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PDE model for protocell evolution and the origin of chromosomes via multilevel selection

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A PDE Model for Protocell Evolution and the Origin of Chromosomes via Multilevel Selection

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Abstract

The evolution of complex cellular life involved two major transitions: the encapsulation of self-replicating genetic entities into cellular units and the aggregation of individual genes into a collectively replicating genome. In this presentation, we formulate a minimal model of the evolution of proto-chromosomes within protocells. We model a simple protocell composed of two types of genes: a "fast gene" with an advantage for gene-level self-replication and a "slow gene" that replicates more slowly at the gene level, but which confers an advantage for protocell-level reproduction. Protocell-level replication capacity depends on cellular composition of fast and slow genes. We use a partial differential equation to describe how the composition of genes within protocells evolves over time under within-cell and between-cell competition, considering an infinite population of protocells that each contain infinitely many genes. We find that the gene-level advantage of fast replicators casts a long shadow on the multilevel dynamics of protocell evolution: no level of between-protocell competition can produce coexistence of the fast and slow replicators when the two genes are equally needed for protocell-level reproduction. By introducing a "dimer replicator" consisting of a linked pair of the slow and fast genes, we show analytically that coexistence between the two genes can be promoted in pairwise multilevel competition between fast and dimer replicators, and provide numerical evidence for coexistence in trimorphic competition between fast, slow, and dimer replicators. Our results suggest that dimerization, or the formation of a simple chromosome-like dimer replicator, can help to overcome the shadow of lower-level selection and work in concert with deterministic multilevel selection in protocells featuring high gene copy number to allow for the coexistence of two genes that are complementary at the protocell level but compete at the level of individual gene-level replication. These results for the PDE model complement existing results on the benefits of dimerization in the case of low genetic copy number, for which it has been shown that genetic linkage can help to overcome the stochastic loss of necessary genetic templates.