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The Physics of Evolution

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The Darwinian concept of evolution through natural selection has been revised and put on a solid physical basis, in a form which applies to self-replicable macromolecules.

Two new concepts are introduced: «sequence space» and «quasi-species». Evolutionary change in the DNA- or RNA-sequence of a gene can be mapped as a trajectory in a sequence space of dimension v, where v corresponds to the number of changeable positions in the genomic sequence. Emphasis, however, is shifted from the single surviving wildtype, a single point in the sequence space, to the complex structure of the mutant distribution that constitutes the quasi-species. Selection is equivalent to an establishment of the quasi-species in a localized region of sequence space, subject to threshold conditions for the error rate and sequence length. Arrival of a new mutant may violate the local threshold condition and thereby lead to a displacement of the quasi-species into a different region of sequence space. This transformation is similar to a phase transition; the dynamical equations that describe the quasi-species have been shown to be analogous to those of the two-dimensional Ising model of ferromagnetism. The occurrence of a selectively advantageous mutant is biased by the particulars of the quasi-species distribution, whose mutants are populated according to their fitness relative to that of the wildtype. Inasmuch as fitness regions are connected (like mountain ridges) the evolutionary trajectory is guided to regions of optimal fitness. Evolution experiments in test tubes confirm this modification of the simple «change and law» nature of the Darwinian concept. The results of the theory can also be applied to the construction of a machine that provides optimal conditions for a rapid evolution of functionally active macromolecules.

An introduction to the physics of molecular evolution by the author has appeared recently[1]. Detailed studies of the kinetics and mechanisms of replication of RNA, the most likely candidate for early evolution[2,3], and of the implications on natural selection have been reported[4,5]. The quasi-species model has been constructed[6,7] using the concept of sequence space. Subsequently various methods have been invented to elucidate this concept and to relate it to the theory of critical phenomena[8-19]. The instability of the quasi-species at the error threshold has been discussed[20]. Evolution experiments with RNA strands in test tubes have been described[21,22].

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