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AUTOPOIESIS AND THE ORIGIN OF BACTERIA

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"Autopoiesis" is the explanatory principle for the organization of living systems, a concept directly applicable to the problematic issues surrounding the origins of life. Because it provides criteria by which a system may be judged as living, autopoiesis can be used to characterize a minimal living system. Once these defining characteristics have been established, we can extrapolate the conditions which would have made possible the emergence of earliest life. Because autopoiesis is a principle of organization, it provides a definition of living systems not restricted to specific molecules or structures -- that is, to those nucleic-acid/protein/lipid cellular life forms with which we are familiar. Autopoiesis provides the conceptual and systematic framework within which any living system may be identified. In examining living systems, then, autopoiesis gives us a literally "meta-physical" view of life.

The term "autopoiesis", from the Greek auto- ("self"-) and poiesis ("production"), was coined by the Chilean biologists Humberto Maturana and Francisco Varela to distinguish living from non-living systems. Such systems are designated according to their different origins: a non-living (engineered) system, assembled by something other than itself, is an "allo-poietic system"; by contrast, a living system, an "autopoietic system", arises from the spontaneous assembly of its constituent parts /1/.

In developing the concept of autopoiesis, Maturana and Varela recognized that a living system may be characterized as an autonomous organization of dynamic processes occurring within a closed operational whole. The concept of "closure" applied here refers not to the chemical components of living systems, but to the organization by which these components interact within the autopoietic system. While living systems are not closed in their interaction with matter and energy, they are operationally closed: the operation of each system is determined by its internal organization. Thus, the operation of a cell includes all the historically-determined physicochemical interactions of its components within a single causal process. By means of metabolism, growth, and replication, a cell establishes its self-perpetuation within an intact boundary /2/.

An organizational or autopoietic definition of living systems as bounded permits any particular living system to be specified. Each has 1) identity (i.e., it is distinct from what surrounds it), 2) circularity (i.e., the organization of its internal activity), and 3) integrity (i.e., its dynamic stability, the product of its internal activity). That an autopoietic system has identity means that the system must be enclosed: its constituent parts are contained within a boundary, giving it coherence in space. The constituent parts of a cellular system include the molecules comprising its structures and its enclosing boundary, the lipoprotein plasma membrane. The circularity of interactions within an autopoietic system refers to the relationships among its constituent parts which provide the organization of the system. Autopoietic circularity means that the constituent parts and the enclosing boundary arise as a consequence of the internal activities, thus within a boundary of the system's own making. In a living cell, the constituent parts interact by means of enzyme-mediated substrate reactions, i.e., by metabolism, providing continuity in space. Finally, integrity refers to the recursive organization of the autopoietic system: there is continual replacement and refinement of components drawn from its surroundings. Internal activity both utilizes and replaces the products of this activity at a rate sufficient to maintain the operations, assuring the system's integrity. The system's autonomy results from the dynamic stability of its operations in the face of external change. Within the cell, the import of nutrient matter, the transport and conversion of that matter using energy, and the export of waste products across the cell boundary (all at rates greater than those tending to disperse the component cell materials) ensure the continuity of the system through time /3/.

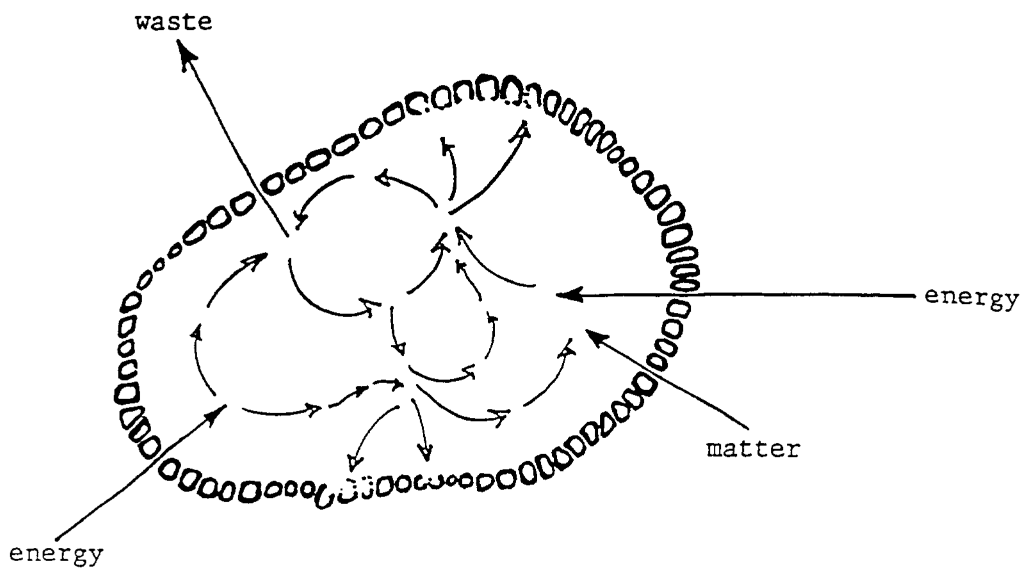

Fig. 1. Identity, circularity, and integrity: properties of a minimal autopoietic system.

Any system which exhibits all three characteristics, identity, circularity, and integrity, is defined as autopoietic. Whereas identity is a result of the structure of the autopoietic system, both circularity and integrity are characteristic of its internal organization. By definition, then, an autopoietic system is a self-producing and self-perpetuating dynamic system, in continuous interaction with its surroundings. The responses of any autopoietic system in that interaction are determined by its own internal organization. These two attributes of organization, circularity and integrity, are true of all living things.

The characterization of living systems as autopoietic provides a definition of life both broad enough to satisfy our conviction that living things are somehow different from non-living things, and specific enough to be useful in origins-of-life research, both theoretical and experimental. Defined as an autopoietic system, an autonomous living system is organizationally closed and dynamically stable. On the other hand, because it is open to matter and energy, a living system is in constant interchange with its environment. It responds to its immediate surroundings within certain ranges of temperature, moisture, nutrient supply, salt concentration, and other limiting variables. Indeed, our intuitive understanding of how we can identify matter as "alive" is captured by the term autopoiesis: living entities are both responsive and dynamically stable.

To accept autopoiesis is to recognize that the "origin of life" problem is considerably more than the origin of the cell components alone. The crucial issue is organization: the most intractable questions in origins of life are those of the origins of living systems. The earliest living system was not merely a collection of the specific molecules present in modern cells: it was a system in which metabolism engendered closure and organization.

Experiments aimed at the laboratory synthesis of life require criteria by which autopoietic systems can be recognized. By insisting on the complementarity of structure and organization in living systems, autopoiesis renders non-sensical the questions, "Which came first: clay, RNA, DNA, or protein?", so devisive within both theoretical and experimental research approaches. The acknowledgment that all living systems are comprised of a highly diverse set of components, and that no living system is separate from the processes which generate and maintain it, prompts us to seek the simultaneous genesis of structure and organization.

Simplest among modern biological systems are bacteria: they are autonomous, self-bounded, and self-producing, i.e., autopoietic systems. Yet bacterial systems are "simple" only in comparison to other modern biological systems. Relative to the non-autopoietic entities from which they evolved, they exhibit elaborate structure and complex dynamic, internal organization. The rich diversity among modern bacteria probably represents the material remains of a history of increasingly complex self-organization, a history which extends to the aboriginal universal minimal cell. The recognition of contemporary bacteria as the smallest known autopoietic system should provide impetus to a search for the simplest types and least number of metabolic pathways capable of sustaining a bacterial system. Complementary to the search for the minimal bacterial system is the laboratory pursuit of the origins of life. The first living system to be produced in the laboratory will most likely be a minimal living system -- the simplest material system to satisfy the autopoietic criteria. Energized metabolism based on carbon chemistry in an aqueous solution will probably be required as the mechanism of self-maintenance in laboratory "origin-of-life experiments". Congruent definitions, for the earliest living system and for the minimal conditions required for formation of living systems in the laboratory, may well emerge from research based on the autopoietic principle.

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