# 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?

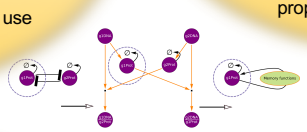
## Techniques you can learn

- 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
- Bayesian inference, variational approximations

## Sample areas for Bachelor projects

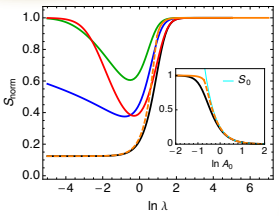
### Fluctuations in reaction networks

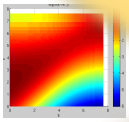
- Chemical reaction / protein interaction networks, gene regulation, …
- Problem: strong fluctuations at small copy numbers (e.g. genes)
- Approximate path integrals using techniques from spin glasses
- Estimate for data likelihood, can use to learn parameters



### 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 than thermal noise?
- Effects of active noise (self-propulsion)? Dimensionality?



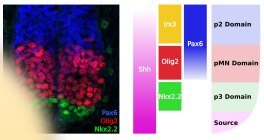



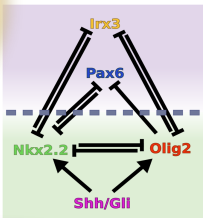
### Trajectory bias, dynamical phases

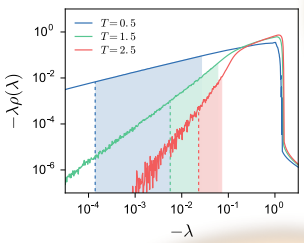
- Study dynamical large deviations: trajectories with high current, activity
- Probe by biasing trajectory distribution: dynamical phase transitions
- Interaction of bias and aging?
- Effective dynamics in biased system?

### Subnetworks, dynamical modules

- Most biological networks too large for intuitive understanding: reduce to subnets
- Gives memory functions, can be nonlinear (for multiple fixed points)
- Identify dynamical modules from memory?
- Extend to general coarse-graining beyond local equilibrium?

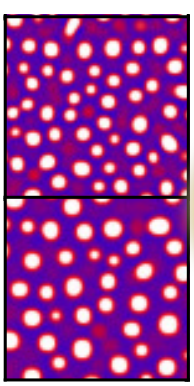


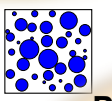




### Dynamics on networks

- Simple picture of amorphous material: hopping on network of metastable states
- Non-eq dynamics: competition of energetic (barriers) & entropic (connectvity) effects
- Flexible model: energy-connectivity correlations (local minima, saddles), …
- Related: diffusion in confined environments





### Phase separation in complex mixtures

- Relevant in soft matter (colloids), biology (cytoplasm, lipid membranes)
- How do particle species redistribute between phases? Effect of crowding?
- Stabilization of non-equilibrium structures by slow kinetics?
- Polymers vs spherical particles? Effect of active components?

### Athermal aging

- Amorphous materials (glass, sand, emulsions) trapped in metastable states
- Local plastic rearrangements can allow movement, leading to aging
- How to model & analyse dynamics?
- Differences entropic glass & elastic jam?
- Effect of pinned particles?
- Extension to active materials? Relaxation time spectra?