On the Interplay of Kinetics, Thermodynamics, and Information in Simple Replicating Systems

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Extended Abstract

Life uses energy to acquire and process information. The process of gaining information through evolutionary search cannot be uncoupled from its physico-chemical embodiment and the energetic needs and entropic constraints of the latter (Morowitz (1979); Smith (2008)). Therefore, a serious study of biological as well as prebiotic information processing requires: *(i)* an explicit accounting of the thermodynamics underlying replication, mutation, and selection of self-replicating systems, and *(ii)* an explicit treatment of the influence of information on the metabolism and kinetics of the replicating system, *(iii)* an explicit description of the thermodynamic instability that drives replication, and *(iv)* a concept of information that explicitly takes into account the evolutionary path through a fitness landscape.

Because this approach clearly exceeds the current description of contemporary living organisms, we develop our framework for a minimal coupled container-information-metabolism system (protocell) that is presumably able to self-replicate and evolve (Rasmussen (2003)). Thanks to the simplicity of this system, it is possible to gain a detailed understanding of the atomistic processes that underlie information replication, metabolic regulation, aggregate replication, as well as mutation and selection.

To study *(i)*, we take into account the detailed thermodynamic needs for replication of the entire protocell and possible mutation of its information component. The simplicity of the protocell allows us to define reasonable estimates for a quantitative fitness function, i.e. kinetic rate influence of the information component on the metabolic rate, which accounts for point *(ii)*. By further estimating the thermodynamic container stability depending on composition (point *(iii)*) we derive a Master equations governing protocell population dynamics in information as well as container fitness spaces.

To deal with *(iv)*, we propose a concept of information that overcomes the explicit treatment of genetic sequences but focuses instead on the complexity of the evolutionary path. This is achieved by identifying a genetic lineage, i.e., a sequence of cell duplications and possible mutations, as a decision making process (where the outcome of each decision is evaluated depending on whether the offspring has a higher or lower fitness). This enables us to express the evolutionary path as a chain of decisions, i.e. evolutionary improvements, stagnations or aggrevations. Under suitable units, the sequence of decisions can be identified as a symbolic string, whose information content is its associated Kolmogorov Complexity – a conceptual, more powerful precursor of statistical information (Li and Vitányi (1993)).

Equipped with this framework, we are able to analyze the interplay of thermodynamics, kinetics, and information in a quantitative manner. In particular, we can quantitatively derive the *maximum power principle* (MPP) (Lotka (1922); Cai (2004)) that postulates a connection between evolutionary acquired information and the underlying kinetics of life, and we derive a quantitative analogue of the *Landauer principle* (Landauer (1961)) for evolving replicators (LPER), that postulates a relation between thermodynamics and acquirable information in a physical system. We explore the outcome of these relations for several limiting cases, as well as for the particular protocell design under consideration.

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