are obtained from a blueprint. The blue print is carried by four characteristic markers (nucleotides) read in blocks of three (codons) on the now-famous double-helix structure of DNA. The reading process is also vastly complicated. It is done mostly by the enzymes themselves. The first step is to construct an intermediate sequence of blueprints (the various forms of RNA). It is a case of the master blueprint of DNA producing through enzymic activity (not through its own activity – by itself DNA is very inactive) blueprint A, which then produces blueprint B, which produces blueprint C, . . . , until ultimately a considerably simplified and fragmented form is used to construct the enzyme in question. The raw materials for constructing the enzyme are separated amino acids which have to be linked together in the order prescribed by the eventual blueprint. A similar logic is used in constructing a human-made building. The architect's drawings are more complicated than those which are issued to individual workmen. But the human situation is simpler than the biological situation by a huge margin.

If one thinks there was a time before which life did not exist, a conundrum arises in understanding its origin. Which came first, the blueprint for an enzyme or the enzyme itself? If one says DNA came first, the problem is that DNA is inactive. If one says the enzymes came first, enzymes apparently cannot copy themselves. The favoured answer among biologists is to say that an intermediate blueprint came first, a blueprint expressed by RNA not by DNA. In recent years, RNA has been shown to possess a limited degree of activity of its own, although whether the activity is sufficiently diverse as to be capable of maintaining a replicative system remains a question. The problem is one already hinted at above. The bond strengths, whether in RNA or proteins, are in the region of 4 eV, much too strong to be broken thermally. Thus a failure to find a working system at the first joining of atoms stops there. Without enzymes to break the bonds a second trial cannot be made, except by flooding the material with so much energy that everything is smashed back into the constituent atoms. But such extreme violence cannot lead anywhere, since floods of energy would also destroy anything useful that might arise. There is but one way out of this logical impasse, in our opinion, which is to make trials, not repeatedly on a limited sample of material as in Darwin's 'Warm little pond', but to make just one trial on a breathtakingly large number of samples. Just how large the number that would be needed before anything interesting happened will be the topic of the next section.

But this is not a situation with which we have much sympathy. It is too remote from observation and experiment to be worth losing sleep over. Indeed, such experiments as have been done show that, while it is not too hard to produce individual amino acids and nucleotides from inorganic materials, no amount of human ingenuity will persuade such products to arrange themselves in biologically interesting ways. Progress in this respect has been so minuscule as to be essentially nil, which it would not have been if matter had some hidden urge (as some mistakenly suppose) to arrange itself in ways suited to the origin of life. The evidence is that an origin, if such there ever was, turned on situations so unlikely that they cannot be rediscovered by chance in the laboratory.

Another reason for not worrying too much about the origin of life is that we have no knowledge or assurance that the problem is a real one. There may have been no origin, no time before which there was no life. Intuitively we may think there must have been, but if we do our instinctive supposition is cultural. It is not analogous to certain intuitive perceptions that lie at the base of mathematics, which everyone has regardless of culture. A Buddhist, for example, might think instinctively that life has always existed for an eternity in time.

Science does not make progress by searching out what appear to us subjectively to be the most important problems and by then hammering away in an attempt to solve them. Science makes progress by doing what happens to be accessible, by not wasting energy or resources on what is inaccessible at the moment. Accessible problems never depart very far from observation and experiment. There are many such issues with which we can be concerned without straying into vague

speculation, issues of great interest with possibilities very different from orthodox positions, with lots of scope for the unusual. It is on such problems that we believe one should concentrate attention, as we shall attempt to do in the rest of this paper.

3. The Information Content of Life

With the invention of computers in the 1940's the idea of measuring the information content of a message was born, and a mathematical theory of how this might be done emerged to widespread applause from the scientific community. We never joined vigorously in the applause because the applicability of the mathematics seemed too restricted in its scope to be of much interest. What one would really like to be able to do would be to give a logical numerate meaning to the difference in the information content in the following two messages, supposed to reach the German Chancellory in Berlin on 1 June 1944:

Message 1

This morning the British Prime Minister, Winston Churchill, ate bacon and eggs for breakfast. Yesterday he smoked eleven cigars and sniffed brandy throughout the day. It is anticipated he will do the same on the 6th of the month.

Message 2

Early on the 6th, the Allies will attempt to land very large forces on the Normandy beaches, from St. Germaine in the west to Quistreham in the east. There will be no landing in the Pas de Calais.

The mathematical theory of information does not attempt to grapple with cases like these. Yet it is situations like these that are most important. Similar but still more awkward problems arise when the information content of life is at issue. Were a refined theory available for estimating the information content of DNA it would, in our opinion, be immediately apparent from its overwhelming content that life could never have arisen on a minuscule planet like on Earth. It would be seen that to match the information content of even the simplest cell nothing less than the resources of the entire universe are needed. This is an opinion that can be backed up by making a shot at estimating the information content, noticing that if on reasonable grounds the answer turns out as vast beyond all precedent, it does not matter in its implications just how vast it really is, because one huge number would have the same implications as another. As a friend once put it:

'I wouldn't see much difference between inheriting £10 million and inheriting £1000 million. The effect on my life would be the same.'

For every enzyme needed to make a chemical reaction 'go' in the large complex of reactions that maintains a living cell, a number can be estimated in the following way. Take first the total number of proteins that can be constructed by assembling

at random the 20 biologically significant amino acids in chains of the same length as the enzyme in question, a length typically of some 300 amino acids. For such a length this number is unequivocal. It is about 10^{390} , i.e., 1 followed by 390 zeros. Next, divide by the number of possibilities in this set that serve to make the particular chemical reaction 'go' at an adequate speed to sustain the cell, a number f on the average say. Do this for every enzyme, 2000 in the case of a simple cell, 100 000 for a complex organism like ourselves. The result for the information content is then:

$$(10^{390} \div f)^{2000} \quad : \quad \text{simple cell}$$

$$(10^{390} \div f)^{100\,000} \quad : \quad \text{complex organism}$$

The situation is still unequivocal. Scope for argument arises only when we come to estimate the likely average value of f . We saw in the previous section that an enzyme has to possess exceedingly specific properties in relation to the reaction which it catalyses. It has to curl up into a three-dimensional structure with a surface cavity that provides a precise and special fit to the shape of the reacting chemicals. Moreover, the amino acids forming the cavity, the active site, have to be capable of jostling the reacting chemicals in a highly organised way. These properties depend crucially, not only on particular amino acids which form the active site, but on the positioning of the water-repellant amino acids which play a critical role in deciding the three-dimensional structure. Another necessary property not mentioned in the preceding section is that an enzyme must be controllable. It must be capable of being switched on and switched off by chemical agents controlling the behaviour of a cell. Uncontrolled behaviour is what happens with cancers and this is to be avoided. Clearly all these drastic and precise requirements will not permit f to be unduly large, nothing like as large as the number 10^{390} appearing in the above formulae.

An extreme position would be to say that all these special requirements demand that the chain of amino acids be unique for each enzyme, demanding $f = 1$. This appears to be close to the truth in some cases. The protein histone-4 is found in both plants and animals and it has essentially the same amino-acid structure in every organism. Little or no variants have been permitted throughout biological evolution. Human DNA has some thirty distinct genes coding for histone-4. Variants are found among the thirty but they are all of the kind that lead to the same chain of amino acids (same-sense mutations). Other proteins are not as restrictive as histone-4 however. But every enzyme that has been examined in detail has been found to vary among plants and animals only to a moderate degree. Summing up what has been found as fairly as we can, about one-third of the amino acids in a typical enzyme are obligate, which is to say a particular amino acid must occupy each of about 100 positions in a chain of 300. The remaining 200 positions are by no means free choices. Each of them can be occupied by three or four among the bag of 20 amino acids, not by any member of the bag. Arguing thus leads to

the universe. This cosmic distribution mirrors quite well the distribution of the life-forming elements, except that hydrogen is much more abundant cosmically than it is in living material. Carbon, nitrogen and oxygen are about ten times more abundant both cosmically and in life than the next group consisting of sodium, magnesium, silicon, phosphorus, sulphur, chlorine, potassium, calcium and iron, while the latter are about a thousand times more abundant than the trace elements. If one had to pick out an exception it would be phosphorus, which is some ten times more abundant in life than it is cosmically.

The complexity of the network of chemical reactions which define the nature of life depends crucially for its remarkable versatility on the properties of the carbon atom. Thus in estimating the quantities of potential life-forming material in various places within the universe, it is sufficient to specify the quantity of carbon, since the other elements follow along with the carbon in generally the required proportions. How these estimates go for a number of locales is shown in Table I.

It is seen that superastronomical numbers appear in the second part of the table, but not in the first part. The meaning of the quantities in the second part is that if one starts with a chemical message (as for instance DNA is a chemical message) at a particular place at a particular time, and if the message can be copied, then after the time intervals in the first column the message will have been spread by copying through the quantities of material in the second column. In the extreme case of the last line of the table, after a hundred million Earth-ages (4.6×10^{17} years) the message will be spread through $10^{90\,000\,000}$ grams of material, a number that is in a class which matches the biological superastronomical numbers of the preceding chapter. This suggests that life might be produced in a time interval of 10^{17} years provided the cosmology is steady-state or quasi steady state.

Table I gives scope for a great deal of discussion. Here we shall simply indicate how the vast quantities of carbonaceous material in the second part of the table have been calculated. Biological cells typically have sizes of the order of one ten-thousandth of a centimetre, which happens to be just the size at which small particles are effectively repelled by the pressure of light, picking up speeds in the galaxy from starlight of several hundred kilometres per second. This is sufficient to spread a biological message everywhere through a galaxy in a time even less than a single Earth-age. It is indeed sufficient, just about, to spread the message from our galaxy to another, but only between neighbours. A still more powerful mode of spreading turns on the properties of iron as it is expelled from a supernova.

When metallic vapours are cooled in the laboratory, condensation eventually occurs, not into more or less spherical globules, but into threads or 'whiskers'. Diameters of whiskers are typically about a millionth of a centimetre and lengths typically about a millimetre, giving the very large ratio of about 100 000 for the length to diameter. Such metallic particles are extremely strongly repelled by radiation in the far infrared region of the spectrum, and since molecular clouds in galaxies emit radiation strongly in the far infrared, whiskers can be repelled from galaxies into extragalactic space at speeds upwards of ten thousand kilometres per

TABLE I

| Place | Amount of Carbonaceous Material (grams) |
|---|--|
| Earth | 10^{23} |
| Outer regions of Solar System (Uranus, Neptune, Comets) | 10^{30} |
| Molecular Cloud (e.g. Orion Nebula) | 10^{35} |
| Interstellar material through our galaxy All detectable galaxies | 10^{40} |
| Limit for interrelated quantities of material in Big-bang cosmology | |
| Time interval in Earth Ages (4.6×10^9 years) | Quantity of interrelated carbonaceous material in Steady State Cosmology (grams) |
| 1 | 10^{50} |
| 10 | 10^{59} |
| 100 | 10^{140} |
| 1000 | 10^{950} |
| 1 000 000 | $10^{900\,000}$ |
| 100 000 000 | $10^{90\,000\,000}$ |

second, when distant galaxies can be reached from the galaxy of their origin in only a single Earth-age. About a million galaxies can be reached in this way. Whiskers from galaxies mix on this scale, the products of a million galaxies together, thereby producing a very uniform distribution for iron whiskers in extragalactic space.

Of course iron carries no biological message in itself. But contiguous particles in a near vacuum have a marked tendency to stick together. A carbonaceous particle carrying a biological message could quite well stick to an iron whisker, hitch-hiking

a life across extragalactic space. One is reminded of the story of how the birds, after quarrelling as to who among them should be King, decided that it should be the one that in a trial was able to fly highest. Each kind fell back in the trial, leaving the eagle eventually to soar above the others. Yet even the eagle at last reached the height of exhaustion. When it did so, the wren, which had so far travelled unnoticed on the eagle's back, took off and with an effort attained a few feet more. So it came about that the wren became the King of birds.

The expansion of the universe does the rest of the spreading of the message. After reaching some million galaxies in the first Earth-age, the expansion approximately doubles the radius of the cosmological region containing the message for every succeeding Earth-age. After a million Earth ages (4.7×10^{15} years) the radius of the region therefore increases by 2^{100000} , and the amount of material in the region increases by $2^{3000000}$. In the latter connection it will be recalled that the essential difference between big-bang cosmology and steady-state cosmology is that the universe does not empty as it expands in the steady-state case. It is this critical property of steady-state cosmology that leads to the vast quantities of material in the second part of Table I, quantities that match biological requirements.

There is no reason why the standard qualitative picture in biology of the origin and evolution of life should not be given expression in this way. But it must be given expression in a cosmological setting, and the cosmology must be steady-state. These are startling conclusions on which a great deal of evidence can be brought to bear. But for the present let us conclude by mentioning another way of arriving at significant supraastronomical numbers. Start with a single living cell, say a bacterium. A typical doubling time by binary-fission for a bacterium supplied with appropriate nutrients would be two or three hours. Continuing to supply materials, the initial bacterium would generate some 2^{40} bacteria in 4 days, yielding a culture of the size of a pinhead. Continuing for a further 4 days and the culture, now containing 2^{80} bacteria, would have the size of a village pond. Another 4 days and the resulting 10^{120} bacteria would have the scale of the Pacific Ocean. Yet another 4 days and the 10^{160} bacteria would in quantity be comparable to a molecular cloud like the Orion Nebula, and another 4 days, bringing the total time interval to only 20 days, and the scale in quantity would be that of a million or more galaxies. In a year there would be some 2^{3650} bacteria and in a thousand years the total would be $2^{3650000}$ bacteria. Thus biology yields supraastronomical numbers as well as depending on them.

Nutrients could not be continuously supplied it might be objected. Yet, cosmically speaking, the situation is nearer to a continuous supply than one might at first think. Formaldehyde (COH_2) is built as a weakly-bound molecule from the two commoner molecules in the universe, carbon monoxide (CO) and hydrogen (H_2). Although formaldehyde is not itself a substance of surpassing interest, take five or six formaldehyde molecules, swop atoms a little from one to another and join them appropriately, and you have all the sugars, the driving foodstuff of biology. Eliminate a water molecule between sugars and you have all the carbohydrates.

Join sugars through nitrogen atoms and you have materials like the shells and claws of prawns and lobsters. A continuous supply is pretty well what one really does have in fact. It is rather here on the Earth where supply is limited, not in the universe at large.

Let us now draw together what can be said from the above considerations. At first sight it might seem from Table I that whereas the steady-state theory is readily consistent with the existence of life the big-bang theory is not. But this is to overstate the situation. The numbers show that once a replicative system emerges in the steady-state theory, a replicative system of any kind, it will spread throughout volumes of space and quantities of material that increase exponentially with time. Life need not have arisen all in one go. There could be a sequence of steps A,B,C,..., with the evolving associations AB, ABC, ABCD,..., one step being piled on another in an evolutionary process, again provided the reproducibility criterion is satisfied at all stages. Then the probability of life arising is of the order of the *sum* of the probabilities for each of A,B,C,... taken separately. For big-bang cosmology, on the other hand, because of the limited timescale, which prevents spreading exponentially to superastronomical numbers, the probability of life arising is of the order of the *product* for each of A,B,C,... taken separately.

Although the probability of life arising in big-bang cosmology is therefore superastronomically small, it is possible to defeat even a superastronomical improbability in an open cosmology. Somewhere among the infinite amount of material in an open cosmology even a superastronomical improbability will occur. The difference between steady-state and big-bang is that when life arises in the former case it will be found to be spread throughout a superastronomical quantity of material. In the big-bang case, however, the appearance of life would be essentially a point affair, not spread throughout any large quantity of material. To proceed further it is evidently necessary, therefore, to take a look at the extent to which life appears to be spread throughout the visible universe. A thoroughgoing discussion of this question would go beyond present-day knowledge unfortunately. To conclude, it is worth noting the extent to which the combination of big-bang cosmology with the point-appearance of life is a creationist position, with both the origin of the universe and of life being two acts of special creation. Ironically, it is just those who hold this position most strongly who are most ready to accuse others of being creationist, an attitude that would have been wellunderstood by George Orwell.