Evolution in Prebiotic Systems: Cooperation In Utility-Based Agents

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***Abstract*— Prebiotic evolution is one of the major challenges in complex systems theory. What differentiates the living from the nonliving is a perennial source of debate. It has been recently affirmed that discussions about if and how we can draw a line that separates life from non-life are useless. He motivates this using a "continuity thesis" (CT) argument i.e the existence of a continuum between inanimate and living state of matter. For other authors CT it is equivalent to say that there is no unbridgeable gap between inorganic matter and living systems, plus the corollary that the emergence of life is considered a highly probable event. This is related to the problem of how the minimal complexity required for a chemical system to start on the path of Darwinian evolution has been achieved. The CT from one side, and a trend towards an increasing complexity on the other, seems to require the existence of a constant driving force behind abiogenesis for two distinct reasons: a) to counterbalance destructive tendencies like hydrolysis in the evolving chemical structures and b) reduce the role played by chance to a minimum acceptable for a scientific discourse. In this work, I present a brief review of what has been considered the main driving forces behind prebiotic evolution i.e. self-organization of far-from-equilibrium open systems and (generalized) Darwinian evolutionary mechanism. I argue that, in order to explain the robustness and sustainability of complex systems not yet fully capable of Darwinian evolution a third element must be added: cooperation between molecular autonomous agents properly defined. In this work, I propose a general theoretical result to show how cooperation formation between a population molecular utility-based agents can give rise to self-sustaining networks.**

***Index Terms*—Prebiotic evolution, entropy production, universal Darwinism, utility-based agents, Pareto equilibrium.**

I. INTRODUCTION

Life is one (between many other) way in which the matter of the universe is organized. The scientific study of evolution of biological systems assumes that complexity emerged through a combination of deterministic laws and boundary conditions of the Earth Many good reviews have been written and I invite the interested reader to refer to them [1], [2], [3], [4], [5], [6], [7], [8], [9]. In [10] the Authors discussed the concept of a *transition zone*, which is a complex pre-life organic that is in a somehow intermediate state: more complex than a molecular assemblage but not yet a fully living machine. The problem se address here is related to the stability of intermediates i.e. the stability of the entities in the transition zone. Since they are not able to adapt as a fully-fledge biological entity but at the same time they are evolving complex systems the question is which kind of pressure acted on these entities in the direction of a more complexity instead of a breaking down to a state of less complexity. We believe that the problem of the robustness of the intermediate entities is one central question of chemical evolution. In this work, I will focus on this problem of the "stability of the intermediate stages". before entering in this issue, I will briefly review few well-known facts about chemical evolution. This is related to the problem of how the minimal complexity required for a chemical system to start on the path of Darwinian evolution has been achieved. An alleged trend towards an increasing complexity seems to be required to counterbalance destructive tendencies.

II. SOME BUILDING BLOCKS IN THEORIZING CHEMICAL EVOLUTION

The term prebiotic (or chemical) evolution refers to the sequence of steps that started from monomeric building blocks to more and more complex molecular structure and chemical networks that eventually aggregated into Earth's first cells. It has been stated many times and in different forms that for prebiotic evolution to be accepted as a scientific endeavor must adhere to the following continuity assumption [11], [12], [13]:

Assumption 1. Chemical evolution has been a continuous process.

Assumption 2. Chemical evolution proceeds from the simple to the complex.

A. Out-Of-Equilibrium Thermodynamics

The observation that under a generalized chemical potential, material self-organizes into systems which augment the dissipation of that potential should be accredited to Ilya Prigogine. The principle of maximum entropy production states that irreversible processes proceed in a direction in which the maximum amount of entropy is produced or that in which entropy production is greatest. Recently, there have been attempts to describe biological evolution mathematically as an equation of motion where energy flows toward a stationary state (as described by the second law of thermodynamics [14], [15]. Evolution as dispersal of energy is described by the overall rate of change in entropy:

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$$\frac{dS}{dt} = R\sum_j \frac{dN_j}{dt}\nabla\frac{\mu_j}{RT},$$

where N_j represents a population of chemical entities, RT the average energy and the term $\nabla(\mu_j/RT)$ represents the potential energy differences and gradients relative to RT, The grand sum of this equation over all constituents j defines the system as an energy transduction network. Recently, different variations of the theme about an alleged maximum entropy production principle (MEPP) has been suggested [16], [17], [18], [19].

According to the MEPP approach, thermodynamic processes far from thermodynamic equilibrium evolve to steady states at which they dissipate energy and produce entropy at the maximum possible rate. Life is a very efficient entropy producer, so, according to this line of reasoning, it is not at all true that laws of thermodynamics play against the evolution of life complexity but quite the opposite, they favor it! The use of MEPP principles in explanations raised several controversies and failed to convince the scientific community so far (For a critical revision of alleged maximum entropy principles in chemistry see [20]).

B. Generalized Darwinism

It has been advocated that the rise of Darwinian evolution represents the very property able to discern between life and non-life [21]. Some authors try to locate the origin of life as just one step in the wider historical path of cosmic evolution. When self-replicating entities entered the scene, a primordial principle of chemical selection boosted and constrained the evolutionary path in a dramatic way. The complexity of life forms that we observe in nature (empirical) can be explained through the understanding of a mechanism situated at a deeper level: genetic mutation (plus some others).

These mechanisms acted on specific environmental context to give rise to specific configurations of structures and patterns. But there is no pre-determined path. For example, it has been recognized that the existence of an "arrow of complexity" in biological evolution must be understood in a "passive" sense: natural selection is not an a priori pressure to complexity but it will push in that direction to the extent that it provides selective advantages [22]. Different attempts to extend the Darwinian logic to non-biological entities has been carried out. Generally, in these attempts it is more correct to talk about *generalized* or *universal Darwinism* (UD). UD assumes a population of non-identical (intentional or non-intentional) not necessarily "living" entities that face locally scarce resources and problems of survival. Some adaptive solutions to such problems are retained through time and may be passed to other entities [23].

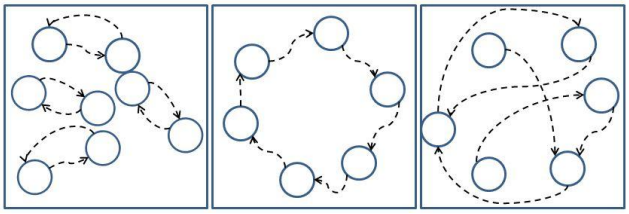


Fig 1. Different possible trade topologies between autonomous agents.

III. MINIMAL AUTONOMOUS ENTITIES AND THE ONSET OF COOPERATION

Thermodynamics and evolutionary forces had a major role in the transition to complexity. However, we argue that a third mechanism played a fundamental role in the transition zone. The starting point is to understand that processes occurred during this phase had involved populations of semi-autonomous entities whose local interactions with one another are governed by a set of simple rules. It is posited that simple rather than complex specifications, local rather than global control, bottom-up rather than top-down modeling and emergent rather than pre-specified behaviors are the main rational principles governing the transition zone. For wat it follows, the term *autonomous agent* deserves a more detailed discussion. It generally refers to an entity that makes its own choices about how to act in its environment without any influence from a leader or global plan.

The concept of an autonomous agent has become important in different fields, from Biology to computer science. Kauffman elaboration on the theme are of primary interest here [24]. He introduced the concept of molecular autonomous agent so defined: a reproducing autonomous system that carries out at least one thermodynamic work cycle. He gives an example of an autonomous agent is a bacterial cell swimming upstream in a glucose gradient. In this work, a different concept of autonomous system will be considered. We introduce the following

Definition 1. A minimal physical utility-based agent (MPUBA) is molecular assemblage able to scan environmental signals and to decide about how to act according to a utility measure. Here utility is related to the maintenance of the agent.

An agent behaves and reacts according to environmental stimuli or may engage in different forms of exchange with other agents. More formally, given a set of possible environment state and a set of possible actions The decision-making process for a MPUBA is conceptualized as a mapping:

$$DM: \mathcal{S} \longrightarrow \mathcal{A}$$

where the action selection mechanism is related to a utility function:

$$u(s): \mathcal{S} \longrightarrow \mathbb{R}$$

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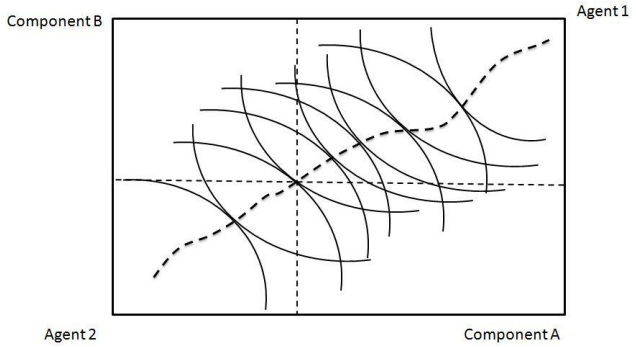


Fig 2. Cooperation between agents that leads to a pareto optima configuration

to each possible environment state S_i to the set of real numbers. An agent will then act to maximize its utility. In the easiest, deterministic case, this is a matter of straightforward evaluation:

$$\tilde{a} = \arg\max_{\mathcal{A}} u(s(a,s))$$

Co-utility, refers to mutual help. It can be a rational option even for purely selfish agents. A population of autonomous agents work under the assumption that an "invisible hand" self-regulates the behavior of the system. This will correspond to a theoretical configuration where free-riders try to maximize their own utility engaging in coordinate interactions. The resulting structures go from anarchy to networks of various topologies (figure 1). This can give rise to robust equilibrium configurations. One important concept is introduced with the following:

Definition 2. An allocation is Pareto optimal when it is not possible to make one agent better off without making any other agent worse off.

Local interaction between MPUBA can be modeled as a pure exchange process.

Proposition 3. Utility-based agents' interaction leads to a Pareto-optimal equilibrium.

Proof: This can be shown with a common Edgeworth-Box argument (figure 2). The diagram neatly includes the endowment for both agent A and B. The set of rectangular hyperbolas that expand away from the origin are those of agent As. Both agents can interact and increase their utilities up to a point where any movement will benefit one agent only. Locally, coalition can grow as far as this represent a benefit for each agent with the advantage of representing a robust complex network that can represent a step forward in the understanding of the "stability of the intermediates" problem.

This onset of this cooperation between MPUBA and competition between coalitions fostered specialization and funneled the direction of prebiotic evolution. Here we assume that autonomous entities so defined proliferated in the gray area of the transition zone. Network formations of variable topologies create more stable entities. Nonetheless, "stability" here does not mean that the systems evolve towards an unchanging structure. Prebiotic networks have to be understood in a constant state of flux. It must be clear in mind that the complexity of prebiotic stages, multiple equilibria and path dependence dominates the history of prebiotic evolution. Much work remains undone on the relation between prebiotic entities and local environment in theoretical as well as experimental and computational terms.

IV. FINAL REMARKS

After Prebiotic evolution to complexity has been the outcome multiple driving forces and environments where at different times different causal mechanism operated in concert. Further, some sudden "catastrophic" events introduced irreversibility and channeled the evolutionary path that led to life in a fundamental way. Together with thermodynamically and evolutionary imperatives and logic, a third organizing principle has been discuses: the emergence of mutual benefit behavior between original utility based entities. Network that emerged from mutual interaction assured stability in the delicate phase of the transition zone and, together with other causal mechanism, fostered an increasing complexity through generation of novelty in self-replicating populations.

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