The Origin of Life

WHEN DARWIN PRESENTED a rational approach to explain the origin and evolution of the diverse species of animals, a question naturally arose: Where is the beginning of this process? If life begets life, and organisms evolve through the process of natural selection, then how did the first organism come into being?

The problem is, no doubt, difficult. There is no witness; neither is there any fossil record of the first living form; none of its characteristics is directly known. Therefore, scientists took the logical approach to the problem. Since the process of evolution proceeds from the simple to the complex, therefore if we go back in time, we should logically expect to find simpler organisms. Fossil evidence also supported this assumption: the earlier a fossil is, the simpler is its anatomy. If one extrapolates this logic further backward in time, one comes to the conclusion that the first organism was the simplest possible living form.

The quest then is: What could be the simplest manifestation of life? We may get a clue if we look around us, at the biological diversity that adorn the face of our planet. For instance, the structural makeup of a unicellular organism is far simpler than that of a multi-cellular one. Among the various single-celled organisms, some have cell-walls, others don't. Obviously the latter is simpler, of which a typical example is the virus — which is simply a large molecule. Like many other chemical substances, it can be crystallized and preserved — and in such a situation there is absolutely no sign of life in it. However, when it enters the cell of a living host, it replicates itself using the ingredients within the host — whereby it shows characteristics of life.

Thus, in case of molecules, the ability to replicate by collecting the ingredients from the surrounding may be viewed as a manifestation of life. And such replicating molecules may be considered as the simplest embodiment of life. Therefore, scientists believe that on the face of our planet, molecules capable of replication might have constituted the earliest life-form.

What was this molecule like? The clue, again, is supplied by the biological world of today. Though there are diverse kinds of species with very many differences between them, is there any aspect that is shared by all life forms? Indeed, there is. If we look for the similarities, we would definitely come across a point of basic unity — which must have been present in the earliest life-form also.

This point of commonness is that all life forms are made of molecules with a basic structural element involving the carbon chain. One important attribute of the element carbon is that it can form long chains linking with other carbon atoms virtually limitlessly, producing complex molecules. In fact, the existence of life is dependent on this special property of carbon which is called catenation. So it is a reasonable assumption that the molecule constituting the first life form also had a long chain of carbon atoms.

Can we guess precisely what had been the shape of the carbon-chain? The answer to even this question comes from the similarities amongst the living organisms today. We may note that the various types of proteins which constitute the body-parts of all living organisms are made of the basic building block called amino acids. The amino acids are considered to be the fundamental constituent of all life forms. So we can safely assume that amino acids played a decisive role in the anatomy of the first life-form also.

But how did the amino acids come into existence in the first place? In 1921, the Russian scientist O. I. Oparin and in 1928 the British scientist J. B. S. Haldane showed that it would have been impossible for life to come into being with oxygen present in the atmosphere at that time. Hydrogen as well as the most simple organic compounds of carbon react with oxygen. So, had oxygen been present in the atmosphere, the smaller carbon-chain molecules would have reacted with oxygen, forestalling any possibility of their reacting among themselves forming larger and more complex carbon-chain molecules.

Today, following a host of observations, geologists have come to the conclusion that the atmosphere of the primitive Earth was without oxygen. It was in fact a reducing atmosphere, rich in hydrogen-donors like methane (CH_4) and ammonia (NH_3). According to Oparin and Haldane, the simpler molecules of carbon reacted among themselves in such a reducing atmosphere, forming relatively complex molecules. Further reaction resulted in more complex ones, finally producing the building blocks of life.

The first experimental support for this hypothesis was provided in 1952 by Professor Harold C. Urey and his student Stanley Miller of the University of Chicago. They created an artificial lightning using an electric arc inside a specially designed glass container filled with the gases which would have been present in the primitive atmosphere (see Fig.1). By maintaining this simulated four billion year old terrestrial atmosphere for a week inside the glass bulb, they found that quite a number of simple organic molecules had formed. Even the very `bricks' of life --- amino acids (glycine, alanine etc.) were produced in the broth.

Thus, the Urey-Miller experiment confirmed that it was possible to have the organic molecules created out of the

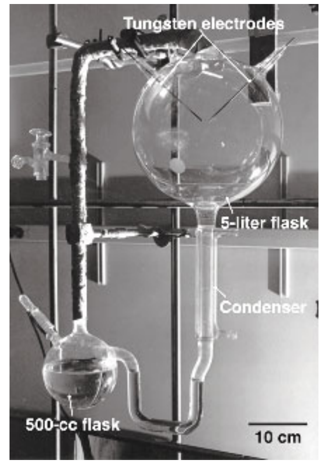

Fig.1: The Miller-Urey experiment apparatus.

inorganic raw-materials through chemical reaction. Later, a number of scientists demonstrated, in a number of different ways, that amino acids and other organic compounds form quite easily in oxygen-free environments. Thus, it is natural that under the action of intense and frequent lightning and ultraviolet rays*, a large quantity of organic molecules were produced in the primitive Earth.

Now we know that amino acids can form even in absence of the Earthly atmosphere. The formation of such molecules requires, simply, the presence of the raw-materials because, as the evidence shows, they were produced even during the formation of the solar system. Spectroscopic studies on the Halley's comet when it came close to the Earth in 1986, revealed that the comet too contained amino acids. Even the far-away Orion nebula has shown traces of these molecules. Thus, we may infer that amino acids are definitely not rare in nature.

Let us now try to imagine the state of the primordial Earth in another way. It is now known that the process of planet

* Those days there was no ozone layer to stop the UV radiation coming from the sun. The ozone layer formed much later, after the atmosphere became oxygen-rich through photosynthesis.

formation was marked by a condition of low temperature, in which condition the silicates and ice crystals of volatile substances could accrete. After the formation of the planet, due to the heat produced by the radioactive substances and other factors, the inside of the Earth got heated up, to such an extent that almost the entire body of the planet went into a molten state. At that stage, the gases like ammonia, methane, carbon dioxide and water --- which were so long trapped in solid form --- turned into gas and gushed out to the Earth's surface. These gases gave rise to the Earth's primitive atmosphere. It is believed that this was the stage when amino acids and other organic compounds were formed profusely due to the reaction of gases in the reducing atmosphere.

Then the Earth began to cool down gradually. This cooling process caused the huge amount of water vapor in the atmosphere to condense and rain down to inundate the low-lying regions of the Earth surface, forming the oceans. The amino acids and other organic substances got dissolved in this sea of water to form what Oparin and Haldane called primordial “hot dilute soup.”

This warm sea became the medium of various types of chemical reactions giving rise to newer, more complicated molecules. In the next article of this series we shall see that amino acids link up to form protein molecules; three types of molecules link up to form nucleotides, and nucleotides link up to form long chain of a nucleic acid molecule. If the bigger molecule is more stable than the smaller ones, the reaction naturally proceeds towards formation of the bigger and more complex molecules.

In those times, multifarious chemical reactions were going on inside the hot dilute soup, producing a variety of stable rearrangements – macromolecules formed through polymerization of monomers or small molecules. There was a kind of molecular evolution going on, where different types of stable macromolecules got naturally selected while the unstable ones got destroyed. Though the formation of a specific molecule was dependent on the chance occurrence of the appropriate collision between suitable small molecules, in the vast open sea the coming together of countless small molecules was very natural and a routine phenomenon. The chances were, therefore, very high and the overall mechanism of the molecular evolution was entirely law-governed, albeit statistical in nature.

Among the various types of stable molecular arrangements evolving out of this mechanism, a special kind of molecule, which by nature could replicate, proved to be pivotal in adding a new dimension to the history of our planet. The origin of the replicating molecule may be regarded as the turning point in the course of evolution.

At this point the reader may ask a pertinent question. The property of replication, in the final analysis, may be solely due to the peculiarity in the structure of this molecule. What is the probability of formation of this special structure out of random collisions of molecules? On calculation doesn’t it come out to be near zero?

The answer to this question can be approached from two different angles. Firstly, in the warm sea, globally, millions and millions of molecules reacted with each other every instant. Again this process continued through thousands of years. This means, even if the chance of formation of a replicating molecule is extremely small, yet if the process goes on for a very long period of time and throughout such a wide expanse, the feasibility of this rare event to occur once in a long while cannot be ignored. While playing the game of *ludo*, the possibility of hitting upon a six consecutively thrice is negligible. However, if the game goes on for an hour, such an improbable event is found to materialize a number of times. Secondly, why is it that the chance of hitting upon a six thrice is so small? The reason is that, in each throw it shows a number between one and six with equal probability. So the probability of hitting upon the number six in the first throw is 1/6, that in the second throw is 1/6, and that in the third throw is also 1/6. Therefore the probability of hitting upon the number six in three consecutively throws is $1/6*1/6*1/6=1/6^3$ = 1/216, which is quite a small number. However, in the case of molecular collisions the perspective is a bit different. Firstly a particular molecule does not react with every other molecule, and its reacts with different molecules with unequal probability. Thus the situation is much like Sakuni's game of dice in the *Mahabharata* – there is a brighter chance of hitting upon a successful combination.

Yet, there is another point to add here. Which molecular reaction will be successful depends on the three-dimensional structures of the colliding molecules. Just as a particular key fits into the suitable groove of a particular lock, a certain type of molecule too can react only with specific molecules where the 3-dimensional structures fit with each other. When a molecule grows bigger, the number of other molecules it can react with becomes smaller. As a result, the probability of reaching the required arrangement is not really very small.

It is not difficult to imagine a molecule which is capable of replicating itself. This molecule can be regarded as a chain of beads arranged like a garland, where the beads represent different types of small molecules. Assume that there are six types of beads, referred to as A, B, C, D, E and F. These beads are in actuality smaller molecules, which are also found in the vicinity of the chain-molecule, as suspended in the hot dilute soup. Now, if a particular type of molecule has an affinity to link up with its own kind, then a C-type molecule moving freely in the neighbourhood of the chain-like molecule will get attached to the bead C. Similarly, an A-type molecule will be attached to an A-bead, F-type to F-bead and so on. Hence, another chain similar to the original is formed and attached alongside. Now if at one point there is a split in the pair, two similar chains are produced — which are both capable of producing more and more chains of the similar type. This is what we call replication.

Again, it may happen that A has an affinity for, say D instead of its own type; likewise B for E, C for F. In this case too, a copy may be formed, but in two steps. In the first step, the original chain say A-B-C-D-E-F forms a complementary chain D-E-F-A-B-C which then yields a copy of the original A-B-C-D-E-F chain, albeit through a second duplication. This is like photography, where a `negative' is first made and the positive image is obtained in the second stage.

The process of replication can follow either of these two alternative mechanisms. It is very difficult to say how the first replicating molecule worked, but today all replicating molecules produce copies by the second mechanism.

Therefore, the process of replication is not as complicated as it first appears to be; it is a normal property of certain special types of molecules. Production of such molecules through polymerization, under suitable condition (e.g., reducing atmosphere, extensive lightning and UV rays) is not impossible. The earth was formed 4.6 billion years ago, and fossil record for the first living organism goes back to 3.8 billion years before present. The time taken to form the first replicating molecule, although a very big span when compared to human lifetime, is indeed small on geological scale.

Following the formation of the replicating molecule, the very make-up of the then warm sea (the organic soup) started to change. So long various types of molecules were producing many macro-molecules through polymerization. There was no scope for preferential formation of any specific macromolecule. But once the replicating molecule was formed, it went on generating its own copies. As a result, within a short span the sea became rich in copies of the replicating molecule. Its number went on increasing as long as there was sufficient raw material, i.e., the smaller "component" molecules.

In any process of replication, it is impossible to get absolutely error-free copies. Occasionally there may be one or two mistakes. Try to copy from a book and after you have finished, you would find that two or three mistakes have inadvertently crept in. May be those mistakes are not so fundamental in nature as to alter the meaning of the statement. But what if another person copies it from the first copy? And then a third copy from the second? The errors would accumulate in each copy and at some stage the meaning of some statements may be different from the original one.

In the warm ocean of that time, the increase in the number of replicating molecule was due to successive copying from its immediate predecessor. Hence any deviation from the original that might have crept in while copying got copied in the next phase of replication. In this way new molecules with different combinations of subunits arose; of course differing in structure from the primitive molecules. Therefore it will not be correct to say that one type of molecule increased in number in that hot soup. Many different molecules were formed, which were obtained through serial replication from the original replicating molecules. Their structures were not absolutely identical; and the cause of the birth of these newer sets of molecules lay in error in the process of copying.

The minute differences in structure must result in some differences in their properties. For instance, some could be more stable while the others degenerated after a short while. In such circumstances, the relatively stable molecules will predominate – because they would not only get more time for replication but also each of the resultant copies would remain in the solution for a longer time. However, the proliferation of different types of molecules is not determined by their stability alone. Different molecules would replicate at different rates. The molecules that replicate quickly would multiply faster.

A third feature that influences the population of each type of molecule is the frequency of occurrence of errors. Let us consider two sets of macromolecules, *A* and *B*. Suppose that all other properties are the same for these two molecules; only *A* makes one error in every ten replications whereas *B* produces one erroneous copy in every hundred replications. Naturally, the molecule of type B would proliferate faster because the erroneous copies will be molecules that do not belong to the sets A and B.

Consequently, in the organic soup, one would observe an evolutionary trend as regards the population of various kinds of replicating molecules. With time, those molecules would come to predominate which are more stable, which replicate faster, and which make less error in replication. Others breeds of molecules which are not favourably placed as regards these properties would decrease in number and would become extinct. This process of evolution implies that the composition of the hot organic soup changed with time as a result of a mechanism similar to that in Darwin's theory. It is immaterial whether we call these molecules living or not. What is certain is that the molecular process going on in the hot soup represented the earliest point from where the process of biological evolution started, ultimately resulting in all the living beings we see on the Earth today.

In any process of evolution, the contradiction between a living organism and its environment is a matter of paramount importance. Hence, it is important to understand the nature of the contradictions in that molecular environment. This contradiction is not any conscious affair. The molecules were not aware that they were involved in any sort of struggle. The very basic laws of chemistry governed the process. But the nature of the process was such that the different types of molecules were involved in a form of unconscious competition, which determined which molecules would be formed, in what numbers.

The competition was for the raw material — the smaller "building-block" molecules. It has already been said that the replication can occur only if the smaller biomolecules are available in the neighbourhood. In that primordial sea, the supply of such smaller molecules was large, but not unlimited. So it was not possible for the replicating molecules to proliferate limitlessly. The more these replicating molecules grew in number, the less became the number of the smaller biomolecules. Ultimately these resources became scarce.

The competition between various types of replicating molecules was for gaining access to the precious raw material. The molecules that could best utilize this provision for replication, gained the upper hand. Sometimes, it happened so that the variant arising out of a copying error could utilize the raw material more efficiently.

Different molecules existing in that soup did this in different ways. Some of them could break up its neighboring competitor and use its fragments—thereby, at the same time destroying its rival and usurping the much-needed building-blocks. Certain molecules might have developed a protective layer around themselves. Some others probably developed the capability to synthesize the necessary small bio-molecules from inorganic molecules present in abundance. All these were possible because of the structural and compositional attributes of those specialized molecules. Thus, only the molecules which, by developing these skills could succeed in the struggle for existence were able to give birth to the next generation of duplicates.

A defense mechanism against adversaries is ingrained in the laws of nature. The biomolecules in the solution naturally tend to come together to form spherical droplets. In fact, in such droplets it would be easier for the molecules to replicate because of the higher density of the small organic molecules. We know that there are two kinds of molecules based on their affinity towards water — the ones that are attracted by water are called hydrophilic and the ones that are repelled by water are called hydrophobic. Naturally hydrophilic molecules tend to aggregate on the outer face of the drop, while the hydrophobic ones aggregate inside, away from water. Thus, a protecting membrane develops around the replicating molecule. In course of evolution these droplets developed into the primordial cells, and the membranes developed into cell-walls. The process of natural selection then started operating on the survival of the cells.

Is there an end to this dialectics of nature? No, there isn't; it is still in action. The biodiversity which we witness today is the fruit of this dialectic. With time, the potential of the primordial organisms increased and their scope of survival became more advanced. Today we cannot recognize them as molecules. Some are plants; some are fishes; some are birds.□