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Eigen’s paradox

5.1 Introduction

Here we examine prebiotic evolution using the coevolutionary machinery of the last chapter to explore a possible linkage between a fundamental ecosystem resilience shift and an important change in evolutionary process. We follow closely the recent paper by R. Wallace and R.G. Wallace (2008).

Applying the homology between information source uncertainty and free energy density, under rate distortion constraints, the famous prebiotic error catastrophe of Manfred Eigen emerges as the lowest energy state for simple prebiotic systems without error correction. Invoking compartmentalization – ‘vesicles’ – and using a Red Queen argument, suggests that information crosstalk between two or more properly interacting structures can initiate a coevolutionary dynamic having at least two quasi-stable states. The first is a low energy realm near the error threshold, and, depending on available energy, the second can approach zero error as a limit. A large deviations argument produces jet-like global transitions which, over sufficient time, may enable shifts between the many quasi-stable modes available to more complicated structures. The transitions ‘lock in’ to some subset of the various possible low error rate chemical systems, which become subject to development by selection and stochastic trajectories.

Energy availability, according to the model, is thus a powerful necessary condition for low error rate replication, suggesting that some fundamental prebiotic ecosystem transformation entrained reproductive fidelity. That is, a basic metabolic shift, such as a new chemical cycle, onset of predation, and/or photofixation of energy, was needed to enable low error rate reproduction.

This work, then, supports speculation that our RNA/DNA world may indeed be only the chance result of a very broad prebiotic evolutionary phenomenon. Processes in vitro, or ex planeta, might have other outcomes.

Manfred Eigen’s (1971, 1996) evolution model is a landmark attempt at coherently relating evolution, molecular biology, and information theory. That work views selection as condensation in information space, and evolution as a
succession of phase transformations. Indeed, Eigen’s quasispecies model, with its error catastrophe, corresponds exactly to a phase transition in a two-dimensional Ising system (Leuthausser, 1986). The essence of Eigen’s paradox is that the error catastrophe limits genome length in RNA precursor organisms to much less than observed in DNA organisms having error correcting enzymes, which, themselves, cannot be created in the absence of just such a long genome.

As Holmes (2005) put it,

“To create more genetic complexity, it is therefore necessary to encode more information in longer genes by using a replication system with greater fidelity. But there’s the catch: to replicate with greater fidelity requires a more accurate and hence complex replication enzyme, but such an enzyme cannot be created because this will itself require a longer gene, and longer genes will breach the error threshold”

Here we reconsider Eigen’s paradox from a highly formal perspective which hews quite closely to the fundamental asymptotic limit theorems of information theory, in particular the Rate Distortion Theorem, and its zero-error limit, the Shannon-McMillan Theorem. These, like the Central Limit Theorem in parametric statistics, permit derivation of ‘regression-like’ models which can be applied to real data. We use these theorems in a principled manner to derive the high rate of mutation inherent to RNA virus replication and suggest a plausible Red Queen coevolutionary ratchet leading toward an evolutionary condensation resulting in effective error-correction mechanisms.

The line of argument is as follows:

[1] An increasingly complicated network of simple interacting ‘RNA-like’ organisms creates a collective biochemical system – a ‘vesicle’ – which, as a parallel communication channel, can have a much higher channel capacity for low-error replication than do the individual components.

[2] Several such distinct, properly interacting, collectives – compartments in the sense of Eigen and Szathmary – become each others’ most intimate environments. The resulting coevolutionary ratchet produces a Red Queen structure which, given sufficient energy, can support quasi-stable states with very low reproductive error rates.

[3] High error rate, but low energy, systems-of-vesicles can become subject to systematic ‘large deviations’ excursions that, over sufficient time, can lead to the establishment of a distribution of low error rate, but higher energy, chemical systems. Even prebiological quasi-organisms can, apparently, build pyramids, as it were. Thus many different chemistry-of-life solutions seem possible, each subject to evolutionary processes of selection and chance extinction.

[4] This latter step depends critically on the availability of adequate energy sources which, we hold, will largely be driven by changes in the protoecosystem. Such changes may well have been in the form of punctuated shifts in resilience domain.