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Emergent Robustness from Multiple Timescale Adaptive Dynamics

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Biological and neural networks are adaptive - their connections slowly change in response to the state of the coupled elements making up the systems. The dynamics of such adaptive networks are intriguingly complex, rendering it extremely difficult to answer the fundamental question of what the energy requirements for maintaining functionally robust collective states under environmental stochasticity are. Aiming to understand the essential role of free-energy consumption in robust adaptation, a basic problem in evolution and learning, we introduce a new framework based on path-integral formalism in non-equilibrium statistical physics. As a specific example of our theory, we apply it to biological evolution, where phenotypes are shaped by gene-expression fast dynamics that are subjected to an external noise while genotypes are encoded by the configurations of a network of gene regulations. This network slowly evolves under natural selection with a mutation rate, depending on how adapted the shaped phenotypes are. Here we establish a relation between the averaged entropy production rate (EPR) and the evolutionary speed which is quantified by the genetic variance. Specifically, EPR is shown to increase with increasing evolutionary speed at a low noise level, while a robust gene-expression pattern is maintained within an intermediate level of noise at a much lower value of EPR. The emergence of such robustness as well as its associated EPR can be characterised analytically within our framework as the onset of instability of the attractor state with zero gene-expression levels.

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