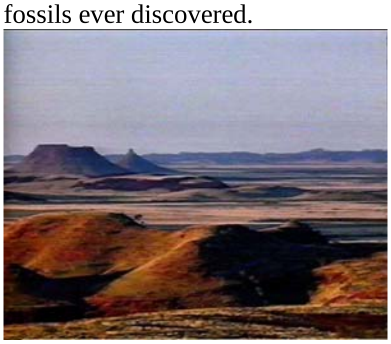
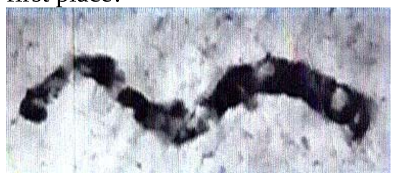
Emergent Properties and the Origin of Life

In the 100° heat of northwest Australia, choking clouds of red dust swirl across a bleak landscape dotted by clumps of brown grass. In the distance, low, rolling hills break the monotony of the flat plain. While barren and unimpressive, these hills contain some of the oldest rocks on the earth. In the 1990s Bill Schopf, a geologist from the University of California, cut thin sections through a kind of rock, called the Apex chert, that he had collected from the hills near Marble Bar, Australia. He polished the sections until light shown through and then carefully examined them under a microscope. What he found were the oldest fossils ever discovered.



Hills in Western Australia containing outcroppings of 3.5 billion year old rocks called the Apex chert.

The picture below shows one of the slices of chert as seen through Schopf's microscope showing a microfossil of an ancient bacterium that existed 3.5 billion years ago. Since the earth was far too hot to support life until about 4 billion years ago, Schopf's discovery meant that living cells had evolved sometime between 4 billion and 3.5 billion years ago. But cells are complex structures and they must have evolved from still simpler forms of life. Unfortunately it's extremely doubtful that we will ever find fossils of these pre-cellular living entities. But even if we did know their precise physical structure and chemical composition, the deepest of all biological questions would still be left unanswered: How did life arise in the first place?



Photomicrograph of a thin section of the Apex chert showing what William Schopf concluded is a microfossil of a 3.5 billion year old filamentous bacteria.

Strangely enough, Charles Darwin never expressed an opinion on how life originated, even though his own theory demanded a naturalistic, evolutionary explanation. Several of his contemporaries, however, proposed that living organisms had arisen in a series of stages from nonliving matter. For the past 150 years we have been trying to work out the details of this process.

Thanks to discoveries by astronomers, we now know that the chemical precursors of life are abundant throughout the universe. These precursors include carbon, oxygen, and nitrogen, which are forged in the interior of stars, and molecules such as water, hydrogen cyanide, and ammonia which form from reactions between carbon, nitrogen, oxygen, and hydrogen. As the earth cooled after coalescing from the dust circling the newborn sun, a complex chemical soup of organic and inorganic molecules became concentrated in the early oceans. How self replicating molecules first emerged from the chemical reactions occurring in this prebiotic cauldron is a hotly debated area of research.

Current theories for the origin of life fall into two categories: "**Genes First**" vs. "**Metabolism First**". The Genes First theory, also known as **RNA World**, says that RNA, one of the most important molecules in living organisms, holds the key to understanding the origins of life. In almost all cells, RNA transcribes information from DNA and shuttles that information to cell structures called ribosomes. This information enables the ribosomes to assemble the proteins needed for metabolism and other cell functions.

RNA World postulates that small strands of RNA arose through chemical reactions in the primeval oceans. Some of these RNA molecules could serve as both templates for creating copies of themselves, and as catalysts that speeded up the copying process. These molecules would have been the first self replicating entities. Given a supply of the chemical building blocks of RNA, the population of these primitive RNA molecules would have been self-sustaining. Thus, inanimate chemicals would have taken the first step towards the evolution of a more complex living organism. Many more steps would be needed, however, before evolution had produced anything nearly as complicated as the fossilized cells in the Apex chert.

The Metabolism First theory predicts that life arose not from a molecule with any particular trait (such as self-replicating RNA), but from a collection of molecules, each of which promoted the creation of others within the set. In this way the whole network of molecules was capable of self replication. Since the set of molecules in a sense "feeds" on the simpler chemicals that it uses to replicate itself, one can think of the set as constituting a primitive metabolic network. Figure 1 below shows a simple example of self-catalyzing set of chemicals.

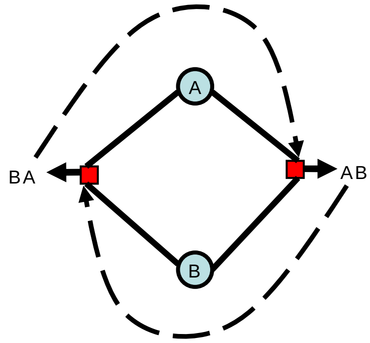


Fig. 1. A simple autocatalytic set. Two molecules, BA and AB, are formed from chemicals B and A. BA and AB speed up the reactions (red squares) that join As and Bs together. Thus BA and AB catalyze their own formation and the whole system is self-sustaining. Given "food", i.e. chemicals A and B, the population of AB and BA molecules "eat" the food and perpetuate themselves.

Proponents of this theory point out that cells are essentially self-catalytic systems of molecules. Alone, any one of the molecules in a cell is dead. Together they form a living system that sustains itself. Once again, it's a long way from networks of interacting chemicals to even the most primitive cells imaginable.

Several laboratories are conducting experiments designed to test these two theories for the origin of life. Self-replicating sets of proteins have been found which provide support for the basic mechanisms behind the Metabolism First theory. Other labs have shown that RNA molecules can not only self-catalyze their own replication, but can also evolve towards larger, more reproductively efficient RNA molecules under conditions of artificial selection. Some RNA World proponents are now predicting that we will be able to create living, artificial cells in a test tube from basic chemical precursors within ten years.

Regardless of whether these theories prove correct or not, it is important to realize that they both imply that life is an ***emergent property*** of the conditions that existed on the early earth. Emergent properties are common in biological and physical systems. In brief they are phenomena (patterns, structures, processes, etc.) that develop from the collective interaction of the separate parts of a system. Thus emergent properties are holistic, systems level phenomena that usually cannot be predicted from the behavior of the individual components.

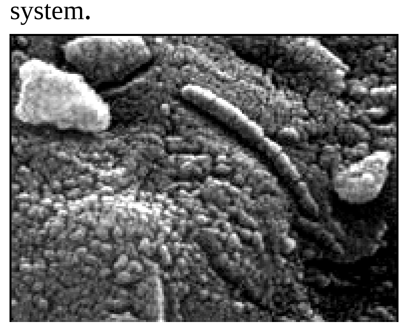
Many examples become apparent once we start applying the concept to the natural world. Snow flakes can be thought of as emergent structures that arise when collections of water molecules self organize to form crystals with branching, symmetrical patterns. The coordinated behavior of a school of fish or a flock of birds is a self-organizing, global property that emerges from the collective activity of the separate individuals in the group. Other examples of emergent properties in biology include the growth patterns of bacterial colonies, the complex structure of termite nests, the synchro-

nized flashing of fire flies, the development of a human being from a fertilized cell, and consciousness. The thing to keep in mind is that each level of biological organization, from molecules to ecosystems, has its own emergent properties.

In the Metabolism First theory, life emerges as a natural property of complex chemical systems that existed on the early earth. When the number of different kinds of molecules in a solution reaches a critical threshold, a self-sustaining network of mutually reinforcing reactions will appear automatically. Similarly, in the Genes First theory, self-replication is an emergent property of molecules like RNA that carry information and can interact with themselves.

The appearance of life, then, is not a mysterious, totally improbable event. On the contrary, life is pretty much "in the cards" whenever we have an appropriate set of conditions; the existence of water, a set of complex molecules, and a broad but constrained range of temperatures being particularly important.

Astronomers estimate that there are over 100 billion (10^{11}) galaxies in the universe, each containing on average about 100 billion (10^{11}) stars. This means there are at least 10^{22} (100 thousand, billion, billion) stars in the universe. This number allows a very conservative estimate of 10-20 billion for the number of planets that have the range of conditions necessary for life to emerge. It follows from current theories for the origin of life that we should find life throughout the universe, perhaps as close as Mars, our next door neighbor in the solar system.



Purported fossil of a bacteria-like, rod-shaped organism that was found inside a meteor that came from Mars.

References

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