Non-Equilibrium Statistical Physics

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Motivation

Equilibrium statistical physics

- Well-defined framework
- Fluctuation-response relations for dynamics
- Changes of scale / coarse-graining straightforward

$$Z = \mathrm{Tr}\, e^{-\beta H} \rightarrow \ ?$$

Non-equilibrium statistical physics

- Many / most systems of interest **not** at equilibrium
- May take too long to equilibrate: transients matter, **aging**
- Or be **driven** from outside (biological systems), which breaks detailed balance (microscopic reversibility)
- Often no Hamiltonian, system defined purely by **dynamics** (e.g. agent-based models, network dynamics)
- Even this dynamical description may be **unknown**

Research questions

- What general **frameworks** for non-equilibrium are there?
- How do we **change scale** or focus on **subsystems**?
- What **structures** and **behaviours** can non-equilibrium dynamics produce?
- How do we analyse systems with many different **timescales**?
- Can we **learn** dynamical models from data?

Techniques you can learn

- Path integrals (coherent states, Martin-Siggia-Rose)
- Trajectory thermodynamics, large deviation techniques
- Projection approaches (nonlinear Zwanzig-Mori)
- Cavity methods for networks
- Long-time scaling, stochastic simulation
- Random matrix theory

Areas for Bachelor projects

Fluctuations in reaction networks

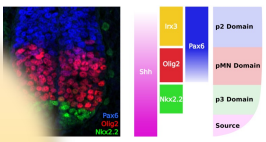
- Chemical reaction / protein interaction networks, gene regulation, …
- Problem: strong fluctuations at small copy numbers (e.g. genes)
- Approximate path integrals, methods from spin glasses, field theory
- Estimate for data likelihood, can use to learn parameters

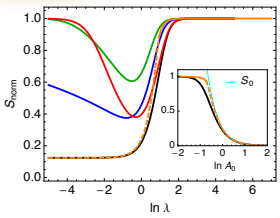
Dynamics with non-Gaussian noise

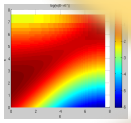
- Relevant in bacterial swimmer suspensions, granular gases, …
- Exact solutions in low noise limit
- Time for crossing potential barrier?
- Is non-Gaussian noise more efficient?
- Effects of activity, e.g. self-propulsion? Dimensionality effects?

Path-based thermodynamics

- Study dynamical large deviations: trajectories with high current, activity
- Probe by biasing trajectory distribution: thermodynamics of fluctuating paths, dynamical phase transitions
- Interaction of driving (bias) and aging?
- Universality classes of aging?

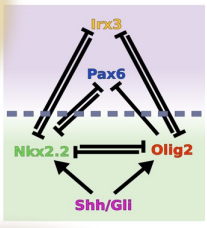


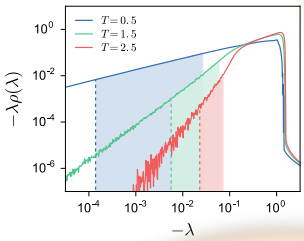




Subnetworks & coarse graining

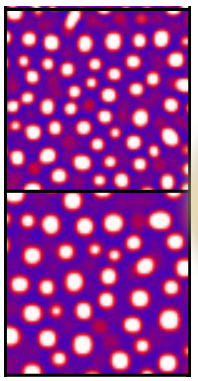
- Most biological networks too large for intuitive understanding: reduce to subnets
- Gives memory functions, can be nonlinear (for multiple fixed points)
- Machine learning network topology from memory effects (boundary structure)?
- Coarse-graining larger networks by "milestoning"?





Dynamics on networks

- Simple picture of amorphous material: hopping on network of metastable states
- Non-eq dynamics: competition of energetic (barriers) & entropic (connectivity) effects
- Flexible model: energy-connectivity correlations (local minima, saddles), …
- Analysis by random matrix theory, links to many-body localization, ...



Phase separation in complex mixtures

- Relevant in soft matter (colloids), biology (cytoplasm, lipid membranes)
- How do particle species redistribute between phases? Effect of crowding?
- Non-eq. structures by slow kinetics?
- Use interaction design to break Gibbs' rule
- Effect of non-reciprocal interactions?

Amorphous & active matter

- Amorphous materials (glass, sand, emulsions) trapped in metastable states
- How do disorder and heterogeneity affect dynamics and mechanical behaviour?
- Jamming vs glass transition?
- Extension to active matter? Important for biophysics, e.g. cytoskeletal rheology