MAR12-2011-001410
Abstract for an Invited Paper
for the MAR12 Meeting of
the American Physical Society

Landscape and Flux Framework for Non-Equilibrium Networks: Kinetic Paths and Rate Dynamics

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We developed a general framework to quantify three key ingredients for dynamics of nonequilibrium systems through path integrals in length space. First, we identify dominant kinetic paths as the ones with optimal weights, leading to effective reduction of dimensionality or degrees of freedom from exponential to polynomial so large systems can be treated. Second, we uncover the underlying nonequilibrium potential landscapes from the explorations of the state space through kinetic paths. We apply our framework to a specific example of nonequilibrium network system: lambda phage genetic switch. Two distinct basins of attractions emerge. The dominant kinetic paths from one basin to another are irreversible and do not follow the usual steepest descent or gradient path along the landscape. It reflects the fact that the dynamics of nonequilibrium systems is not just determined by potential gradient but also the residual curl flux force, suggesting experiments to test theoretical predictions. Third, we have calculated dynamic transition time scales from one basin to another critical for stability of the system through instantons. Theoretical predictions are in good agreements with wild type and mutant experiments.We further uncover the correlations between the kinetic transition time scales and the underlying landscape topography: the barrier heights along the dominant paths. We found that both the dominant paths and the landscape are relatively robust against the influences of external environmental perturbations and the system tends to dissipate less with less fluctuations. Our theoretical framework is general and can be applied to other nonequilibrium systems.