# Finite-time Thermodynamics in Biology

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An overall synthesis of biology and non-equilibrium thermodynamics remains a challenge at the interface between the physical and life sciences. Herein, theorems from finite-time and control thermodynamics are applied to biological processes to indicate which biological strategies will succeed over different time scales. It is emphasized that biological processes are not driven by entropy production but rather, by informed exergy flow. In fact, the entropy production is the generalized friction that should be minimized insofar as the constraints and technology allow. In general, living systems maximize power at the expense of efficiency during the early stages of their development while proceeding at slower rates to maximize efficiency over longer time scales. Theorems concerning thermodynamic path length and minimum entropy production, show that there is a direct tradeoff between the efficiency of a process and the process rate. To quantify this tradeoff, the concepts of compensated heat and waste heat are introduced. Compensated heat is the exergy dissipated, which is necessary for a process to satisfy constraints. Conversely, waste heat is exergy that is dissipated as heat, but does not provide a compensatory increase in rate or other improvement. We hypothesize that it is waste heat that is minimized through natural selection. This can be seen in the strategies employed at several biological scales including organismal development, ecological succession, and large-scale macro-evolution. Better understanding the roles of compensated heat and waste heat in biological processes will provide novel insight into the underlying thermodynamic mechanisms involved in metabolism, ecology, and evolution.