Improved bounds on entropy production in living systems

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DATE: Friday, November 12, 2021
TIME: 12:00 PM
PLACE: Webex

ABSTRACT: Living systems maintain or increase local order by working against the second law of thermodynamics. Thermodynamic consistency is restored as they consume free energy, thereby increasing the net entropy of their environment. Recently introduced estimators for the entropy production rate have provided major insights into the efficiency of important cellular processes. In experiments, however, many degrees of freedom typically remain hidden to the observer, and, in these cases, existing methods are not optimal. Here, by reformulating the problem within an optimization framework, we are able to infer improved bounds on the rate of entropy production from partial measurements of biological systems. In contrast to prevailing methods, the improved estimator reveals nonzero entropy production rates even when non-equilibrium processes appear time symmetric and therefore may pretend to obey detailed balance, and can bound entropy production from waiting time statistics alone. We demonstrate the broad applicability of this framework by providing improved bounds on the energy consumption rates using experimental trajectory data from a diverse range of biological systems including bacterial flagella motors, growing microtubules, and calcium oscillations within human embryonic kidney cells. We are also able to gain bounds on the energy consumption rate of gene regulatory networks, mammalian behavioral dynamics and bacterial sensors from waiting time distribution alone.

References:
[1] D. Skinner and J. Dunkel. “Improved bounds on entropy production in living systems”: PNAS, 118 : e2024300118, 2021
[2] D. Skinner and J. Dunkel. “Estimating entropy production from waiting time distributions”: Phys. Rev. Lett., 12 : 198101, 2021

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