The Teachers' File

BIOLOGY: WHAT ONE NEEDS TO KNOW

by Ursula Goodenough

Abstract. Biology on this planet represents an astonishing experiment in carbon-based chemistry which, over billions of years, has generated billions of species adapted to countless major and minor fluctuations in ecological circumstances. In one sense there is no way to generalize about biology. While biological activities can all be ultimately explained by physical laws (like everything else in the universe), it is the emergent intensely particular properties of organisms that most interest us. This essay represents an attempt to describe some of the more prominent patterns that emerge from the sea of biological particularities, patterns that present many opportunities for religous reflection.

Keywords: biology; death; evolution; meaning; natural selection; sex.

WHAT IS LIFE?

Since its Big Bang inception, the universe has been a one-way course, expanding and cooling, running downhill. Living organisms buck this trend, creating greater from lesser order. In the larger scheme of things, of course, organisms do not violate thermodynamics; they have simply learned to extract energy from the nonliving world to drive their own chemical reactions. When the sun finally goes out, roughly 5 billion years from now, life will cease as well. Organisms have also learned to remember how these chemical reactions are carried out and to pass these instructions along from one generation to the next. And finally, they have learned to encode these instructions in a format that can be edited, allowing novelty to appear in the text. Novelty that generates organisms

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better suited to a particular context is likely to prevail in that context, and it is this natural selection that generates biological evolution. The extraordinary diversity of living things is the product of repeated selections of selections of selections wrought by nature.

How Did Organisms Get Started?

Organisms appeared on the planet roughly 3.5 billion years ago, or about a billion years after the earth formed. Nothing is known about how life got started, but there are plenty of theories. The general idea is that things began with a "primeval soup" of small organic molecules such as sugars, amino acids, and ribonucleotides, and that some of these came to assemble into larger molecules. Any large molecule that acquired the capacity to make copies of itself would by definition become more abundant than those that could not, and apparently the first molecules to accomplish this feat were polymers of ribonucleotides called RNA. Once the soup's supply of precursor ribonucleotides became limiting, the RNA molecules that became the most abundant were those that acquired the capacity to direct the synthesis of their own supply of ribonucleotides. This was followed by the capacity to produce other small molecules, a process we now collectively call biosynthesis. A key invention here was the elaboration of a thin membrane around the RNA and its biosynthetic products so they remained together; the resultant entity could be called the first cell. A second key invention was the ability to convert the sun's energy into chemical bonds, a process called photosynthesis (upon which all life now depends). The final invention was to store biological information in DNA rather than the more unstable RNA, with RNA serving as the translator of the encoded information and proteins becoming the key products of the information output. Proteins serve as the major players in biological activities, mediating photosynthesis, membrane function, DNA replication, the perception of external stimuli, and most other activities we associate with being alive.

Proteins Are Patchworks of Ancient Ideas

Proteins are polymers of amino acids, with each kind of protein having a different amino-acid sequence. The amino acids of a given protein are grouped into functional modules called domains. Thus an odorant receptor in the membrane of a human nose cell has a domain that detects the odorant, plus a domain that tells the brain that an odorant molecule has been detected, plus a domain that makes sure that the receptor is correctly located in the nose-cell membrane. Once a particular domain is optimized for a particular function during the course of evolution, it tends to be used repeatedly. Thus most human proteins carry modified, but still recognizable, versions of domains found in the proteins of simple creatures. For example, a domain found in all mammalian odorant receptors is found as well in the receptors utilized by soil amoebae to detect chemicals in their environment. Another domain serves to target proteins to the cell membranes of all known organisms, even the "lowly" bacteria. Such domain sharing means that we are deeply related to the rest of life.

LIFE IS MEDIATED BY THE INTERACTION OF SHAPES

The protein domains important for function are usually displayed on the protein surface, where they fold and loop to create particular shapes. These shapes interact with shapes displayed by other molecules, very much like jigsaw-puzzle pieces in three dimensions; the resultant fit is known as complementarity. The interactions can occur between two proteins, or they can occur between a protein and another kind of molecule, such as a sugar or a lipid. During evolution, domains are altered to generate new kinds of complementary associations, and hence new kinds of functional possibilities.

MAKING LIFE GO: CATALYSIS

Cells carry out many kinds of chemical reactions. Small precursor molecules are synthesized and then hooked together to form long polymers. In addition, once organisms began to feed on one another, cells developed the capacity to take up small molecules synthesized by other creatures and to use them as a source of biosynthetic energy, a process collectively called metabolism. Cells also developed the capacity to take up large molecules synthesized by other creatures and break them down into smaller precursors, a process called catabolism. All of this chemistry will very occasionally occur as the result of random collision, but it happens much more frequently when it is mediated, or catalyzed, by the shapes of proteins called enzymes. Some enzymes induce molecules to form chemical bonds with each other, as when small sugar molecules line up to form a polysaccharide. Other enzymes induce molecules to change their shape, perhaps thereby acquiring the capacity to modify yet other molecules. Much of biological evolution has gone into refining the catalytic efficiency of enzymatic domains, so that most biochemical reactions occur at astonishingly rapid rates.

THE WAY LIFE GOES: CASCADES

Life proceeds as a series of shape changes. When two small molecules are catalyzed to combine and form a larger molecule, the new molecule may now have the correct shape to associate with a membrane, which in turn renders the membrane permeable to a particular ion. The resultant ion influx causes another enzyme to change its shape and hence catalyze yet another reaction—and so on until the final product is produced. Such a sequence is called a cascade. Cascades also describe how life transmits signals. When an odorant interacts with its specific domain in an olfactory receptor, this catalyzes a change in the shape of the receptor, which in turn catalyzes a change in the shape of a molecule with which the receptor interacts. This in turn brings about a shape change in the next molecule—and so on, down the line, one change catalyzing the next until we experience the odor.

WHAT IT'S LIKE INSIDE A CELL

All early organisms, and most extant organisms, are single cells; our multicellular organization is a relatively recent invention, an add-on, which takes the idea of complementary interaction to the level of cell-cell interactions. A cell is defined by its outer boundary, or cell membrane. The membrane separates the inside of the cell from its outside and determines what can enter and exit and what cannot. The inside of the cell is set up to optimize catalysis and the flowing of cascades. Molecules destined to interact with one another are endowed with domains called addresses, which dictate where they should be in the cell, thereby assuring that they co-localize with their functional partners. Each destination is designed for particular reactions. Thus some destinations are greasy and stable, some are aqueous and fluid, some are acidic, some are loaded with calcium, and so on. Each of these environments, or phases, is delimited by its own boundary, often again a membrane. Some phases stand alone, like fortresses, but many undergo elaborate branching and anastomosis, mixing their products and then separating again. Thus the inside of the cell is a direct analog to a community, the cell's inner workings segregated into interacting phases, its boundaries defining its interactions with the rest of the world.

LIFE MUST REMEMBER

What makes biological evolution different from general evolution (change) is that it is endowed with a memory. Without a memory, a complex system might randomly form in a given cell, but there is no reason to expect that this system would be transmitted to other cells or that it would become more efficient, building on what has gone before, optimizing and then swapping domains. Biological memory is stored in DNA, which uses a code to specify the sequence of amino acids and hence the shape of protein molecules. Each sector of DNA that encodes a protein is called a gene, and the collection of all the genes necessary to specify an organism is called its genome; the human genome, for example, contains about 100,000 genes. For a lineage to continue, the entire genome must be copied (DNA replication) and then transmitted to the next generation.

THE MEMORY CAN CHANGE

DNA replication is designed to be accurate, very much as a computer is designed to make an accurate copy of a document or file. But a DNA molecule can also be changed by mutation, analogous to changing a word in a computer document, whereupon the mutated version, rather than the original, is copied. If the mutant version of a gene changes the amino-acid sequence so that the resultant protein is nonfunctional, then the gene is eventually eliminated by natural selection. In contrast, if the mutation happens to change a domain so that it functions more optimally—it might fit better with its partner or more accurately specify a cellular address—the changed version of the gene is likely to be preserved by natural selection. Particularly germinative are mutations that create domains with the capacity to perform novel functions or interact with novel partners. These often set the stage for a new adaptive idea, that is, for a new type of organism, a process called speciation. Those who seek a theistic agency in the evolution of life often suggest that mutations are orchestrated. Most biologists believe that mutations arise by chance. There is no obvious way to distinguish between these possibilities.

LIFE DEPENDS ON PERCEPTION

All organisms possess sensory systems that gather information about the environment. Even the simplest bacteria are capable of perceiving light, thermal motion, and the presence of a variety of ions and molecules in their media, and many creatures owe their distinctiveness to particular modes of perception (e.g., the use of sound by a bat or a bird). Humans perceive in five ways (seeing, hearing, tasting, smelling, touching), and an enormous proportion of our genome and our brain is devoted to these sensory systems; for example, we carry more than 1,000 genes for olfactory receptor proteins alone. The continuous acquisition of information about the environment is, of course, critical to survival.

LIFE DEPENDS ON MEANING

Information is not the same as meaning—a salt crystal has the information to seed the crystallization of more salt, but this is not meaning. Nor is memory the same thing as meaning—our DNA transmits lots of sequences that have no meaning. In a meaning system, one thing functions as a symbol, a token, *for* something else. It is not the something else, nor does it transform into the something else. A particular sequence of codons in a DNA molecule *means* that a particular protein with particular domains will be synthesized. A shape change in an olfactory receptor and the subsequent cascade of shape changes in the nervous system *means* that a particular odorant is present in the airways. Our experience with language offers a valid analog to the way biological meaning is constructed and transmitted: it is dependent on syntax, on content, on sequence of presentation, and so on. Nervous systems are conspicuous organs for detecting meaning, but they utilize the same underlying principles as does a bacterium swimming about in search of meaningful food products.

LIFE DEPENDS ON VALUATION

Closely coupled to meaning, but distinct in implication, is the concept of valuation. Organisms not only ascertain the meaning of information and of external stimuli; they also evaluate and then prioritize so that one meaning typically wins out over another. The systems governing these choices generate much of the complexity we associate with life, allowing a cascade to operate under some circumstances and not others, or a gene to be expressed at only certain stages of development. Organisms also pay major attention to evaluating their environment, affiliating with positive conditions and avoiding negative ones. Our human preoccupation with evaluation and hierarchy is deeply rooted.

HOW DOES AN ORGANISM HAVE VALUE?

A creature survives to produce offspring if it remembers, if it encodes meaning systems, and if it is capable of perceiving and valuating its circumstances. But a creature is also, of course, evaluated by its environment, not in the literal sense but in the sense we call natural selection—a creature survives or perishes as a consequence of environmental evaluation. The organisms that exist now, and that existed in the past, are totally contingent on the particular course of this planet's evolution. When there was no oxygen, life had to function anaerobically; once oxygen was generated, the anaerobes were forced underground and a whole new spectrum of creatures became dominant. The planet proves to be particularly diverse, with countless kinds of niches creating opportunities for countless kinds of adaptations. Moreover, many niches have been created or profoundly modified by the organisms that occupy them. Hence speciation and environmental change are inexorably yoked together. An ecosystem is invariably a hierarchy from the perspective of its food chain, but it is in fragile equilibrium from the perspective of its integrity.

THE COURSE OF BIOLOGICAL EVOLUTION

The first cells in the primeval soup were doubtless very inefficient at carrying out their biology, but with time a core set of functional genes, encoding a core set of functional protein domains, came to comprise the genome of what we would now call the Progenitor Cell (fig. 1). This progenitor gave rise to three types of organisms—the archaebacteria, the eubacteria, and the eukaryotes—which share common genetic ideas but have otherwise evolved independently. The archaebacteria, while very important in evolution, now inhabit thermal springs and other bizarre habitats and are not major players. The eubacteria comprise all the bacteria and cyanobacteria and are by far the most abundant organisms on the earth. Eubacteria can be said to be chemical machines—their

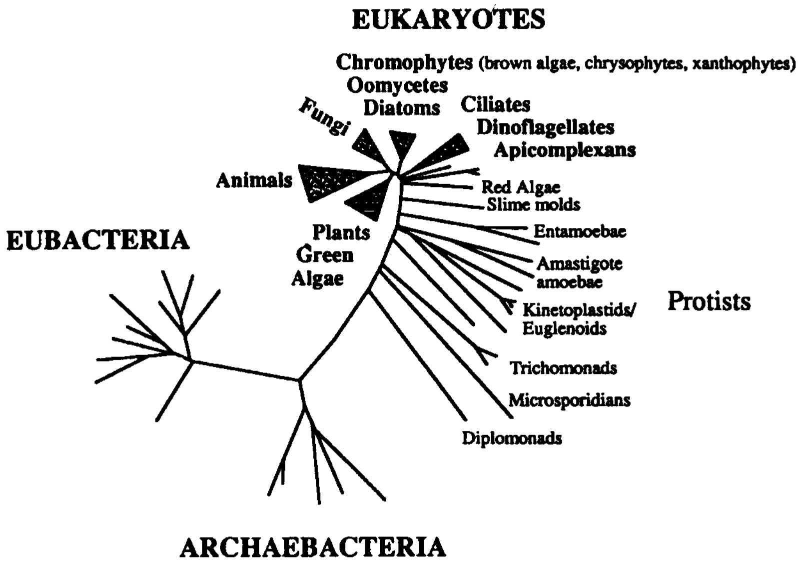

Fig. 1. The evolution of life. The original Progenitor Cell gave rise to three major lineages: the archeabacteria, the eubacteria, and the eukaryotes. The eukaryotic line continues for about 2 billion years, giving rise to the ancestors of modern unicellular organisms called protists, and then experiences a "sunburst" of radiation at the time of the Cambrian period, generating most of the modern phyla. The Cambrian "explosion" transpired very rapidly—perhaps within 10 million years. (From M. L. Sogin, *Current Opinion in Genetics and Development* 1 : 457 [1991])

strategy is to engage in the fastest possible metabolism, biosynthesis, and DNA replication so that they divide as rapidly as possible and generate as many of themselves as they can. The eukaryotes, in contrast, can be said to be morphogenetic machines—their adaptive strategies are more dependent on form than on numbers. Their subcellular organization includes a number of features not found in eubacteria—a true nucleus containing a large genome arrayed in multiple chromosomes; an elaborate internal membrane system for the production and storage of proteins; and a cytoskeleton that allows them to adopt all sorts of shapes and to engulf prokaryotic prey. Some of these engulfed bacteria became resident organelles rather than food, giving rise to the modern mitochondria and chloroplasts that provide eukaryotes with the ATP molecules they need for biosynthesis and metabolism.

MULTICELLULARITY

Eukaryotes apparently remained unicellular for about 2 billion years, burrowing through the soil as amoebae and swimming about in ponds and oceans as algae. About 600 million years ago, however, in an evolutionary discontinuity called the Cambrian explosion (fig. 1), a burst of innovation gave rise to the major phyla that exist today, most of them multicellular. The three major multicellular lineages—the plants, the animals, and the fungi—constitute the organisms with which we are most familiar, and the morphogenetic potential of the eukaryotes was given full reign as they diversified. A key invention was embryogenesis—the differential expression of genes in space and time. Starting with a fertilized egg cell, particular groups of daughter cells come to express unique subsets of genes; as a result, they form specialized tissues and organs during the larval and adult stages. To coordinate the diverse activities of these many tissues, all multicellular organisms came to employ hormones; animals also came to develop nervous systems. By the time humans began to evolve from their primate ancestors, an astonishing diversity of unicellular and multicellular creatures had come to inhabit a stabilized but still evolving planet.

DEATH AND SEX

If death is defined as the loss of organization, then we can say that stars die and that bacteria die when we boil them. But bacteria do not die in the way we usually think of death. Instead, a bacterium usually doubles in size and then divides in two, and each daughter doubles in size and divides in two, and so on ad infinitum. Death as we usually think of it—the inexorable ending of a life—is a very recent phenomenon, an adaptation made possible by the evolution of eukaryotic sex. It is not known why or how sex originated, but it allowed multicellular organisms to emerge with two different kinds of cells: germ-line cells (eggs and sperm) endowed with the potential for ad infinitum immortality and somatic (body) cells destined for mortality. This dichotomy effectively parceled out the job of being alive: long-term memory, including the memory of mutant genes, is entrusted to the germ line, while meaning, valuation, and selectability have become the province of the soma. With the soma no longer constrained to remember and replicate accurately, it became free to form the tissues and organs specialized to negotiate the countless niches available. Therefore, in a very real sense, the invention of sex allowed not only the invention of somatic death *but also* the invention of our splendid bodies and our sentient brains capable, ironically, of experiencing deep remorse and fear at the prospect of death, but capable as well of understanding the wonders of existence.

SPECIALIZATION

All of the species on the planet are specialized for particular role(s) in their particular ecosystems. At a global level, the cyanobacteria, the algae, and the land plants generate the fixed carbon in the food chain and the oxygen in the atmosphere, and certain kinds of bacteria are responsible for most of the fixed nitrogen in the soil. At a more local level, various species coexist with one another and with their environment, each organism taking advantage of its specific skills and adaptions. The most conspicuous human specialization is an impressive brain—10^{12} nerve cells making 10^{15} connections with one another—specialized for self-reflection. Our brains have allowed us to develop the meaning systems we call laws, religions, and poetry, systems that are transmitted through language rather than through genes. They have also allowed us to understand, through empirical science, the nature of our universe.

ARE WE ALONE IN THE UNIVERSE? DOES IT MATTER?

It seems highly likely, given the abundance of stars and presumably, therefore, the abundance of planets in the universe, that carbon-based life has arisen elsewhere. Given the contingent nature of evolution and its dependence on planetary context, it seems much less likely that life forms as we know them have emerged elsewhere, but we are dealing here with probabilities and with a very large number of possible experiments. Were we to encounter a spaceship of bona fide sentient aliens, the consequences for our self-concept would be profound. But it can be argued that the scientific discoveries of the past one hundred years have had consequences for our self-concept that are in fact far more profound. From this perspective, our existence is an astonishingly contingent and fragile occurrence within a vast, beautiful, and apparently disinterested universe. It is a perspective that has engendered deep fear and hence denial. But there is another response, which is to say, Yes, we are in effect completely alone—and it doesn't matter. This is our reality, this is our gig; we are nothing more than highly organized atoms and yet—and yet—the organization of our particular human brains has generated the capacity to care and to laugh and to want all of this to continue.