ASTROBIOLOGY: A SYSTEMS LEVEL SCIENCE.

B. C. Clark[1] and V. M. Kolb[2], [1]Space Science Institute, Boulder, CO 80301, USA, bclark@spacescience.org , [2]University of Wisconsin-Parkside, Kenosha, WI 53141, USA, kolb@uwp.edu

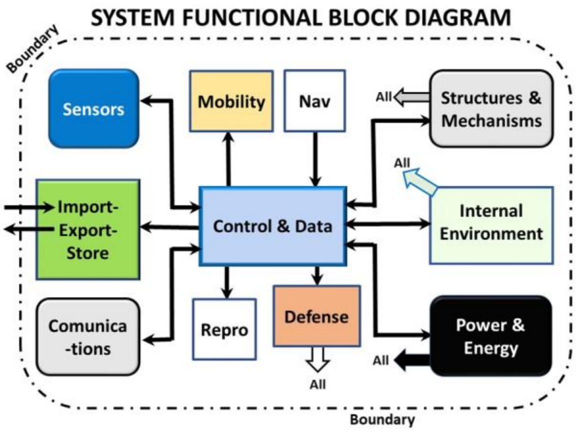
Introduction: The field of astrobiology covers the origin and evolution of life, wherever it occurs in the universe. Based on terrestrial experience, biological entities proliferate only in so-called “habitable” environments. Research into prebiotic chemical pathways which could lead to an origin of terrestrial-like life appear to proceed only under more constrained, “urable” environments [1, 2]. What are the requirements for an entity which characterizes the differences between animate, functional life forms and non-living matter? The distinction is not trivial – our ancient civilizations hypothesized that what we now consider “natural” phenomena are the result of dictates by so-called gods and goddesses of the heavens, earth, sea, air, weather, rivers, and light. Modern science has shown these are, rather, various manifestations of natural matter under the influence of the laws of physics and the rules of chemistry. Biological processes themselves, from metabolic chemical pathways to athletic physical or intellectual performances, can also be shown to follow these same laws of physics and rules of chemistry.

Biology vs Inanimate. The challenge, then, is to achieve a general formulation of what is the fundamental difference between, for example, a microorganism and a same-sized crystal. After all, crystals grow and reproduce, and often eventually “die” by disintegration or replacement. Crystals in nature are ubiquitous, whether as minerals in geological specimens or ice grains in cirrus clouds, fogs, or snowflakes. In short, biological entities arise from reproduction by a precursor parent(s), with passing along the documentation of a modifiable design template from which the progenies were formed. This template is nominally DNA, or in some cases RNA (viruses, RNA World, primordial cells?).

Biology as a System: To build a new organism from the design template is non-trivial. With crystals, the template is constrained by the physics of condensed matter. With biology, various DNA-encoded instruction sets produce everything from microbes to mice, magpies, manta rays, magnolias, or maple trees. Unlike crystals, each biological organism is a complex system composed of separately identifiable functional components or subsytems [3].

Global Characteristics of Systems: A System is characterized as having one or more high level functions which are enabled by an assemblage of components working in concert. Systems are generally found to share many attributes, such as having a boundary yet interacting with its environment and performing functions that cannot be performed without concerted action of its constituent components.

In formal systems analysis, some or all components are often found to also be complex, i.e., subsystems comprised of additional components. In comparing different systems with one another, the same functional subsystems are often found, although implementations may be different. In the context of this conference, we choose as engineering analogy for comparison to a primitive organism, the planetary rover (see also [3]).



At the core of a typical System is a control center, which orchestrates the activities of the components that make up the system in order to meet system goals. In the case of a microbe, the goal is to survive and generate another microbe (reproduce). For a rover, it is to survive and explore its environment (e.g., Mars).

At the heart of the **System**, the **Control** process must operate from a set of instructions and operands (which may include both preset and acquired **Data**). For the microbe, this is control of metabolic processes as well as the eventual construction of the progeny organism (“**Reproduction**”). For the rover, it is a computer with data that includes both the uploaded command file for operations as well as data that is acquired from cameras and other **Sensors**.

Any system must have a source of **Energy** to operate. This energy must be acquired and supplied to power all subsystems needing it to function. For rovers, it is solar electric or RTG energy; for microbes, it is solar energy or chemical energy obtained by facilitating redox reactions in the environment.

Reproduction requires **Import** of nutrients for microbes. Rovers import samples for analysis; sunlight for thermal control and electrical power.

Export functions are also typically required. For microbes, it is especially the chemical waste products that otherwise would be toxic to highly orchestrated metabolic functions. For rovers, it is export of excess thermal energy from the RTG that otherwise would overheat critical components. **Storage** functions may also be required, especially for acquired data that goes into memory. Rovers may also store samples. Microbes store acquired nutrients for producing **Structure**s for the upcoming generation of progeny.

Rovers and biological organisms need to control their **Internal Environment** within tolerance limits, maintaining homeostasis to protect critical components. For rovers, it is typically thermal energy to prevent over-heating or under-cooling. For microbes, it is maintaining chemical balance, especial of H_2O levels and concentrations of critical ions (active ion pumps) which can affect enzyme catalytic activity.

Both rovers and microbes can have sensors which allow them to characterize their environment, and then affect **Mobility** (wheels for rovers; pili for microbes) and even **Navigation** to reach a new environment. Rovers need to **Communicate** with its operators on Earth (to receive commands and transmit acquired data), and microbes can have quorum sensing capabilities to enhance survival of the colony.

The **Defense** function includes the rudimentary immune system in bacteria that fights off parasites. There are no predators on Mars, so rovers are safe.

Reverse Engineering the Cell: Major efforts are underway to derive a minimalist cell by removing genes from a species which already has a small genome. Still, several hundred genes seem necessary [4], not counting syntheses of amino acids and other essential biomolecules. This top-down approach may not obtain the correct answer for the original minimalist cell, however. After all, it would be fruitless to reverse engineer a luxury ocean cruise liner to attempt to reveal the first birchbark canoe or Egyptian sail-powered rafts. Engineered systems are designed and built from the *bottom-up*, but according to performance requirements that are derived from the *top-down*. Adopting this approach, we consider what might comprise the subsystems within a colonizer cell.

Colonizer Cell: Once the first cells form, they will be accustomed to conditions within the macrobiont's urable environment and hence will not be optimized for life in less specialized environments. The colonizer cell is a version derived from the macrobiont specialist cell which has a capability to survive and procreate in more common, widespread aqueous environments that are habitable, but not necessarily urable. Lakes, ponds, perhaps even seawater, would be likely habitats.

The minimalist functions such a cell would need to embody from the system block diagram would of course include energy, control, and import-export. However, it would not necessarily need mobility or nav because it would be transported by winds and stream flows, much as seeds of plants are dispersed. It could survive without communications, or defenses since competitors and predators would not yet exist.

Growth (import) and reproduction would be essential, however, to reproduce. Metabolism would presumably be limited to chemolithoautotrophy, or methanotrophy if atmospheric CH_4 were available.

What if reproduction, for example, were not yet so sophisticated that it was orchestrated by the systematics of equal-binary fission? Could it be instead that unhampered growth alone would be adequate, with reproduction consisting of fracturing into two or more non-identical subsidiary entities?

Could it be that enzymatic functions were not yet so sophisticated, but harnessing of catalytic ions and clusters (e.g., Fe-S) had become sufficiently effective to direct the flow of fundamental metabolic processes and energy capture (ATP/early equivalent; anabolism)? Could it be that primitive proteins needed only 4 or 8 different amino acids (a.a.'s) [5] to achieve useful configurations? And could some of these a.a.'s be environmentally available or more simply synthesized?

The advantage of an unfettered population explosion of sub-par cellular entities is that it provides more opportunities for evolution, especially if bacterial transformation (i.e., exchange of naked DNA segments) were in effect. For example, even a low population density of only 10^3 cells/ml in a nutrient limited stationary-like phase but spread throughout a thousand liters of aqueous media, would be a total population of 10^9 cells. And with a mean cell turnover time of one week, the number of evolutionary experiments (i.e., progeny) would be over 10^{13} per millennium. Furthermore, this would be enormously greater once exponential growth became predominant.

Conclusion: A systems approach provides a framework and insights for generating hypotheses of the constructs and functions of the earliest colonizer cells, which may depart significantly from LUCA and so-called "minimalist" modern cells, while being more consistent with the rise of life via prebiotic processes.

References: [1] Clark, B. & Kolb, V. (2021) *Life. 11*(6): 539. [2] Deamer, D. et al. (2022), *Astrobiol. 22* (7). [3] Kolb, V. M. & Clark, B. C., (2023) *Astrobiology: A Systems-Level Science*, CRC Press,. [4] Breuer, et al. (2019) *eLife* 8:e36842 [5] Van Der Gulik, et al. (2009 *J. Theoret. Biol.* 261.4 (2009): 531-539.