Technical note 1: Two toy models

Photosynthesis and the cytoskeleton can be seen as a chemical network. Sunlight drives fuel production, which powers filament growth or motor activity. Molecules are nodes, reaction rates are edges, and the network defines energetics and possibly fitness.

For bird migration, we can use the boids model. Birds are active Brownian particles with propulsion, alignment, noise, and an added term for magnetic alignment. With weak flocking or magnetoreception, paths look like random walks. Fitness can then be quantified as the shortest migration path.

Technical note 2: Mean back relaxation and the thermodynamic uncertainty relation

Mean back relaxation measures how diffusion in living systems departs from the fluctuation-dissipation theorem. Experiments show clear breaking of detailed balance.

The thermodynamic uncertainty relation connects the precision of biological processes to their energy cost. Robustness requires dissipation, setting a tradeoff between noise and efficiency.

Together, these measures let us probe how far life is from equilibrium and how it resists entropy.

******Technical note 3: Time reversal symmetry and the Eigenstate thermalization hypothesis******

Noether's theorem ties energy conservation to time-reversal symmetry. Biology breaks this: living systems are open and dissipative, requiring constant energy input.

The eigenstate thermalization hypothesis (ETH) explains how isolated quantum systems thermalize. But since life is never isolated, ETH does not apply directly. The open zone where matter organizes into life may reveal physics beyond both equilibrium thermodynamics and standard quantum theory.