ORIGINS OF LIFE: AN OPERATIONAL DEFINITION

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Abstract. Two very different models are used for the scientific study of life's origins: in the Troland-Muller model, life is molecular and its defining characteristic is gene function; in the Oparin-Haldane model, life is cellular and its defining characteristic is metabolic function. While each of these models implicitly defines the living, neither provides criteria by which the emergence of life could be recognized in the laboratory.

An operational definition of the living makes explicit the system logic of metabolic self-production: (1) that whatever form it may take, life is a function of its biochemical processes; (2) that no single biochemical process has integrity apart from an entire network of processes; (3) that a network of processes can have continuity only by being enclosed within a boundary structure, i.e., by the selective partition of a microenvironment as a domain for the bioenergetic-biosynthetic network; and (4) that life is a single phenomenon, distinct in its continuity of capture and storage of energy in such networks, driving the processes that produce its material constituents.

This paper presents autopoiesis as life-defining and discusses the utility of its criteria in our search for the origins of life on Earth. Enactment of the autopoietic criteria would result in a minimal cell and would demonstrate the experimental recapitulation of life's Archaean origins.

Introduction

At our meeting three years ago in Berkeley, Harmke Kamminga outlined two lineages of twentieth-century scientific theory on the origins of life (Kamminga, 1988). Those lineages, the 'molecular' and the 'metabolic', provide two very different approaches to the problems of life's origins because they offer two fundamentally different answers to Schrödinger's question, 'What is Life...?' (Schrödinger, 1945). In the first approach, derived from Troland's work on enzymes and Muller's work on genes, life is molecular and its defining characteristic is gene function (Troland, 1917; Muller, 1929). In the second approach, derived from the work of Haldane and the early work of Oparin, life is cellular and its defining characteristic is metabolic function (Oparin, 1924; 1938; Haldane, 1929).

Yet even as these approaches describe the living and suggest pre-biological conditions that could give rise to biological form, they leave unanswered two questions that are fundamental to the study of life's origins: How are we to locate the shift from pre-biology to biology? and, How are we to recognize life elsewhere in the universe? Neither approach gives us a standard against which we can identify the emergence of life from non-life – historically during the Archaean or experimentally in our laboratories. And neither approach provides a model for extraterrestrial life if its form were to differ significantly from what we know on Earth.

A recent branch of the Oparin-Haldane line is being formed from work that
deals directly with these two questions. This branch combines concepts from several different fields: from systems theory comes the concept of autopoiesis, providing an operational definition of the living that is derived from a system-logical analysis of metabolic organization; from biology and biophysics comes the construct of a minimal cell, the simplest possible form combining the bioenergetic and biosynthetic processes. Taken together, these concepts provide a theoretical frame for origins-of-life research: emergence of the living is identifiable in its novelty of operation, and the living is itself identifiable not by its parts but by operations made possible by the properties of its parts. These same concepts also provide an experimental directive for research, making a demonstration of those novel operations an agenda for the origins-of-life laboratory.

**Autopoiesis...**

The term ‘autopoiesis’ was coined from the Greek auto-['self-'] and poiesis ['making', 'producing', or 'generating'] by two Chilean biologists, Humberto Maturana and Francisco Varela, to distinguish the living by its unitary operation as a self-producing molecular system (Maturana & Varela, 1972; 1980), where ‘unitary operation’ refers to operation of the system as a single entity, that is, with system function distributed throughout the whole, not localized to any point within the system. Now, to define the living by its self-production seems only to claim the obvious, that life is metabolic – that the metabolic self (the physical living system) is made up of molecular parts (the result of metabolic production). But the concept goes beyond metabolic processes to examine the logic of autopoietic organization that enables metabolic operation at the outset, claiming that in establishing continuity of life’s unitary operation, autopoietic organization itself is sufficient to define the living.

It is not new, of course, to point out that life requires energy to drives its processes of production. Nor can it be claimed that life is alone in requiring energy for the integrity of its internal organization: fluid or gaseous convective systems utilize heat-driven density gradients to that same end. These complex dynamical systems are non-living, but they, too, transform energy from the environment in maintaining themselves at a distance from equilibrium, and they hold energy in non-linear relationships among system components, that is, in circular (self-amplifying) relationships in which effects become cause (Swenson, 1989). What is unique to living systems is the organized coupling of energetic and material interactions in a single network of processes whose outcome is the production of all system components, including the constituents of its membraneous boundary structure. In living systems such a network of operations must include energy capture, energy storage in high-energy chemical bonds, and electrochemical transformation of matter transported across the system membrane. Autopoietic organization – the integrity of a network of these dynamic molecular relationships – is made evident by continuous molecular transformation in the production and replacement of system components, marking the living as categorically distinct in the universe.