Life as a Thermodynamic Regulator: Rewiring of Dissipation Channels and Phase Transitions in an Agent-Based Model

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Abstract

Life is traditionally understood as a dissipative structure that accelerates entropy production by converting free energy into heat. Here we present an agent-based model combining spatial energy diffusion with adaptive metabolic agents, and demonstrate that life can fundamentally alter not only the amount but also the pathways of energy dissipation.

Our simulations show that biological agents suppress physical diffusive frictional heat (heatDiff) by up to 97%, redirecting dissipation into controlled metabolic heat production (heatAct). By sweeping energy inflow rate and metabolic cost, we construct a phase diagram revealing a transition between a suppression phase, where life reduces total dissipation, and an acceleration phase, where dissipation exceeds that of the purely physical system.

These results suggest that life should be interpreted not merely as a dissipative structure, but as a thermodynamic regulator that actively reorganizes dissipation channels to stabilize non-equilibrium environments. An interactive simulation is available at https://my-life-sim.vercel.app/

1 Introduction

Life has long been framed within non-equilibrium thermodynamics as a dissipative structure that maintains order by accelerating entropy production [1]. However, this formulation largely ignores the structure of dissipation itself. Does life merely increase dissipation, or does it qualitatively transform how dissipation occurs?

We address the question of whether life can suppress uncontrolled physical entropy production by reorganizing energy dissipation pathways.

2 Model

2.1 Spatial domain

We consider a two-dimensional square lattice of size $N \times N$, where each cell stores a continuous energy density $E(x, y)$.

2.2 Physical diffusion (OFF mode)

Energy diffuses between neighboring cells according to a discrete diffusion equation. Dissipated energy due to spatial gradients is accumulated as $heatDiff$.

2.3 Biological agents (LIFE mode)

Each agent is characterized by position (x, y), internal energy E_a, and metabolic cost c. At each timestep, agents move toward higher energy gradients, absorb local energy, release metabolic heat $heatAct$, divide if energy exceeds a threshold, and die if energy falls below a threshold. Upon death, remaining energy is returned to the grid.

2.4 Energy accounting

At every timestep we verify

$$\Delta E_{total} = E_{inflow} - (heatDiff + heatAct). \tag{1}$$

The conservation error remains below 10^{-3}.

3 Experimental design

3.1 Baseline comparison

We fix $inflowRate = 5$ and $consumptionRate = 1.0$ and compare OFF, LIFE, and RANDOM modes.

3.2 Phase diagram sweep

We vary $inflowRate \in \{1, 3, 5, 7, 9\}$ and $consumptionRate \in \{0.5, 1.0, 1.5, 2.0, 3.0\}$ for 25 conditions. Each simulation runs for 500 timesteps, and averages over the final 100 steps are used.

4 Results

4.1 Time series of dissipation

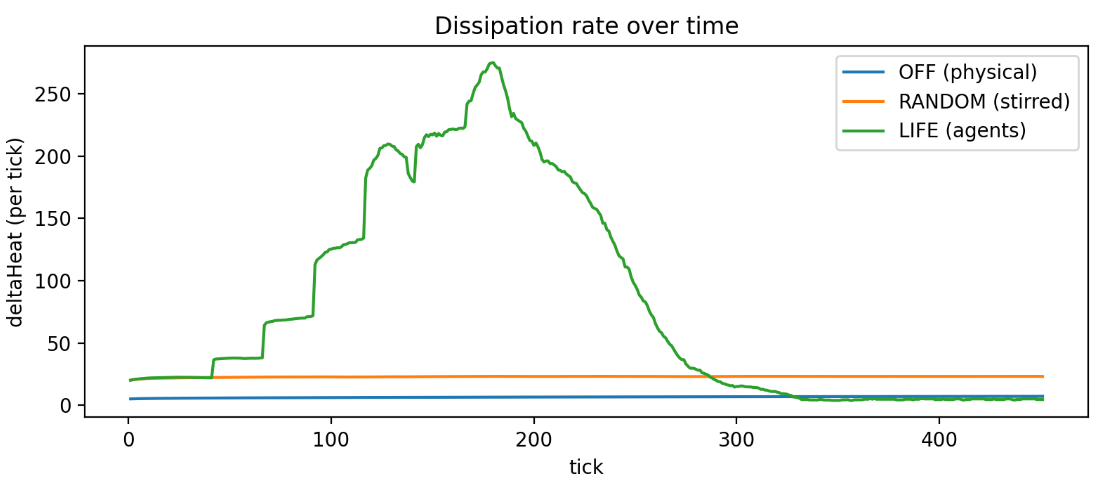

Figure 1: Time series of dissipation rates in OFF, RANDOM, and LIFE modes.

4.2 Rewiring of dissipation channels

Representative results are shown in Table 1 and Fig. 2.

Mode	heatDiff	heatAct	total ΔH
OFF	10.86	0	10.86
LIFE	0.33	3.80	4.13

Table 1: Decomposition of dissipation channels.

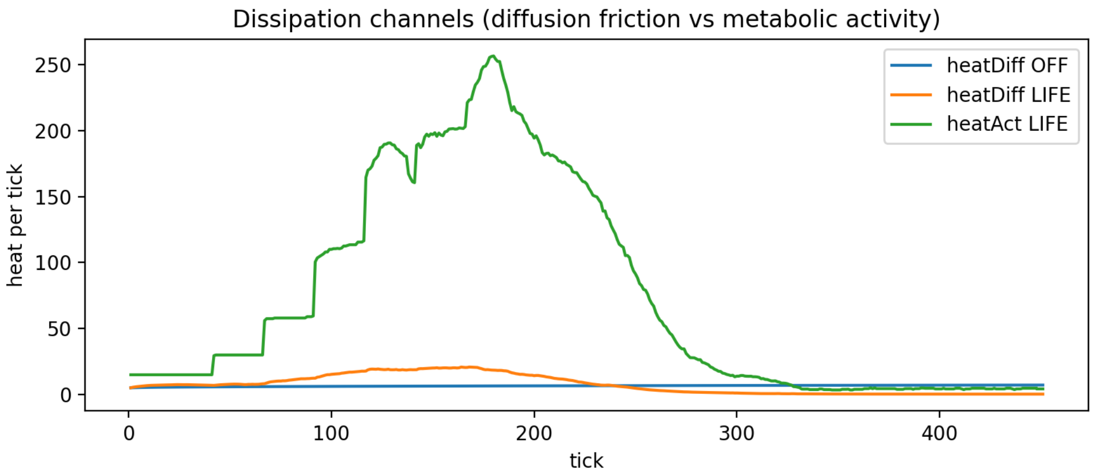

Figure 2: Time evolution of diffusive heat (heatDiff) and metabolic heat (heatAct).

Physical frictional dissipation is reduced by 97

4.3 Phase diagram

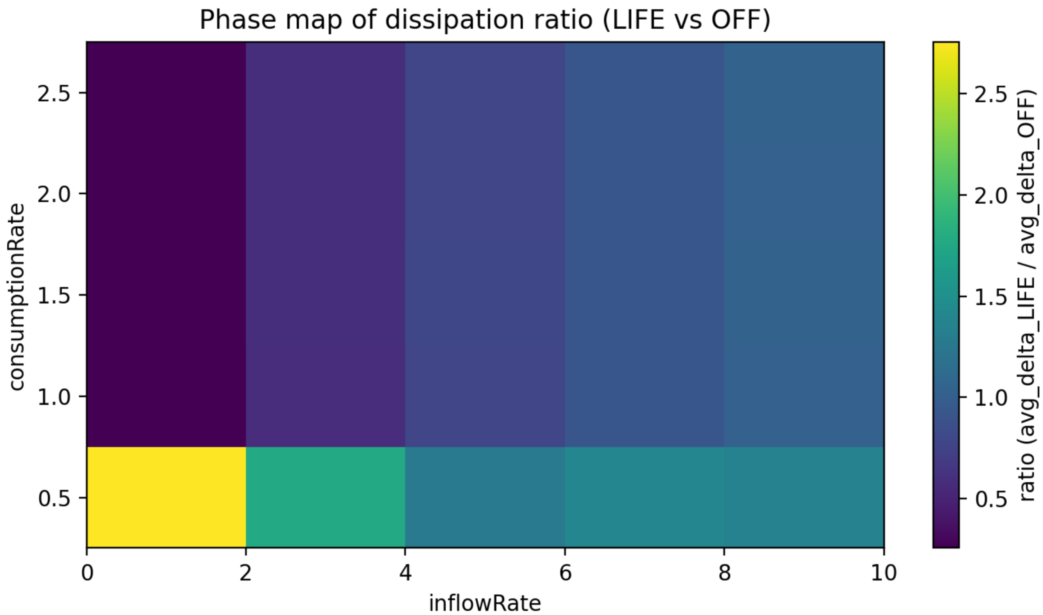

Figure 3: Phase diagram showing the ratio of biological to physical dissipation as a function of inflowRate and consumptionRate.

We observe a phase transition near $inflowRate \approx 8$ for $consumptionRate \geq 1.0$, separating suppression and acceleration regimes.

4.4 Phase classification

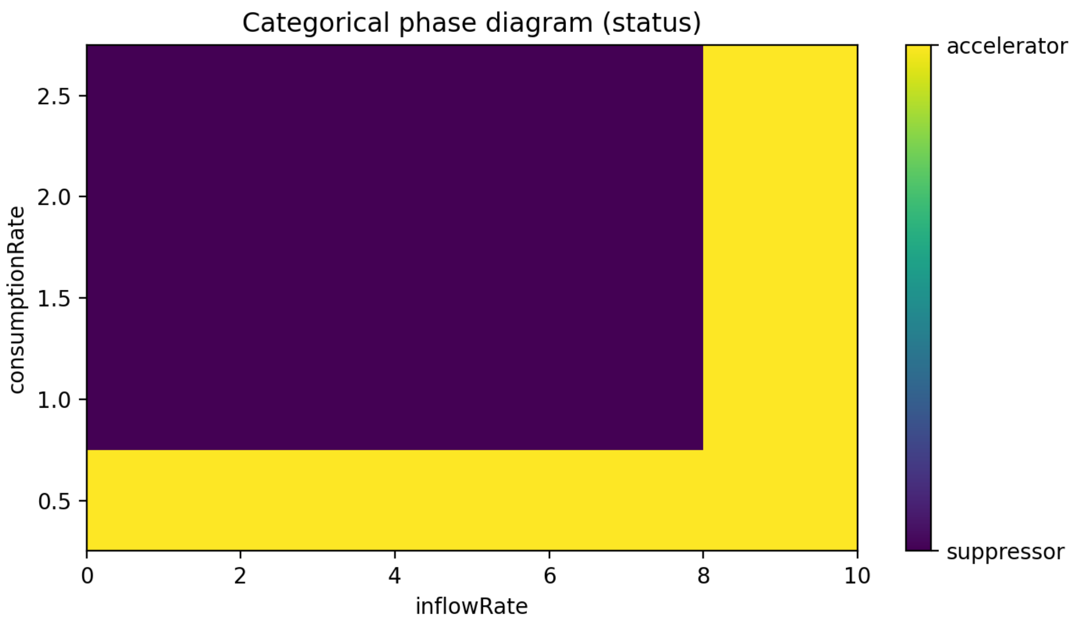

Figure 4: Classification of regimes into suppression, acceleration, and extinction phases.

Figure 4 visualizes the boundaries between dynamical regimes based on dissipation dominance and population persistence.

4.5 Population dependence

Higher average population correlates with increased dissipation.

5 Discussion

Life reorganizes dissipation mechanisms rather than simply increasing entropy production. Biological systems suppress uncontrolled diffusion losses and convert energy into regulated metabolic heat.

6 Conclusion

We demonstrate that life controls dissipation pathways, suppresses physical frictional entropy production, and undergoes a phase transition between suppression and acceleration regimes. We propose that life should be characterized as a thermodynamic regulator rather than merely a dissipative structure.

7 Future work

Future work includes robustness tests over random seeds, three-dimensional extensions, continuum-limit formulations, and experimental validation.

References

[1] I. Prigogine, Time, Structure and Fluctuations (1977).

[2] E. Schrödinger, What is Life? (1944).

[3] J. England, Statistical physics of self-replication, J. Chem. Phys. (2013).