Minimal architecture for adaptation in non-equilibrium chemical signaling networks

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Biological systems have to reliably sense and process multiple cues in a noisy and dynamic environment. These operations are mediated by intricate chemical signaling networks and are instrumental in supporting the emergence of complex behaviors. In particular, adaptation to repeated stimulations is a ubiquitous phenomenon that takes place at different biological scales. Informed by both experimental observations and theoretical constraints, we propose a minimal architecture for chemical signaling networks that incorporates energy consumption, information storage, and negative feedback. We show that these are the minimal necessary mechanisms for the emergence of dynamical memory and adaptation. Crucially, adaptation is associated with both an increase in the mutual information between external and internal variables and a reduction of dissipation of the internal chemical processes. By simultaneously minimizing energy consumption and maximizing information, we find that far-from-equilibrium operations are optimal in the low-noise regime. Our framework draws a path toward the unraveling of the essential ingredients connecting adaptation and memory in biochemical systems, along with their molecular implementation.

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