BIOLOGICAL SCIENCE FOUNDATIONS

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Summary
Life is a very complex process and its foundations go back up to four billion years. To

understand the processes of life today requires insight into what occurs today, as well as how evolution created these processes. The diversity of life and the limits to where it can exist expand on a regular basis. The limits of life as we know it remain an unknown quantity, and biological science continues to expand its horizons both at micro- and macro-level.

1. Introduction

Study of the biological environment must have started when humankind began to exhibit some degree of control over its surroundings. To survive more effectively, people must have learnt quite quickly to recognize a wide range of plants and animals. This must have included whether they were dangerous or safe if animals, and if they were edible or poisonous if plants. The complete visible world of fauna and flora that surrounded humanity needed to be studied to improve survival. As an intelligent ape, group survival would also depend on the ability to pass on this information to other members of the group and offspring. The development of language would have provided the tools for this, and one can imagine early members of *Homo* informing the children of the group that certain plants made you ill if you ate them, and that certain insects could sting you and this would be very painful.

It is obvious that the above studies, by definition, were not organized in any way and were totally ad hoc. That is not to say that they were not and in fact are not useful. Such so-called “folk knowledge” is a valuable resource even today and many learned institutions use such knowledge as a starting point for modern scientific studies. Every time an aspirin (from willow bark) is taken for a headache, or digitalis (from foxglove) for a heart condition, it is important to remember that both these medicines originated from plants whose medicinal properties were described many years before modern medicine came about. However humans seem to have a need to classify and organize and it was when these needs started to be filled that modern biological science began.

It is usually argued that modern society looks towards the Greeks and Romans for the beginning of the scientific study of biological systems. This is because Western society is still based and centered on this ancient civilization. It is really one continuous civilization lasting perhaps from the Classical Age in Greece about 500 B.C. until the fall of Byzantium in A.D. 1453, with written records covering the whole of this period. These records do include various studies on fauna and flora, but these are unsystematic and although they formed the base from which the Renaissance created the scientific study of biology, their usefulness was limited to that of lists. Unwritten, but well-recorded in the ecology of Europe, the Middle East, and North Africa is the distribution of useful plants and animals by this civilization to all parts of the Roman Empire and beyond. The vine, wheat, and many herbs are probably the best examples. Also recorded in the ecology is attempted elimination of various predators and dangerous animals from the “civilized” parts of the empire, although complete extinction might have to wait until more modern times. The wolf and the bear in England are good examples of this. But one should not be Eurocentric. Chinese civilization commenced at an even earlier date and in some ways is still in continuity with that start. Chinese written records form a similar listing for Asian fauna and flora to that described above for Europe.

The effects of civilizations (and this must include all major world civilizations) on fauna and flora should not be imagined to be limited to listing, distribution, and elimination. All civilizations have caused genetic modification of important species to improve them for the use of humanity. Although genetic modification by breeding was slower than modern *in vitro* genetic modification techniques, the results are in many ways much more profound and obvious than modern genetically modified plants and animals. Whereas, a scientist in the field would be unable to tell a normal maize from a herbicide-resistant, genetically modified maize without some laboratory access, everyone can see the difference between modern wheat and its ancient ancestors from the Tigris and Euphrates valleys. Similarly, the modern horse is very different from its wild ancestors. One can go on and include rice, maize, vines, dogs, cats, cattle, chickens, etc.

Thus, when the fauna and flora started to be scientifically described during the seventeenth century, the scientific method with its ideas of classification, hypothesis, theory, and experimental testing, began analyzing a world that had already been greatly affected by humankind.

2. The Beginning of Modern Biological Science

The sixteenth, seventeenth, and eighteenth centuries provided two major starting points for the study of biology. First, the physical sciences provided tools for the study of biological systems, such as the microscope. Second, the creation throughout the world of scientific societies, such as the Royal Society, together with the expansion and increase in the number of universities in most major cities, provided a base from which research on biological science could begin. Finally, the move away from a deistic mind-set towards a more questioning mind-set allowed scientific analysis of the more complex biological systems to take place. From the eighteenth century onwards, the foundations of modern biological knowledge were built using the tools provided by physical science.

2.1. What Is Biological Life?

Historically, the question "What is life?" was not a question that was asked in any serious way. To Plato, Aristotle, and Confucius, it was obvious. Man, animals, and plants were alive. Rocks, soil, and water were not alive. Whereas man, animals, and plants could make a transition from life to not alive, in general, rocks, plants, and water did not make a transition from non-alive to alive. That is not to say that they believed the latter to be impossible, but just not normal. As scientists began to try and classify animals and plants during the seventeenth and eighteenth centuries, it became necessary to be able to decide what is alive and what is not alive. The result was a definition of biological life that, in general, works quite well, but has a number of now well defined limitations. A living organism should exhibit the following characteristics:

- Reproduction. Probably the most important aspect of life and is central still to even modern molecular approaches.
- Movement. Closely related to the macroscopic nature of this definition and clearly

orientated towards animals, although plants do show movement at a macroscopic (e.g., phototropism) and a microscopic (e.g., stomata) level.

- Growth. An important macroscopic characteristic, but also present at a microscopic level and in terms of a decrease of internal entropy.
- Irritability. Basically, the ability of a living organisms to respond to its environment and identifiable at both a macroscopic and a microscopic level.

Using the above criteria, a person could classify as living or non-living almost all macroscopic entities encountered. However, the discovery of a totally new microscopic world invisible to the naked eye except with the aid of an instrument – the microscope – opened up how to define life.

2.2. Microscopic Life

Antony van Leeuwenhoek (1632–1723) of Delft in the Netherlands is usually credited with the discovery of micro-organisms. In fact, he was not the first to use lenses and microscopes to study invisible "animalcules" (named as such by him), but his enthusiastic and detailed study of the micro-organisms he found in his environment was recorded in a series of letters to the British Royal Society. These letters are in such detail that his animalcules can be identified as bacteria, fungi, and protozoa even today with ease. His drawings are the first of bacilli, cocci, and spiral bacteria, and include a description of bacterial motility. His work more than anyone else's created modern microbiology.

However, his work created a major argument with respect to life and its origin. Three schools of thought came about during the eighteenth century. The first suggested that micro-organisms arose as a result of the decomposition of plant and animal matter (i.e., that the changes on death produced micro-organisms rather than the micro-organisms producing the changes). The second was related to the first and suggested that micro-organisms spontaneously generated from inanimate matter. The third supported the concept that micro-organisms reproduced in a similar manner to higher organisms and reproduced as offspring from parents. Until this controversy was resolved, a general definition of life was impossible and this took almost 100 years. This was partially because the idea of spontaneous generation dates back at least to the classical Greeks who believed frogs arose spontaneously from ponds and maggots from decaying meat.

Spontaneous generation was disproved in 1854 by Schroder and Von Dusch by passing air into a sterile flask containing medium for bacterial growth through a cotton wool filter. This removed airborne bacteria and the broth remained uncontaminated as long as the filter was in place. However, it was Louis Pasteur who proved the converse of spontaneous generation: that micro-organisms reproduced just like macro-organisms. His work using goose-necked flasks opened in various environments strongly supported the concept that micro-organisms only arose from previously existing micro-organisms. Further work on wine fermentation confirmed this. The development of pure culture techniques based on glass dishes filled with a solidified media (the petri dish) allowed Robert Koch and his pupils to isolate the causative agents of a wide range of human and animal diseases, including typhoid, diphtheria, tetanus, and glanders. Koch put forward a series of criteria to be used to prove that a particular micro-organism was the cause of a particular phenomena. These are still generally used today, and controversy on the origin of diseases such as AIDS and human-variant bovine spongiform encephalopathy ("mad cow disease") revolve around the interpretation of Koch's postulates, which are:

1. A specific micro-organism should always be found associated with a particular disease or phenomena.
2. The micro-organism should be isolated and grown in pure culture in the laboratory.
3. It should be possible to inject/inoculate uncontaminated animal/plant/material with the pure culture and produce the same disease or phenomena as in point 1.
4. It should be possible to recover the same micro-organism as in point 2 from the newly infected source.

Although not infallible, they form the basis of all modern microbiology and in many ways modern biology.

2.3. The Origin of Life

The demise of the spontaneous generation theory left an intellectual vacuum with respect to the origin of life on earth. On the one hand, there were the proponents of special creation by God, while others looked for a scientific basis for the origin of life. During the eighteenth and nineteenth centuries the discovery of fossils of animals and plants placed pressure on the supporters of the special creation theory, although even today a deistic biological scientist is not unusual. The idea that there had been species and life on earth that had died out millions and millions of years ago, and could be related to modern day species by taxonomy, begged the question of an event in the past where life originated.

The earth has been dated as about 4.6 billion years old by radioactivity measurements, and rocks almost 4 billion years old have been identified in several locations; among these, the Isua formation in Greenland is around 3.8 billion years old and the Swaziland series around 3.5 billion years old. There is fossil evidence for micro-organisms in rocks that are 3.6 billion years old and these *Stromatolites* represent diverse layers of filamentous bacteria. Thus the origin of life can be dated to sometime before 3.6 billion years ago and perhaps as early as 3.8 billion years ago. This is because part of the Isua formation is sedimentary and this implies the presence of liquid water.

The atmosphere of the early earth was devoid of significant amounts of oxygen and formed a so-called "reducing atmosphere" made up mostly of water vapor, methane, carbon dioxide, nitrogen, and ammonia with trace amounts of carbon monoxide, hydrogen, hydrogen cyanide, and hydrogen sulfide. For the first 500 million years, it is likely that the earth's temperature was above the boiling point of water and liquid water did not exist. The rate of cooling is not known, but the first organisms must have been heat tolerant and originated in a window from about 3.6 billion to 4.2 billion years ago.

Experiments have shown quite clearly that many biological molecules, including the most important, can be synthesized in an artificial earth reducing atmosphere by heat, ultraviolet radiation, and electric discharge. These compounds, such as sugars, amino acids, purines, pyrimidines, nucleotides, thioesters, and fatty acids, would have accumulated in solution and polymerized to form polypeptides and polynucleotides. In the absence of living organisms, these compounds would be stable for many years and vast accumulations could have occurred with time. It has been suggested that pyrite formed the basis for the origin of the earliest life form.

Three factors were required for a primitive life form to arise: first, a metabolism allowing the accumulation, conversion, and transformation of the chemical in the surrounding liquid; second, a hereditary mechanism allowing the transfer of properties to offspring; and finally, a method of isolating the above from the environment, that is a cell membrane. How many times such a primitive organism arose then died out due to a fault cannot be estimated, but sometime within a window of perhaps 200–400 million years ago one or more primitive cellular forms arose and survived. They were simple, did not use oxygen, and probably had a very primitive replicating mechanism. In terms of chemical reactions 200–400 million years is a very long time and chance becomes very important. Someone “won the lottery” eventually. It is quite possible that there were a number of winners and life as we see it today is the result of the competition between those winners for resources. However, it is more accepted that a single organism survived that early competition, called the cenancestor, from which all life on earth is derived.

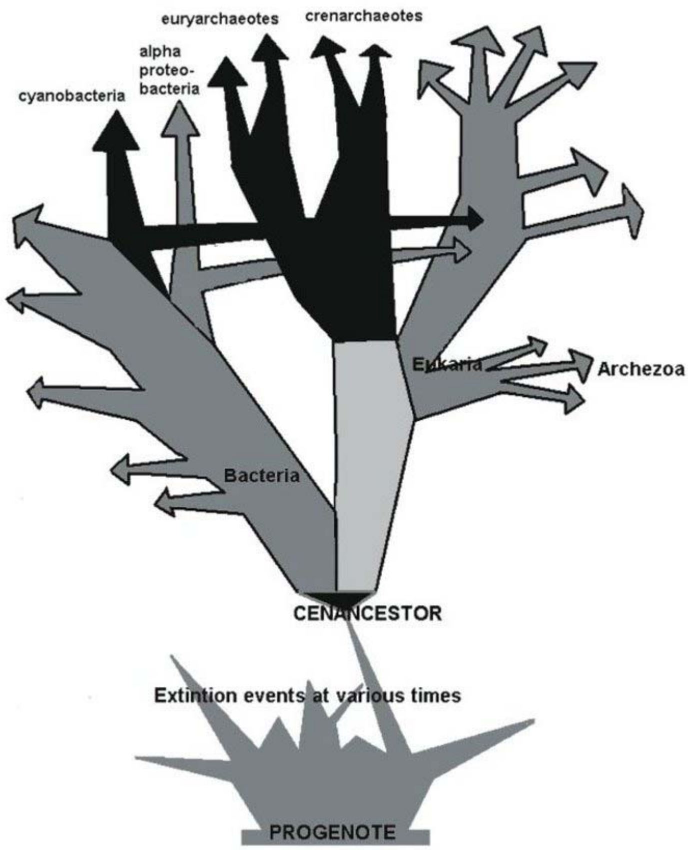

Figure 1. Overview of the Evolution of Life on Earth (after Woese)

Over the next 3 billion years life evolved into three major lineages – the Bacteria, the Archaea, and the Eucaria – that have distinctive features at the molecular level. Two other major events occurred during this evolution. The first was the symbiotic engulfing of an alpha proteobacteria by an Eucaria to give rise to the chemical energy production unit of most eukaryotes: the mitochondrion. Next and later was a similar symbiotic engulfing event of a cyanobacterium by a mitochondriate Eucaria to give rise to a second energy source for the cell, the plastid or chloroplast, and creating the group of eukaryotes called plants. Whether these different symbiotic events were single events or multiple events is open to debate, but does not contradict the symbiotic origin of most eukaryotes either way. However, there are eukaryotes that lack a mitochondrion: the Archezoa. Certainly, many of these evolved very early in the evolution of life on earth and there is evidence to suggest that they represent the pre-symbiotic Eucarial cell. However, some are also simply derived eukaryotes that have lost their mitochondrion later in evolution and, of course, the mitochondrion cannot be replaced once lost (Figure 1).

2.4. Evolution and the *Origin of Species*

The discovery of extinct fossil species during the nineteenth century led quite quickly to the question of which mechanism had given rise to the wide diversity of species on earth. Without a mechanistic basis to how hereditary works, two quite distinct theories came to the fore. The first, the Lamarckian theory, proposed that the environment of an organism could directly affect the hereditary of the organism and produce changes to the genetic makeup of that organism, which could be passed on to the next generation. The alternative, proposed in Charles Darwin's *Origin of the Species*, proposed that the environment selected the most fit of a population of organisms, removing the less fit, resulting in the more fit producing more offspring. The genetic makeup of these offspring would be, in general, more fit for a particular environment. Thus, a step-wise selection towards an optimum genetic makeup for a particular environment would take place, with resultant changes in the appearance of the species.

The latter theory became quite generally accepted, but without a mechanism for the hereditable changes, remained controversial. In 1900 the work of Gregor Mendel was rediscovered, having been published thirty-five years earlier. Scientists confirmed his concepts. He had proposed that the hereditary material was particulate in nature and did not blend on crossing (that is, the unit of genetic information is the gene). He also showed that these genes segregated during crosses and could be followed from generation to generation. This allowed the development of neo-Darwinism, whereby during evolution the selection for fitness acted on the individual, but resulted in changes to the genes present in a species' population, and thus the whole population structure. Such a concept allows one to imagine the same mechanism at work during the 400 million year window during which life began on earth. The competition for diminishing resources would provide a strong selection for the fittest primitive organism to evolve to a more efficient state and take over new ecological niches.

It is obvious that we can only see the results of such evolution almost 4 billion years on. However, the concept can be modeled quite successfully using computer programs. Such "Artificial Life" models consist of primitive programs that are able to reproduce, compete, and evolve in a comparable manner to that of the first life forms on earth. In many cases in these simplistic studies a "lifeform" evolves that develops a strategy that out-competes all other "lifeforms" and dominates its computer world. Because the parameters are very simple in these simulations, they probably mirror, at least in part, how the very early lifeforms competed. Evolution and selection giving rise to the origin of species is not just a theory, but a testable model that works both in life and in simulation. In a similar manner, programers have developed "genetic programs" that use the same concepts of mutation, recombination, and selection to evolve new programs for complex processes. Thus it can be put forward that concepts of genetics and evolution have a more general application in the worldview.

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Biographical Sketch

Ralph Kirby is Professor of Microbiology at Rhodes University, Grahamstown, South Africa. He has held this position for the last ten years. He graduated with his B.A. at Trinity College, Cambridge, UK, in 1972, and completed his Ph.D. at the University of East Anglia, UK, in 1976. Post-doctoral research followed at the University of Bristol, UK, then a lectureship and senior lectureship at the University of Cape Town, South Africa. His major interests are the molecular genetics of Actinomycetes, horizontal gene transfer, molecular population genetics, and the interaction between law and science. He is presently completing a LL.B.