dence with Popper, just before his death, was concerned with the validity of this work. In my view the models were not correctly described as local. Popper himself admitted that the whole matter was too technical for him to check everything fully, but urged that the latest work of Angelidis should be ...

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... interpretation lies in its claim to finality and completeness'. I entirely agree with the view that we should not rule out criticism by fiat or authority. Popper fought a lone battle against the Copenhagen interpretation at a time when anyone attempting to criticize orthodoxy was liable to be labelled at best an 'outsider' or at worst a crank. But Popper's carefully argued criticisms won the support of a number of admiring and influential physicists. He has done a great service to the philosophy of quantum mechanics by emphasising the distinction between state preparation and measurement and trying to get a clearer understanding of the true significance of the uncertainty principle, but above all by spearheading the resistance to the dogmatic tranquilising philosophy of the Copenhagenists. Because some detailed arguments are flawed, this does not mean that his overall influence has not been abundantly beneficial.

[10] See, for example, M. L. G. Redhead, *Incompleteness, Nonlocality, and Realism* (Oxford: Clarendon Press, 1987), pp. 98ff.

The Uses of Karl Popper

W

GÜNTER WÄCHTERSHÄUSER

Karl Popper's work is of great diversity. It touches on virtually every intellectual activity. But he himself considered his philosophy of science one of his most important achievements. And indeed his achievement here is revolutionary. It destroyed the philosophy of inductivism which held sway over science for hundreds of years.

It should not surprise us that the recognition of this fact is resisted by most philosophical schoolmen. Usually the debate is carried out among philosophers. Their papers are philosophical papers and science comes in by way of interspersed examples. In this paper I shall try it the other way around, from the perspective of the scientist. I shall try to give you an account of my scientific field, the inquiry into the origin of life. And the philosophy of science will come in by way of interspersed references.

I

Before I come to my scientific story, let me briefly summarize and contrast the major tenets of inductivism and of Popper's deductivism (*LSD*, *RAS*, *BG*, *CR*). I begin with a caricature of inductivism in the form of eight theses:

1. Science strives for justified, proven knowledge, for certain truth.
2. All scientific inquiry begins with observations or experiments.
3. The observational or experimental data are organized into a hypothesis, which is not yet proven (context of discovery).
4. The observations or experiments are repeated many times.
5. The greater the number of successful repetitions, the higher the probability of the truth of the hypothesis (context of justification).
6. As soon as we are satisfied that we have reached certainty in that manner we lay the issue aside forever as a proven law of nature.
7. We then turn to the next observation or experiment with which we proceed in the same manner.
8. With the conjunction of all these proven theories we build the edifice of justified and certain science.

In summary, the inductivist believes that science moves from the particulars to the general and that the truth of the particular data is transmitted to the general theory.

Now let me give you a caricature of Popper's theory of deductivism, again in the form of eight theses:

1. Science strives for absolute and objective truth, but it can never reach certainty.

2. All scientific inquiry begins with a rich context of background knowledge and with the problems within this context and with metaphysical research programmes.

3. A theory, that is, a hypothetical answer to a problem, is freely invented within the metaphysical research programme; it explains the observable by the unobservable.

4. Experimentally testable consequences, daring consequences that is, are deduced from the theory and corresponding experiments are carried out to test the predictions.

5. If an experimental result comes out as predicted, it is taken as a value in itself and as an encouragement to continue with the theory, but it is not taken as an element of proof of the theory of the unobservable.

6. As soon as an experimental result comes out against the prediction and we are satisfied that it is not a blunder we decide to consider the theory falsified, but only tentatively so.

7. With this we gain a deeper understanding of our problem and proceed to invent our next hypothetical theory for solving it, which we treat again in the same way.

8. The concatenation of all these conjectures and refutations constitutes the dynamics of scientific progress, moving ever closer to the truth, but never reaching certainty.

In summary, the Popperian deductivist believes that science moves from the general to the particulars and back to the general—a process without end. Let me inject a metaphor. I might liken the Popperian view of science to that of a carriage with two horses. The experimental horse is strong, but blind. The theoretical horse can see, but it cannot pull. Only both together can bring the carriage forward. And behind it leaves a track bearing witness to the incessant struggle of trial and error.

II

We now come to my story of science. It may be broadly characterized as the development of the relationship between chemistry and biology. How is dead matter transformed into living matter?

The year 1644 marks the death of a great scientist, the Belgian physician Jan Baptist van Helmont. He had spent his life and fortunes on scientific research. Yet during his lifetime he published nearly nothing for fear of the Inquisition. In his last will he asked his son to publish his results in the form of a book: *Ortus medicinae*.

It became an instant success, with translations into several vernacular languages. It culminated in a most daring thesis: 'All life is chemistry'. With this he established one of the most sweeping metaphysical research programmes in the history of science. To this day, all the life sciences, notably biochemistry, molecular biology and molecular evolution and certainly the problem of the origin of life are situated squarely within van Helmont's research programme. All the key problems in these fields come down to the problem of the relationship between animate and inanimate matter. In an ingenious approach to this vexing problem van Helmont carried out the first quantitative experiment in the history of biology and he did it quite methodically. I present his report in the English translation:

> I took an earthenware pot, placed in it 200 pounds of earth dried in an oven, soaked this with water, and planted in it a willow shoot weighing 5 pounds. After five years had passed, the tree grown therefrom weighed 169 pounds and about 3 ounces. But the earthenware pot was constantly wet only with rain ... water. ... Finally, I again dried the earth of the pot, and it was found to be the same 200 pounds minus about 2 ounces. Therefore, 164 pounds of wood, bark, and root had arisen from the water alone.[1]

Now, what is the philosophical methodology behind this experiment? Unfortunately, the record is silent on this point. So it would seem to be legitimate to look at this report through the spectacles of our current philosophy of science; in fact alternatively through inductivism and through Popperian deductivism. We may hope for a double benefit: (1) a clear understanding of the historical report; and (2) a clue as to which of the two mutually exclusive philosophies is right and which is wrong.

From the platform of our current state of knowledge it will strike the inductivist as most important that van Helmont's conclusion is wrong. This must mean to him that van Helmont did not apply the proper inductive method of science. He reports only one single experiment. There are no repetitions. He did not repeat the test with 500 willow trees, or with different kinds of trees, or

[1] Cited by T. D. Brock and H. G. Schlegel, in H. G. Schlegel and B. Bowien (eds), *Autotrophic Bacteria* (Berlin: Springer Verlag, 1989).

with different kinds of soils. One single experiment was enough for him. This makes no sense to the inductivist. And so the inductivist must come to view van Helmont as one of those queer, irrational, prescientific characters, amusing but irrelevant.

Now let us apply the Popperian view of science. Van Helmont was operating within a rich context of Renaissance knowledge. It was widely accepted that matter does not spring from nothing, nor disappear into nothing. And it was an equally widely held theory that the substance of growing plants comes from soil. The first theory was to van Helmont what Popper calls unproblematic background knowledge. The second theory was to him problematic and in need of testing. From both theories jointly he deduced a testable consequence. The weight gain of a growing willow tree must be equal to the weight loss of the soil in which it is rooted.

He carried out an ingenious experiment, bringing the soil before and after the growth period to the same reference state by drying. The result did not come out as predicted. 164 pounds of added tree weight compared to only 2 ounces of loss of soil weight, a small amount well within the experimental error. In the face of such a glaring result, van Helmont rightly decided that repeating such an experiment would be a waste of time and money. And so he decided to consider the soil theory falsified.

Van Helmont operated with a limited set of two possible material elements: earth and water. Having eliminated earth, the only remaining possibility was water. His result then was to him proof by elimination. This makes it understandable why he ends his report with a definitive conclusion: '*Therefore*, 164 pounds of wood, bark and root had arisen from water alone.'

Today we hold that this is wrong. One of the important nutrients of plants is carbon dioxide, a gas. Gases, however, were to van Helmont non-material spiritual entities. Therefore, by his own prejudice, he was prevented from including gases in his set of possibilities. It is ironic that it is van Helmont, who discovered that there are gases other than air, who coined the name 'gas', and who even discovered carbon dioxide.

There is an important Popperian lesson to be learned here. In science our sets of possible solutions should never be taken as exhaustive. They are limited by our limited imagination and by our more or less unconscious prejudices. Inductivist philosophers have always missed that simple point.

Here we have now a stark difference between inductivism and Popper's deductivism. The inductivists lead us to view science as a gigantic book-keeping affair and major parts of the history of science as irrelevant or even ridiculous. By Popper's account the

same history of science is seen as a fascinating intellectual adventure story and instead of heaping ridicule on our scientific forebears we see them as the giants they are.

III

After van Helmont's famous thesis: 'All life is chemistry', and the recognition that plants feed on carbon dioxide and light while animals feed on plants, it became accepted belief that plant chemistry and animal chemistry were deeply divided, as deeply as both were divided from mineral chemistry. In this situation, in the year 1806, Jöns Jacob Berzelius, a Swedish chemist, came out with two bold conjectures. He held that there was an essential unity between plant and animal chemistry which he came to call 'organic chemistry'. This he distinguished from 'inorganic chemistry'. But more importantly, he held that there was an unbridgeable gap between organic and inorganic chemistry. His central dogma can be formulated as follows:

> The generation of organic compounds from inorganic compounds *in vitro*, outside a living organism, is impossible.

He believed that a special force was at work inside all living beings which he called '*vis vitalis*'.

The year 1828 marks a watershed in the relationship between chemistry and biology. Friedrich Wöhler published a simple experiment. He reacted two wholly inorganic compounds, ammonium chloride and silver cyanate, and he produced urea, a compound which had only been found in the urine of animals. Wöhler wrote triumphantly: I can make urea, and don't need a dog for this. He knew, with one single falsifying experiment, he had written himself into the annals of chemistry. There is not a shred of inductivism in this story. In fact Justus von Liebig, Wöhler's contemporary and friend, wrote a whole book to free science from the plague of inductivism.[2] But against his burning protest the nineteenth century sees the relentless spreading of this plague.

But let us go on with our story. The nineteenth century had already acquired a rich chemical picture of the world. Living organisms synthesized their constituents *in vivo* from inorganic matter, and chemists were able to synthesize these same constituents *in vitro* and also from inorganic matter. Against this backdrop the next major question came into scientific focus. Aside from the obvious reproduction of higher organisms, where do living organisms come from in the first place?

[2] J. v. Liebig, *Induktion und Deduktion* (1865).

There was an intuitively obvious answer, which had come down through the ages. The simpler organisms, the insects, the worms, the bacteria arise by spontaneous generation from decaying dead organic matter. In the year 1861 the French microbiologist Louis Pasteur published an ingenious experiment. He used two identical bottles with the now famous Swan-neck. He filled both with a sterilized nutrient broth. The first bottle was kept upright so that bacteria in the air would not enter. The second was tipped so that the bacteria could come in contact with the broth. The first stayed perfectly free of bacteria while the second quickly developed a dense growth. This was a resounding refutation. The theory of spontaneous generation of living organisms was laid to rest.

Now microbiology had its central dogma:

> The generation of whole living organisms from chemical compounds, outside a living organism is impossible. Life can only spring from life.

Again, there was no inductivism here. There was merely a refutation of an alternative.

In the year 1859 Charles Darwin published his daring hypothesis, that all organisms are the evolutionary descendents of a common ancestor.[3] This led automatically to the question of the origin of this primordial ancestor. In the year 1871 Darwin himself gave an answer to this question. He wrote in a letter

> It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc. present, that a protein compound was formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which would not have been the case before living creatures were formed.[4]

Eight years earlier the German biologist Mathias Jacob Schleiden, one of the founders of the cell theory, had suggested that a first cell might have been formed under the entirely different atmospheric conditions of the young earth.[5]

[3] C. Darwin, *On the origin of species by means of natural selection of the preservation of favoured races in the struggle for life* (London: Murray, 1859).

[4] F. Darwin, *The life and letters of Charles Darwin* (London: Murray, 1887), Vol. III, 18.

[5] M. J. Schleiden. *Das Alter des Menschengeschlechts: die Entstehung der Arten und die Stellung des Menschen in der Natur—drei Vorträge für gebildete Laien.* (Leipzig: Engelmann, 1863).

Neither Darwin's nor Schleiden's proposals can be said to have great scientific value. They were not concrete enough to have explanatory or predictive power. They were components of a very vague metaphysical research programme.

IV

In the early 1920s the Communist party of the Soviet Union came to the conclusion that its atheistic campaign would be bolstered if it could be shown scientifically that the origin of life did not require a divine intervention. And so, by the account of Christian de Duve,[6] it was Alexandro Iwanowitsch Oparin, the biochemist, and later Lyssenkoist who received the order from the party to produce such a theory. It was produced and published in 1924.[7] This theory incorporated the suggestions of Darwin and Schleiden. By Popper's standards Oparin's theory should have departed from these vague proposals by going in the direction of greater concreteness. This would have generated explanatory power. That means the power to explain many facts of today's organisms with few assumptions. And it would have generated predictive power, which means testable, falsifiable consequences.

But this is precisely what did not happen. Oparin's primary impetus was political. He strove for convincing power. And so he designed his theory to be immune to criticism or falsification. He invented the so-called 'prebiotic broth', but its contents were left completely vague. This basic flaw was not corrected by the other men who published early papers after Oparin, notably the Marxists J. B. S. Haldane[8] and J. D. Bernal.[9] The theory remained vague and untestable, and so it remained untested for thirty years.

The situation changed decisively when the American chemist Harold C. Urey published his theory that the primordial atmosphere of the earth consisted mainly of methane and ammonia.[10] In the same paper he proposed that the prebiotic broth was stocked with the compounds which are formed when lightning strikes such a primordial atmosphere. Now, for the first time, a portion of

[6] Ch. de Duve. *Ursprung des Lebens* (Heidelberg: Spektrum Akademischer Verlag, 1994).

[7] A. I. Oparin. *Proiskhozhdenie zhizny* (Moscow: Izd. Mosk. Rabochii, 1924).

[8] J. B. S. Haldane, *Rationalist Ann.*, **3** (1929).

[9] J. D. Bernal, *Proc. Phys. Soc.* (*London*) *Sect. A*, **62** (1949), pp. 537–558.

[10] H. Urey. *The Planets: Their Origin and Development* (New Haven: Yale University Press, 1952).

Oparin's theory of a prebiotic broth was testable. Stanley L. Miller, a student of Urey, carried out the test: electric discharges in an atmosphere of methane and ammonia above water. He produced mostly a brown tar, but also, amazingly, small amounts of amino acids.[11]

Now the science community made what some may call an inductive inference. From something experimental and observable they inferred something historical and unobservable: The prebiotic broth contained amino acids. Amino acids alone cannot make an organism. Many other components are needed: purines, pyrimidines, sugars, lipids, tetrapyrrols and coenzymes. In the next forty years numerous Miller-style experiments were carried out. The conditions were modified with the aim of generating some of these other components. As soon as traces of another compound were found, this too was claimed to have been in the prebiotic broth. In this way the broth became stronger and stronger but the theory became weaker and weaker. In 1982 the German physicist Manfred Eigen proclaimed that he had no doubt that the prebiotic broth contained all kinds of biomolecules and that it was something like a nourishing beef tea.[12] And about five years later the American Alan M. Weiner wrote in a standard textbook of molecular biology:

> Indeed, it would not be an exaggeration to say that every expert in the field of molecular evolution has a different notion of what exactly was in the prebiotic soup.[13]

The situation grew still worse. Most of the supposed 'prebiotic' reactions require chemical conditions which are incompatible with the conditions of most of the others. Therefore, it was concluded that there must have been several separate cauldrons with prebiotic broth, with different chemical conditions. Others claimed that the soup was significantly enriched with meteor material or unknown cometary material or unknown ingredients from interstellar dust grains. Others speculated that the prebiotic broth would run out of one lake, and on to hot volcanic rocks and then with more rain into another lake. If we check this situation against Popper's theory of science we can make two observations:

[11] S. L. Miller, *Science*, **117**, (1953), pp. 528–529.

[12] M. Eigen, W. Gardiner, P. Schuster and R. Winkler-Oswatitsch, *Scientific American*, **244** (1981), pp. 88–118.

[13] A. Weiner, in J. D. Watson, N. H. Hopkins, J. W. Roberts, J. A. Steitz and A. M. Weiner (eds), *Molecular Biology of the Gene* (Menlo Park: The Benjamin/Cummings Publishing Company, Inc., 1987), pp. 1098–1163.

1. With every modification, the prebiotic broth theory increased in vagueness and ambiguity and it decreased in falsifiability and it decreased in explanatory power. The development of the theory is counter-scientific.

2. *Most workers in the field were inductivists. They believed that the sum total of the experimental results would tell us all* about the prebiotic broth. There is perhaps no other example in the whole of science which violates the principles of Popper's theory of science more thoroughly. And there seems to be no other scientific enterprise, which has suffered a similar devastation from the attitudes of justificationism and inductivism as the prebiotic broth theory. It is a perfect example for the consequences of a continued application of the wrong methodology of science.

V

Let us now apply the Popperian methodology. We recognize at once: the problem is not how we can strengthen atheism. Our problem is one of explanation. How can we explain the mountain of facts of biochemistry. Now we see the magnitude of the problem. We have to explain biological facts which exist today with a chain of evolutionary events which stretches over four billion years. Our explanatory problem is clearly complex.

Now, many, scientists have been very successful without ever thinking about the theory of knowledge. Others have been philosophical inductivists, but in their scientific practice—quite inconsistently—deductivists. In the face of our complex problem we cannot hope to succeed with either attitude. I propose, that we can succeed only if we consciously and consistently apply a methodology of science and only if this methodology is not fundamentally flawed.

Our problem is biological. The solution will be a theory of biology, a theory about the overall process of biological evolution. But let us be clear about our metaphysical outlook. We consider the process of evolution a historic process. If in a thought experiment we would start it again under exactly identical conditions we would expect it to run quite a different course. And if started again, another different course. This is because we consider that at any point in this long process the number of possibilities exceeds by far the number of simultaneous actualizations. This is what we mean when we consider the process of evolution contingent and indeterministic.

If we could trace this historic process backwards, we would expect to end up in purely chemical processes. But the theories of chemistry are universal, independent of space and time. Here we see the next difficulty: our desired comprehensive theory of evolution must trace a unique historic process of biological evolution into a universal process of chemistry. This means that we have to aim at a universal theory of evolution independent of the particular chemical situations on the planet earth and notably independent of special assumptions about nucleic acids or the like.

Next we have to consider the metaphysical problem of determinism. Most physicists agree with Karl Popper that the laws of physics are indeterministic in the sense that we cannot predict the fate of individual particles, atoms, molecules with precision. The process of evolution is based on singular events of mutation in the replication of singular DNA molecules in singular cells. They are therefore indeterministic in the sense of physics. Chemistry, however, is a science that is concerned not with single molecules but with huge ensembles of molecules. The experimental results are statistical results and in this sense of course predictable. If we consider additionally that evolution proceeds in the direction of increasing complexity, we arrive at the following overall picture of evolution. Think of a landscape of chemical possibilities. The first form of reproduction and the earliest phases of evolution may occur in a narrow canyon, perhaps with unique singular possibilities. As the complexity increases the number of chemical possibilities increases. But all possibilities are actualized. Only after a certain degree of complexity has been reached will the number of possibilities begin to exceed the number of actualizations.

This means that the whole picture of self-organization may well be mistaken. Instead we might have to evoke the picture of a self-liberation process, a process which creates its own prospects—an unfolding of possibilities; a process that begins in necessity and ends in chance. In the earliest phases of this overall process of evolution, a biological selection is not required. It comes into the picture only later to keep the explosion of possibilities at bay. This is how the interface between the historic process of evolution and the universal laws of chemistry may well turn out to be.

How shall we proceed in building a more concrete theory? Karl Popper spent a lifetime fighting against reductionism; against the metaphysical notion that biology can be reduced to chemistry. If we adopted for a moment the reductionist position we would try to derive the desired universal theory of evolution from first chemical principles, say from the differential equations of quantum chemistry and chemical initial conditions. Nobody has ever seriously entertained such a reductionist position. We must expect that the landscape of chemical possibilities has huge unknown continents. The chemist will not have the solution to our problem.

This means we have to turn to biology. We have to begin with today's organisms and try—hypothetically—to follow the river of evolution upstream—backwards in time; with the hope of arriving at its source. If we do this, we do it with a certain hope. That all organisms have highly conserved features which tell us about our distant past. The earth is 4.6 billion years old. The oldest microfossils are 3.5 billion years old. The oldest sedimentary rocks are 3.8 billion years old. But life on earth must be still older. So this is now our hope: That the conserved features in the organisms living today are older than the most ancient rocks.

What was the earliest organism like? At this point many philosophers and scientists tend to fall into a trap, into the trap of essentialism—of definitionalizing. They expect to gain real wisdom by finding a definition of the word 'life'. Popper spent a lifetime fighting against such essentialism. So we will avoid this trap. We will try instead to elucidate the process of evolution and treat the problem of naming as secondary.

I now introduce two hypothetical postulates of my general theory of evolution:[14, 15]

(1) All processes of biological evolution are based on a process of reproduction: An entity takes up food, grows and divides into two entities that take up food.

(2) Variations occur due to by-products with a dual catalytic feedback effect: with an altruistic feedback and an egoistic feedback.

By the altruistic feedback the catalyst promotes the reproduction process from which it is derived. By the egoistic feedback the catalyst promotes its own formation. An altruistic feedback alone is not inheritable. An egoistic feedback alone is destructive. Only both jointly constitute evolution.

At this point I am still operating in a Popperian metaphysical research programme. As a scientist I have to get much more concrete. We have to ask a particular question: How did the particular process of evolution on the planet earth begin and how did it go on?

Our inquiry may be divided into two phases which may partly overlap. The first phase is one of a strictly theoretical inquiry. The second phase is the experimental phase.

How can we make progress with a theory without experiments? Popper has given the answer. We orient ourselves on the principle

[14] G. Wächtershäuser, *Microbiol. Rev.*, **52**, (1988), pp. 452–484.

[15] G. Wächtershäuser, *Progr. Biophys. Mol. Biol.*, **58** (1992), pp. 85–201.

of relative explanatory power. And of course we check our modifications constantly against the backdrop of unproblematic theories of physics, chemistry, geology, etc. And now comes a most important point. With every step in the ascent of our theory we are confronted with a plurality of possibilities. Of course we should try to formulate them all. But, of course, we will not succeed. If our imagination is very limited and we think of only one single possibility, then we might have the illusion that our task is the task of proving this result of our poor imagination. But if we are lucky enough to think of several alternative possibilities, then we recognize instantly, that our task is the task of elimination. If we are lucky, then we can eliminate all but one possibility, or one set of possibilities. We then proceed to our next problem which we treat in the same manner. The trick in such procedure is this: We should begin with those problems for which our theoretical elimination process promises to be least ambiguous.

In this fashion I confronted the following questions.

- What was the first food?
- What was the first energy source?
- What was the first autocatalytic reproduction cycle?
- What was the first form of division?
- What was the first form of structural coherence?

For each of these questions I tried to steer the process of elimination so that the explanatory power would be maximized. Each answer was chosen such that it explained not only one, but several facts of today's biochemistry.

My present, tentative set of answers may be summarized in simplified form.

- The first food for life was carbon dioxide.
- The first energy source was the formation of pyrite from iron sulphide and hydrogen sulphide.
- The first autocatalytic cycle was an archaic version of the reductive citric acid cycle.
- The first form of division was the cleavage of a large, unstable molecule into two molecules.
- The first form of structural coherence was the bonding of the constituents onto the pyrite surface.

And now comes an interesting observation. My theory instantly found many supporters, among them great scientists. They all said that they were not convinced of its truth, but they liked it for its explanatory power. In this fashion my theory had a peculiar degree of success before the first experimental shot was fired.

The experimental programme is now coming into full swing. With each experimental problem you are facing a huge variability of the parameters. So the function of the experiments is again mainly that of elimination. You always have expectations of course. But any positive result *vis-à-vis* such an expectation is situated within a field of negative results—if the experiments are set up with the right attitude; an attitude based on the understanding of the poverty of our imagination. And if we run into a situation, where all results are negative, we have to modify the theory again or we stop since we are at our wits' end.

I call my theory of the early evolution of life on earth the 'Iron-Sulphur-World', for iron-sulphide is part of the energy source, the battery, that is seen as driving the whole press. But is this the only possible world of life? Could there be a cobalt-sulphur world, or a nickel-sulphur world, or an iron-selenium world? The Universe is a huge place. But from a chemical point of view it is quite monotonous. This is what our theories tell us. The same some ninety stable elements will be found anywhere. And they are all formed by the same few nuclear processes. And by the laws of these processes—as our theories see them—the proportions of the elements would be similar everywhere. For example where there is nickel for a possible nickel-sulphur world, there will always be a predominance of iron.

This gives us a peculiar cosmological outlook. Throughout the universe, life might well have basically only one way of getting started. And wherever the conditions are right, it would start continuously—anywhere, anytime in the same unique way.

With this highly speculative cosmological view, our whole problem situation appears to shift. There are many different chemical spaces. In perhaps only one of them—perhaps very narrowly restricted—we expect to find the original homestead of life. Here the starting process will run continuously. So the origin is not a time—it is a place. And the process of evolution is seen as a process of conquering ever new spaces; it is seen primarily as a spatial affair; and time comes in by way of the history of the conquering of space.

Metaphorically speaking, the process of evolution is a process of liberation—of liberation from the narrower chemical confines of an iron–sulphur world and from a two-dimensional existence on pyrite surfaces. This process of liberation has now been going on for some four billion years. And it is still gioing on. But only at a price; at the price of unfathomable complications and ever more sophisticated controls.