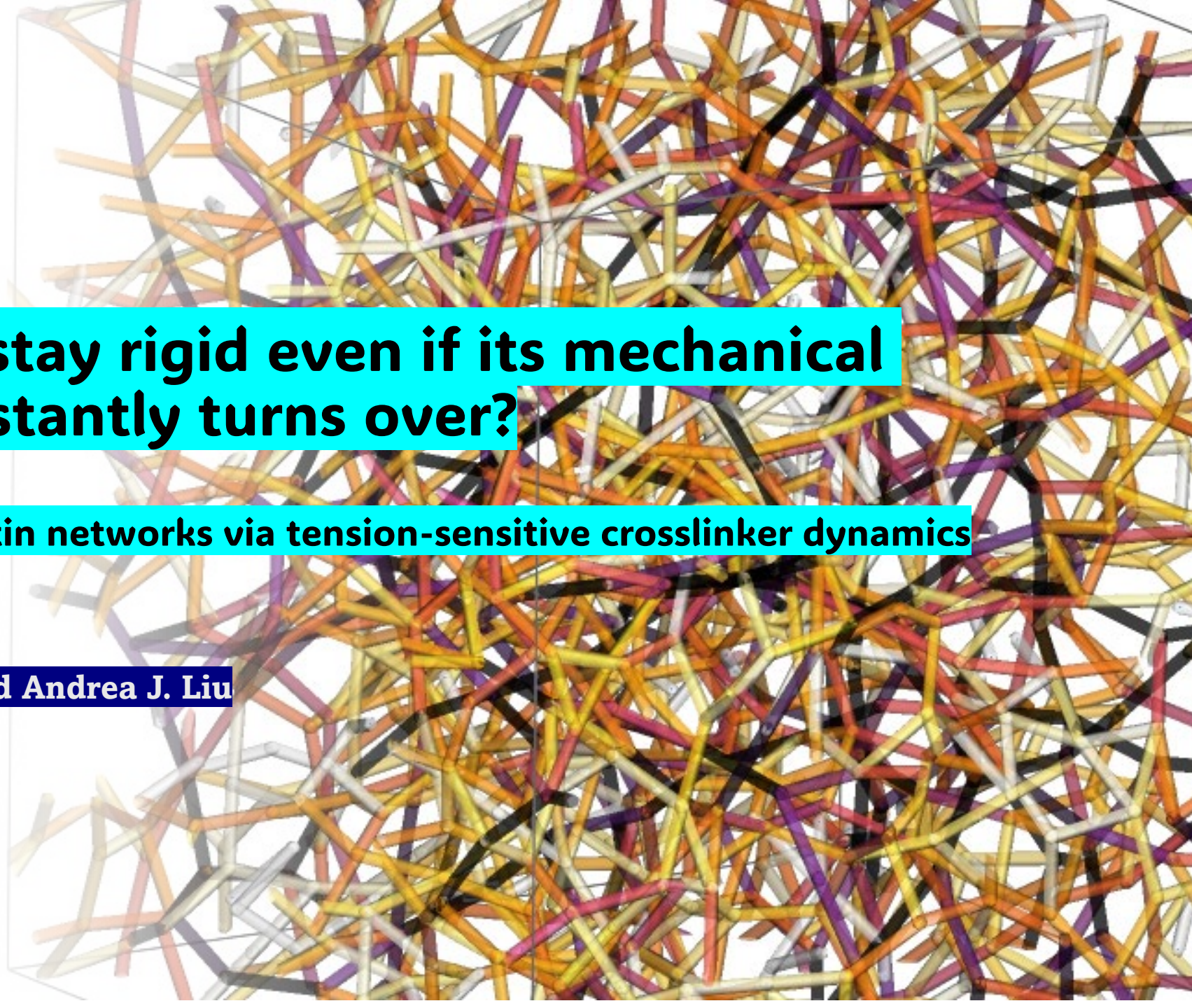


How does a cell stay rigid even if its mechanical architecture constantly turns over?

Rigidity homeostasis of actin networks via tension-sensitive crosslinker dynamics

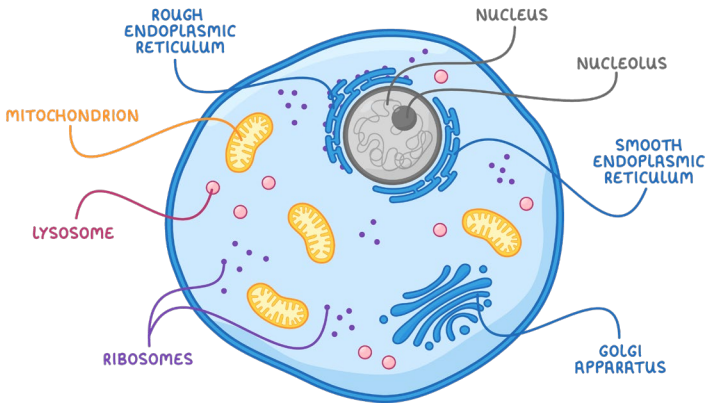
Haina Wang, John Crocker and Andrea J. Liu

University of Pennsylvania

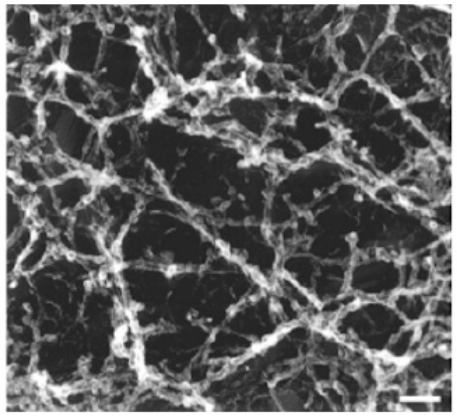
APS Global Physics Summit

Anaheim, March 2025

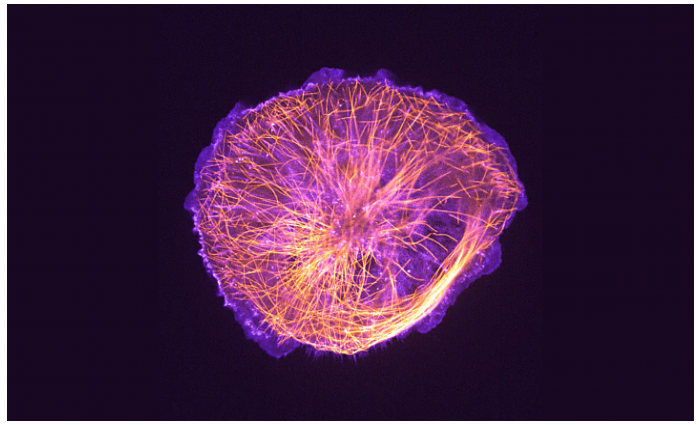
The cell cortex is a rigid and dynamic network.



ACTIN CORTEX



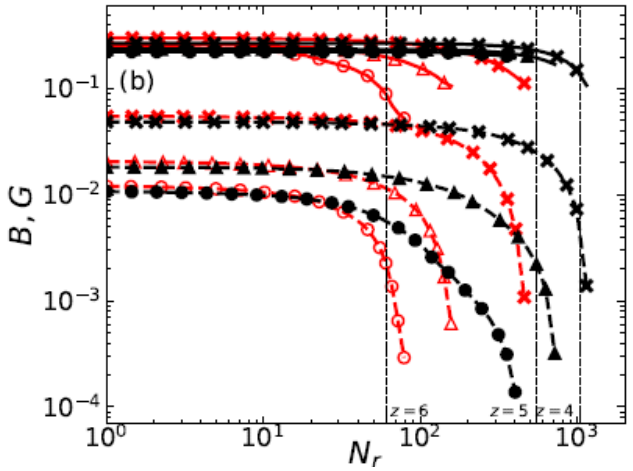
Stossel et al. 2001



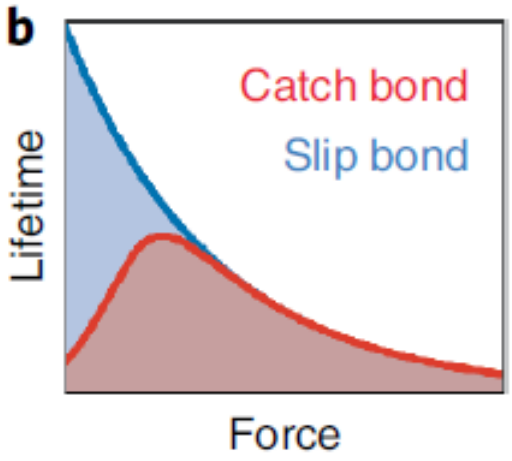
Van Haren 2016

- Maintains cell rigidity and essential in mechanical activities, e.g., division.
  - See works of Gardel, MacKintosh, Manning, …
- Regulated by many actin-binding proteins, e.g., motors and crosslinkers.
- Average coordination number is below Maxwellian isostaticity: **Tensional rigidity**
- Both filaments and crosslinkers undergo **fast turnover**; $t_{1/2}$~seconds. (Fritzsche 2013)

Tension/force-sensitive disassembly can be crucial to rigidity homeostasis.



Galvani et al. 2025

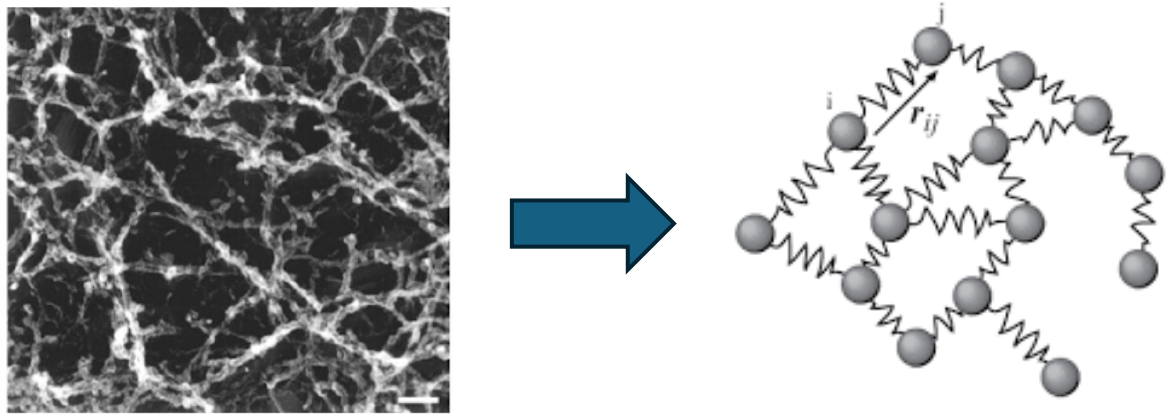


Mulla et al. 2022

- Tension-inhibited pruning of **filaments** maintains rigidity better than random pruning.

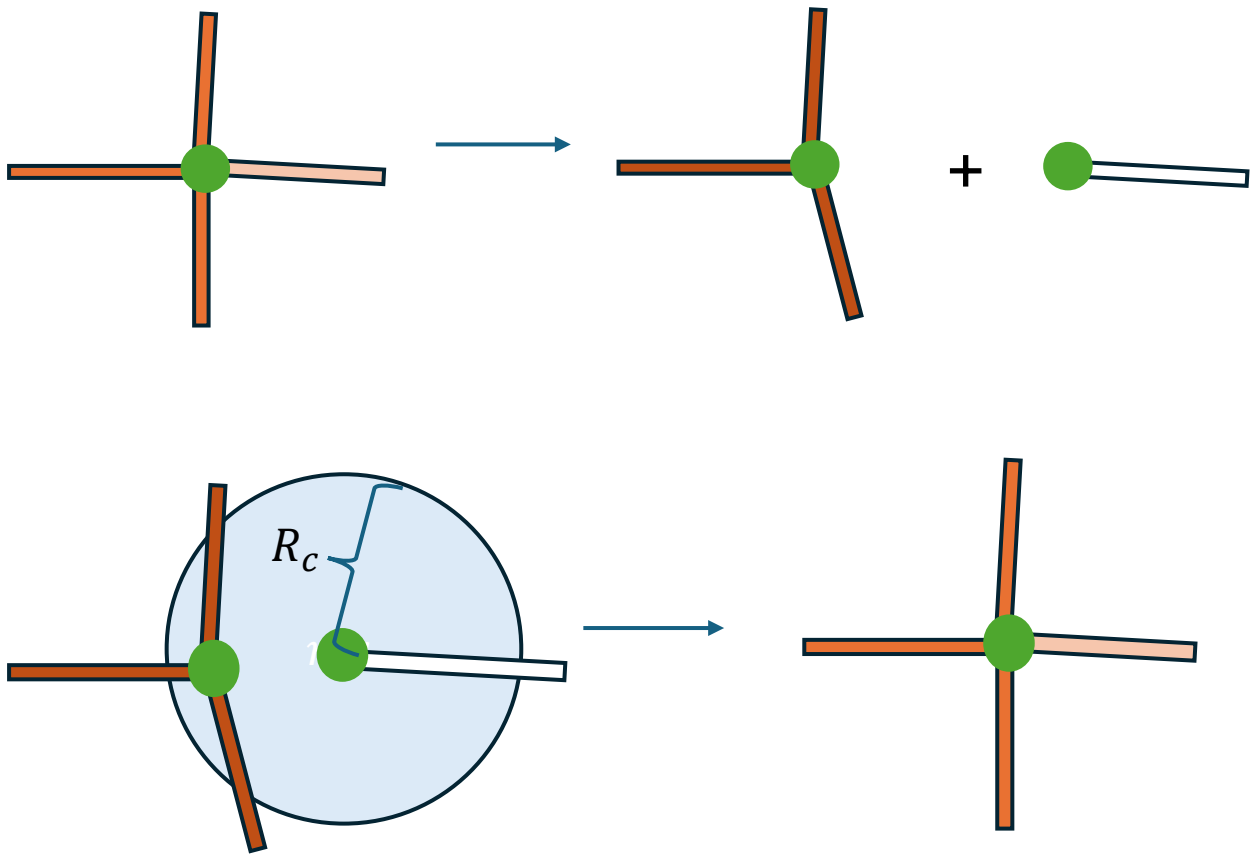
- Weak **catch bonds** can make stronger networks; supported by 1D simulation.
- **What dynamics must crosslinkers possess for the cortex to achieve rigidity with turnover?**

We model the cortex as a spring network.



- Actin filaments → edges
- Nodes → crosslinkers; Coordination number ≤ 4.
- Assume tension-dominated regime: bending rigidity not considered.
- Inspired by our group's work on edge dynamics, my goal is to **find node dynamics that yields rigidity homeostasis with complete node turnover.**

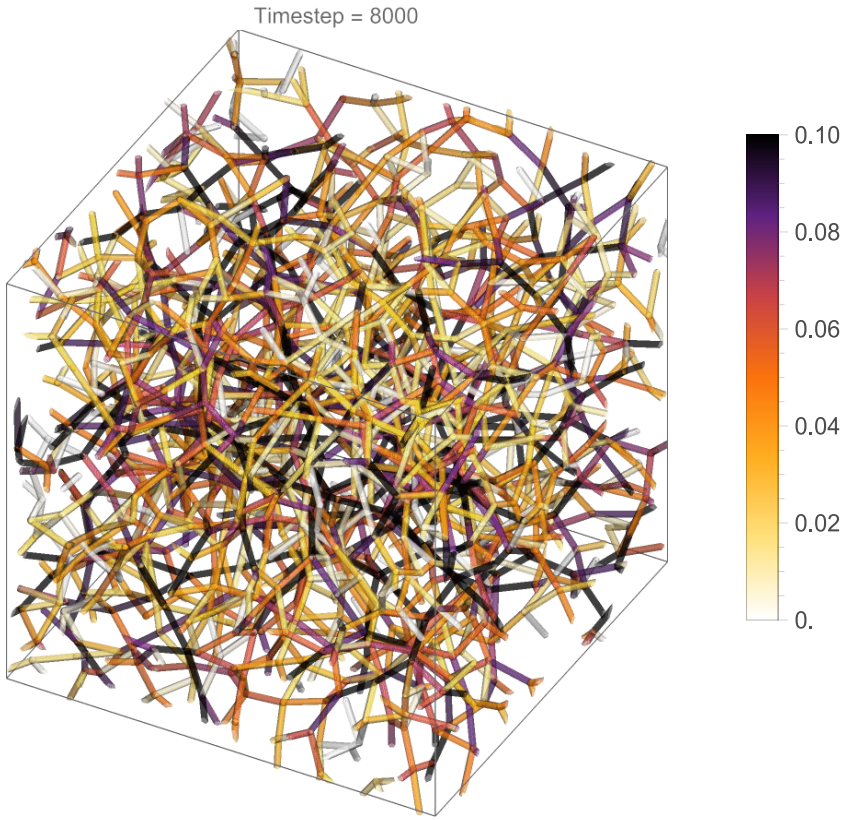
Here are the ingredients that made the model work (We need all of them.)

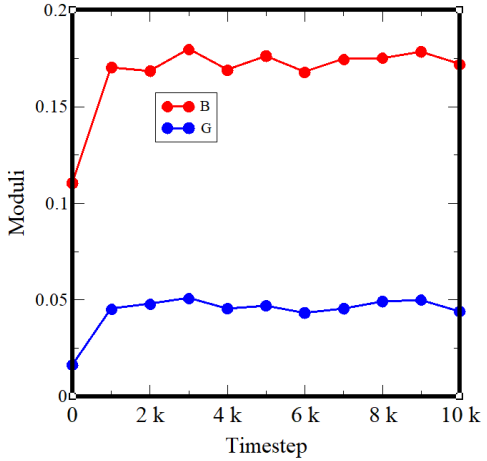


- **Force-sensitive disassembly.** A node splits with probability $k_{cb}dt$, if the tension on one of its edges < threshold f_{cb}.
- **Small fraction of random disassembly.** All nodes can be randomly split with probability $k_r dt$, where $k_r \ll k_{cb}$.
- **Assembly + Energy injection.** A $z \leq 3$ node with merges with its nearest degree-1 node within a capture sphere of radius R_c, with probability $k_m dt$.
- **Steric repulsion.** To compensate for phantom edges & prevent density instability.

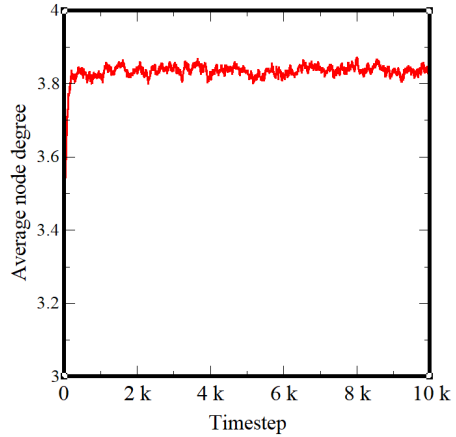
Our model achieves rigidity homeostasis with complete node turnover.

$t_{1/2}$ for random splits = 693 timesteps.

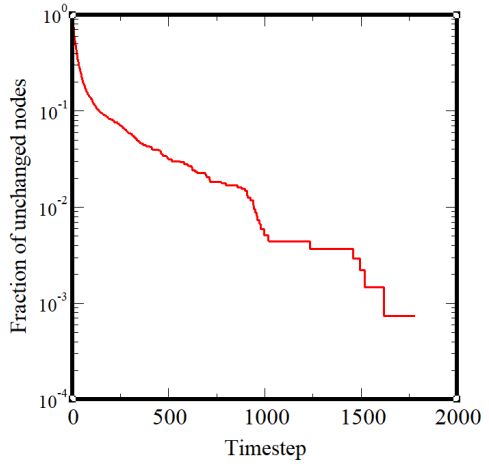




Elastic moduli reach steady state.



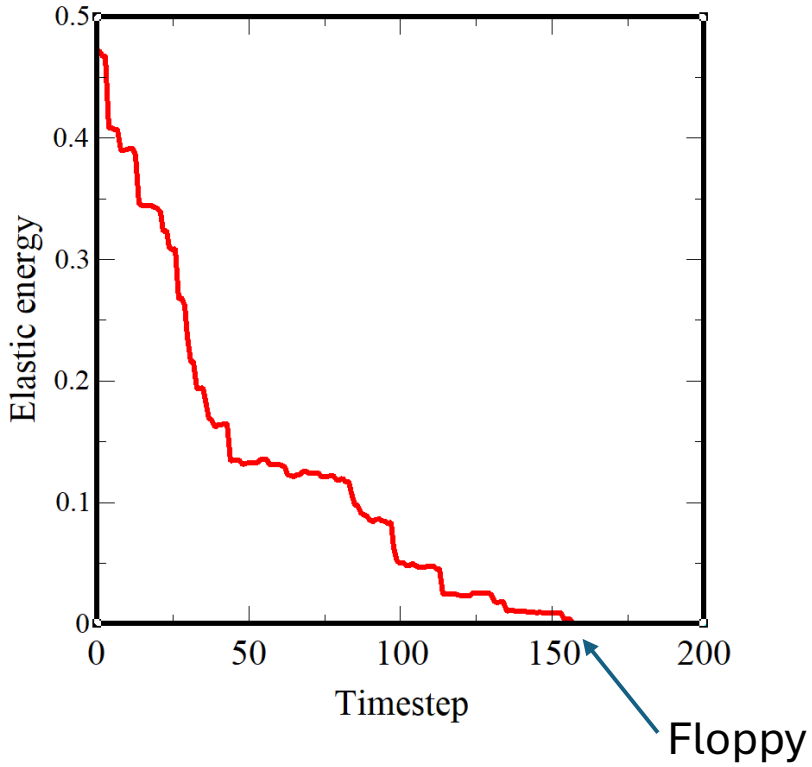
Mean node degree reaches steady state.



% of surviving node labels decay exponentially.
Complete turnover is reached.

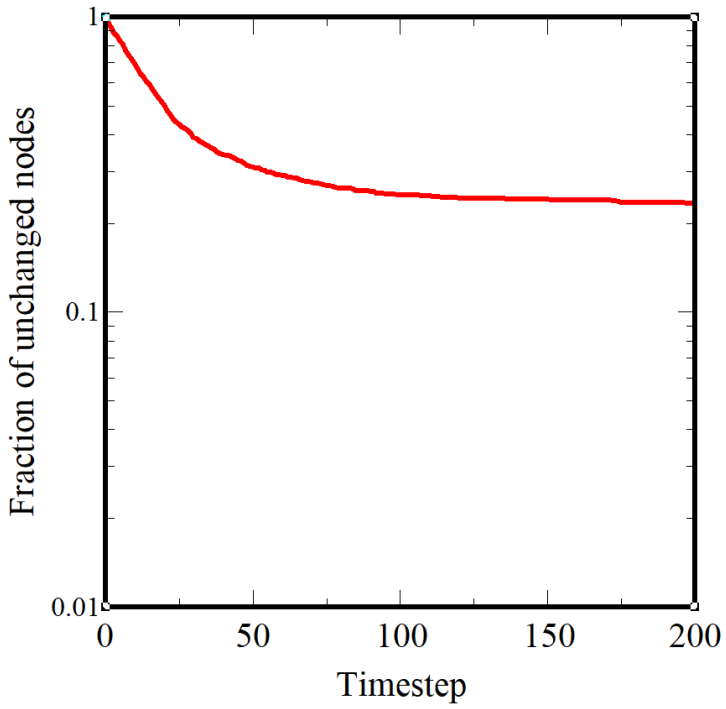
Both catch bonds' splits and random splits are required for homeostasis.

$k_{cb} = 0, k_r = 0.001$



No rigidity without catch bonds.

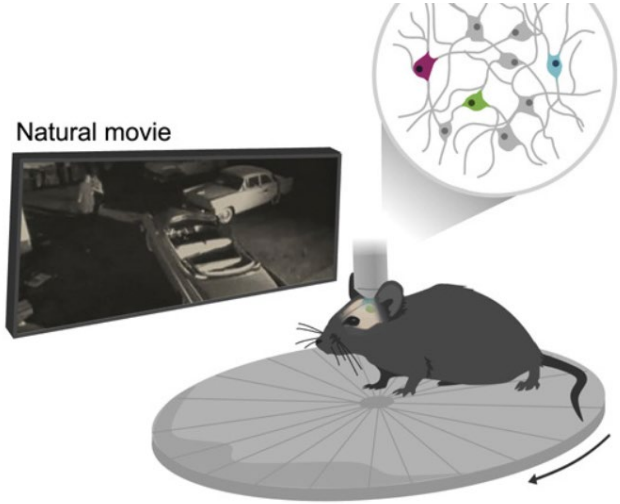
$k_{cb} = 0.1, k_r = 0$

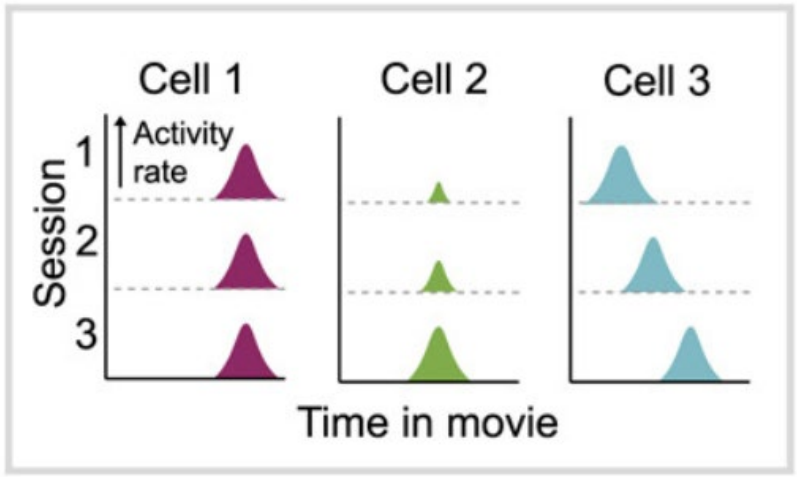


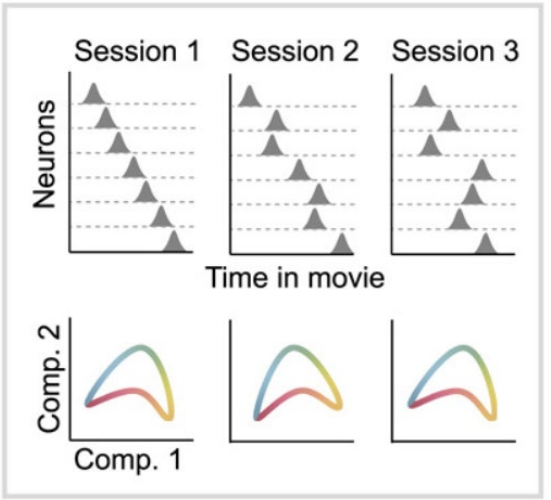
No turnover without random splitting.

We hypothesize that the cortex is a learning metamaterial.

- Why does the cortex spend so much energy turning over?
- Solving mechanical tasks while maintaining rigidity → Flexible learning capability.
- A signature of many learning systems is **representational drift**.
  - Shifting microscopic encoding for the same functionality.

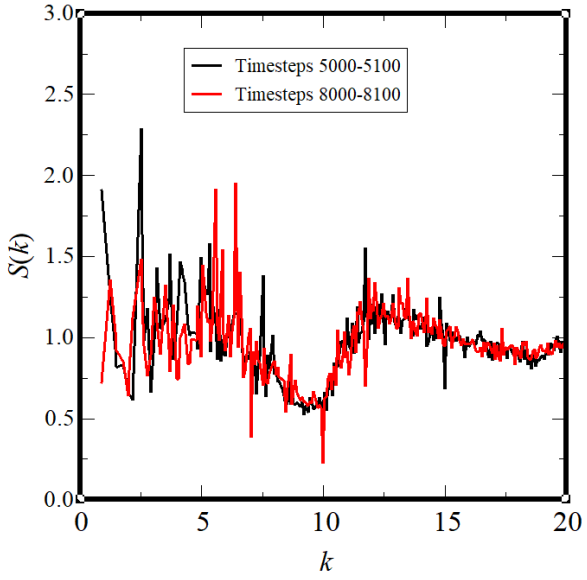




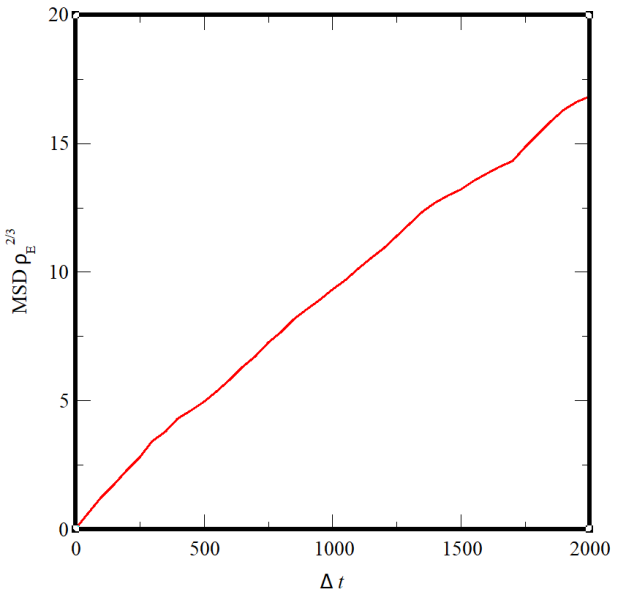


Deitch et al. 2021

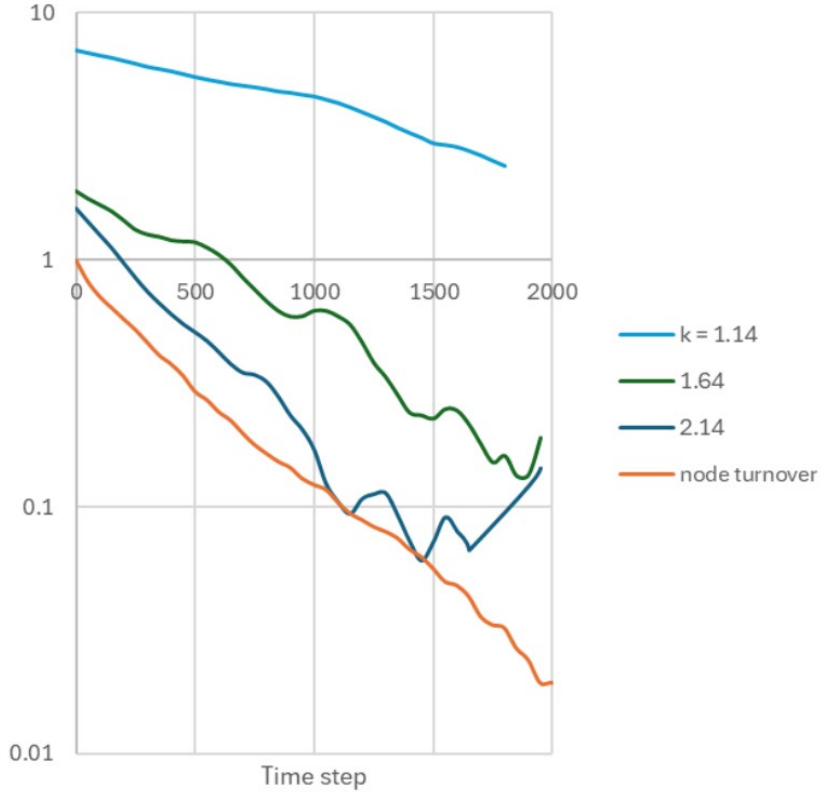
Our model has signatures analogous to representational drift.



Structure factors at times $4.3t_{1/2}$ apart match one another.



The edges are clearly diffusive.
[Need horizontal line around 1 for mesh size/edge length]



Large-scale structure decorrelates slower than the node turnover.

Need to know

- Force-sensitive disassembly, a small fraction of random disassembly and energy injection are elements required to achieve rigidity homeostasis.
- Our model has signatures of representational drift, typically found in learning systems.

- Future work: Mechanical responses and tasks that our cortex models can learn.

Acknowledgements

Andrea J. Liu

John C. Crocker

Marco A. Galvani Cunha

Building a model biopolymer network that remodels and maintains rigidity

3:48 pm – 4:00 pm

Presenter: Marco Aurelio Galvani Cunha (University of Pennsylvania)

Authors: Marco Aurelio Galvani Cunha (University of Pennsylvania), John Crocker (University of Pennsylvania), Andrea Liu (University of Pennsylvania)

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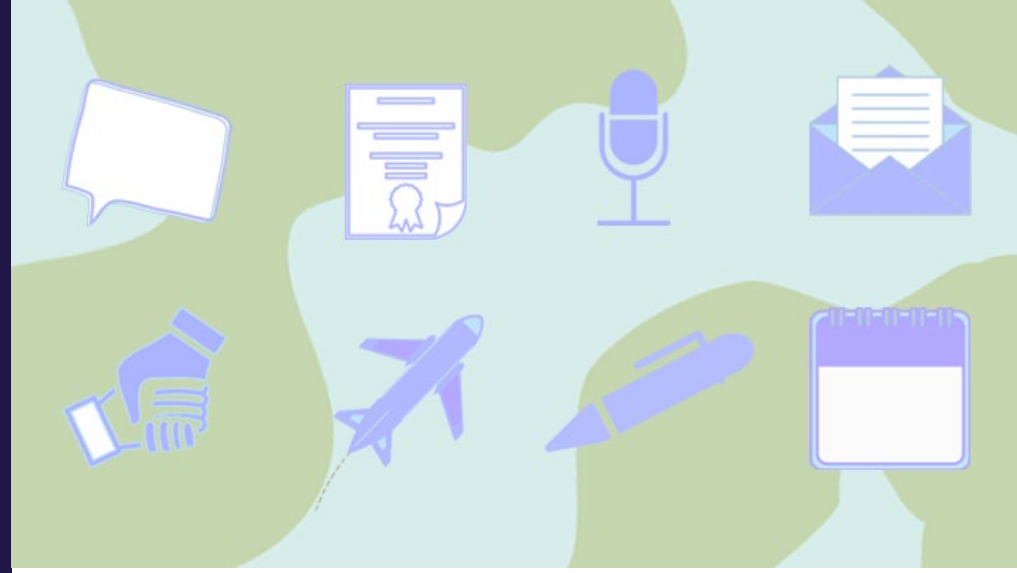
to Promote Human Rights in Science, Engineering, and Medicine

1. Highlight the Importance of Free Speech and the Dangers of Political Censorship for Work
2. Use your Expertise to Help Address Human Rights Challenges
3. Host a Discussion on Human Rights and/or Integrate Human Rights into your Teaching
4. Notify Human Rights Monitoring/Advocacy Bodies if you Suspect Rights Violations
5. Urge Institution to Assist Colleagues Fleeing Persecution Through Fellowships and Other Means
6. When Planning Travel, Learn about the State of Human Rights in your Destination
7. Write to U.S. and International Officials in Support of Colleagues
8. Stay Informed by Attending Human Rights Events

+ Ask me for this slide for you to share in your talks!



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