PENTAGON OF LIFE

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Ever Since Darwin

REFLECTIONS IN NATURAL HISTORY

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WHEN I WAS 10 years old, James Arness terrified me as a giant, predaceous carrot in *The Thing* (1951). A few months ago, older, wiser, and somewhat bored, I watched its latest television rerun with a dominating sentiment of anger. I recognized the film as a political document, expressing the worst sentiments of America in the cold war: its hero, a tough military man who wants only to destroy the enemy utterly; its villain, a naively liberal scientist who wants to learn more about it; the carrot and its flying saucer, a certain surrogate for the red menace; the film's famous last words—a newsman's impassioned plea to "watch the skies"—an invitation to extended fear and jingoism.

Amidst all this, a scientific thought crept in by analogy and this essay was born—the fuzziness of all supposedly absolute taxonomic distinctions. The world, we are told, is inhabited by animals with conceptual language (us) and those without (everyone else). But chimps are now talking (see essay 5). All creatures are either plants or animals, but Mr. Arness looked rather human (if horrifying) in his role as a mobile, giant vegetable.

Either plants or animals. Our basic conception of life's diversity is based upon this division. Yet it represents little more than a prejudice spawned by our status as large, terrestrial animals. True, the macroscopic organisms surrounding us on land can be unambiguously allocated if we designate fungi as plants because they are rooted (even though they do

not photosynthesize). Yet, if we floated as tiny creatures in the oceanic plankton, we would not have made such a distinction. At the one-celled level, ambiguity abounds: mobile "animals" with functioning chloroplasts; simple cells like bacteria with no clear relation to either group.

Taxonomists have codified our prejudice by recognizing just two kingdoms for all life—Plantae and Animalia. Readers may regard an inadequate classification as a trifling matter; after all, if we characterize organisms accurately, who cares if our basic categories do not express the richness and complexity of life very well? But a classification is not a neutral hat rack; it expresses a theory of relationships that controls our concepts. The Procrustean system of plants and animals has distorted our view of life and prevented us from understanding some major features of its history.

Several years ago, Cornell ecologist R. H. Whittaker proposed a five-kingdom system for the organization of life (*Science,* January 10, 1969); his scheme has recently been championed and expanded by Boston University biologist Lynn Margulis (*Evolutionary Biology,* 1974). Their criticism of the traditional dichotomy begins among the single-celled creatures.

Anthropocentrism has a remarkably broad range of consequences, ranging from strip mining to whale killing. In folk taxonomy it merely leads us to make fine distinctions among creatures close to us and very broad ones for more distant, "simple" organisms. Every novel bump on a tooth defines a new kind of mammal, but we tend to lump all single-celled creatures together as "primitive" organisms. Nonetheless, specialists are now arguing that the most fundamental distinction among living things is not between "higher" plants and animals; it is a division *within* single-celled creatures—bacteria and blue-green algae on the one side, other groups of algae and protozoans (amoebae, paramecia, and so on) on the other. And neither group, according to Whittaker and Margulis, can be fairly called either plant or animal; we must have two new kingdoms for single-celled organisms.

Bacteria and blue-green algae lack the internal structures, or "organelles," of higher cells. They have no nucleus, chromosomes, chloroplasts, or mitochondria (the "energy

factories" of higher cells). Such simple cells are called "prokaryotic" (roughly, before nuclei, from the Greek *karyon,* meaning "kernel"). Cells with organelles are termed "eukaryotic" (truly nucleate). Whittaker considers this distinction "the clearest, most effectively discontinuous separation of levels of organization in the living world." Three different arguments emphasize the division:

1. The history of prokaryotes. Our earliest evidence of life dates from rocks about three billion years old. From then until at least one billion years ago, all fossil evidence points to the existence of prokaryotic organisms only; for two billion years, blue-green algal mats were the most complicated forms of life on earth. Thereafter, opinion differs. UCLA paleobotanist J. W. Schopf believes that he has evidence for eukaryotic algae in Australian rocks about a billion years old. Others contend that Schopf's organelles are really the postmortem degradation products of prokaryotic cells. If these critics are right, then we have no evidence for eukaryotes until the very latest Precambrian, just before the great Cambrian "explosion" of 600 million years ago (see essays 14 and 15). In any case, prokaryotic organisms held the earth as their exclusive domain during two-thirds to five-sixths of the history of life. With ample justice, Schopf labels the Precambrian as the "age of blue-green algae."

2. A theory for the origin of the eukaryotic cell. Margulis has stirred a great deal of interest in recent years with her modern defense of an old theory. The idea sounds patently absurd at first, but it quickly comes to compel attention, if not assent. I am certainly rooting for it. Margulis argues that the eukaryotic cell arose as a colony of prokaryotes—that, for example, our nucleus and mitochondria had their origins as independent prokaryotic organisms. Some modern prokaryotes can invade and live as symbionts within eukaryotic cells. Most prokaryotic cells are about the same size as eukaryotic organelles; the chloroplasts of photosynthetic eukaryotes are strikingly similar to the entire cells of some blue-green algae. Finally, some organelles have their own self-replicating genes, remnants of their formerly independent status as entire organisms.

3 . The evolutionary significance of the eukaryotic cell.

Advocates of contraception have biology firmly on their side in arguing that sex and reproduction serve different purposes. Reproduction propagates a species, and no method is more efficient than the asexual budding and fission employed by prokaryotes. The biological function of sex, on the other hand, is to promote variability by mixing the genes of two (or more) individuals. (Sex is usually combined with reproduction because it is expedient to do the mixing in an offspring.)

Major evolutionary change cannot occur unless organisms maintain a large store of genetic variability. The creative process of natural selection works by preserving favorable genetic variants from an extensive pool. Sex can provide variation on this scale, but efficient sexual reproduction requires the packaging of genetic material into discrete units (chromosomes). Thus, in eukaryotes, sex cells have half the chromosomes of normal body cells. When two sex cells join to produce an offspring, the original amount of genetic material is restored. Prokaryotic sex, on the other hand, is infrequent and inefficient. (It is unidirectional, involving the transfer of a few genes from a donor cell to a recipient.)

Asexual reproduction makes identical copies of parental cells, unless a new mutation intervenes to yield a minor change. But new mutation is infrequent and asexual species do not maintain enough variability for significant evolutionary change. For two billion years, algal mats remained algal mats. But the eukaryotic cell made sex a reality; and, less than a billion years later, here we are—people, cockroaches, seahorses, petunias, and quahogs.

We should, in short, use the highest taxonomic distinction available to recognize the difference between prokaryotic and eukaryotic single-celled organisms. This establishes two kingdoms among one-celled creatures: Monera for the prokaryotes (bacteria and blue-green algae); Protista for the eukaryotes.

Among multicellular organisms, Plantae and Animalia remain in their traditional senses. Whence, then, the fifth kingdom? Consider the fungi. Our Procrustean dichotomy forced them into Plantae, presumably because they are rooted to a single spot. But their resemblance to true plants stops with

this misleading feature. Higher fungi maintain a system of tubes superficially like those of plants; but while nutrients flow in plants, protoplasm itself courses through the fungal tubes. Many fungi reproduce by combining the nuclei of several individuals into a multinucleate tissue without nuclear fusion. The list could be extended, but all its items pale before one cardinal fact: fungi do not photosynthesize. They live embedded in their food source and feed by absorption (often by excreting enzymes for external digestion). Fungi, then, form the fifth and final kingdom.

As Whittaker argues, the three kingdoms of multicellular life represent an ecological, as well as a morphological, classification. The three major ways of making a living in our world are well represented by plants (production), fungi (reduction), and animals (consumption). And, as another nail in the coffin of our self-importance, I hasten to point out that the major cycle of life runs between production and reduction. The world could get along very well without its consumers.

I like the five-kingdom system because it tells a sensible story about organic diversity. It arranges life in three levels of increasing complexity: the prokaryotic unicells (Monera), the eukaryotic unicells (Protista), and the eukaryotic multicells (Plantae, Fungi, and Animalia). Moreover, as we ascend through the levels, life becomes more diverse—as we should expect since increasing complexity of design begets more opportunity for variation upon it. The world contains more distinctively different kinds of protistans than monerans. At the third level, diversity is so great that we need three separate kingdoms to encompass it. Finally, I note that the evolutionary transition from any level to the next occurs more than once; the advantages of increased complexity are so great that many independent lines converge upon the few possible solutions. The members of each kingdom are united by common structure, not by common descent. In Whittaker's view, plants evolved at least four separate times from protistan ancestors, fungi at least five times, and animals at least three times (the peculiar mesozoans, sponges, and everything else).

The three-leveled, five-kingdom system may appear, at first glance, to record an inevitable progress in the history of life. Increasing diversity and multiple transitions seem to reflect a determined and inexorable progression toward higher things. But the paleontological record supports no such interpretation. There has been no steady progress in the higher development of organic design. We have had, instead, vast stretches of little or no change and one evolutionary burst that created the entire system. For the first two-thirds to five-sixths of life's history, monerans alone inhabited the earth, and we detect no steady progress from "lower" to "higher" prokaryotes. Likewise, there has been no addition of basic designs since the Cambrian explosion filled our biosphere (although we can argue for limited improvement *within* a few designs—vertebrates and vascular plants, for example).

Rather, the entire system of life arose during about 10 percent of its history surrounding the Cambrian explosion some 600 million years ago. I would identify two main events: the evolution of the eukaryotic cell (making further complexity possible by providing genetic variability through efficient sexual reproduction) and the filling of the ecological barrel by an explosive radiation of multicellular eukaryotes.

The world of life was quiet before and it has been relatively quiet ever since. The recent evolution of consciousness must be viewed as the most cataclysmic happening since the Cambrian if only for its geologic and ecological effects. Major events in evolution do not require the origin of new designs. The flexible eukaryotes will continue to produce novelty and diversity so long as one of its latest products controls itself well enough to assure the world a future.