A network science for complexity & society

Brennan Klein

Northeastern University
Network Science Institute

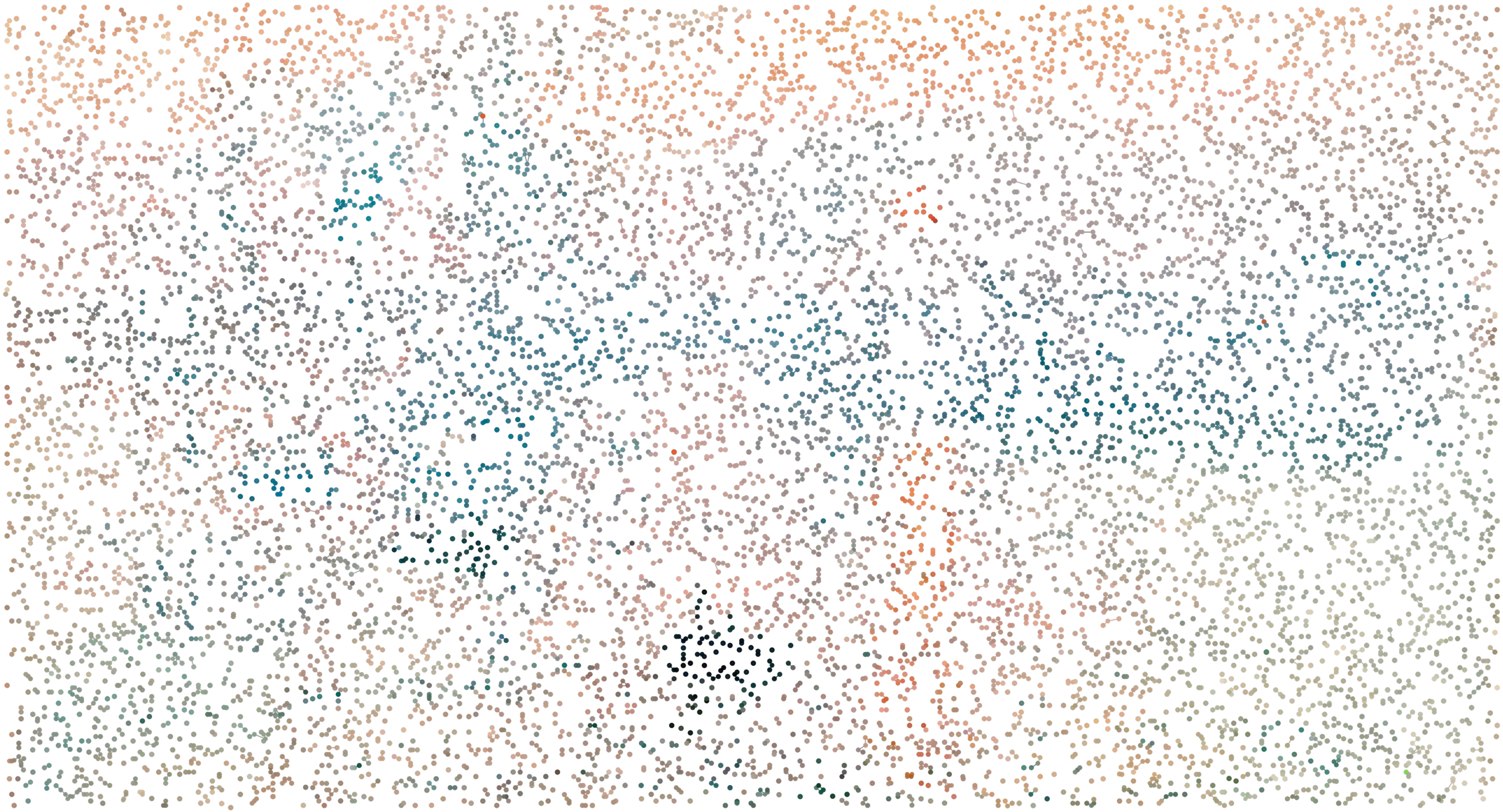
01 June, 2023

b.klein@northeastern.edu || @jkbren || brennanklein.com

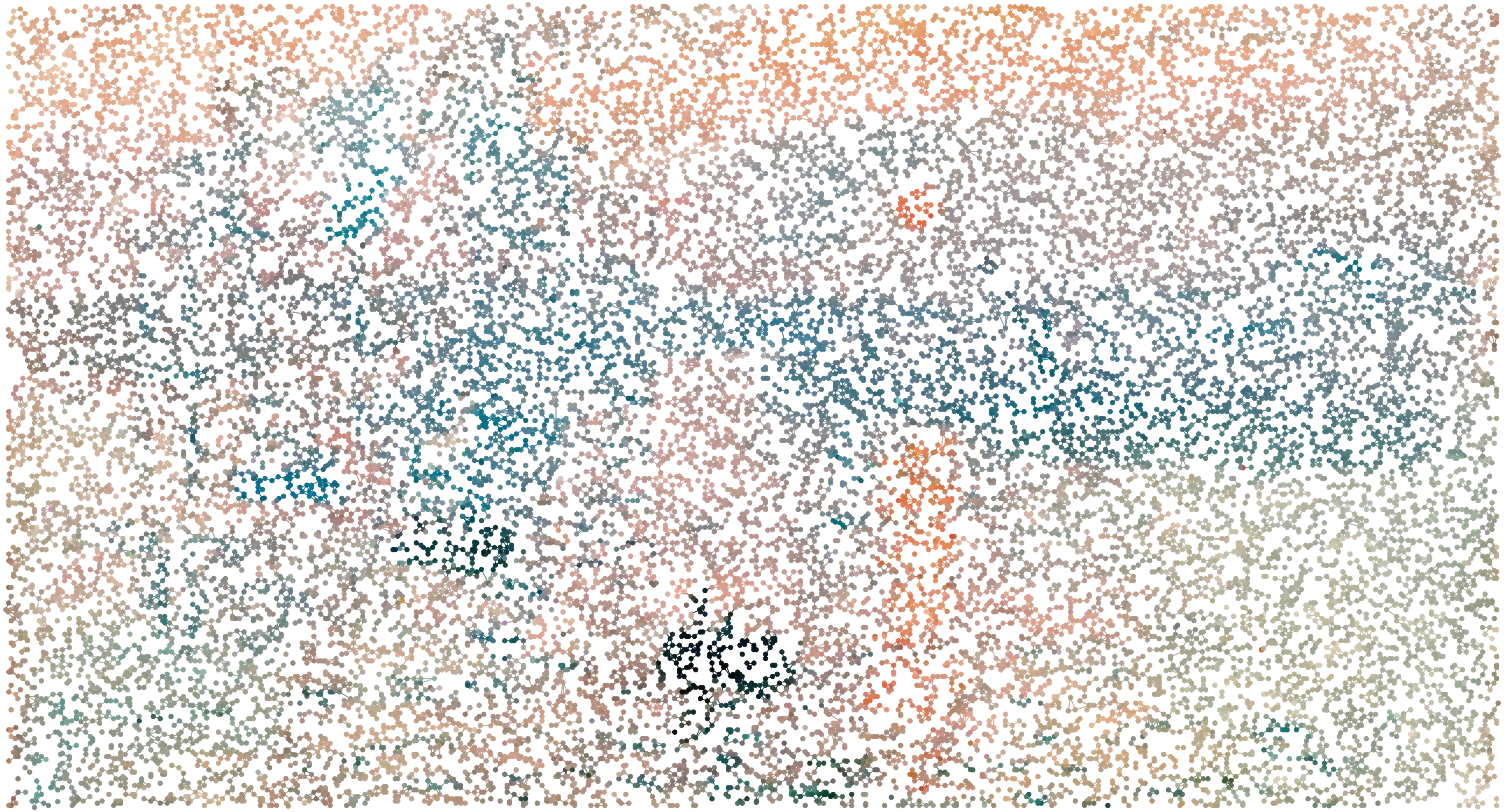
France Regional Conference on Complex Systems

Northeastern University Network Science Institute | Complexity & Society Lab @ Northeastern University | Harvard University | Hutchins Center for African & African American Research | VERSES | FRCCS

Network art based on "Impression, soleil levant" - Monet



Network art based on "Impression, soleil levant" - Monet



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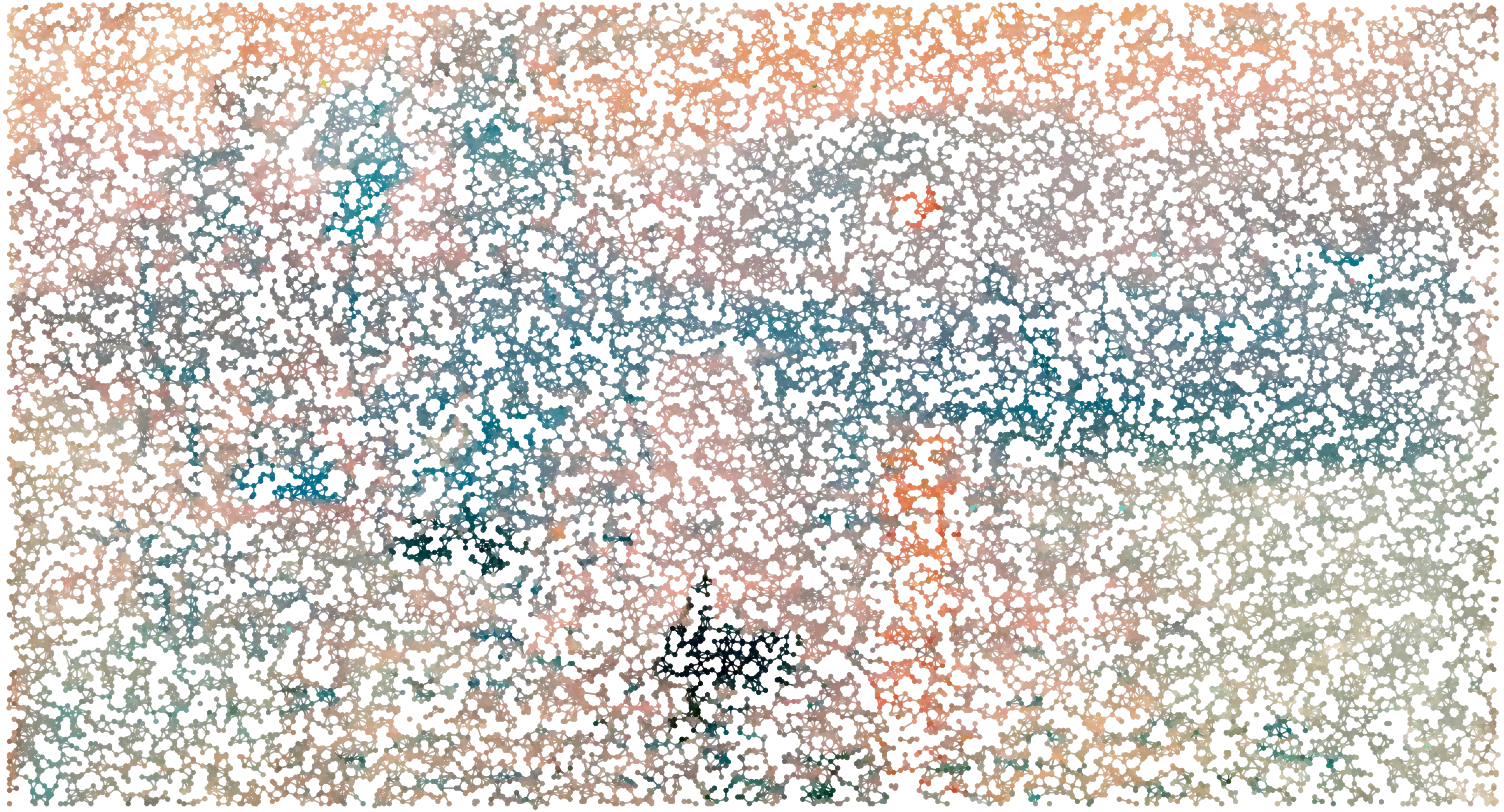
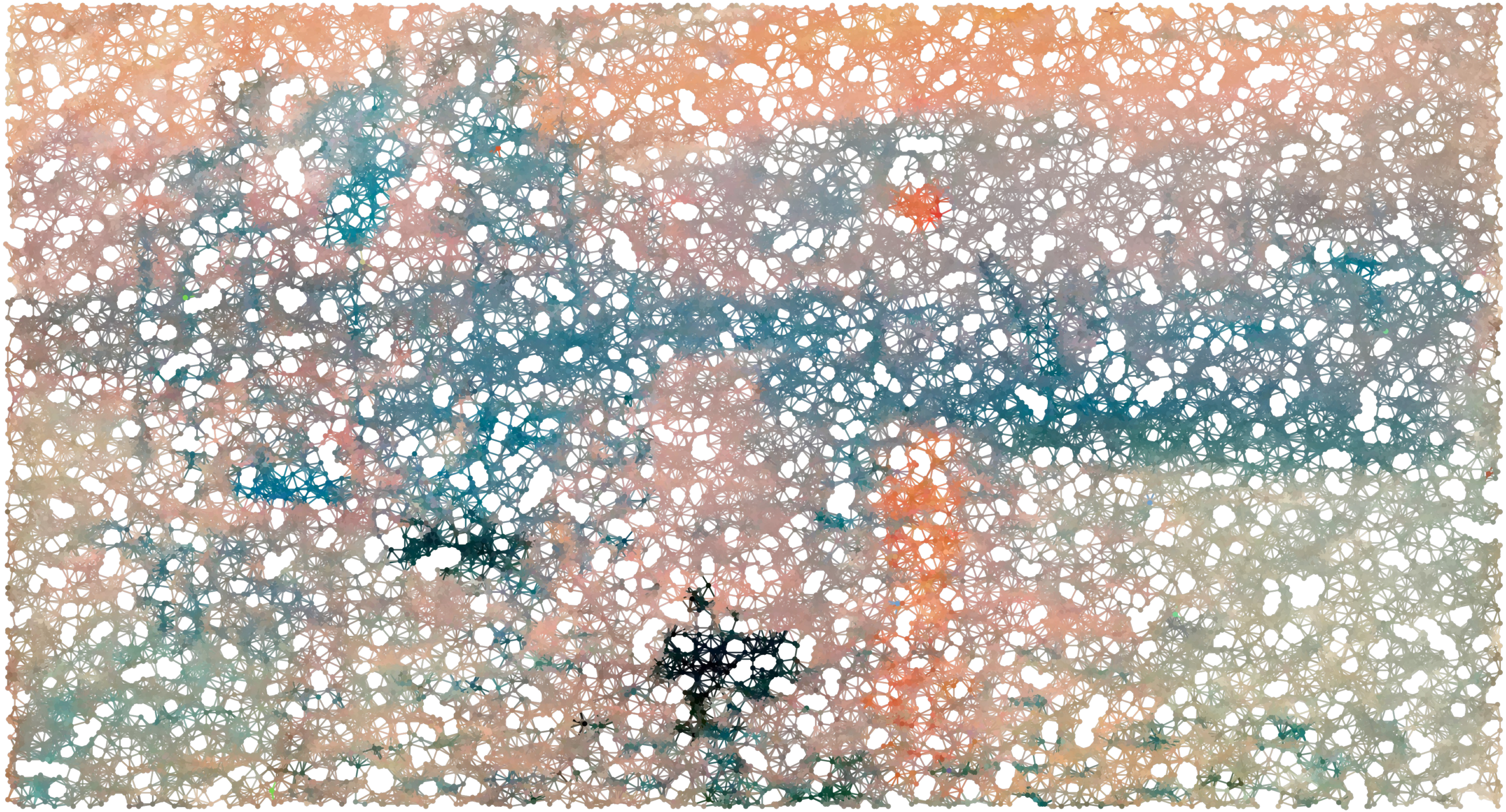
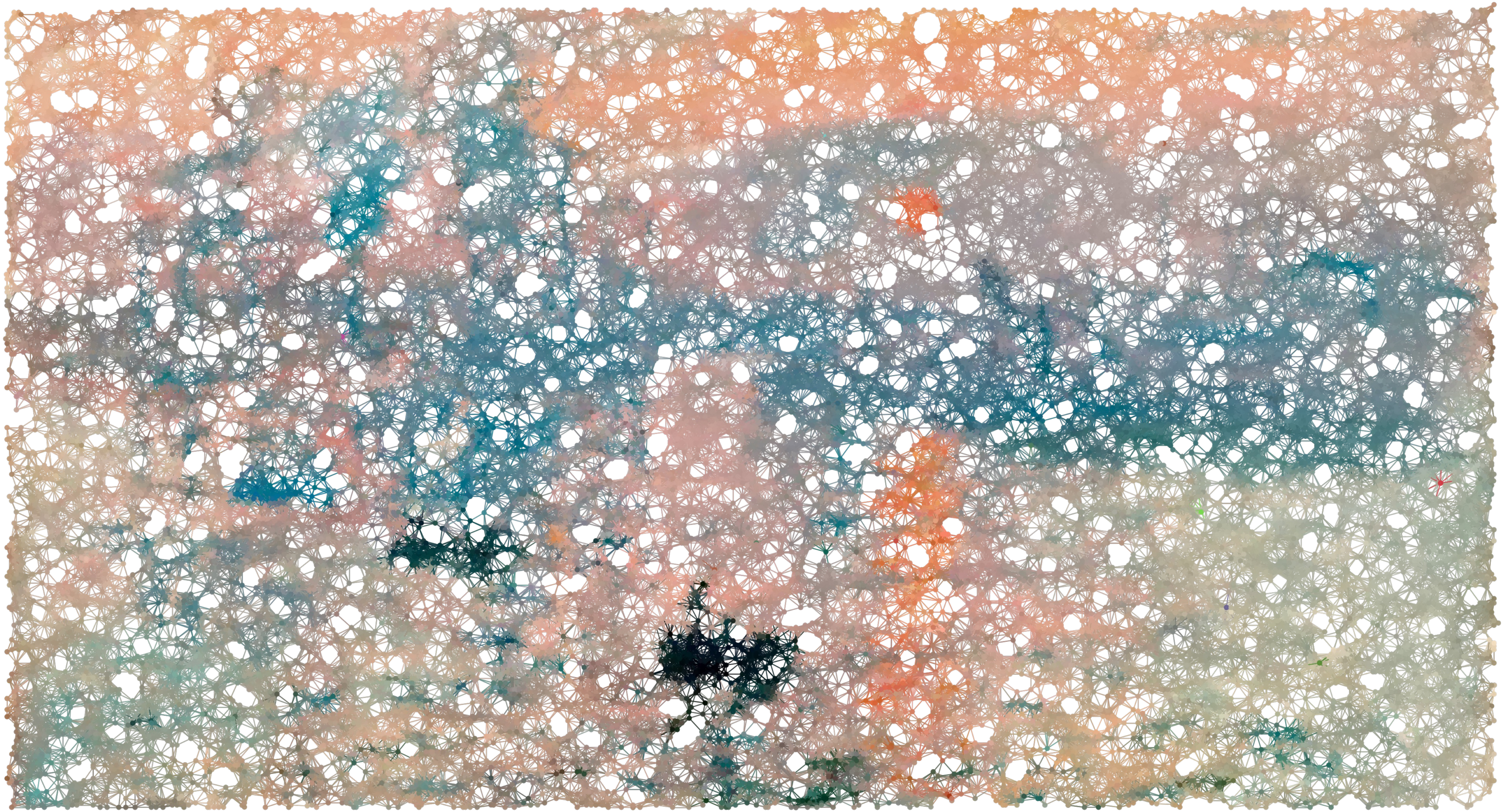


Network art based on "Impression, soleil levant" - Monet



Network art based on "Impression, soleil levant" - Monet



Network art based on "Impression, soleil levant" - Monet

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A network science
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France Regional Conference on Complex Systems

netsi Northeastern University *Network Science Institute*

Complexity & Society Lab @ Northeastern University

HARVARD UNIVERSITY

Hutchins Center for African & African American Research

VERSES

FRCCS

Network art based on "Impression, soleil levant" - Monet

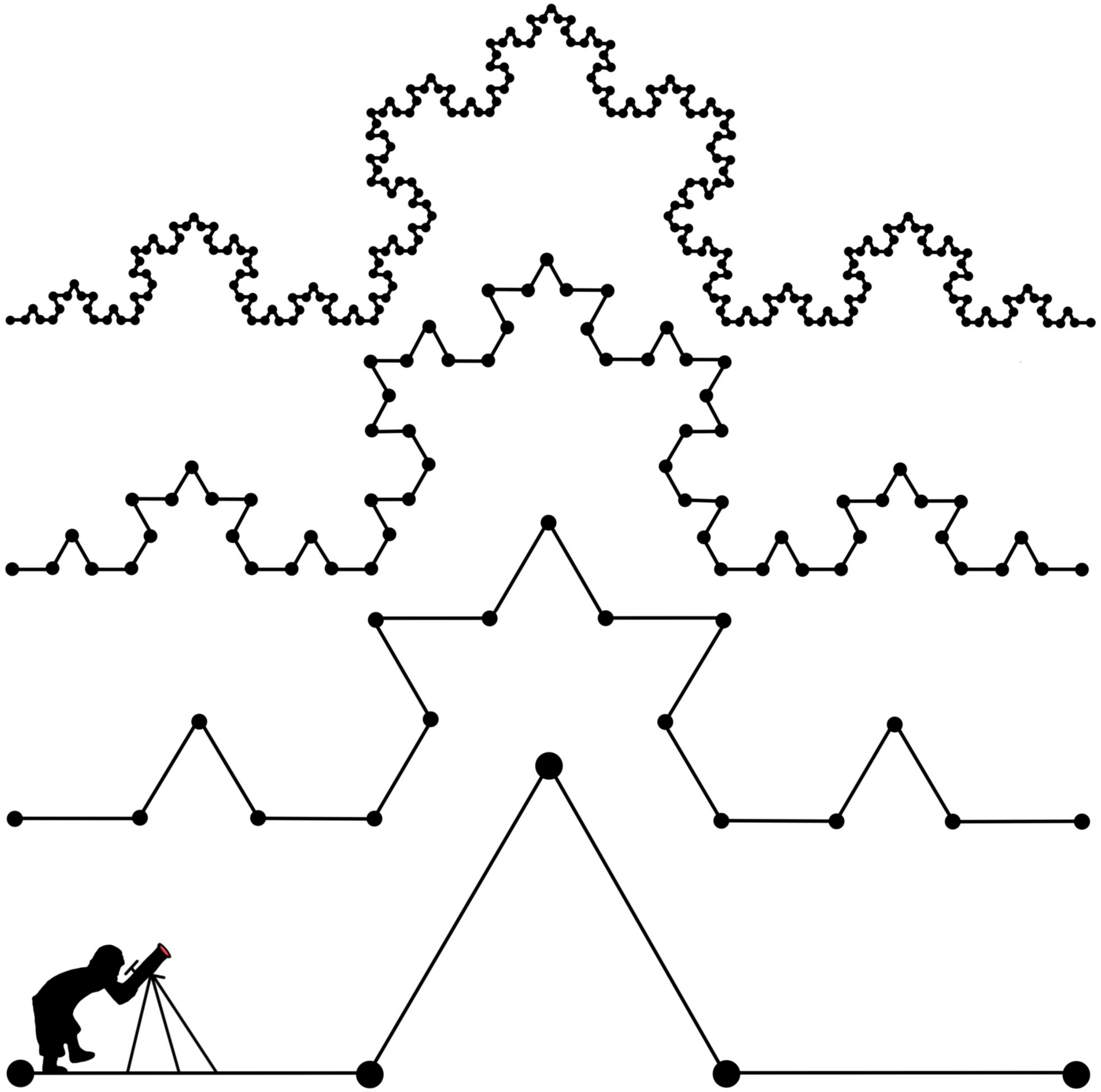
Thank you

FRCCS Organizing Committee
FRCCS Award Committee

Prof. Sam Scarpino
Prof. Alessandro Vespignani

Many collaborators

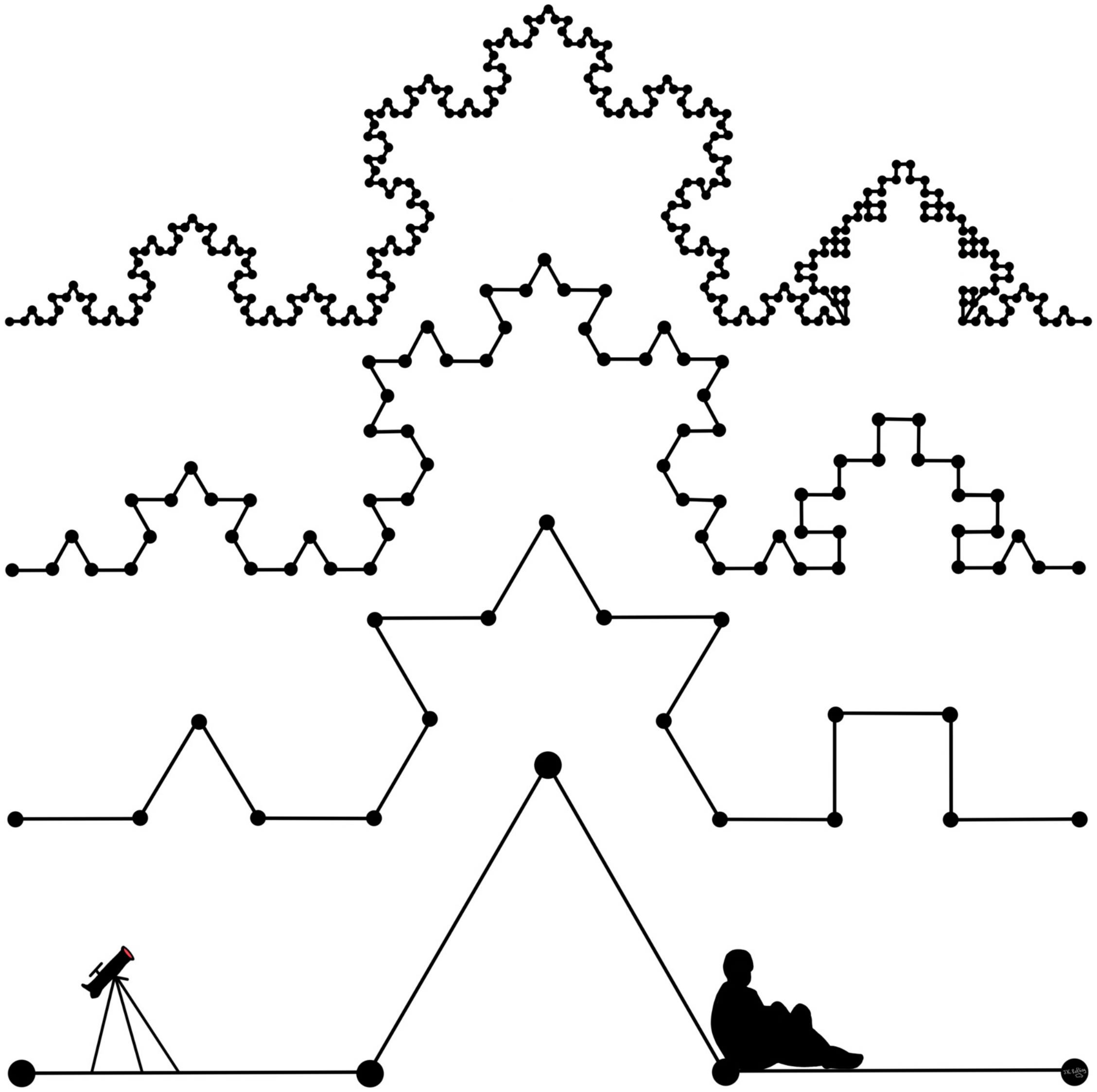
You all!



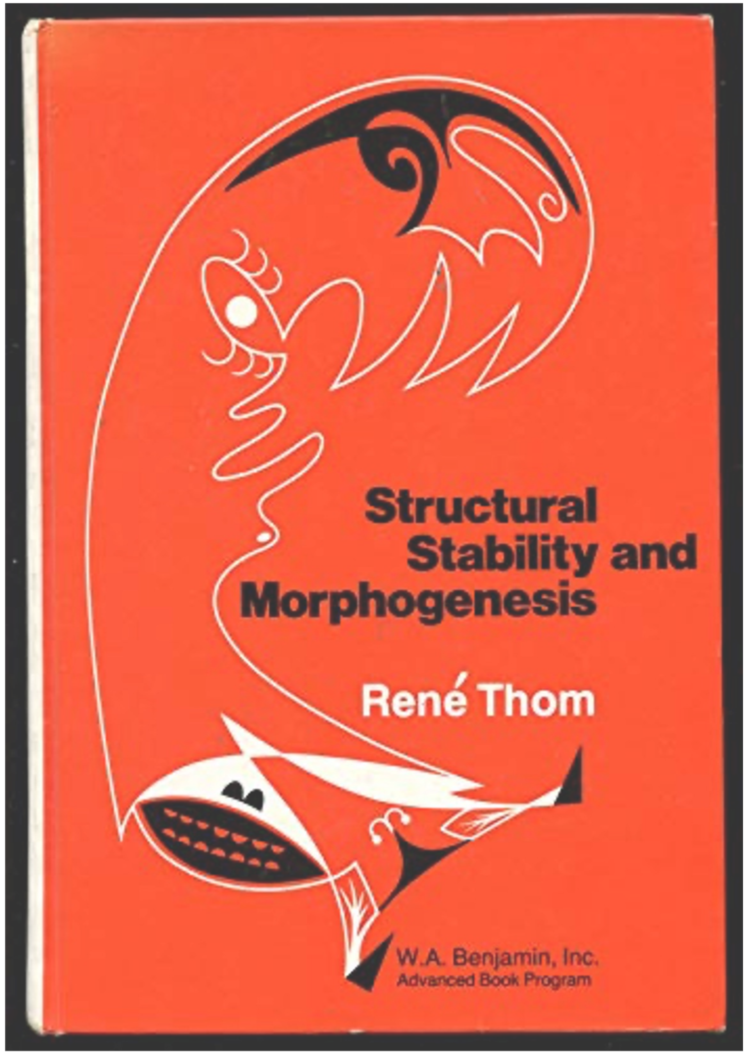
René Thom

“If one must choose between rigor and meaning, I shall unhesitatingly choose the latter.”

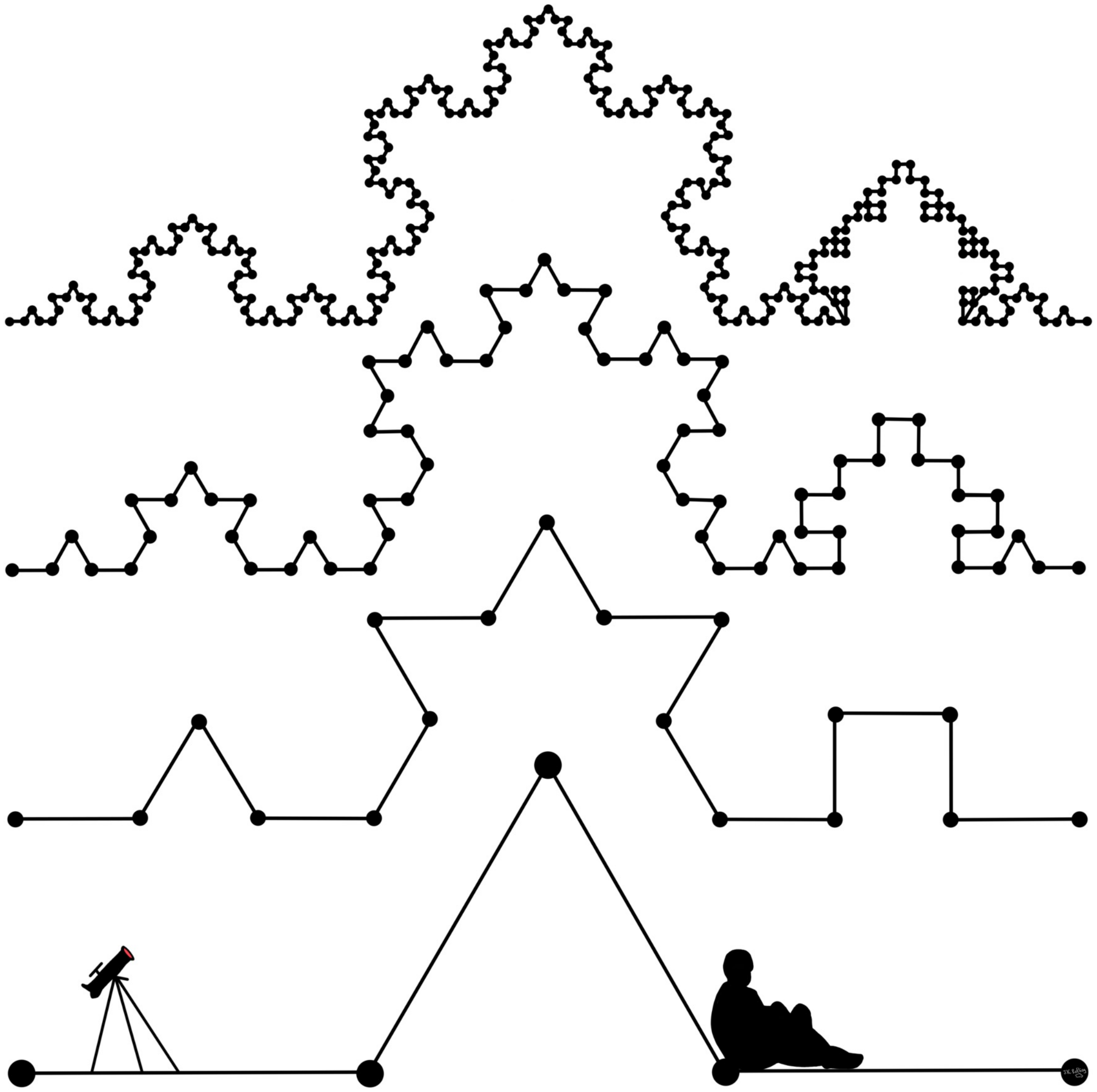
— René Thom



René Thom

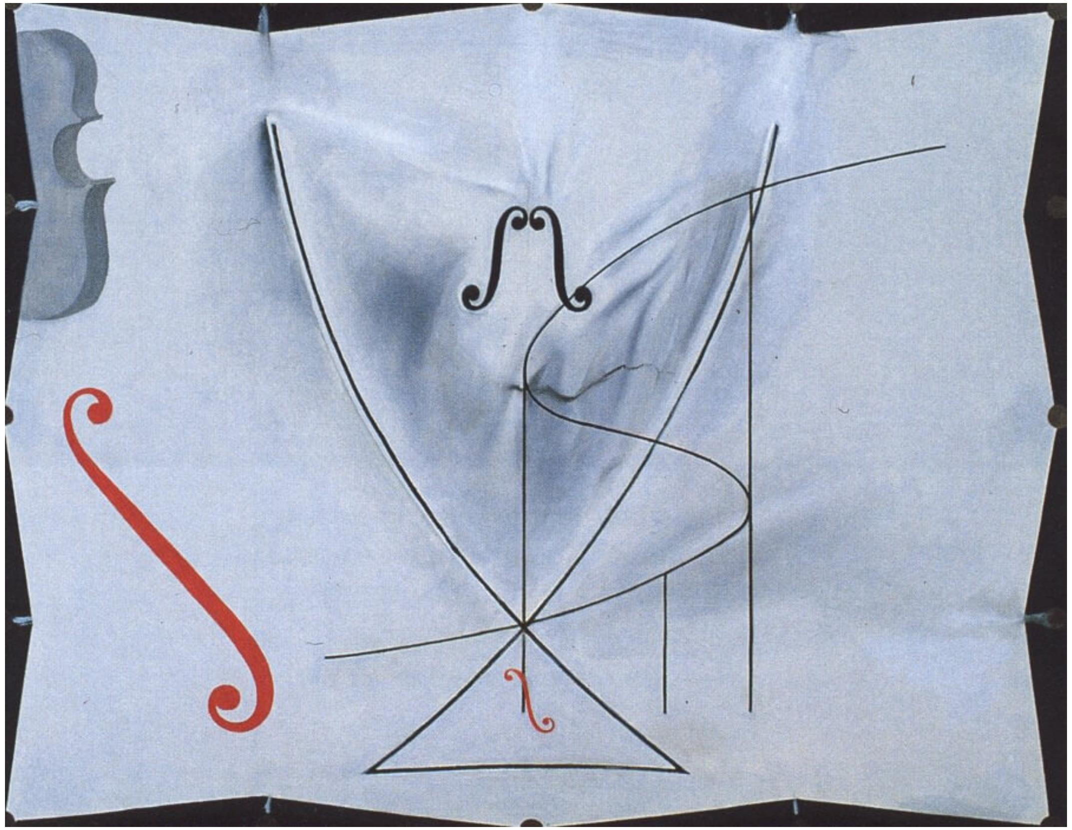


Structural Stability and Morphogenesis
René Thom
W.A. Benjamin, Inc.
Advanced Book Program

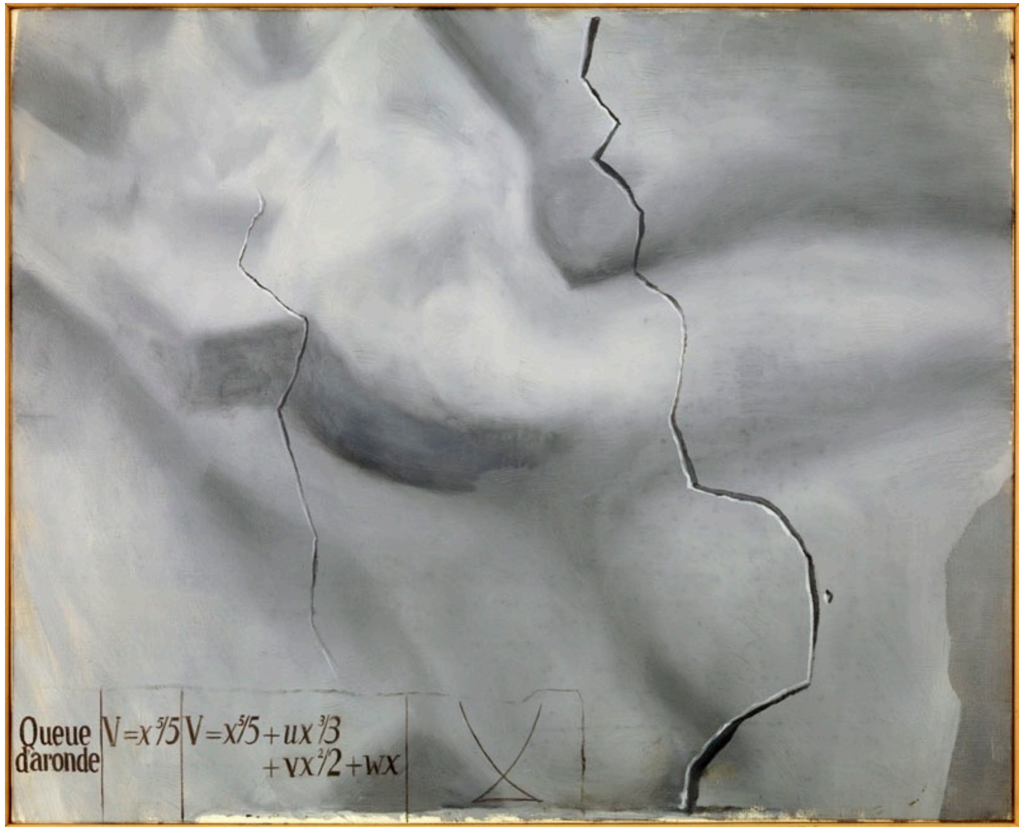


René Thom

Inspired works of art from Salvador Dalí…



“The Swallow's Tail” from the Series on Catastrophes, 1983



“Topological Abduction of Europe: Homage to Rene Thom”

About me

- Background: Cognitive Science
  (Swarthmore College: Philadelphia, USA)

- PhD: Network Science
  (Northeastern University: Boston, USA)

- Current position: Postdoctoral Researcher
  (Northeastern University: Boston, USA)
  - Also: Data for Justice Fellow, The Hutchins Center @Harvard
  - Also: Senior Research Scientist, VERSES Inc.

Prior work: Complexity

Research Article

WILEY Hindawi

The Emergence of Informative Higher Scales in Complex Networks

Brennan Klein[1,2] and Erik Hoel[3]

communications biology

ARTICLE

https://doi.org/10.1038/s42003-021-02867-8 OPEN

A computational exploration of resilience and evolvability of protein-protein interaction networks

Brennan Klein[1,2✉], Ludvig Holmér[3], Keith M. Smith[4✉], Mackenzie M. Johnson[5], Anshuman Swain[6], Laura Stolp[7], Ashley I. Teufel[5,8,9] & April S. Kleppe[10,11✉]

JOSS The Journal of Open Source Software

netrd: A library for network reconstruction and graph distances

Stefan McCabe[1], Leo Torres[1], Timothy LaRock[1], Syed Arefinul Haque[1], Chia-Hung Yang[1], Harrison Hartle[1], and Brennan Klein[1, 2]

JOSS The Journal of Open Source Software

pymdp: A Python library for active inference in discrete state spaces

Conor Heins[1,2,3,4¶], Beren Millidge[4,5], Daphne Demekas[6], Brennan Klein[4,7,8], Karl Friston[9], Iain D. Couzin[1,2,3], and Alexander Tschantz[4,10,11¶]

Received: 15 April 2021 | Accepted: 3 January 2022

DOI: 10.1111/2041-210X.13805

Methods in Ecology and Evolution

APPLICATION

Exploring noise, degeneracy and determinism in biological networks with the einet package

Brennan Klein[1,2] | Anshuman Swain[3] | Travis Byrum[3] | Samuel V. Scarpino[1,4,5,6] | William F. Fagan[3]

Evolution and emergence: higher order information structure in protein interactomes across the tree of life

Brennan Klein[1,2,*], Erik Hoel[3], Anshuman Swain[4], Ross Griebenow[5] and Michael Levin[3]

[1]Network Science Institute, Northeastern University, Boston, MA, USA
[2]Laboratory for the Modeling of Biological and Socio-Technical Systems, Northeastern University, Boston, MA, USA
[3]Allen Discovery Center, Tufts University, Medford, MA, USA
[4]Department of Biology, University of Maryland, College Park, MD, USA
[5]Department of Computer Science, Drexel University, Philadelphia, PA, USA
*Corresponding author. E-mail: b.klein@northeastern.edu

PROCEEDINGS A

royalsocietypublishing.org/journal/rspa

Research

Cite this article: Hartle H, Klein B, McCabe S, Daniels A, St-Onge G, Murphy C,

Network comparison and the within-ensemble graph distance

Harrison Hartle[1], Brennan Klein[1,2], Stefan McCabe[1], Alexander Daniels[3], Guillaume St-Onge[4,5], Charles Murphy[4,5] and Laurent Hébert-Dufresne[3,4,6]

Experimental Economics (2021) 24:772–799

https://doi.org/10.1007/s10683-020-09680-w

ORIGINAL PAPER

Optimal design of experiments to identify latent behavioral types

Stefano Balietti[1,2] · Brennan Klein[3] · Christoph Riedl[3,4,5,6]

International Workshop on Active Inference

↳ IWAI 2022: **Active Inference** pp 75–98 | Cite as

Home > Active Inference > Conference paper

Spin Glass Systems as Collective Active Inference

Conor Heins, Brennan Klein, Daphne Demekas, Miguel Aguilera & Christopher L. Buckley

Conference paper | First Online: 22 March 2023

INTERFACE FOCUS

royalsocietypublishing.org/journal/rsfs

On Bayesian mechanics: a physics of and by beliefs

Maxwell J. D. Ramstead[1,2,†], Dalton A. R. Sakthivadivel[1,3,4,5,†], Conor Heins[1,6,7,8], Magnus Koudahl[1,9], Beren Millidge[1,10], Lancelot Da Costa[2,11], Brennan Klein[1,12] and Karl J. Friston[1,2]

under review (*Journal of Consciousness Studies*)

The inner screen model of consciousness: applying the free energy principle directly to the study of conscious experience

Maxwell J. D. Ramstead*[1,2,A], Mahault Albarracin[1,3,A], Alex Kiefer[1,4], Brennan Klein[1,5], Chris Fields[6], Karl Friston[1,2], and Adam Safron[7,8]

under review (*Collective Intelligence*)

Designing Ecosystems of Intelligence from First Principles

Karl J. Friston[1,2], Maxwell J.D. Ramstead*[1,2], Alex B. Kiefer[1,3], Alexander Tschantz[1], Christopher L. Buckley[1,4], Mahault Albarracin[1,5], Riddhi J. Pitliya[1,6], Conor Heins[1,7,8,9], Brennan Klein[1,10], Beren Millidge[1,11], Dalton A.R. Sakthivadivel[1,12,13,14], Toby St Clere Smithe[1,6,15], Magnus Koudahl[1,16], Safae Essafi Tremblay[1,17], Capm Petersen[1], Kaiser Fung[1], Jason G. Fox[1], Steven Swanson[1], Dan Mapes[1], and Gabriel René[1]

Prior work: Society

RESEARCH

CORONAVIRUS

The effect of human mobility and control measures on the COVID-19 epidemic in China

Moritz U. G. Kraemer[1,2,3]*, Chia-Hung Yang[4], Bernardo Gutierrez[1,5], Chieh-Hsi Wu[6], Brennan Klein[4], David M. Pigott[7], Open COVID-19 Data Working Group†, Louis du Plessis[1], Nuno R. Faria[1], Ruoran Li[8], William P. Hanage[8], John S. Brownstein[2,3], Maylis Layan[9,10], Alessandro Vespignani[4,11], Huaiyu Tian[12], Christopher Dye[1], Oliver G. Pybus[1,13]*, Samuel V. Scarpino[4]*

RESEARCH

CORONAVIRUS

Spatiotemporal invasion dynamics of SARS-CoV-2 lineage B.1.1.7 emergence

Moritz U. G. Kraemer[1]*†, Verity Hill[2]†, Christopher Ruis[3]†, Simon Dellicour[4,5]†, Sumali Bajaj[1]†, John T. McCrone[2], Guy Baele[5], Kris V. Parag[6], Anya Lindström Battle[7], Bernardo Gutierrez[1], Ben Jackson[2], Rachel Colquhoun[2], Áine O'Toole[2], Brennan Klein[8], Alessandro Vespignani[8], COVID-19 Genomics UK (COG-UK) Consortium‡, Erik Volz[6], Nuno R. Faria[1,6,9], David M. Aanensen[10,11], Nicholas J. Loman[12], Louis du Plessis[1], Simon Cauchemez[13], Andrew Rambaut[2]*, Samuel V. Scarpino[8,14,15]*, Oliver G. Pybus[1,16]*

ARTICLE

https://doi.org/10.1038/s41467-021-22521-5 OPEN

Check for updates

The effect of eviction moratoria on the transmission of SARS-CoV-2

Anjalika Nande[1,7], Justin Sheen[2,7], Emma L. Walters[3], Brennan Klein[4,5], Matteo Chinazzi[4,5], Andrei H. Gheorghe[1], Ben Adlam[1], Julianna Shinnick[2], Maria Florencia Tejeda[2], Samuel V. Scarpino[4], Alessandro Vespignani[4,5], Andrew J. Greenlee[3], Daniel Schneider[3], Michael Z. Levy[2,8]✉ & Alison L. Hill[1,6,8]✉

communications medicine

nature > communications medicine > articles > article

Article | Open Access | Published: 14 February 2023

Forecasting hospital-level COVID-19 admissions using real-time mobility data

Brennan Klein, Ana C. Zenteno, Daisha Joseph, Mohammadmehdi Zahedi, Michael Hu, Martin S. Copenhaver, Moritz U. G. Kraemer, Matteo Chinazzi, Michael Klompas, Alessandro Vespignani, Samuel V. Scarpino & Hojjat Salmasian

Clinical Infectious Diseases

CORRECTED PROOF

Examining the Robustness of 3 Versus 6 Feet of Physical Distancing in Schools: A Reanalysis of van den Berg et al FREE

Brennan Klein ✉, Daniel A Harris

PLOS DIGITAL HEALTH

RESEARCH ARTICLE

Higher education responses to COVID-19 in the United States: Evidence for the impacts of university policy

Brennan Klein[1,2]*, Nicholas Generous[1,2,3], Matteo Chinazzi[1,2], Zarana Bhadricha[1,4], Rishab Gunashekar[1,4], Preeti Kori[1,4], Bodian Li[1,5], Stefan McCabe[1], Jon Green[1,6], David Lazer[1], Christopher R. Marsicano[7,8], Samuel V. Scarpino[1,9,10], Alessandro Vespignani[1,2]*

nature

nature > articles > article

Article | Open Access | Published: 19 April 2023

COVID-19 amplified racial disparities in the US criminal legal system

Brennan Klein, C. Brandon Ogbunugafor, Benjamin J. Schafer, Zarana Bhadricha, Preeti Kori, Jim Sheldon, Nitish Kaza, Arush Sharma, Emily A. Wang, Tina Eliassi-Rad, Samuel V. Scarpino & Elizabeth Hinton

under review (*PNAS*)

Spatial scales of COVID-19 transmission in Mexico

Brennan Klein[*1,2], Harrison Hartle[1], Munik Shrestha[1], Ana Cecilia Zenteno[3], David Barros Sierra Cordera[4], José R. Nicolas-Carlock[5], Ana I. Bento[6], Benjamin M. Althouse[7,8], Bernardo Gutierrez[9,10,11], Marina Escalera-Zamudio[9,11], Arturo Reyes-Sandoval[12,13], Oliver G. Pybus[9,14,18], Alessandro Vespignani[1,2], Alberto Diaz Quiñonez[*†15], Samuel V. Scarpino[*‡1,16,17], and Moritz U.G. Kraemer[*§9,18]

revision (*PLOS Digital Health*)

Characterizing collective physical distancing in the U.S. during the first nine months of the COVID-19 pandemic

Brennan Klein[*1], Timothy LaRock[*1], Stefan McCabe[*1], Leo Torres[*1], Lisa Friedland[*1], Maciej Kos[*1], Filippo Privitera[4], Brennan Lake[4], Moritz U.G. Kraemer[5], John S. Brownstein[6,7], Richard Gonzalez[8], David Lazer[1], Tina Eliassi-Rad[1], Samuel V. Scarpino[1,9,10], Alessandro Vespignani[1,3], and Matteo Chinazzi[§1,2]

Complexity & Society Lab (the “And Lab”)

Harrison Hartle
PhD Candidate,
Network Science

Brein Mosely
PhD Student,
Education

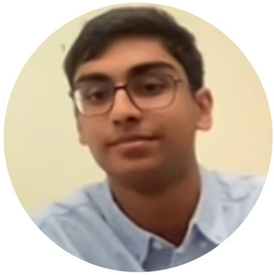
Conor Heins
PhD Student,
Collective Behavior

Christina Steele
Research Assistant,
Data for Justice

Moritz Laber
PhD Student,
Network Science

Daphne Demekas
Research Assistant,
Artificial Intelligence

Oghenetega Ogodo
MS Student,
Urban Planning

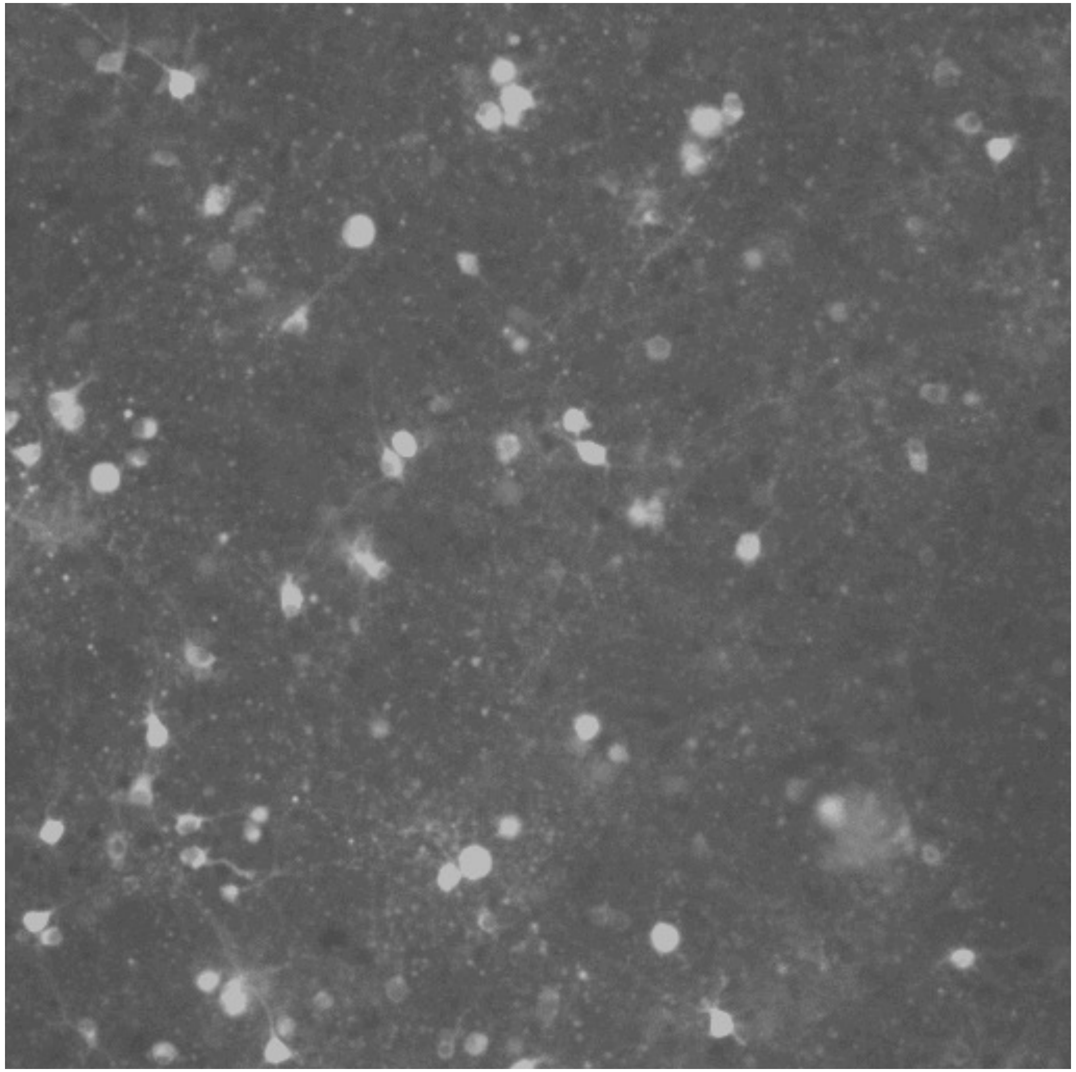


Arush Sharma
Research Assistant,
Data for Justice

Today

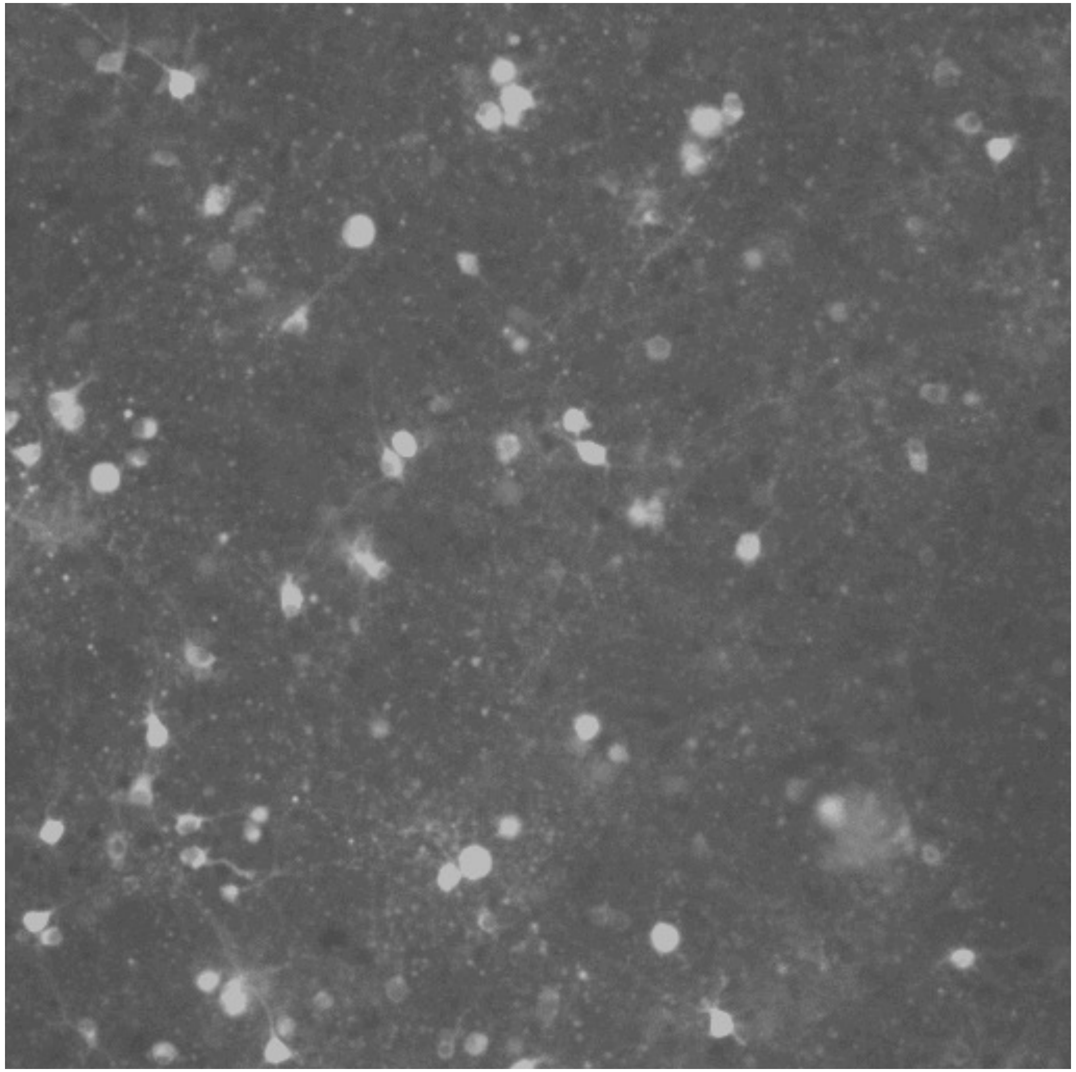
1. Introduction
2. Complexity
   i. *Representation & comparison*
   ii. *Informative scales in networks*
3. Society
   i. *Mobile device data for disease modeling*
   ii. *Assorted COVID-19 projects*
4. Research vision and outlook

Networks of thought



This is a recording of neurons from the hippocampus of a brain suffering from Alzheimer's.

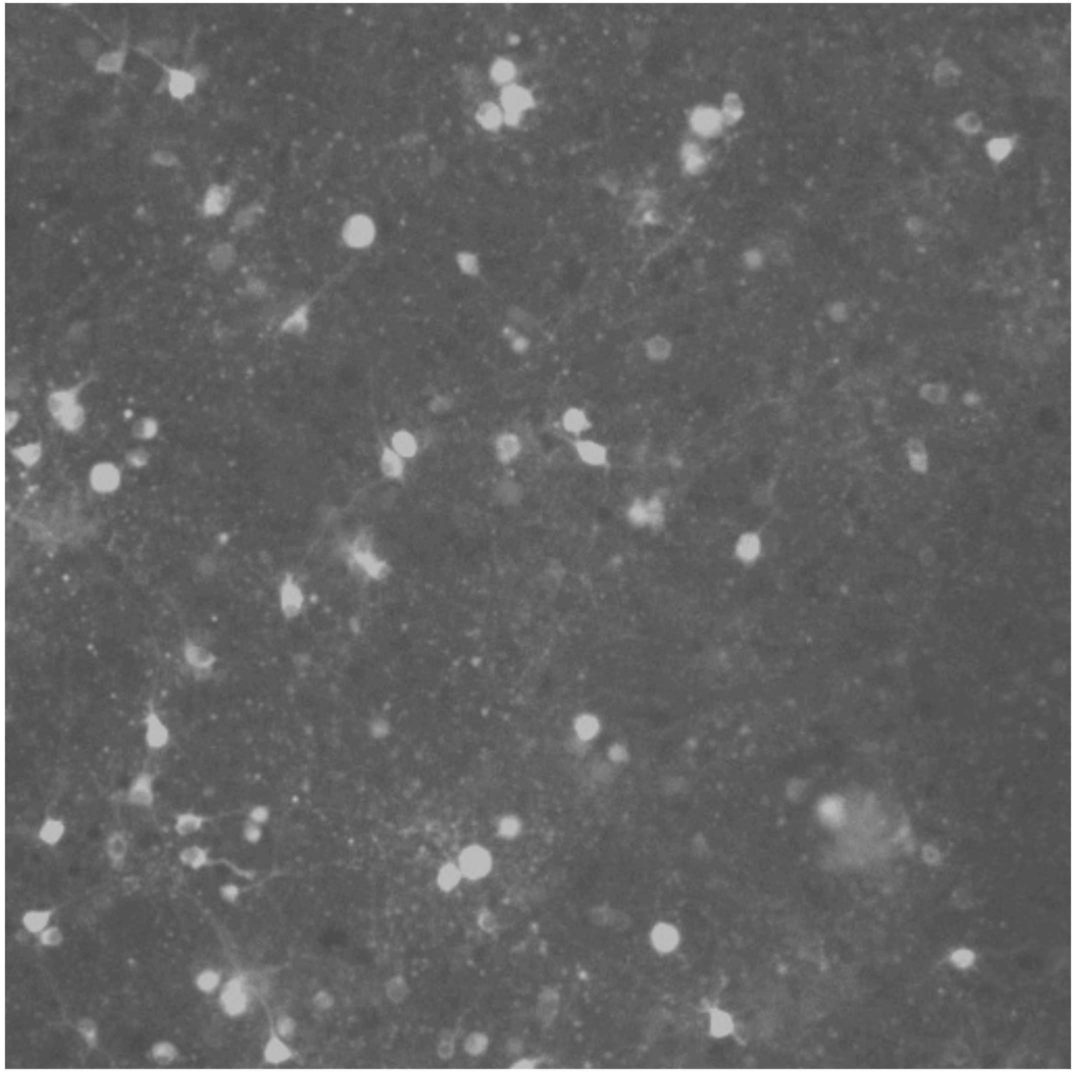
Networks of thought



This is a recording of neurons from the hippocampus of a brain suffering from Alzheimer's.

I want to cure this disease by studying ecosystems.

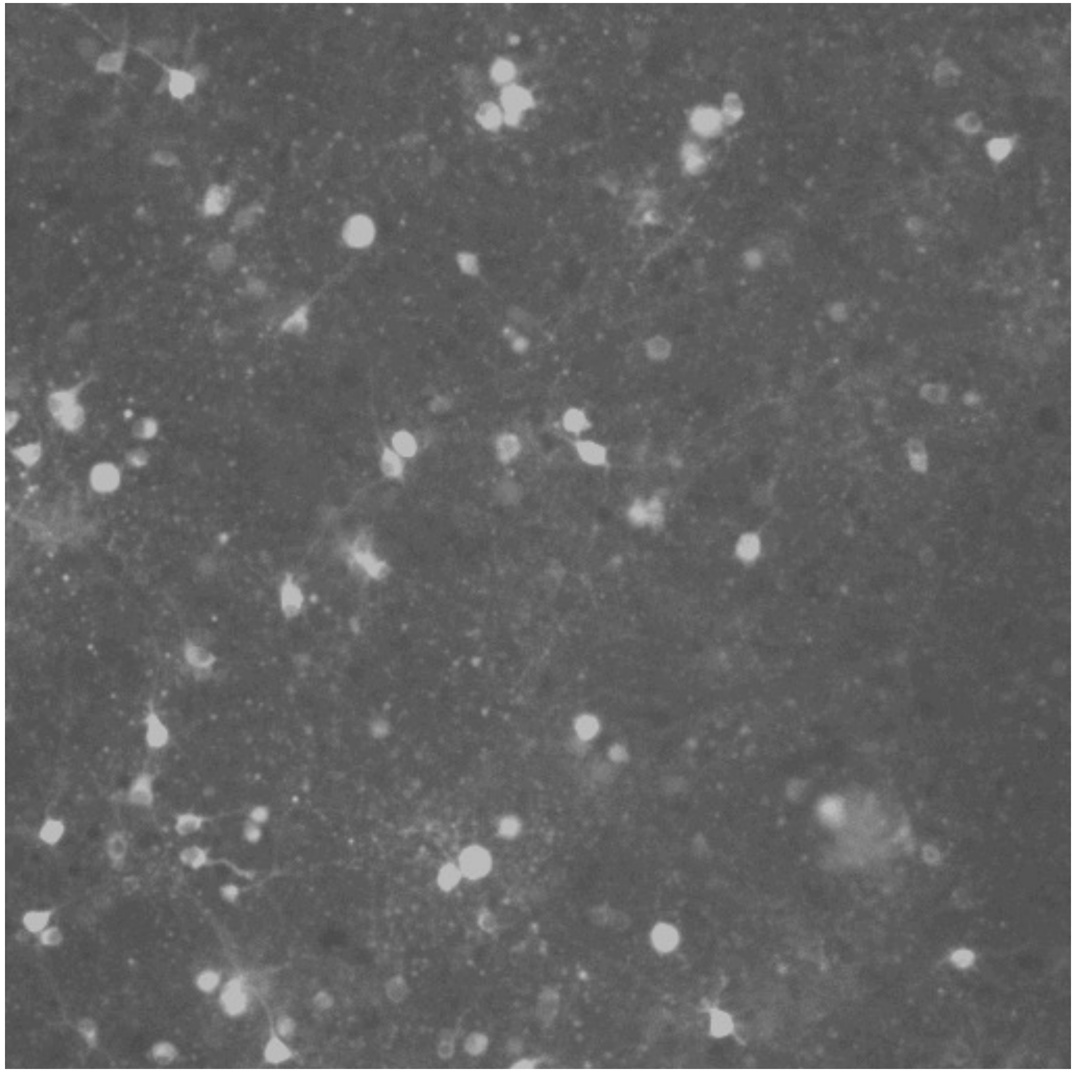
Networks of thought



This is a recording of neurons from the hippocampus of a brain suffering from Alzheimer's.

I want to cure this disease by studying the economy.

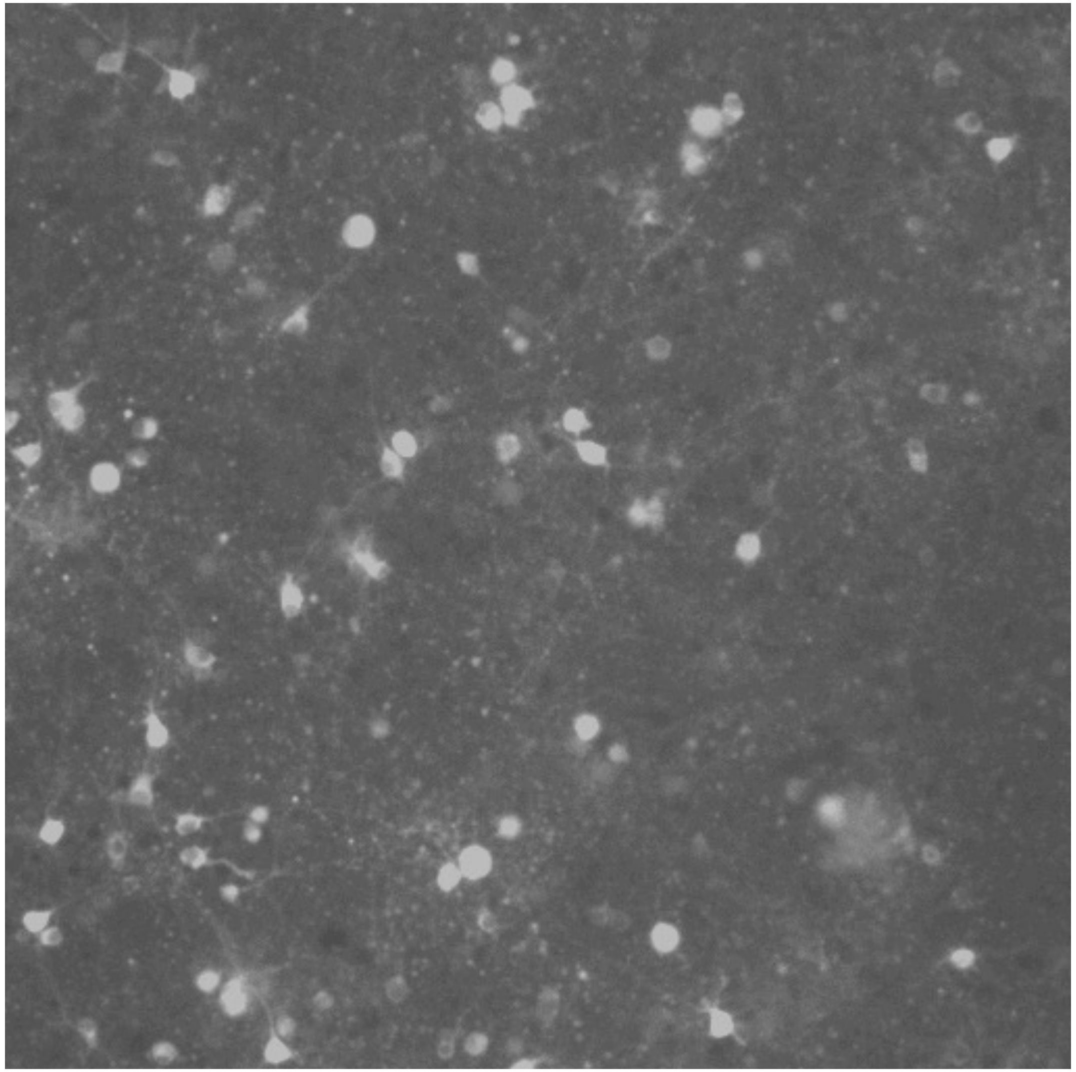
Networks of thought



This is a recording of neurons from the hippocampus of a brain suffering from Alzheimer’s.

I want to cure this disease by studying schools of fish.

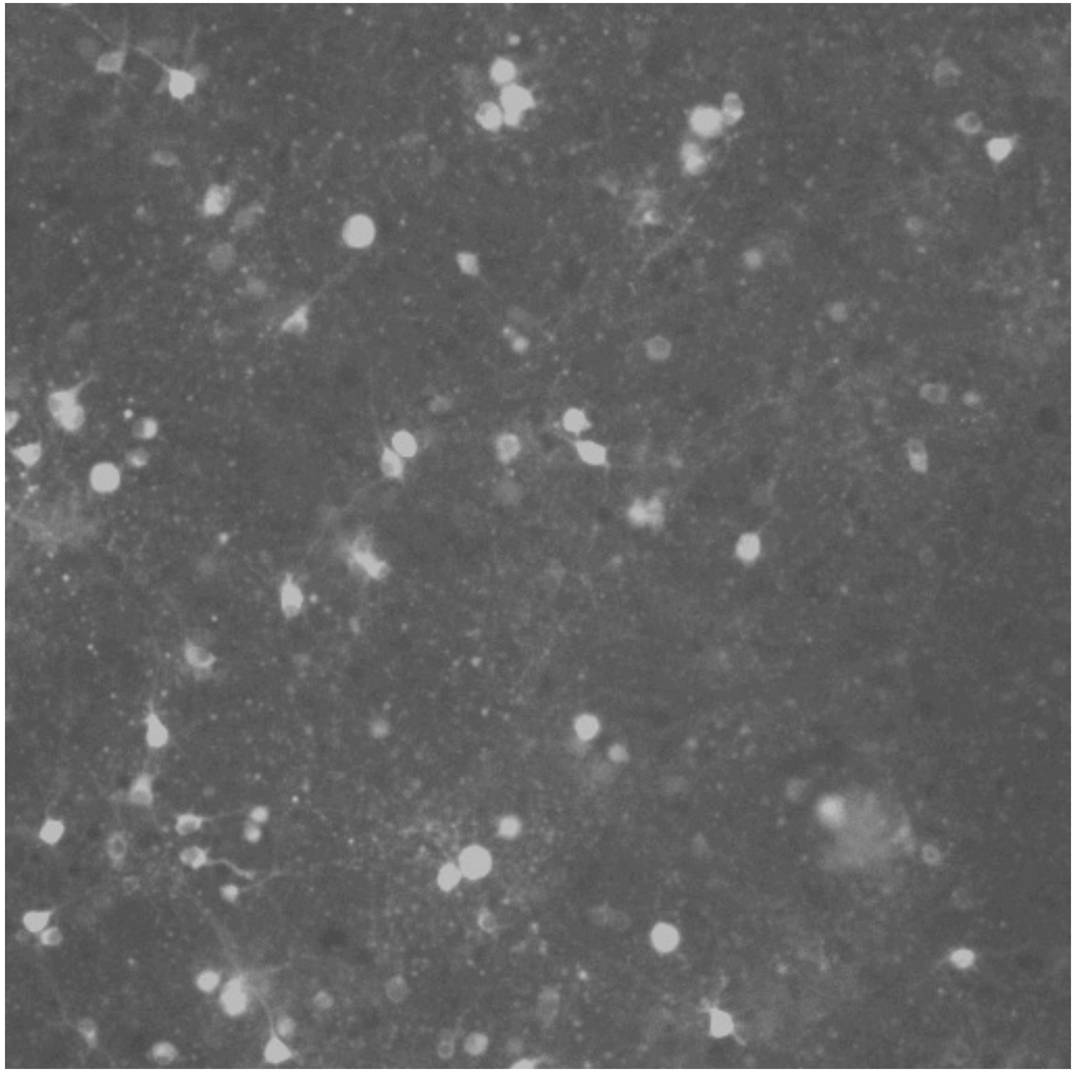
Networks of thought



This is a recording of neurons from the hippocampus of a brain suffering from Alzheimer's.

I want to cure this disease by studying fractals.

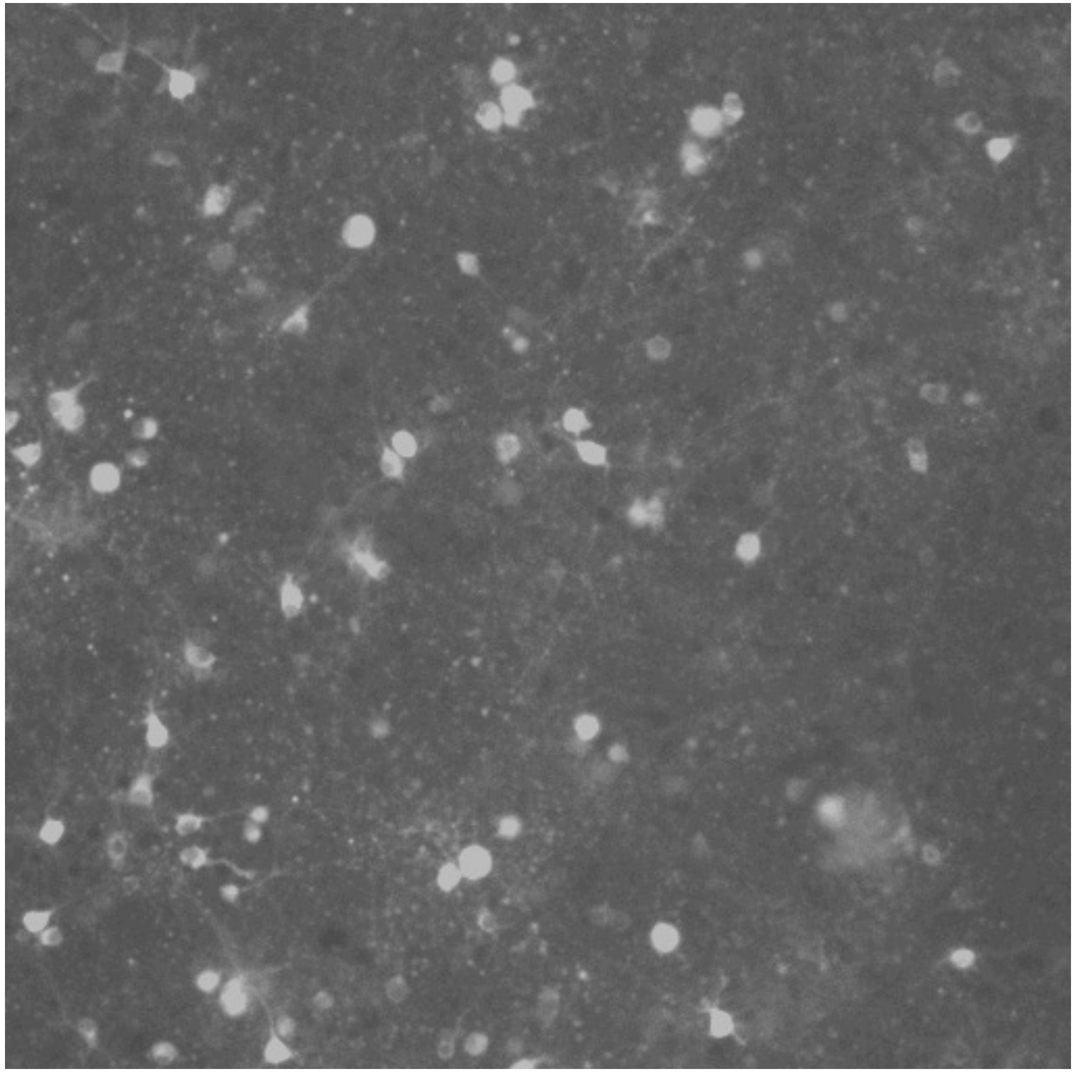
Networks of thought



This is a recording of neurons from the hippocampus of a brain suffering from Alzheimer's.

I want to cure this disease by studying epidemics.

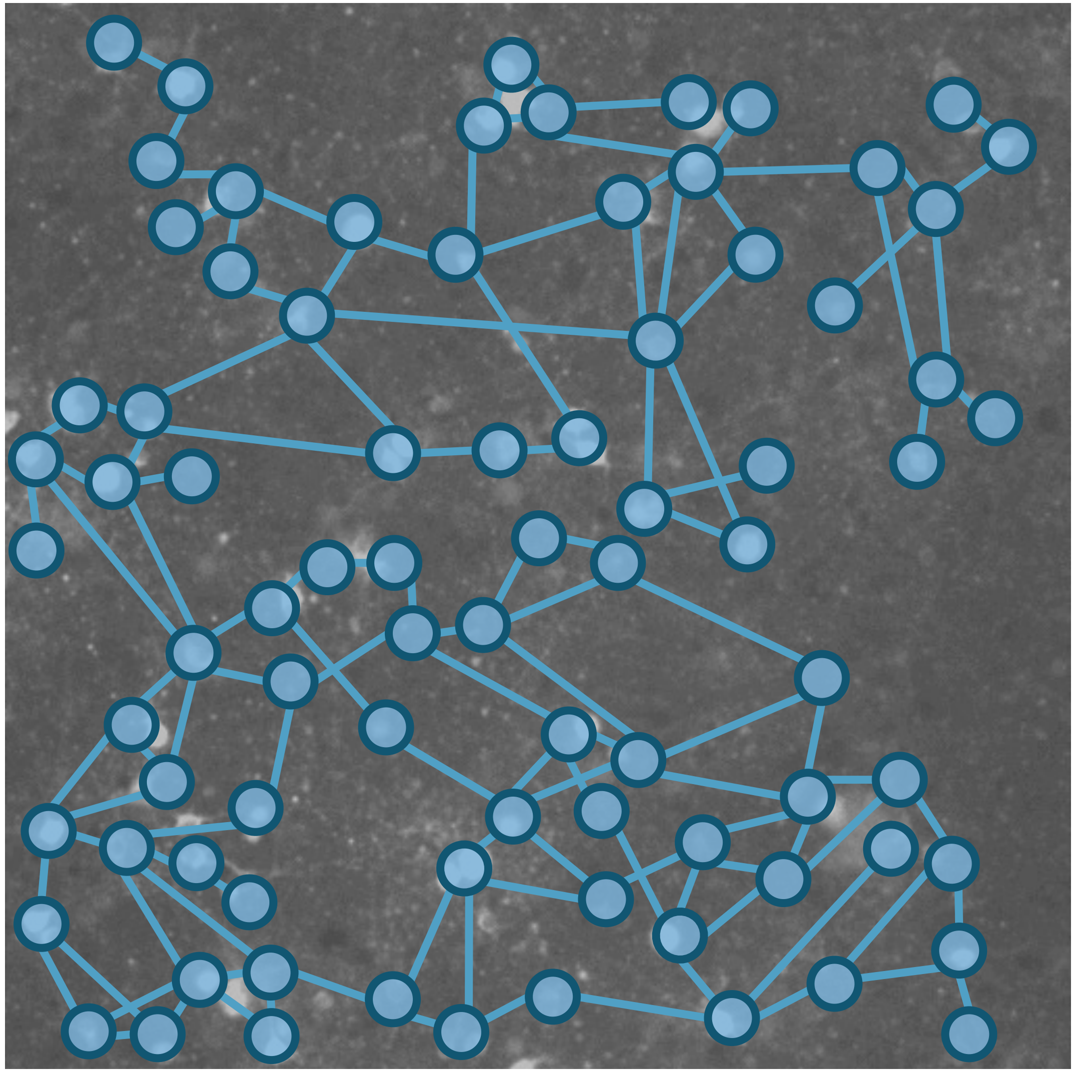
Networks of thought



This is a recording of neurons from the hippocampus of a brain suffering from Alzheimer's.

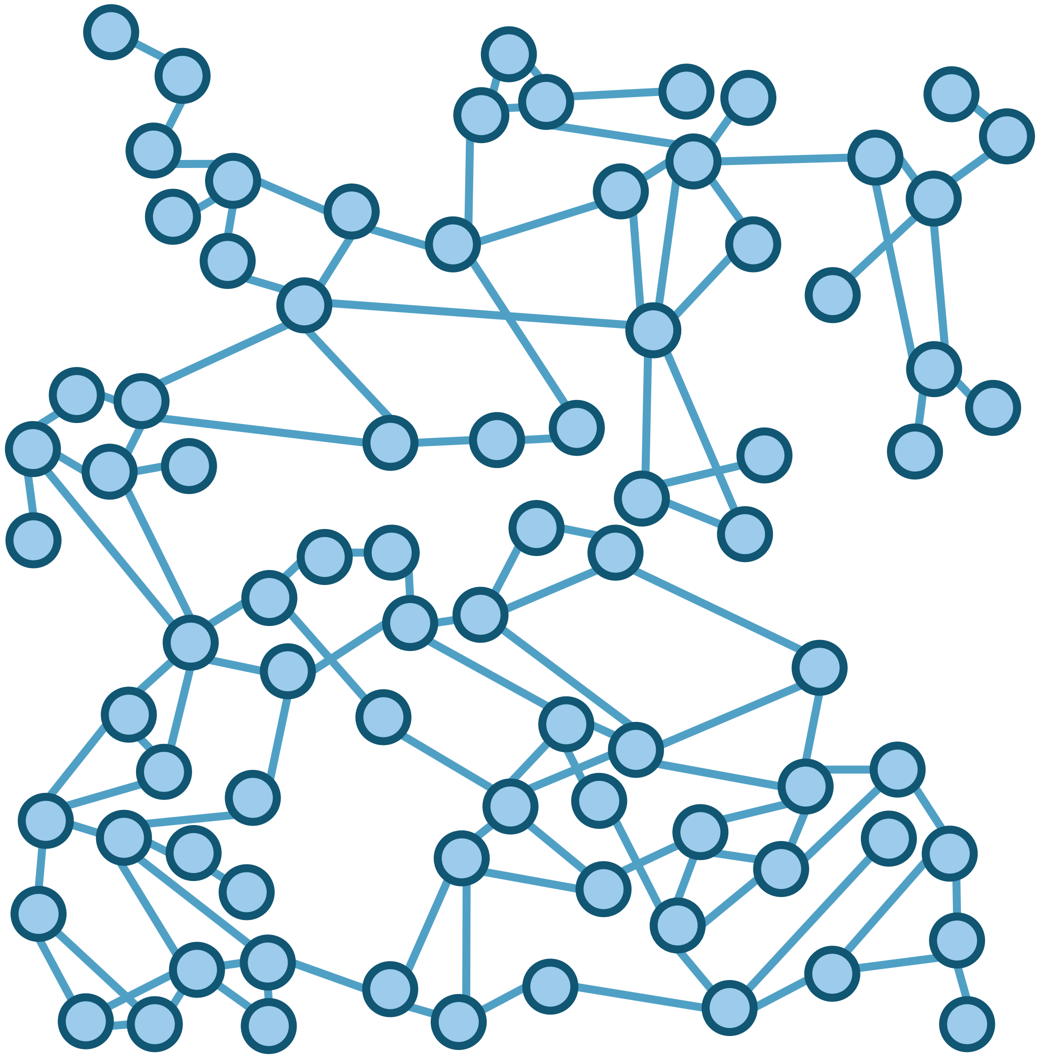
I want to cure this disease by studying **networks**.

The problem



We're good network scientists, so let's just draw some nodes …and edges.

The problem

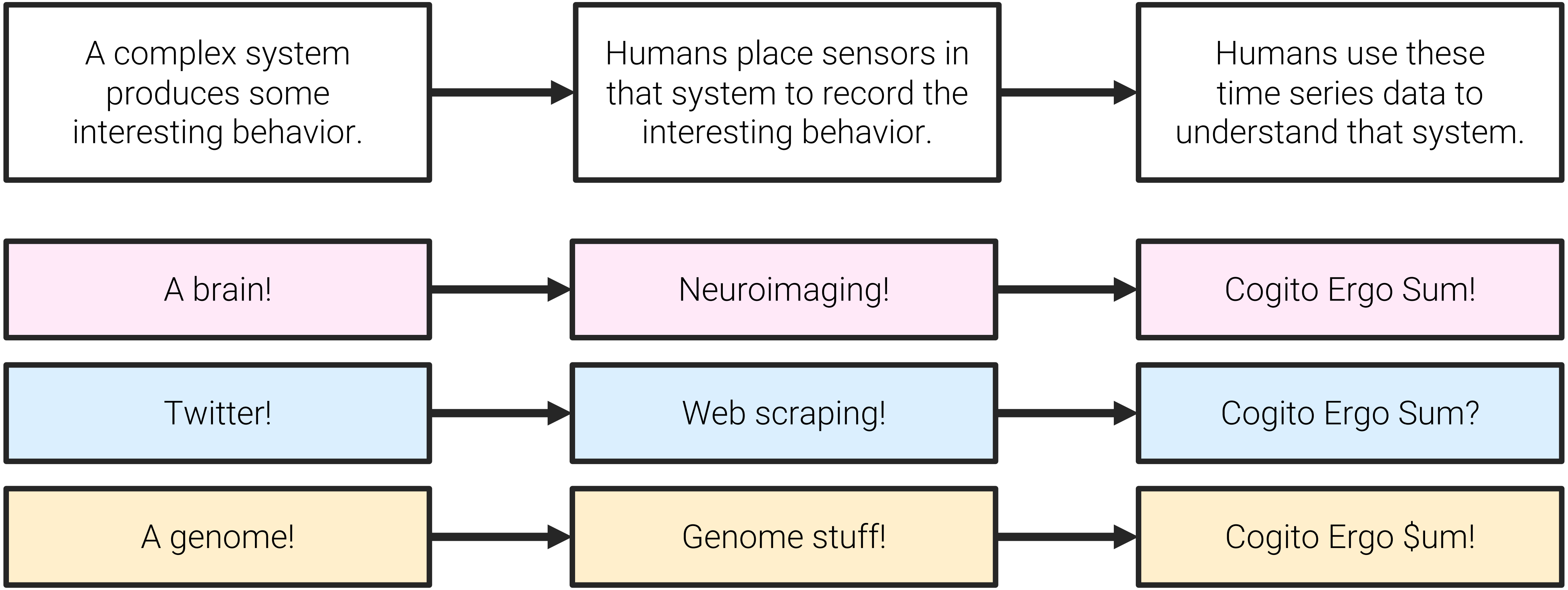


We're good network scientists, so let's just draw some nodes …and edges.

Easy, right?

Network (re)construction

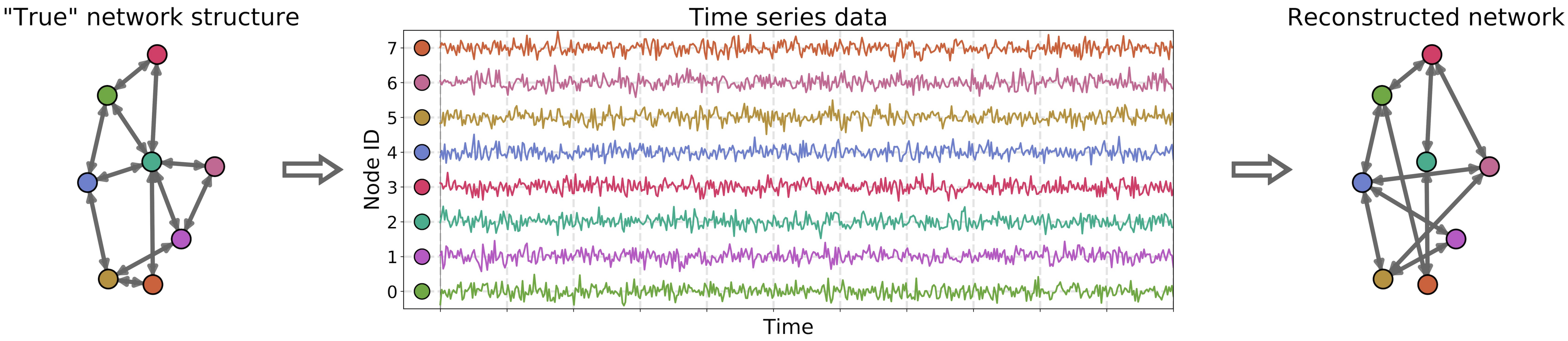
The problem



A complex system produces some interesting behavior.
Humans place sensors in that system to record the interesting behavior.
Humans use these time series data to understand that system.
A brain!
Neuroimaging!
Cogito Ergo Sum!
Twitter!
Web scraping!
Cogito Ergo Sum?
A genome!
Genome stuff!
Cogito Ergo $um!

The problem

A complex system produces some interesting behavior. → Humans place sensors in that system to record the interesting behavior. → Humans use these time series data to understand that system.

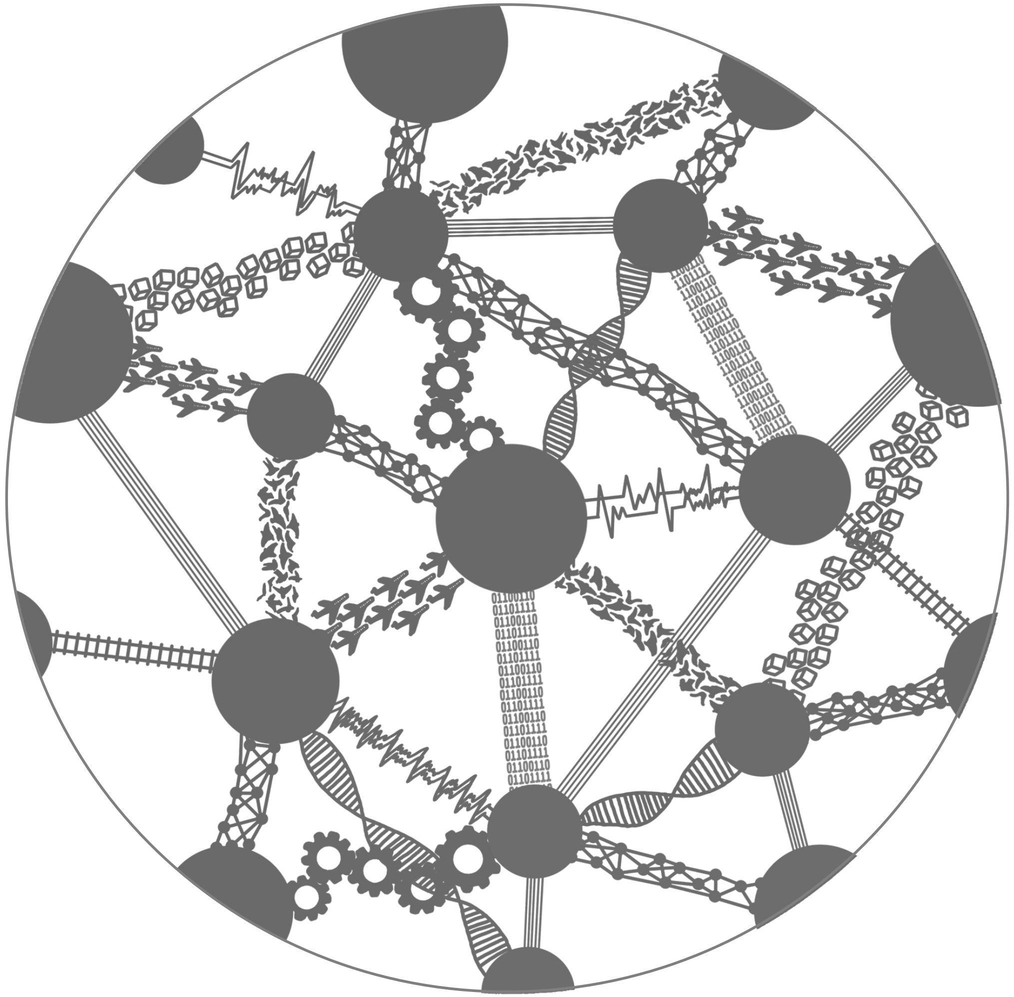


Networks as models, networks as maps

We want a **useful** network science.

A good model can help understand and predict the behavior of a system.

To make good models of systems, we need adequate toolkits, strong benchmarks, standardization, etc.



Search projects

netrd 0.2.2

```
pip install netrd
```

PePy

Search...

netrd

Summary

PyPI link

https://pypi.org/project/netrd

Total downloads

32,099

Total downloads - 30 days

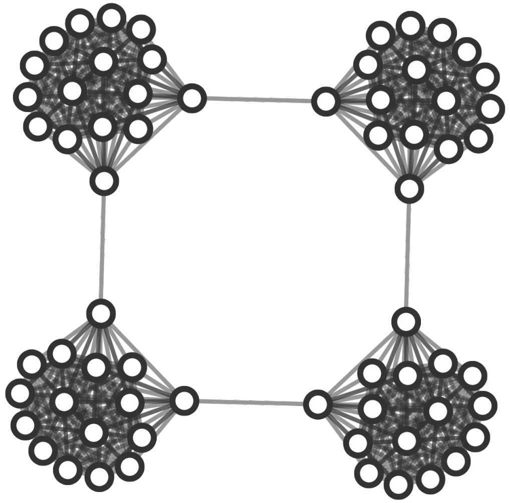
515

Total downloads - 7 days

78

netrd: A library for network {reconstruction, distances, dynamics}

Basic pipeline



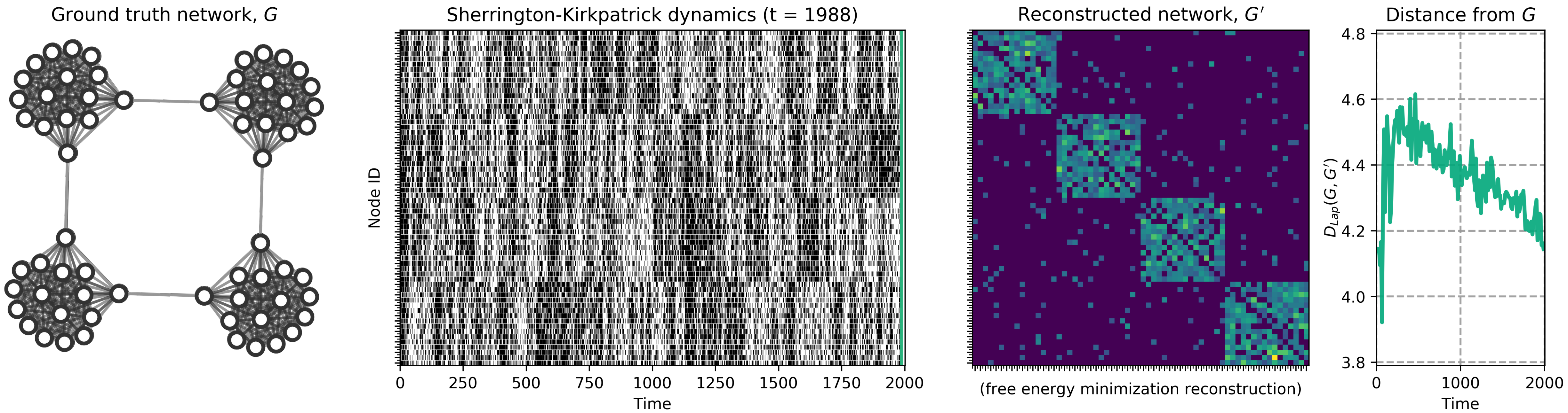
network → dynamics → reconstruction → distance*

generates observable

from which we make a

and measure the

Basic pipeline



network → dynamics → reconstruction → distance*

generates observable

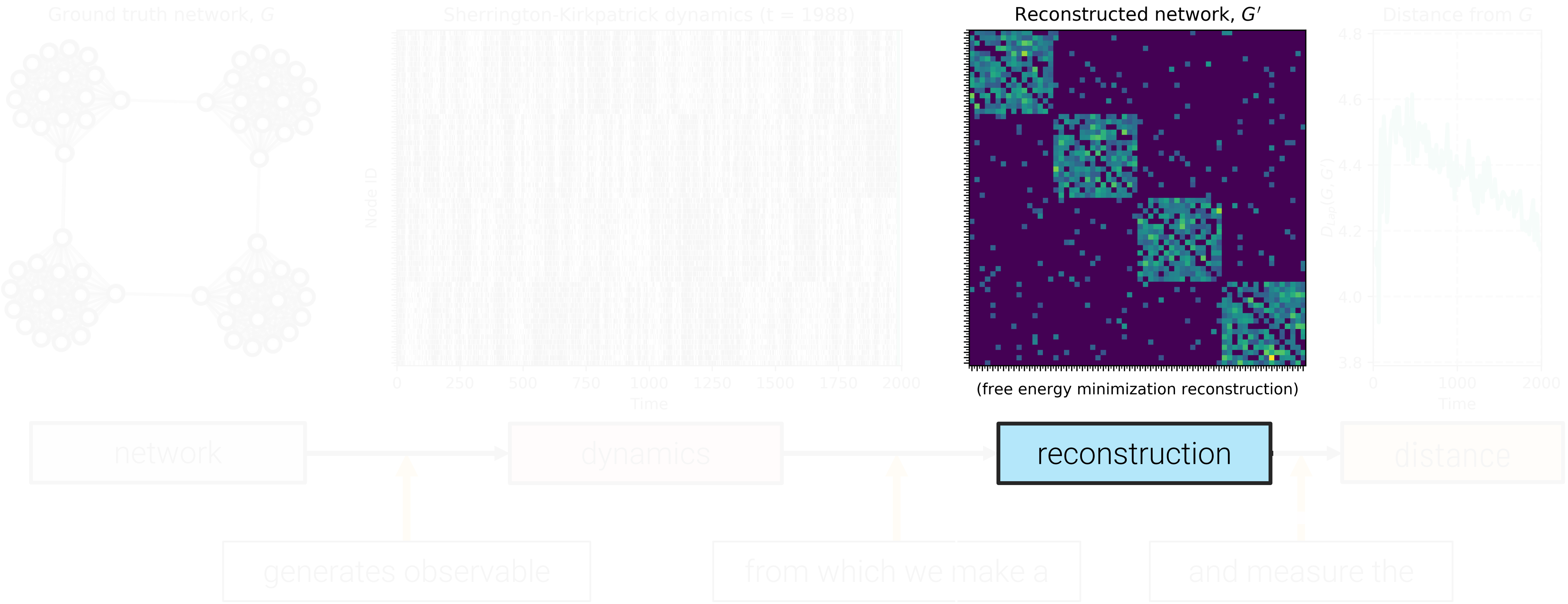
from which we make a

and measure the

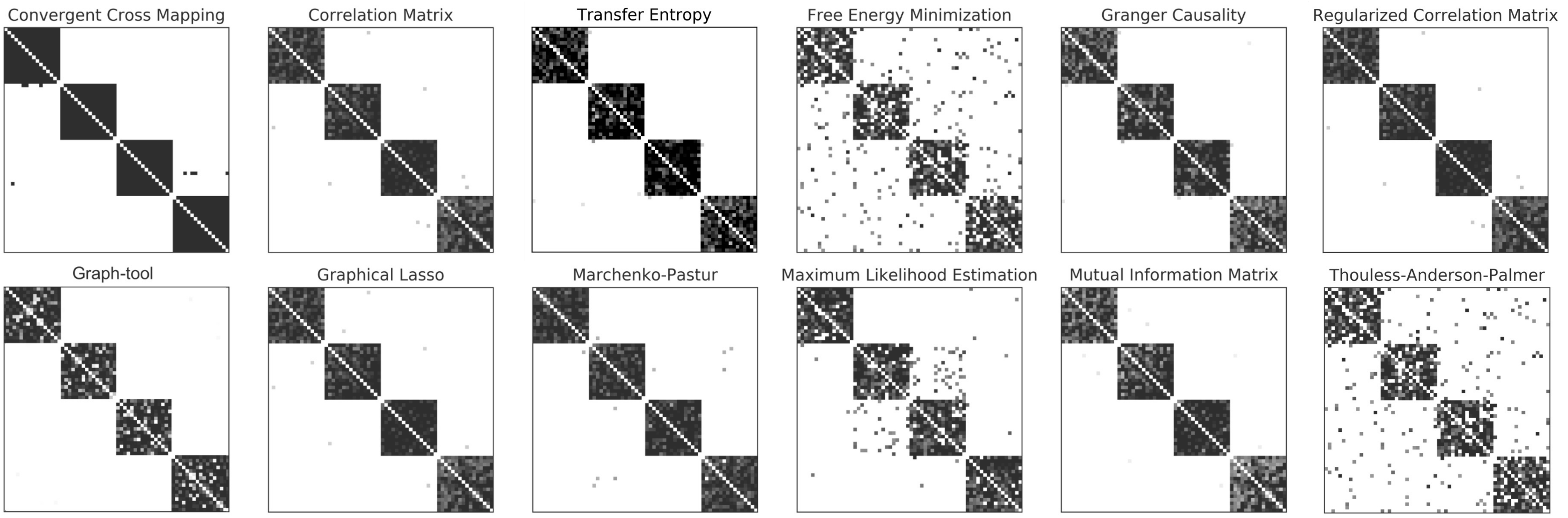
McCabe, Torres, LaRock,, Haque, Yang, Hartle, & **Klein** (2021). *Journal of Open Source Software*. 6 (62), 2990. doi: 10.21105/joss.02990

Bagrow, J., Bollt, E. An information-theoretic, all-scales approach to comparing networks. *Appl Netw Sci* 4, **45** (2019).

Basic pipeline



Systematic comparison of different tools

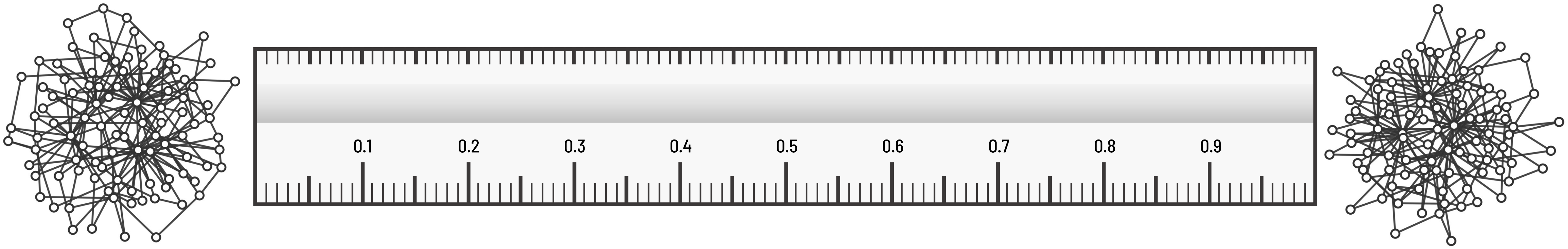


Hartle, **Klein**, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

Klein, Hartle, Laber, et al., (in prep.). Ensembles of reconstructed networks from dynamics.

McCabe, Torres, LaRock,, Haque, Yang, Hartle, & **Klein** (2021). *Journal of Open Source Software*. 6 (62), 2990. doi: 10.21105/joss.02990

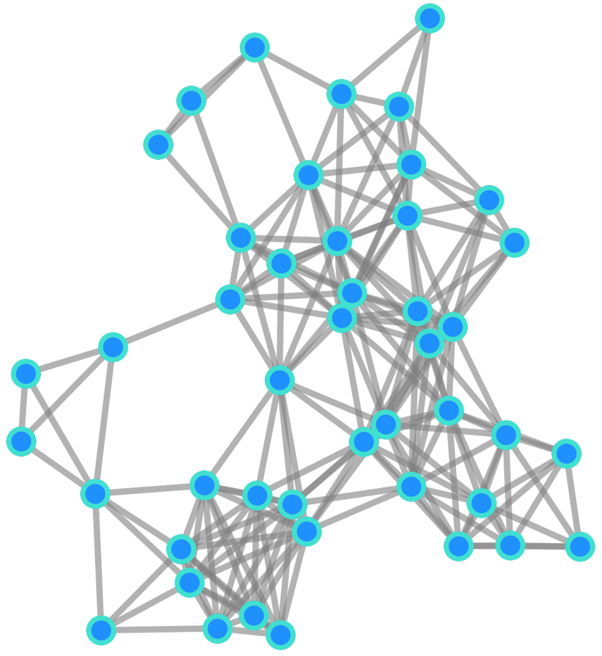
Systematic comparison of *graphs in general*

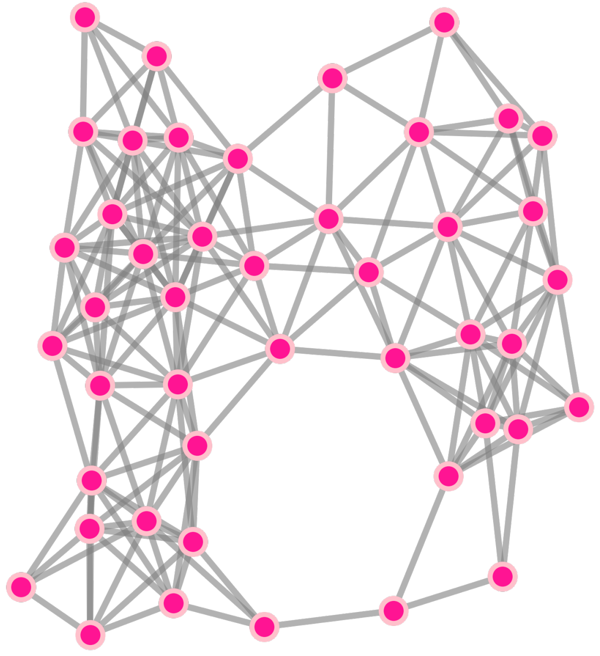


Hartle, Klein, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

On measuring distances

How close (similar) are these two graphs?





Hartle, Klein, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

On measuring distances

How close (similar) are these two mugs?

Hartle, **Klein**, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

On measuring distances

How close (similar) are these two mugs?

How do their positions differ?
meters

How do their volumes differ?
liters

How do their temperatures differ?
degrees

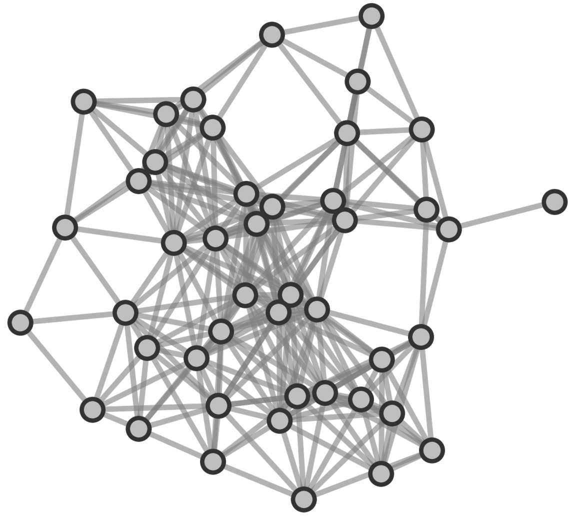
How do their functions differ?
…ask someone at a café?

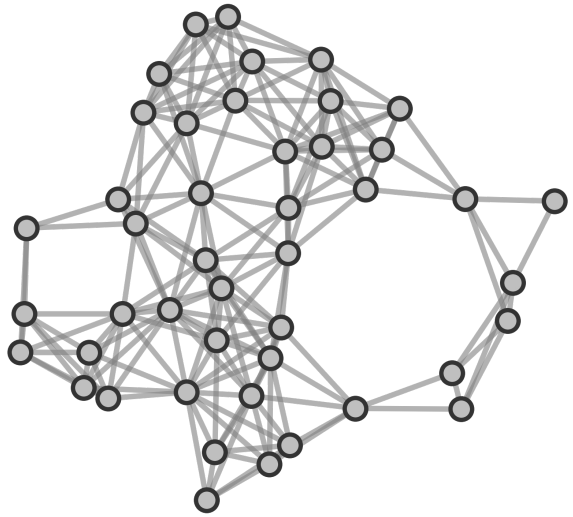
Hartle, Klein, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

Graph distances

We calculate the dissimilarity between pairs of graphs by measuring the distance between their descriptors.

dissimilarity —> the graph distance in question
descriptors —> a graph observable of interest
distance —> a (well-motivated) distance metric





Hartle, **Klein**, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

Graph distances

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dissimilarity —> the graph distance in question
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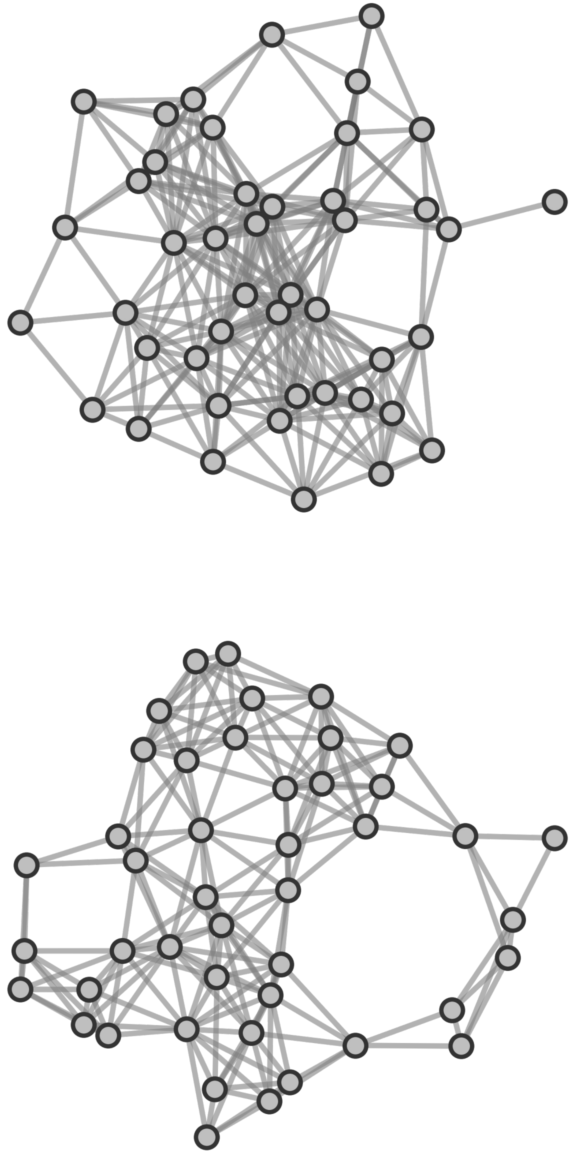
Definition. *Given a set of graphs $\mathcal{M} \subseteq \mathcal{G}$, a graph description Ψ, its descriptor space $\mathcal{D}$, and a distance d on $\mathcal{D}$, the associated graph distance measure $D : \mathcal{M} \times \mathcal{M} \to \mathbb{R}_+$ is a function defined by*

$$D(G, G') = d(\psi_G, \psi_{G'}).$$

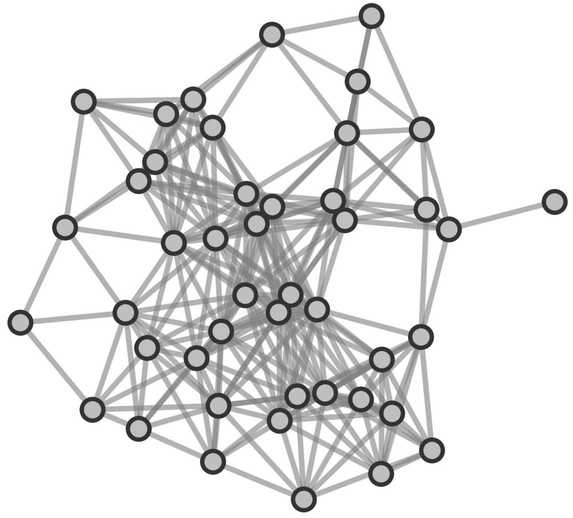


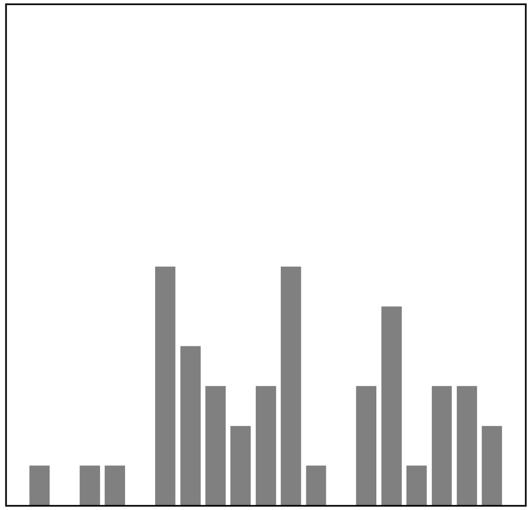
Hartle, Klein, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

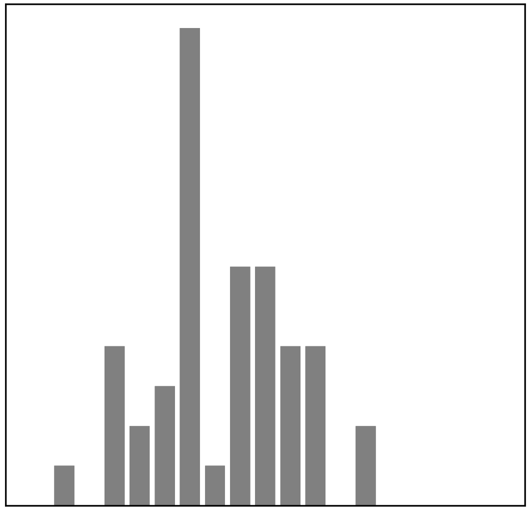
Graph distances

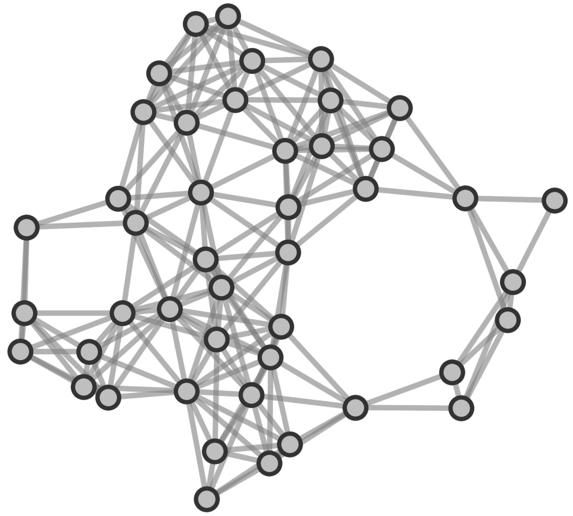
We calculate the dissimilarity between pairs of graphs by measuring the distance between their descriptors.

dissimilarity —> Degree distribution JSD (DJS)
descriptors —> the degree distribution
distance —> Jensen-Shannon divergence









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Graph distances

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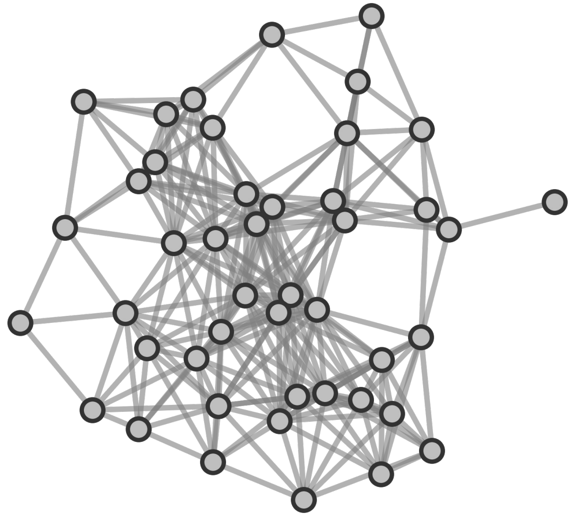
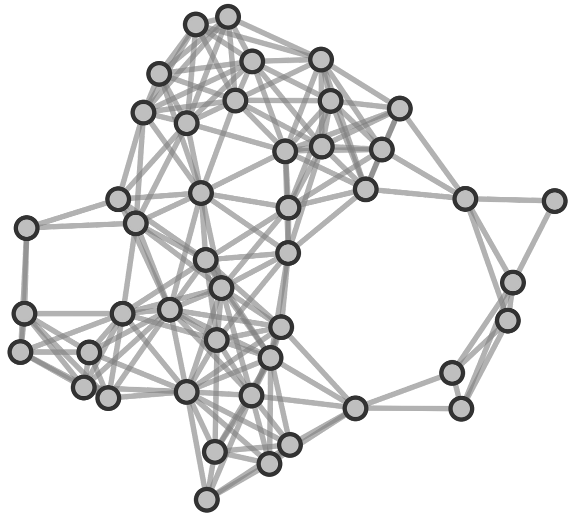
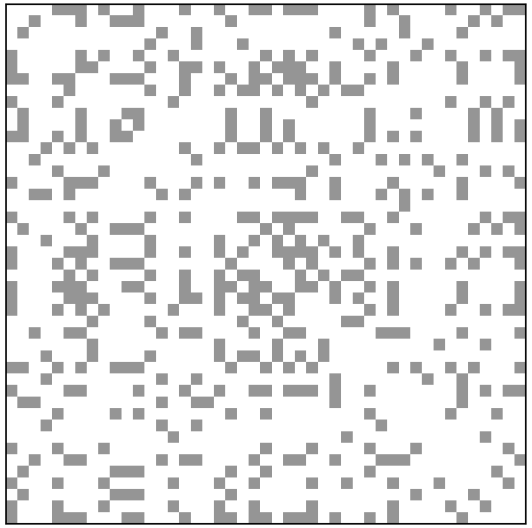
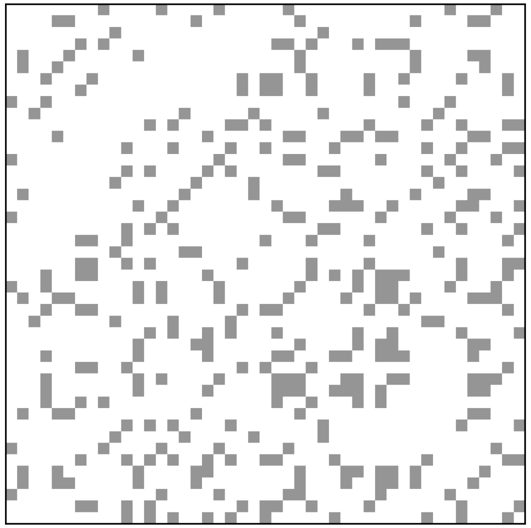
dissimilarity —> Hamming distance (HAM)
descriptors —> the adjacency matrix
distance —> Euclidean distance (squared)



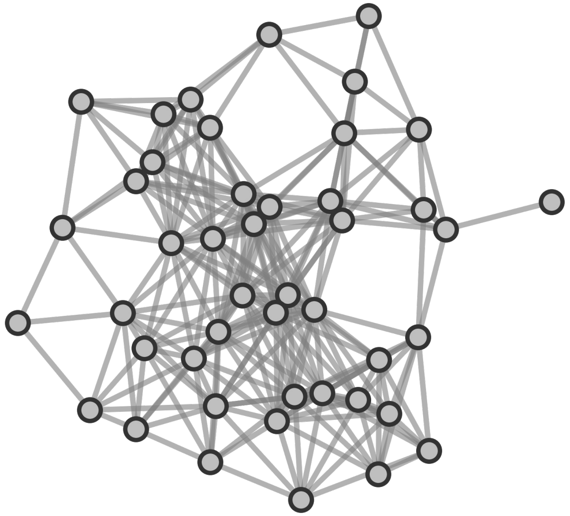






Hartle, **Klein**, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc. A.* 476: 20190744

Graph distances



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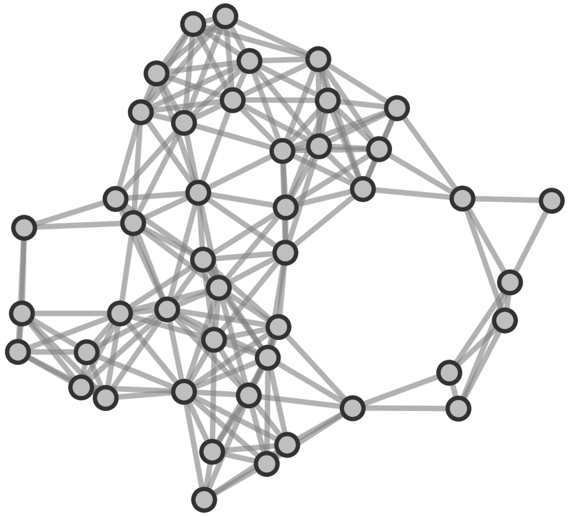
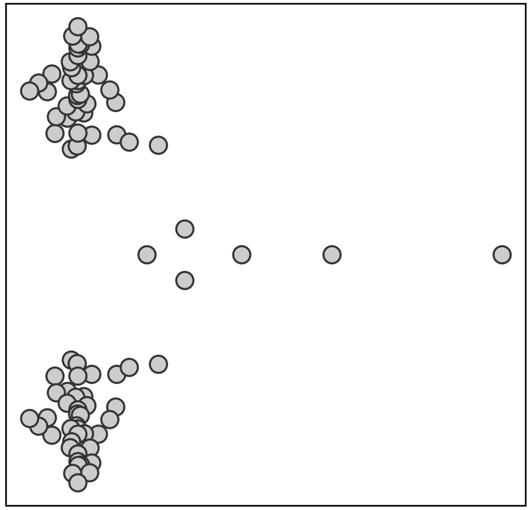
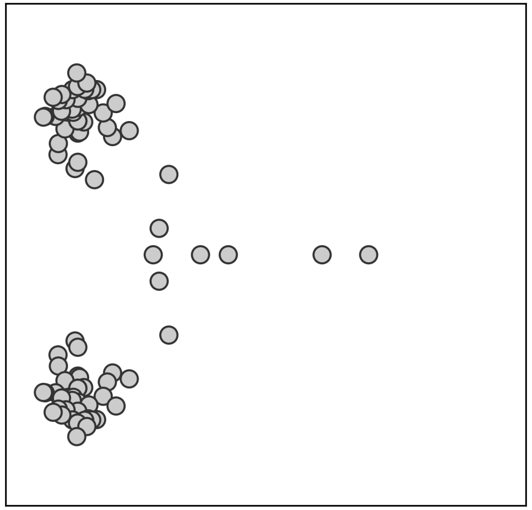


dissimilarity —> Non-backtracking Spectral (NBD)
descriptors —> eigenvalues of the NBM
distance —> Earth-mover's distance



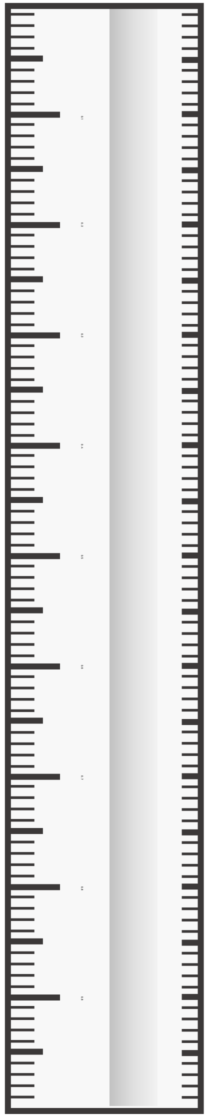


Hartle, **Klein**, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

Graph distances

We calculate the dissimilarity between pairs of graphs by measuring the distance between their descriptors.

	Graph distance	Label
1	Jaccard (Jaccard, 1901)	JAC
2	Hamming (Hamming, R.W., 1950)	HAM
3	Hamming-Ipsen-Mikhailov (Jurman, Visintainer, Filosi, Riccadonna, & Furlanello, 2015)	HIM
4	Frobenius (Golub & van Loan, 2013)	FRO
5	Polynomial dissimilarity (Donnat & Holmes, 2018)	POD
6	Degree JSD (Carpi, Rosso, Saco, & Ravetti, 2011)	DJS
7	Portrait divergence (Bagrow & Bollt, 2019)	POR
8	Quantum spectral JSD (De Domenico & Biamonte, 2016)	QJS
9	Communicability sequence (Chen, Shi, Qin, Xu, & Pan, 2018)	CSE
10	Graph diffusion distance (Hammond, Gur, & Johnson, 2013)	GDD
11	Resistance-perturbation (Monnig & Meyer, 2018)	REP
12	NetLSD (Tsitsulin et al., 2018)	LSD
13	Lap. spectrum; Gauss. kernel, JSD (Jurman et al., 2011)	LGJ
14	Lap. spectrum; Loren. kernel, Euc. (Jurman et al., 2011)	LLE
15	Ipsen-Mikhailov (Ipsen & Mikhailov, 2002)	IPM
16	Non-backtracking eigenvalue (Torres et al., 2019)	NBD
17	Distributional Non-backtracking (Mellor & Grusovin, 2019)	DNB
18	D-measure distance (Schieber et al., 2017)	DMD
19	DeltaCon (Koutra et al., 2016)	DCN
20	NetSimile (Berlingerio et al., 2012)	NES



Hartle, Klein, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc. A.* 476: 20190744

The within-ensemble graph distance (WEGD)

Definition:

the average distance between pairs of graphs with the same parameterization independently sampled from a given ensemble.

Random graph ensembles are the ideal setting to define a network comparison benchmark.

1. They are well-studied objects on their own.
2. We understand key properties quite well.
3. We can tune them to suit our questions.

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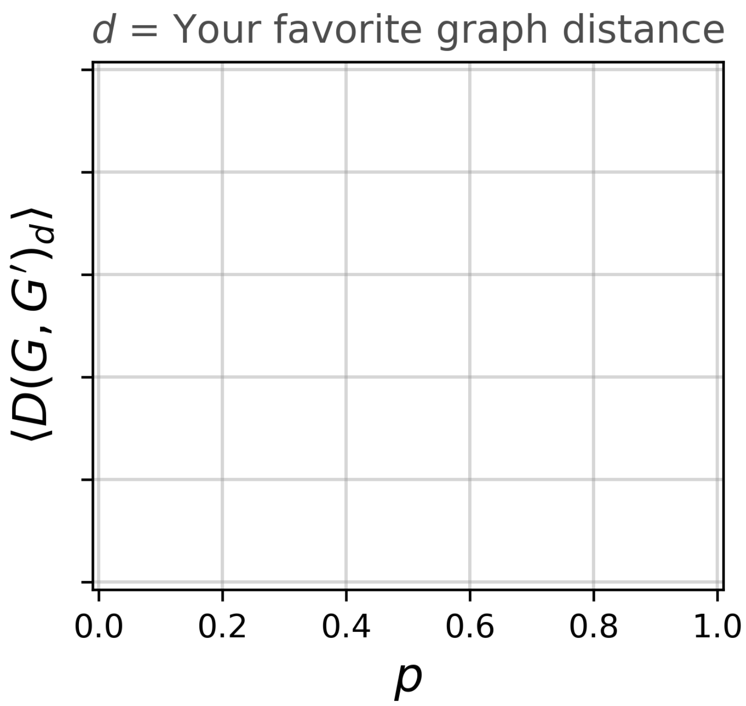

For example, $G(n,p)$

- fixed value for n
- vary p

What should a graph distance capture?
Sparsity? Symmetry around p=0.5? Etc.

Hartle, Klein, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

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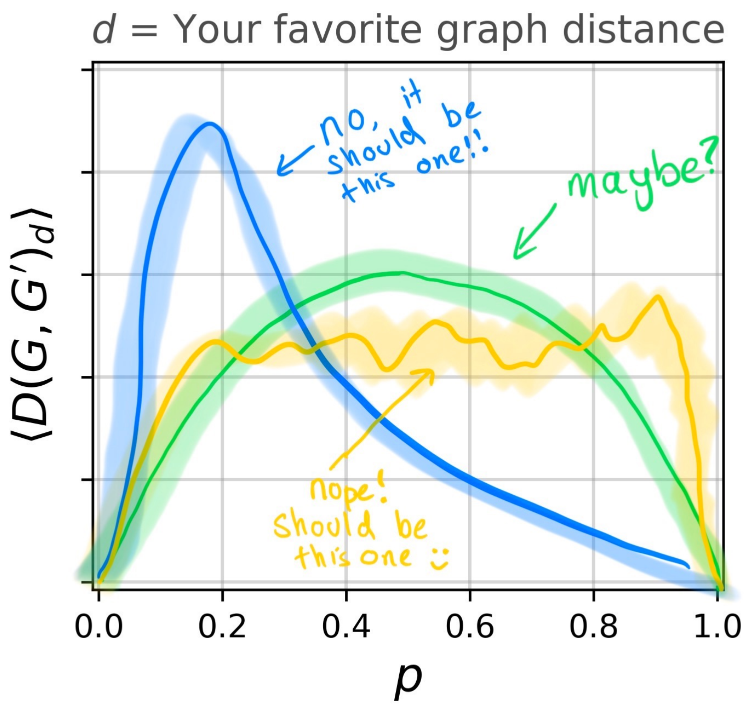

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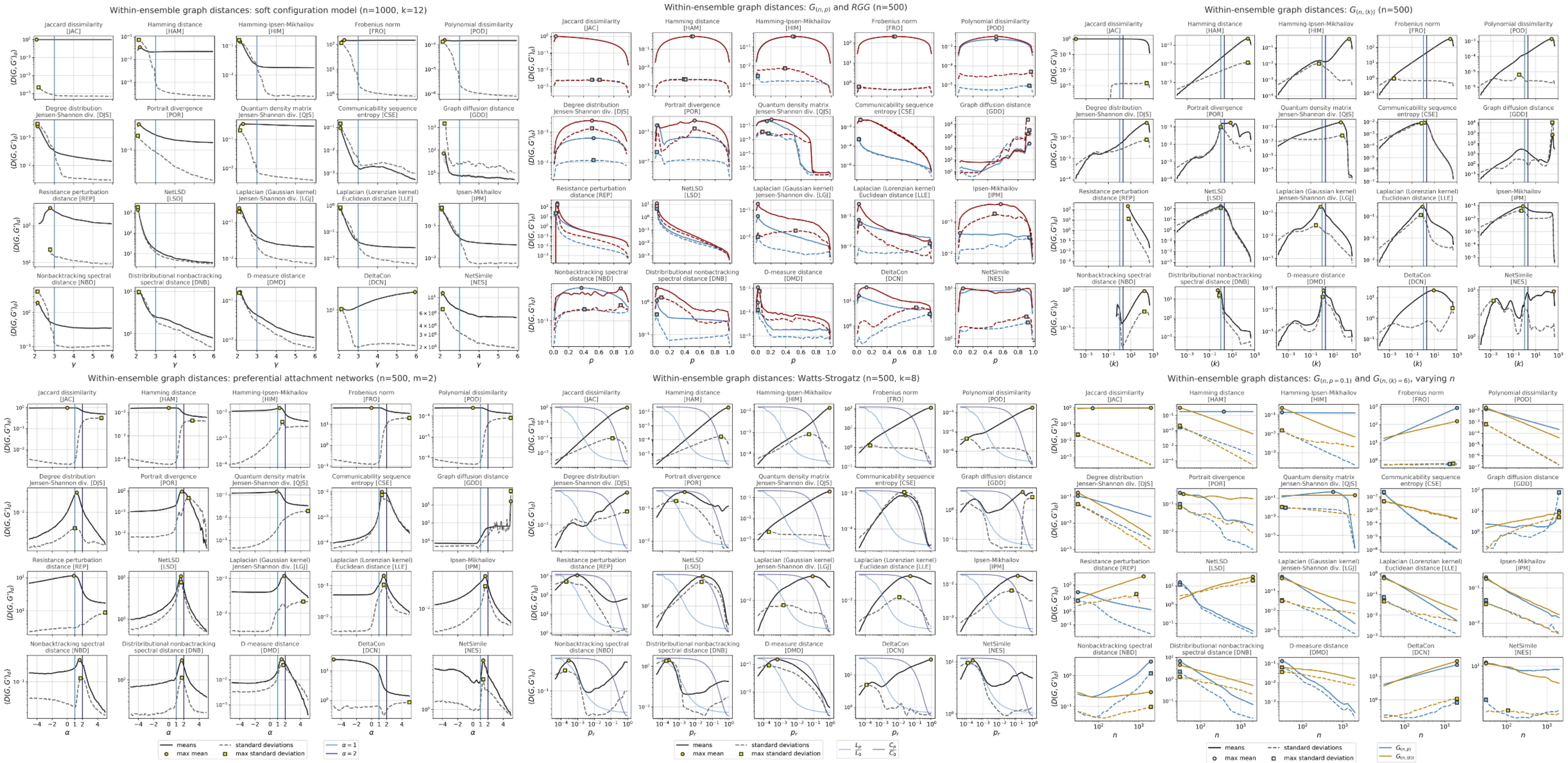

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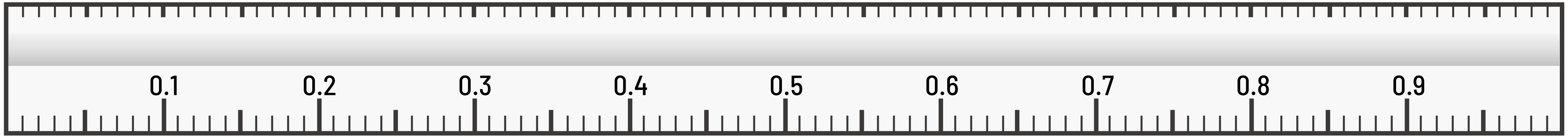
Toward a *standardized* graph distance



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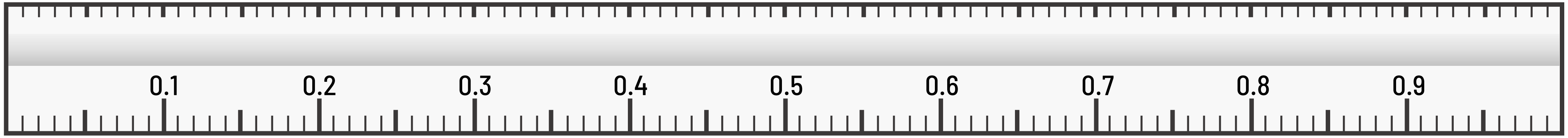

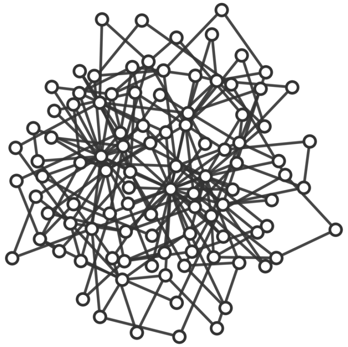

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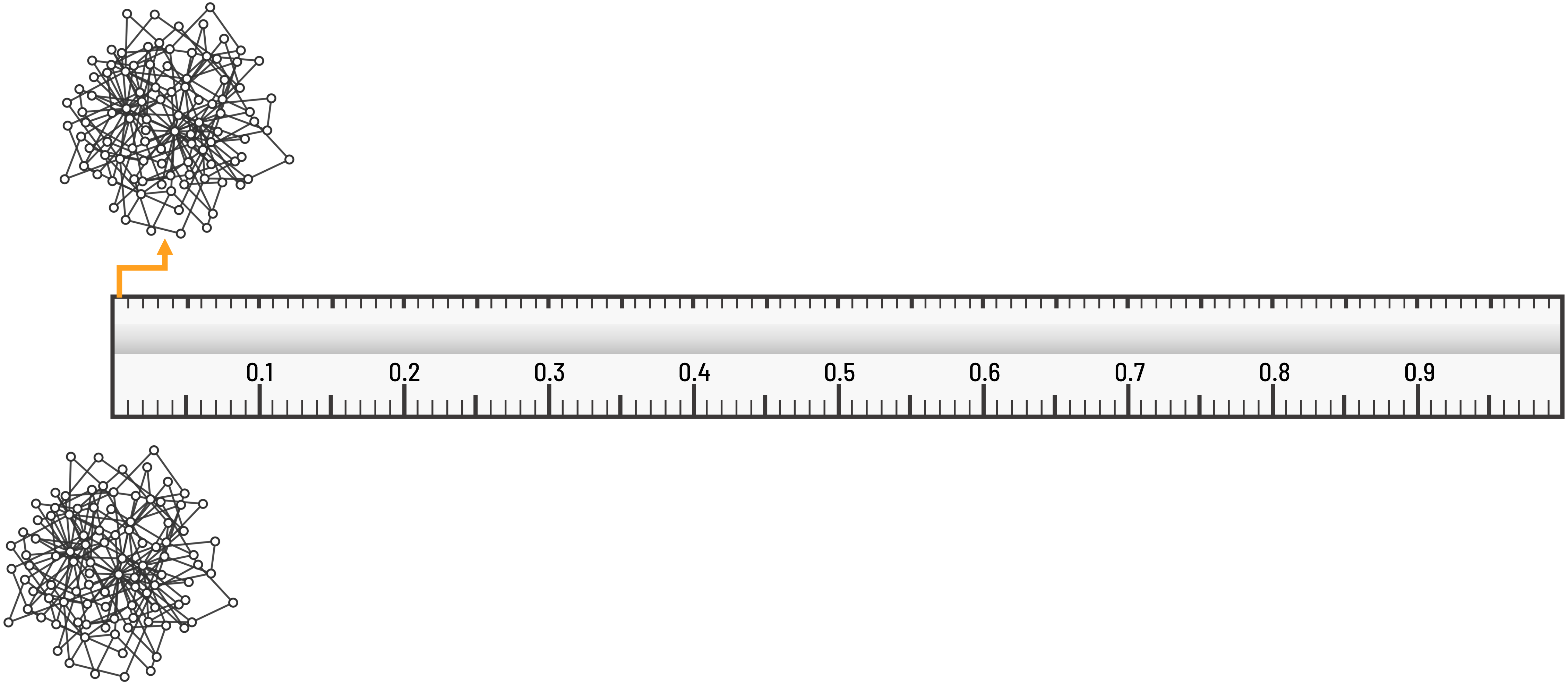

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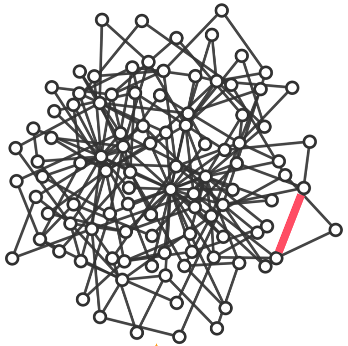
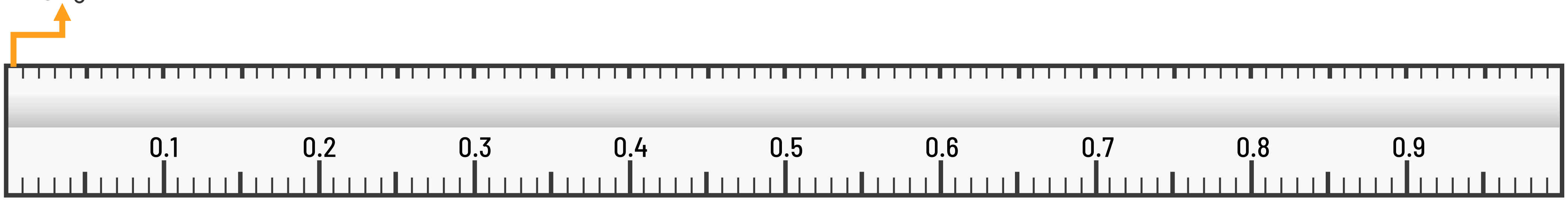
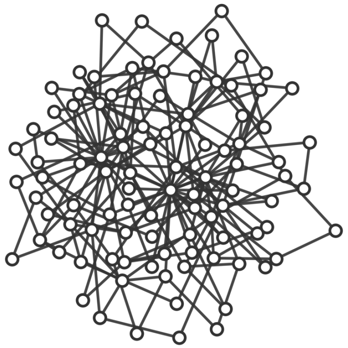


One randomly rewired edge:
a very close graph.





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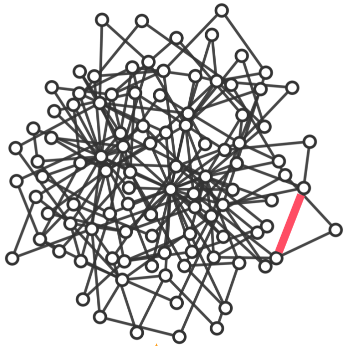

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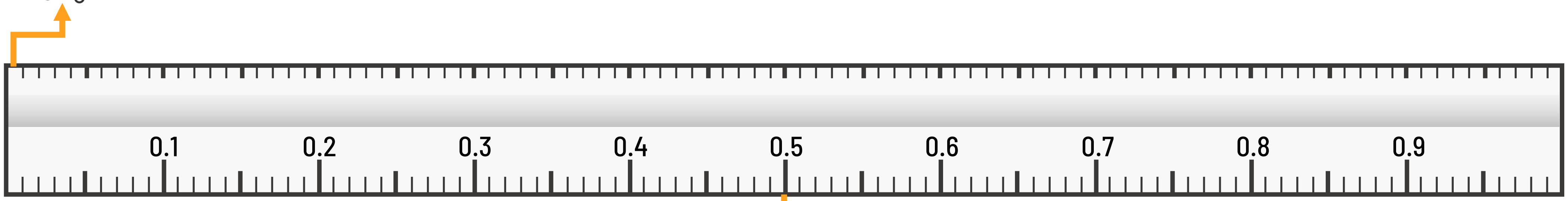
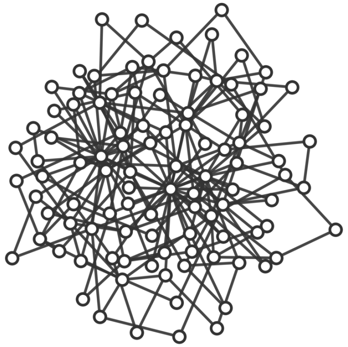
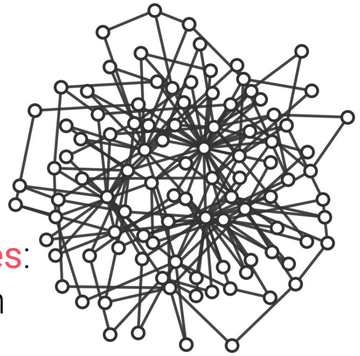




50% rewired edges:
a less close graph



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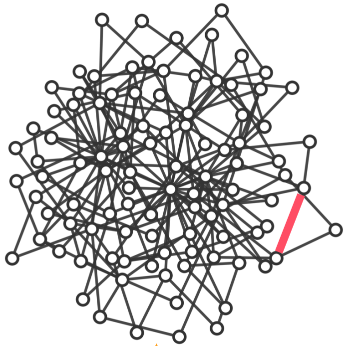
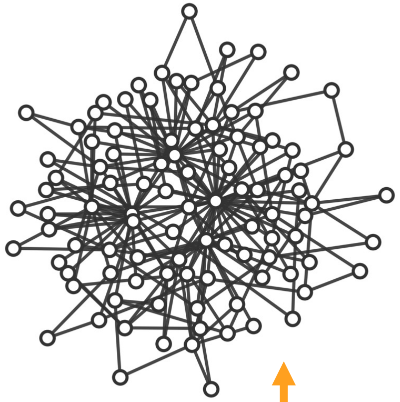
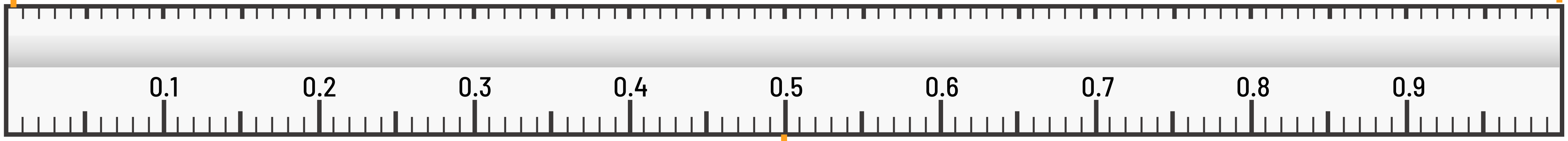
Toward a *standardized* graph distance

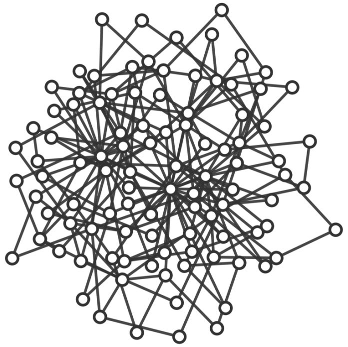


One randomly rewired edge:
a very close graph.

100% rewired edges:
a notion of standardized
graph distance







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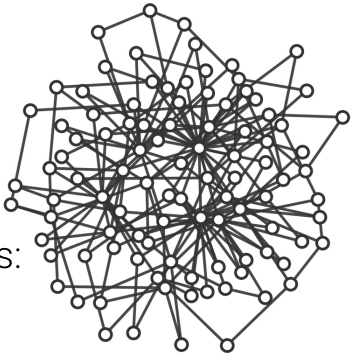
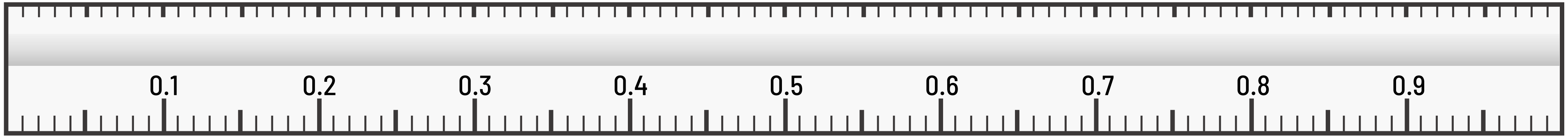


Hartle, **Klein**, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

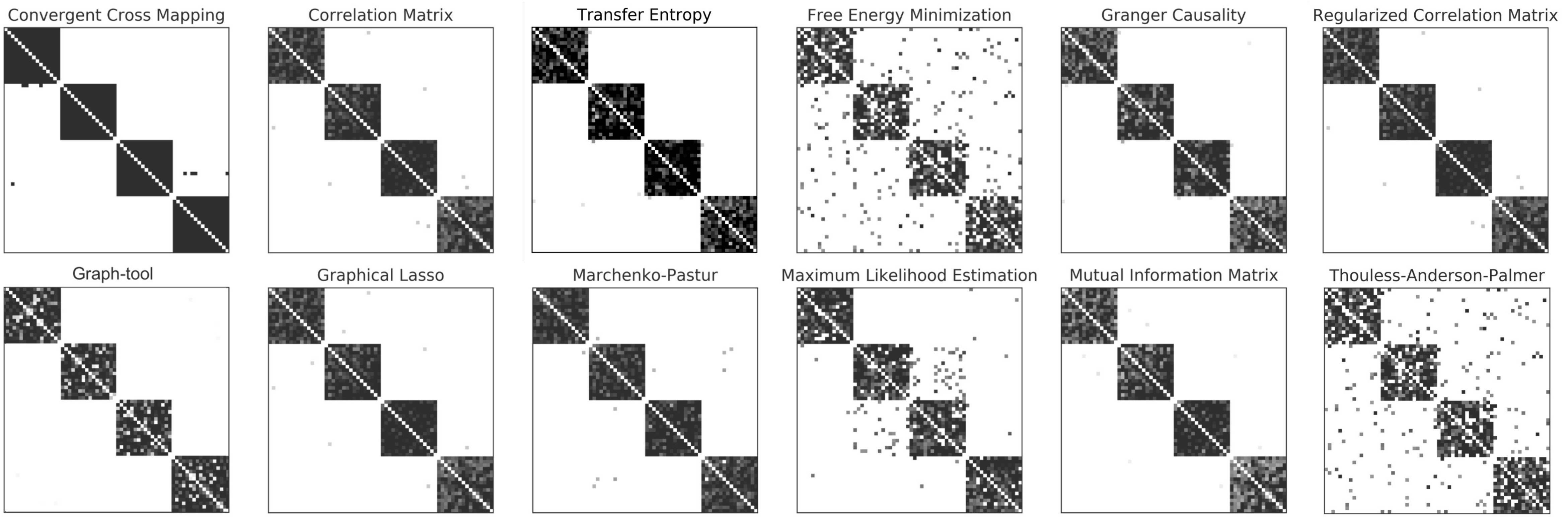
Toward a *standardized* graph distance: the metER

$$D_{d,s}(G_1, G_2) = \frac{D_d(G_1, G_2)}{\langle D_d(G_{n,p}, G'_{n,p}) \rangle}$$



Hartle, Klein, McCabe, Daniels, et al. (2020) Network comparison and the within-ensemble graph distance *Proc. R. Soc.* A. 476: 20190744

Systematic comparison of different tools



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Klein, Hartle, Laber, et al., (in prep.). Ensembles of reconstructed networks from dynamics.

McCabe, Torres, LaRock,, Haque, Yang, Hartle, & Klein (2021). *Journal of Open Source Software*. 6 (62), 2990. doi: 10.21105/joss.02990

Models, representation, theory

- Can we quantify how informative a given network structure is?
- Are certain networks more or less informative? If so, why?
- Are there principled ways to identify the right scale to model a system?
- Do networks in nature and society differ in information or scale?

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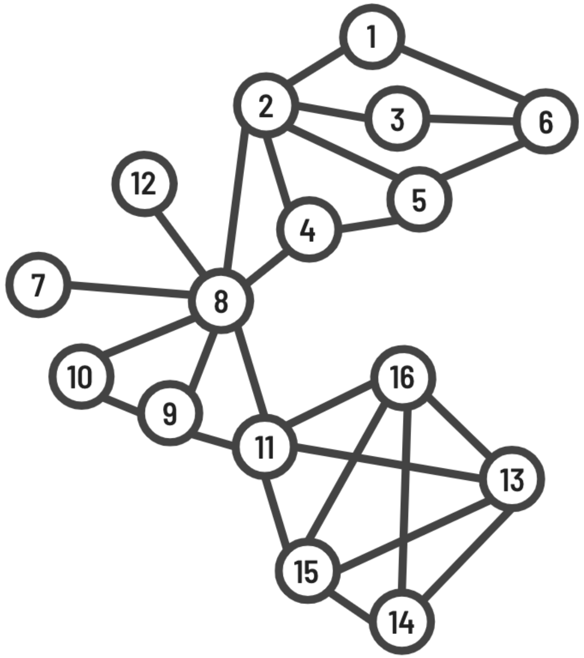
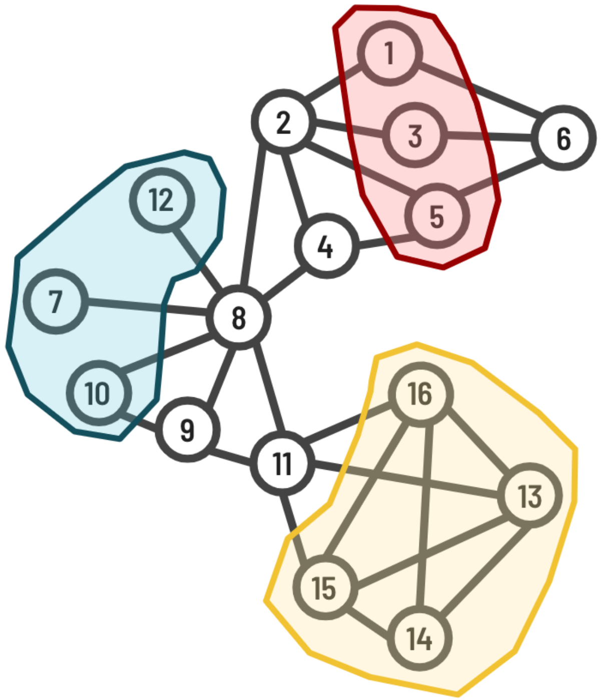
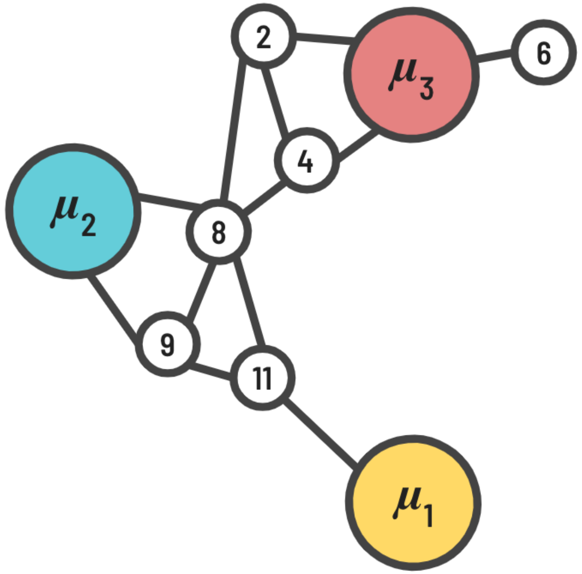
Informative *higher scales* in complex networks



microscale



grouping

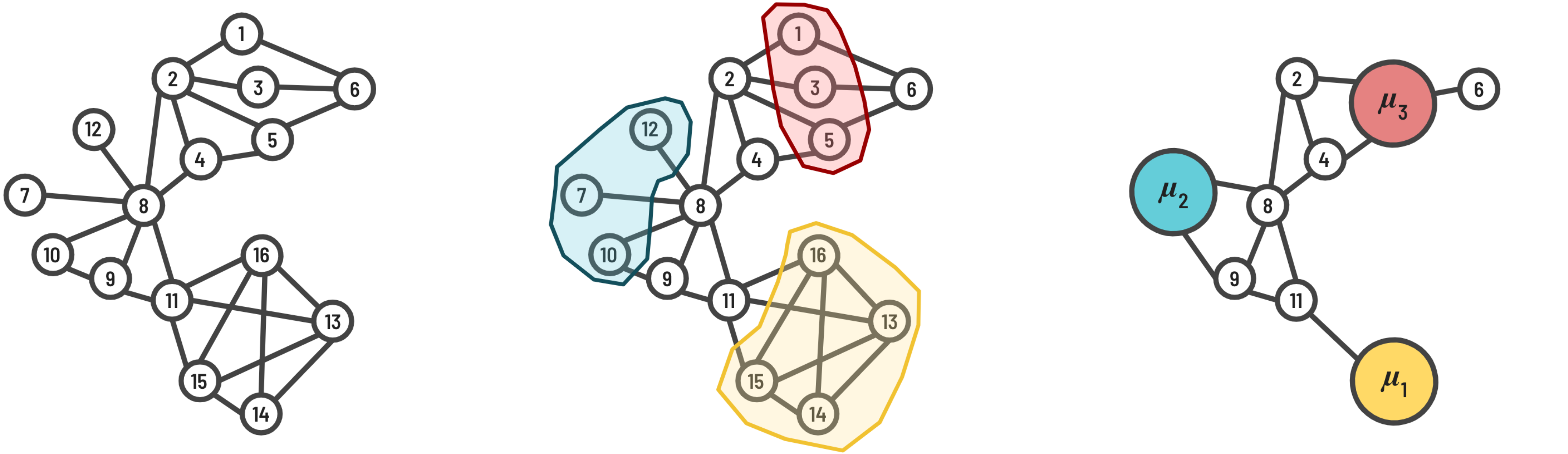


macroscale

Causal emergence

a phenomenon where a coarse-grained "macroscale" network has more effective information than its corresponding "microscale" network

$$EI = H(\langle W_i^{out} \rangle) - \langle H(W_i^{out}) \rangle$$



microscale *grouping* *macroscale*

Campbell (1974). Downward causation in hierarchically organised biological systems. *Studies in the Philosophy of Biology*. pp. 179–186. Hoel, Albantakis, & Tononi (2013). Quantifying causal emergence shows that the macro can beat the micro. *PNAS*. 110, 19790. Flack (2017). Coarse-graining as a downward causation mechanism. *Philosophical Transactions of the Royal Society A*. 375(2109).

Causal emergence

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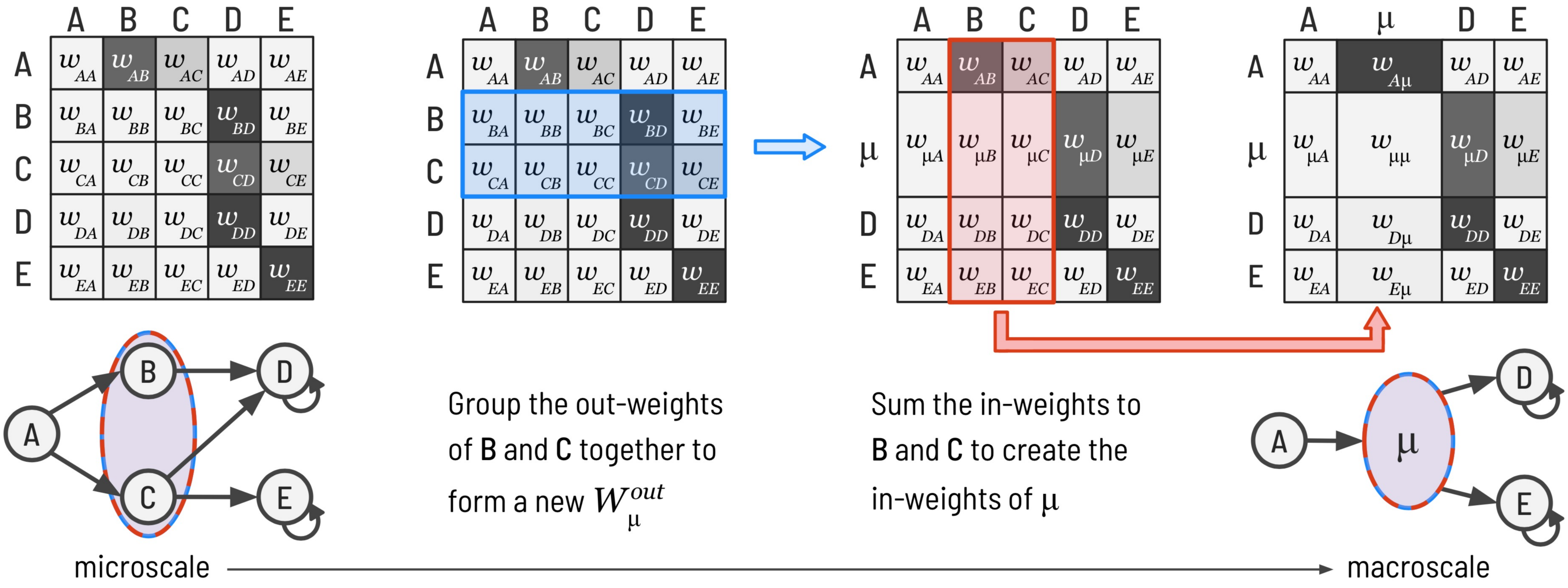

Klein & Hoel (2020). The emergence of informative higher scales in complex networks. *Complexity*.

Causal emergence

*a **quantity** that indicates how much higher-scale structural information a network contains.*

Increase in effective information

Decrease in network size

Klein & Hoel (2020). The emergence of informative higher scales in complex networks. *Complexity*.

Causal emergence

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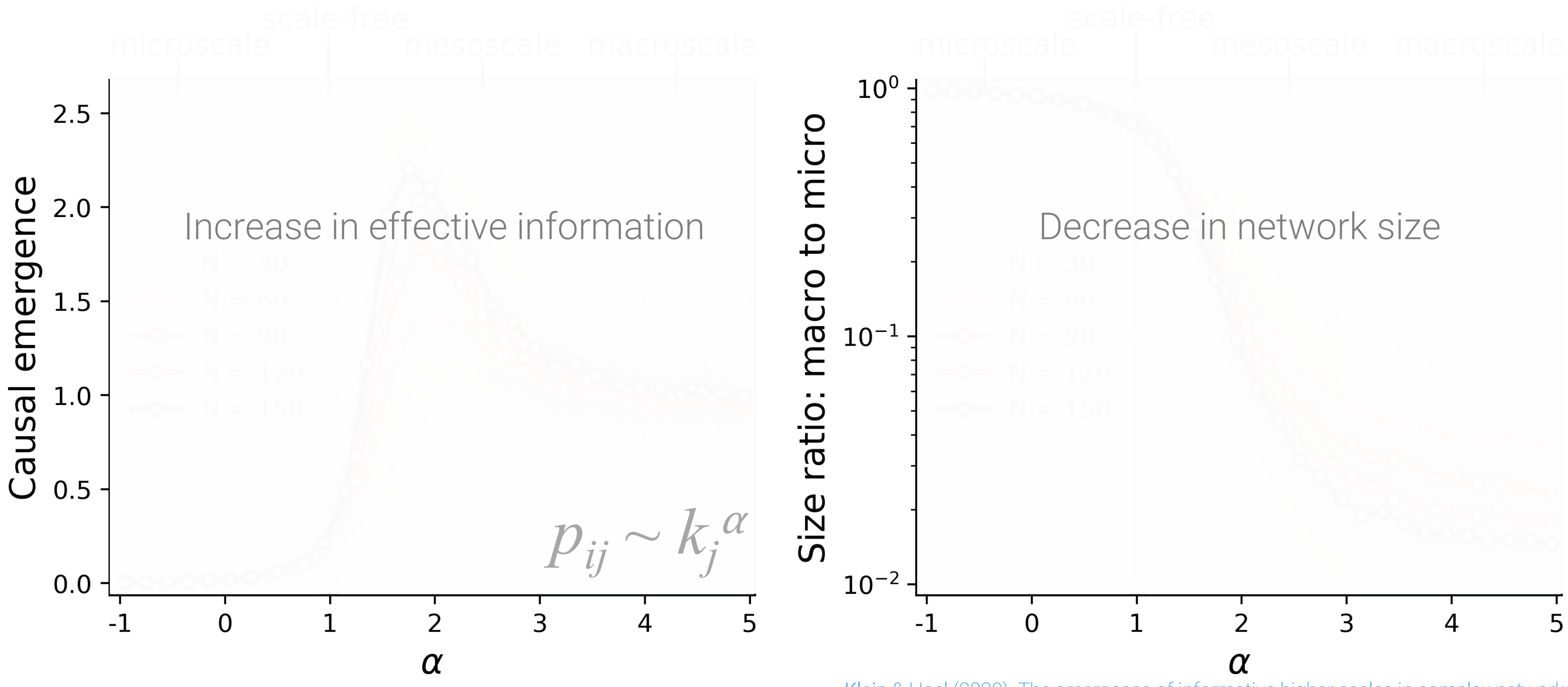

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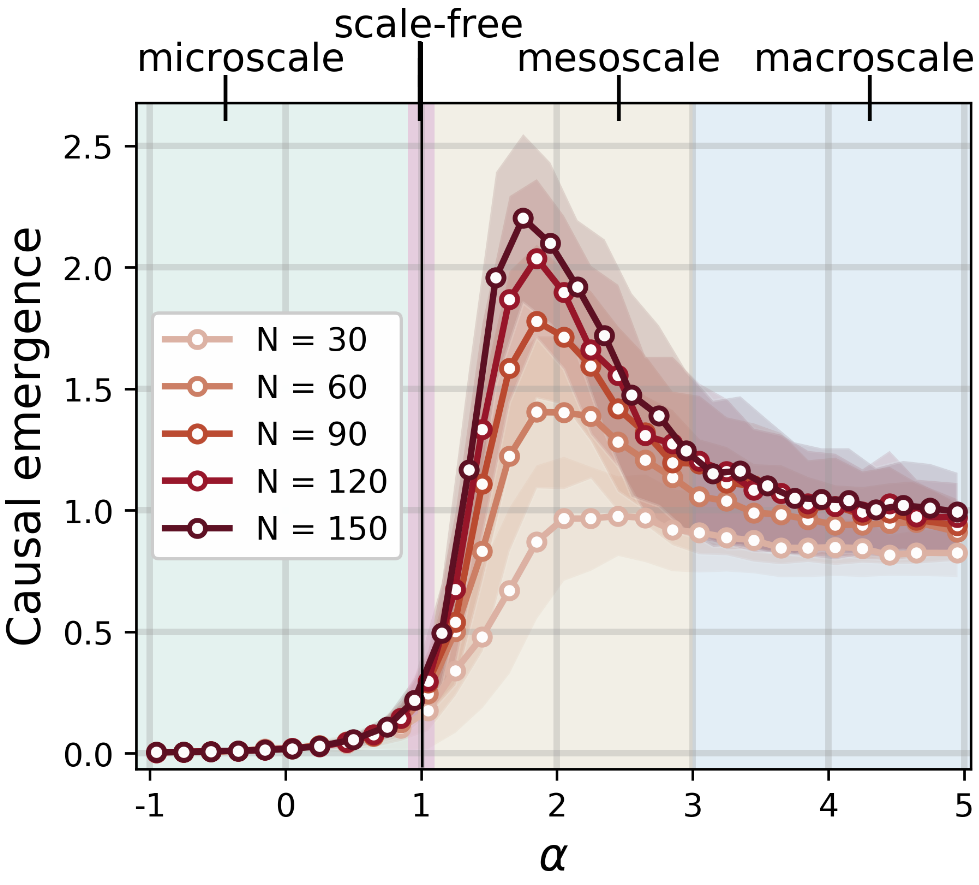
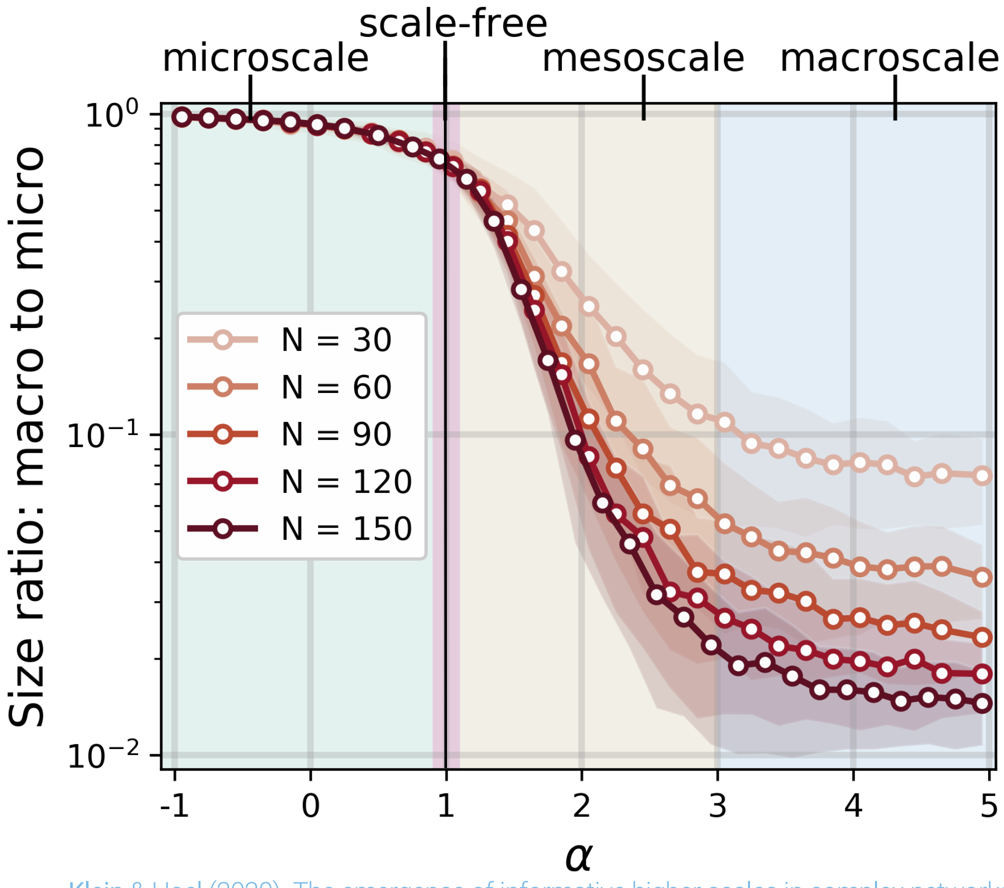
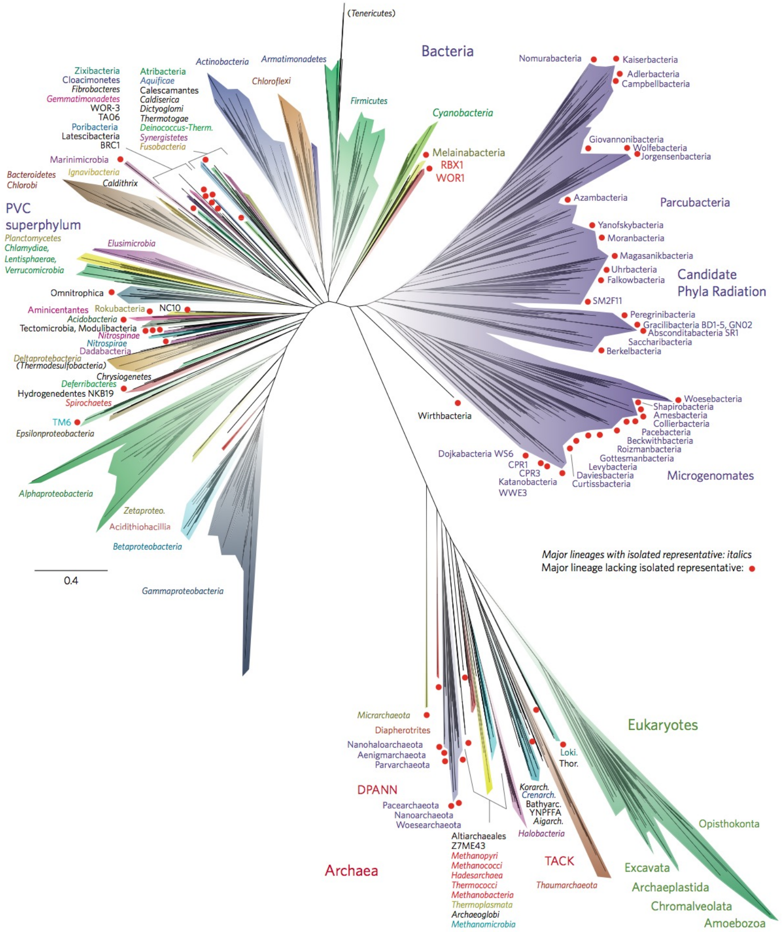




Klein & Hoel (2020). The emergence of informative higher scales in complex networks. *Complexity*.

Causal emergence in biological systems

*a **quantity** that indicates how much higher-scale structural information a network contains.*



Biological systems are characterized by noisy microscale interactions leading to emergent macroscale behavior.

- Carlile, M. (1982). Prokaryotes and eukaryotes: Strategies and successes. *Trends in Biochemical Sciences*. 7.4, pp. 128–130.
- Edelman G.M. & Gally, J.A. (2011). Degeneracy and complexity in biological systems. *PNAS*. 98.24, pp. 13763–13768.
- Lukeš, J., et al. (2011). How a neutral evolutionary ratchet can build cellular complexity. *IUBMB Life*. 63.7, pp. 528–537.
- Tsimring, L.S. (2014). Noise in biology. *Reports on Progress in Physics*. 77.2.
- Brunet, T.D.P. & Doolittle, W.F. (2018). The generality of constructive neutral evolution. *Biology and Philosophy*. 33.1-2.

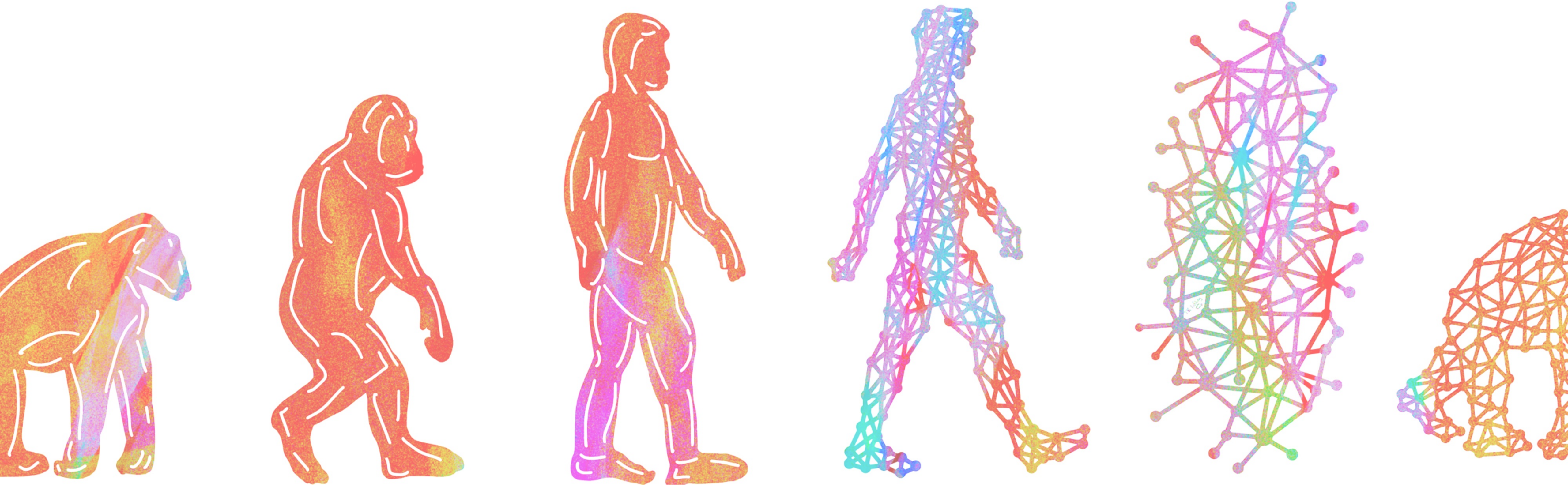
With a dataset of 1800+ species of protein-protein interaction networks, we find that **eukaryotic species** have more causal emergence than **prokaryotic species**.

Hug et al. (2016). A new view of the tree of life. *Nature Microbiology*. 1 (5): 16048.

Klein. et al. (2021). Evolution and emergence: higher order information structure in protein interactomes across the tree of life. *Integrative Biology*. 13(12), 283–294.

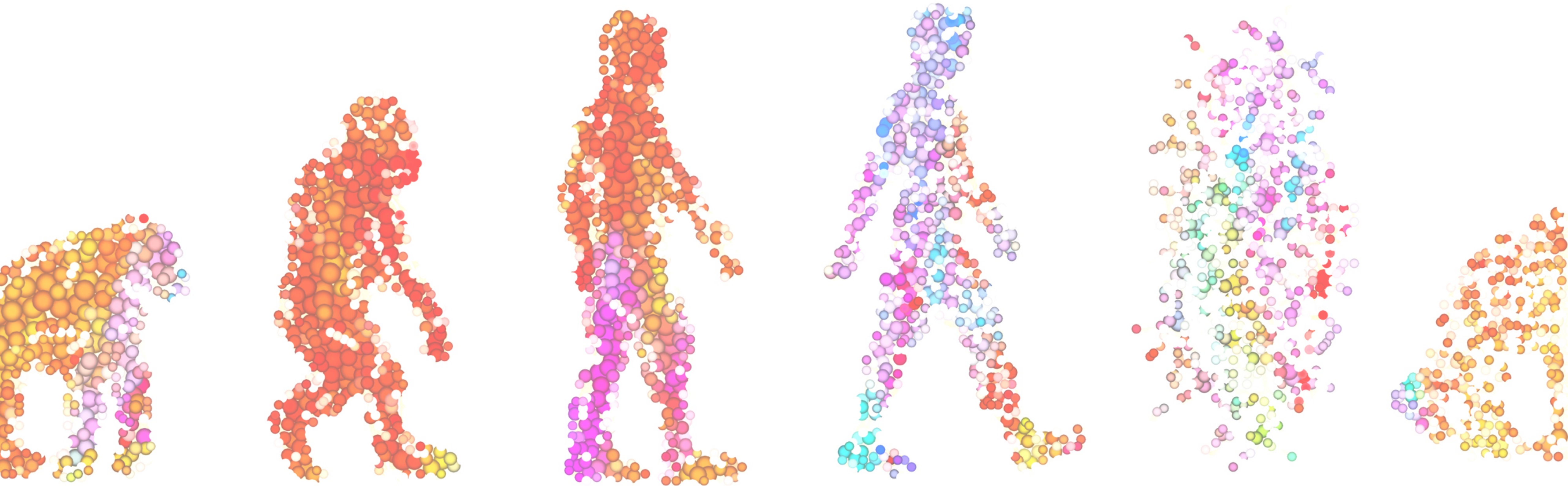
Zitnik et al. (2019). Evolution of resilience in protein interactomes across the tree of life. *PNAS*. 116.10, pp. 4426-4433.

Higher-order structure in networks…



Higher-order structure in networks…

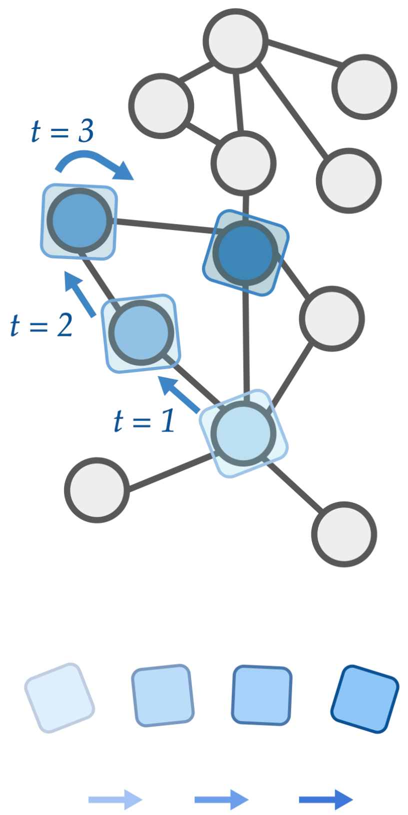
…what about higher-order dynamics?



Higher-order structure in networks…

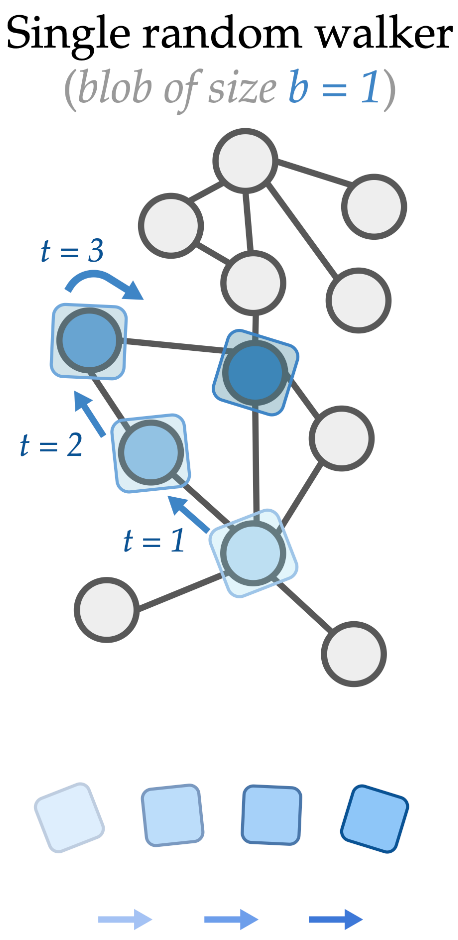
…what about higher-order dynamics?

Single random walker



Laber, Hartle, St-Onge, & Klein (forthcoming). Higher-order random walkers: Blob diffusion on complex networks

Higher-order dynamical process: "Blob walks"



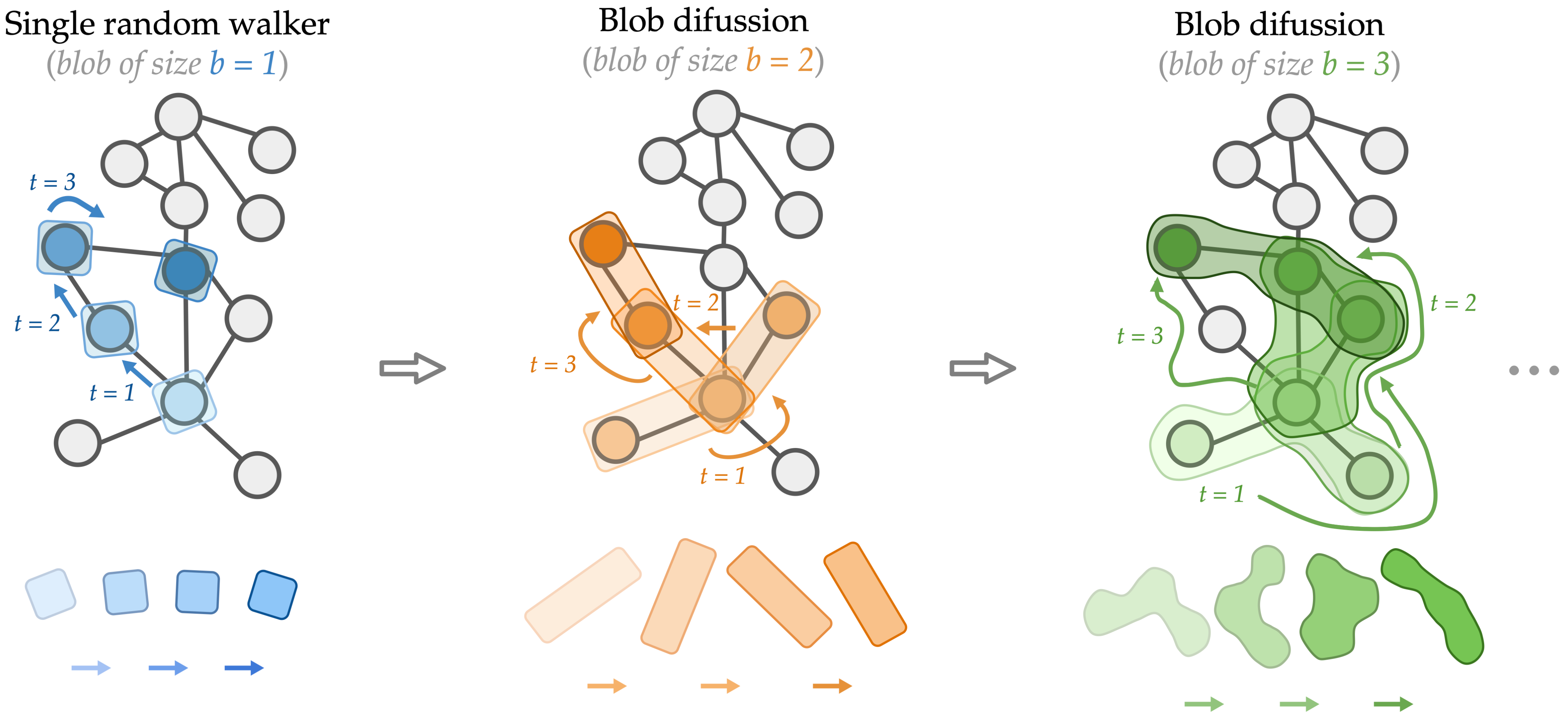
Higher-order random walks:

- Diffusion of a connected subgraph (a "blob"), B_t of size b on a graph.
  - A blob of size b occupies an entire connected subgraph of size b. At each timestep, the blob transitions into a new configuration B_{t+1} subject to the constraint that the new configuration retains b-1 nodes in B_t while again forming a connected subgraph.

A classic random walker in this framework is simply a blob of size $b=1$.

Laber, Hartle, St-Onge, & Klein (forthcoming). Higher-order random walkers: Blob diffusion on complex networks

Higher-order dynamical process: "Blob walks"



Laber, Hartle, St-Onge, & Klein (forthcoming). Higher-order random walkers: Blob diffusion on complex networks

Higher-order dynamical process: “Blob walks”

Moritz Laber
PhD Student,
Network Science

Led by Northeastern University PhD student, **Moritz Laber**, who will discuss these results at NetSci 2023 in Vienna.

NetSci

Laber, Hartle, St-Onge, & Klein (forthcoming). Higher-order random walkers: Blob diffusion on complex networks

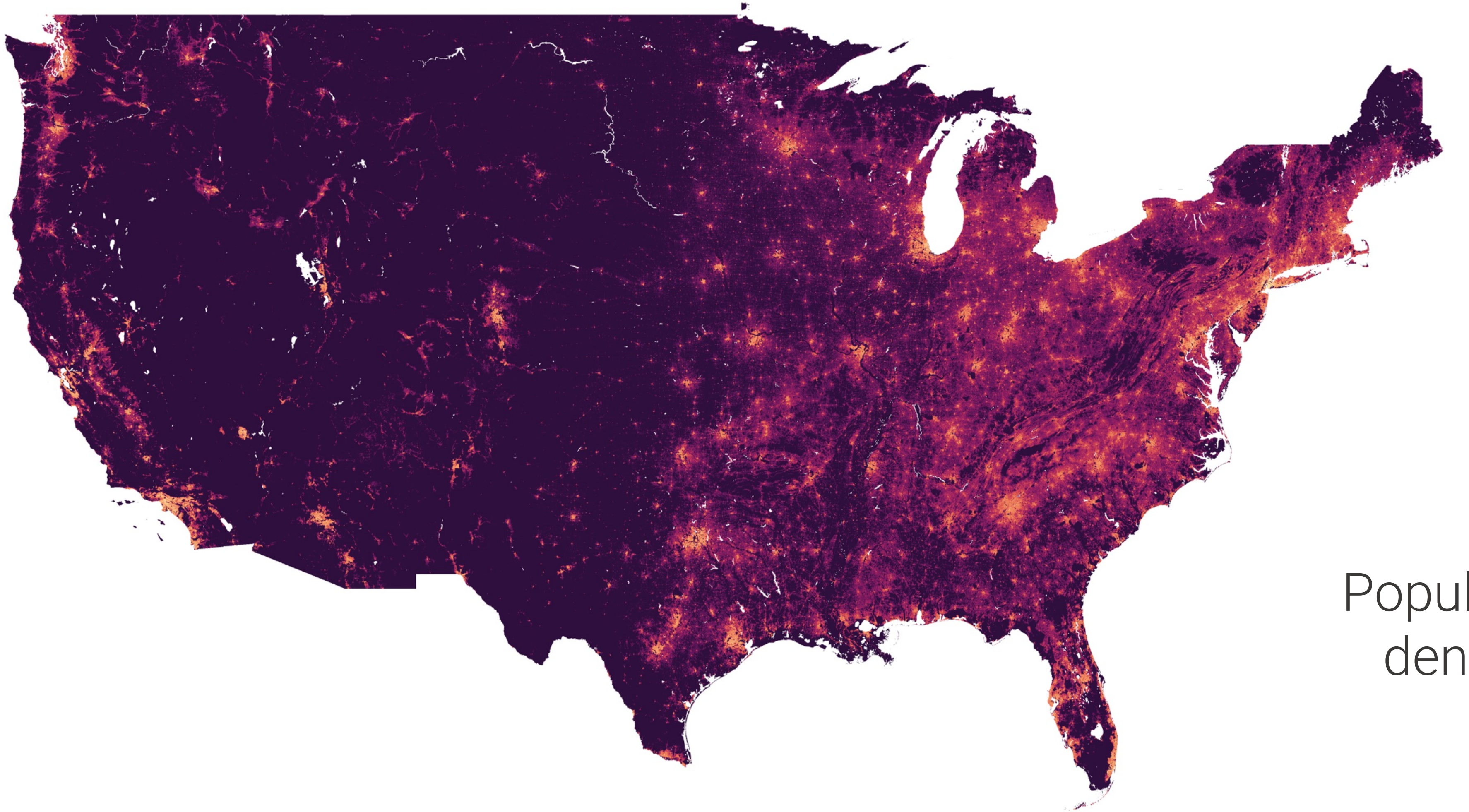
Today

1. Introduction
2. Complexity
    i. *Reconstruction & comparison*
    ii. *Informative network scales & representation*
3. Society
    i. *Mobile device data for disease modeling*
    ii. *Assorted COVID-19 projects*
4. Research vision and outlook

Models, representation, theory

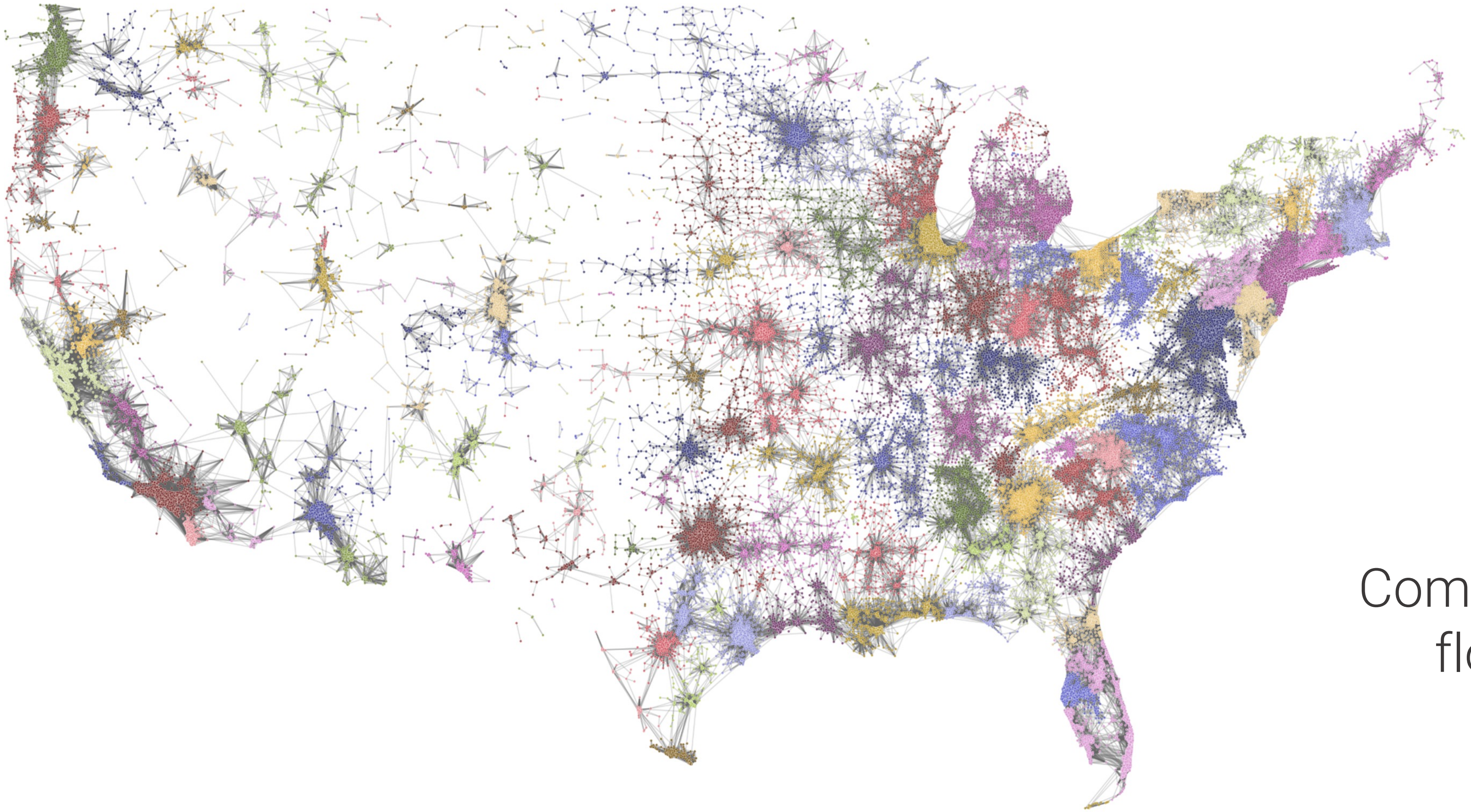
Administrative
(i.e., states)

Models, representation, theory



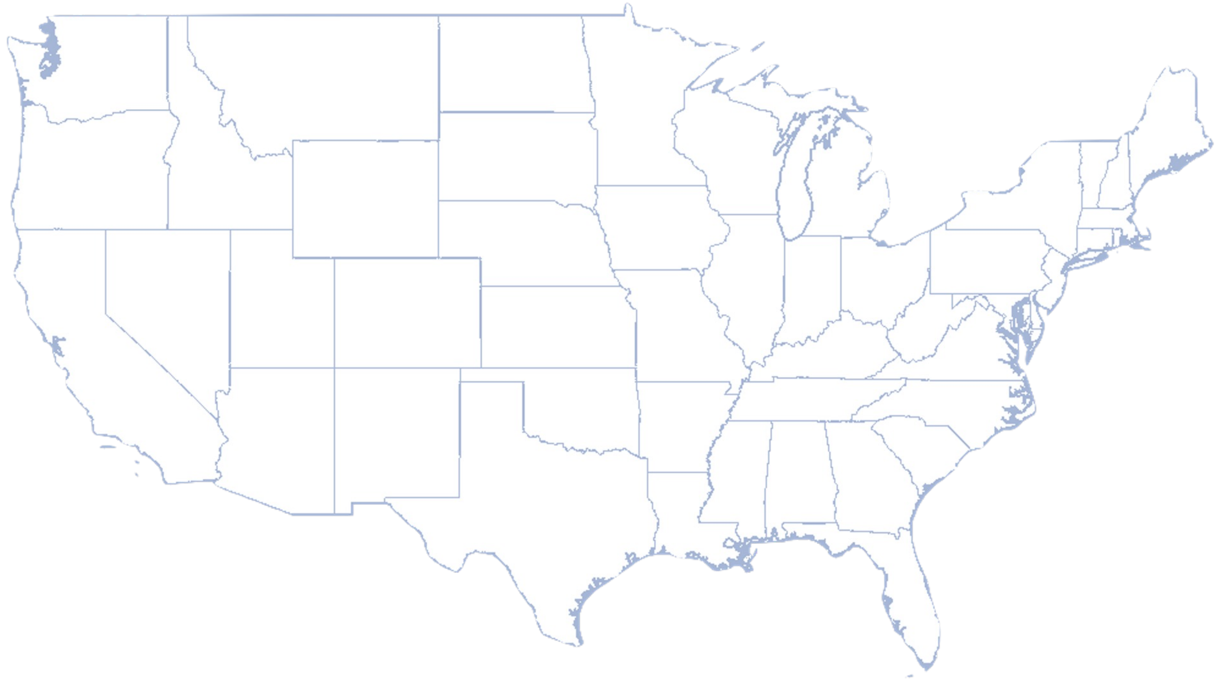
Population density

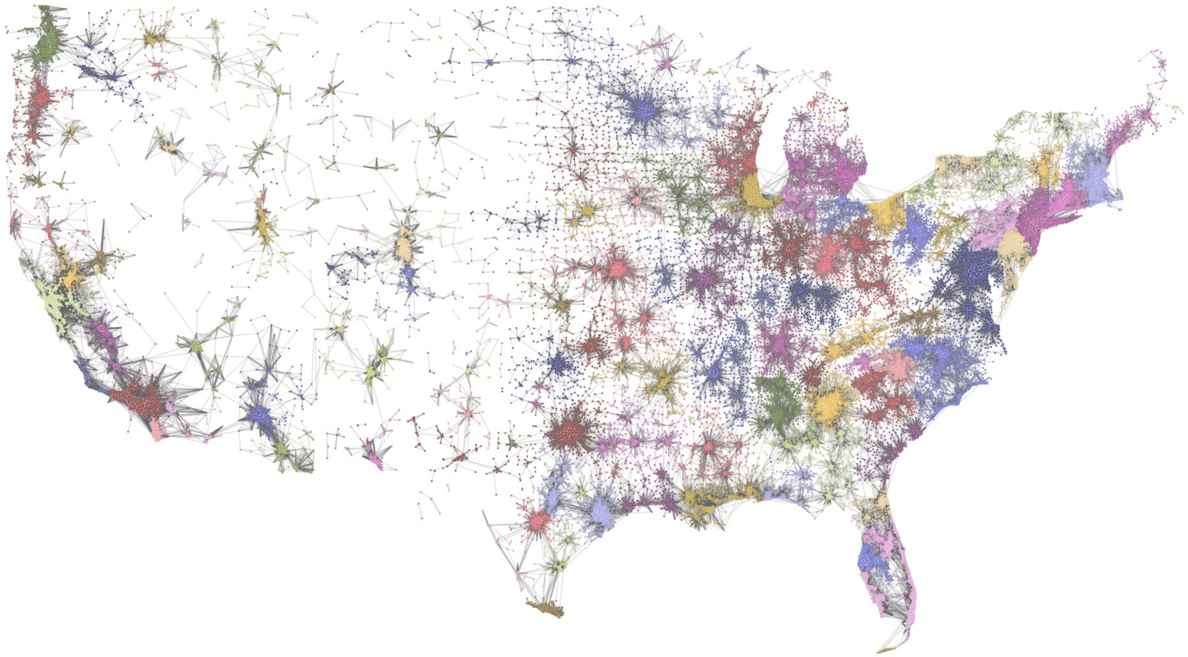
Models, representation, theory



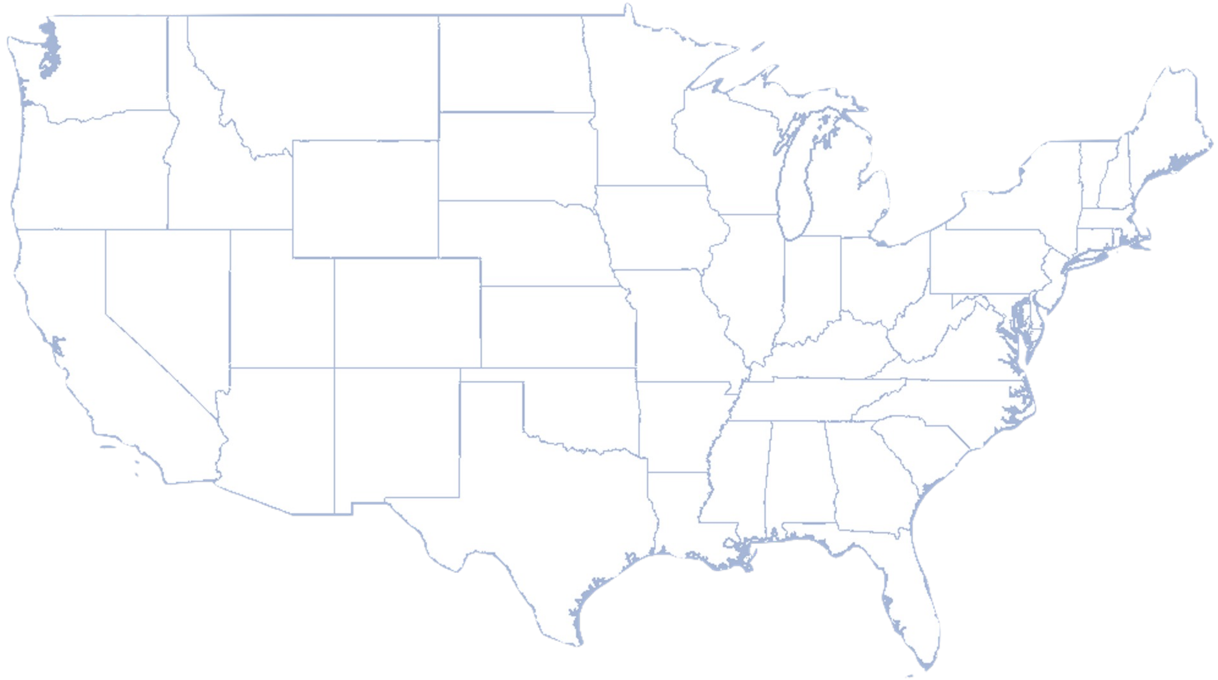
Commuter flow

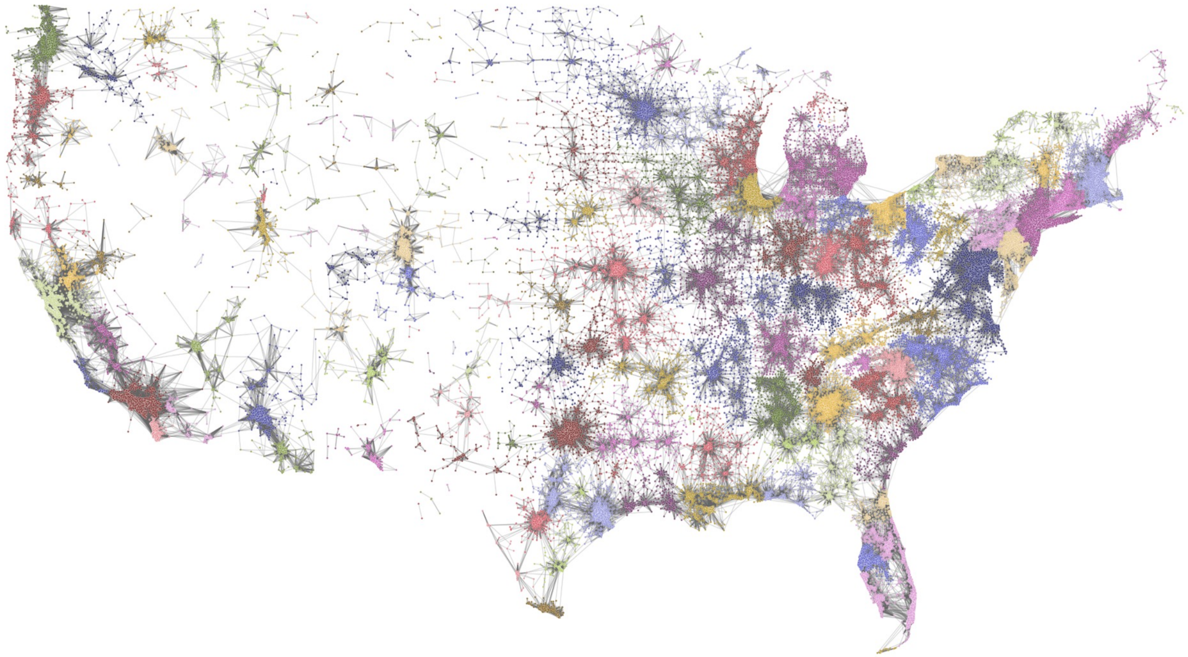
Which is better for comparing policy differences?





Which is better to model spread of diseases?





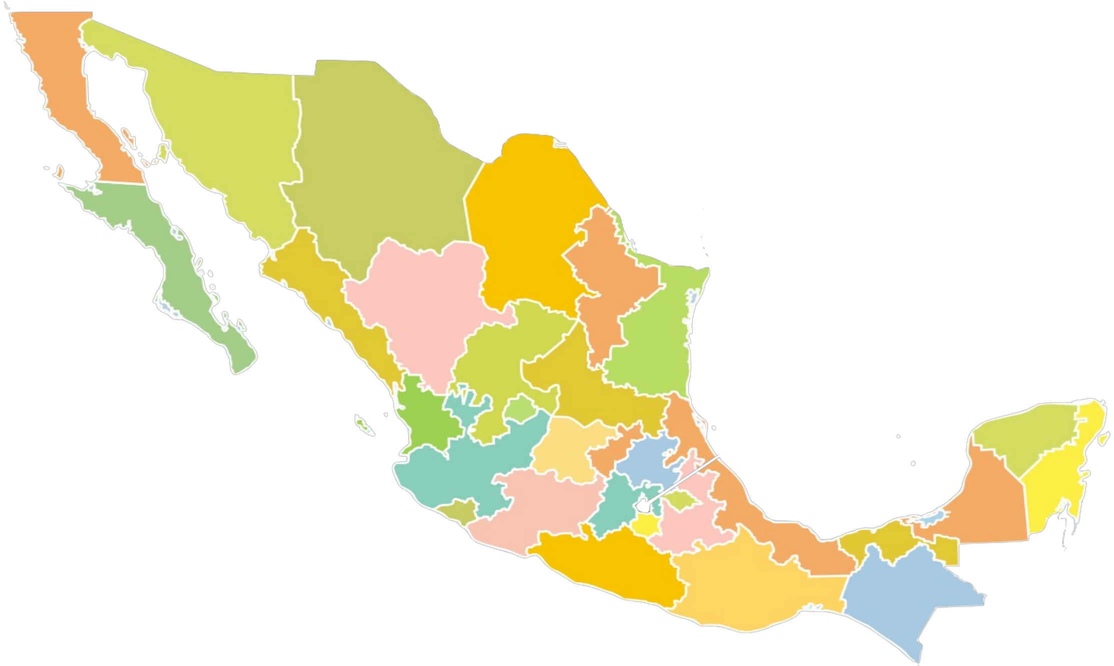
Networks, scale, and disease dynamics

Spatial scales of COVID-19 transmission in Mexico

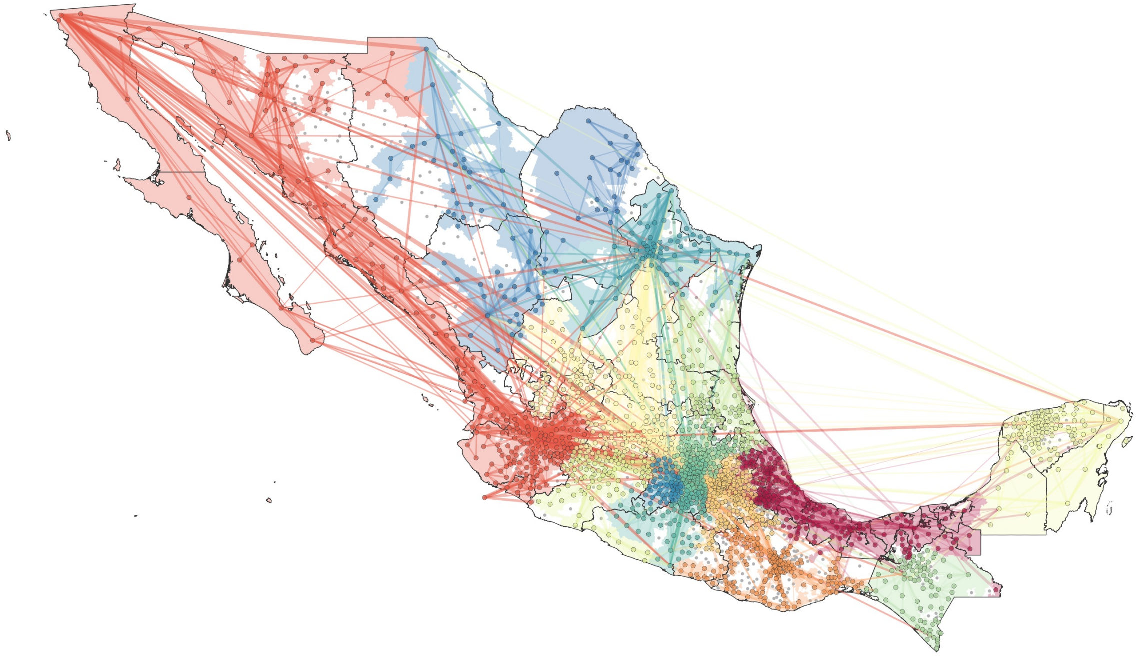
Brennan Klein[*1,2], Harrison Hartle[1], Munik Shrestha[1], Ana Cecilia Zenteno[3], David Barros Sierra Cordera[4], José R. Nicolas-Carlock[5], Ana I. Bento[6], Benjamin M. Althouse[7,8], Bernardo Gutierrez[9,10,11], Marina Escalera-Zamudio[9,11], Arturo Reyes-Sandoval[12,13], Oliver G. Pybus[9,14,18], Alessandro Vespignani[1,2], Jose Alberto Diaz-Quiñonez[*†15], Samuel V. Scarpino[*‡1,16,17], and Moritz U.G. Kraemer[*§9,18]

Klein, Hartle, Shrestha, Zenteno, ... Scarpino, & Kraemer (2023). Spatial scales of COVID-19 transmission in Mexico. under review, *PNAS*.

Networks, scale, and disease dynamics



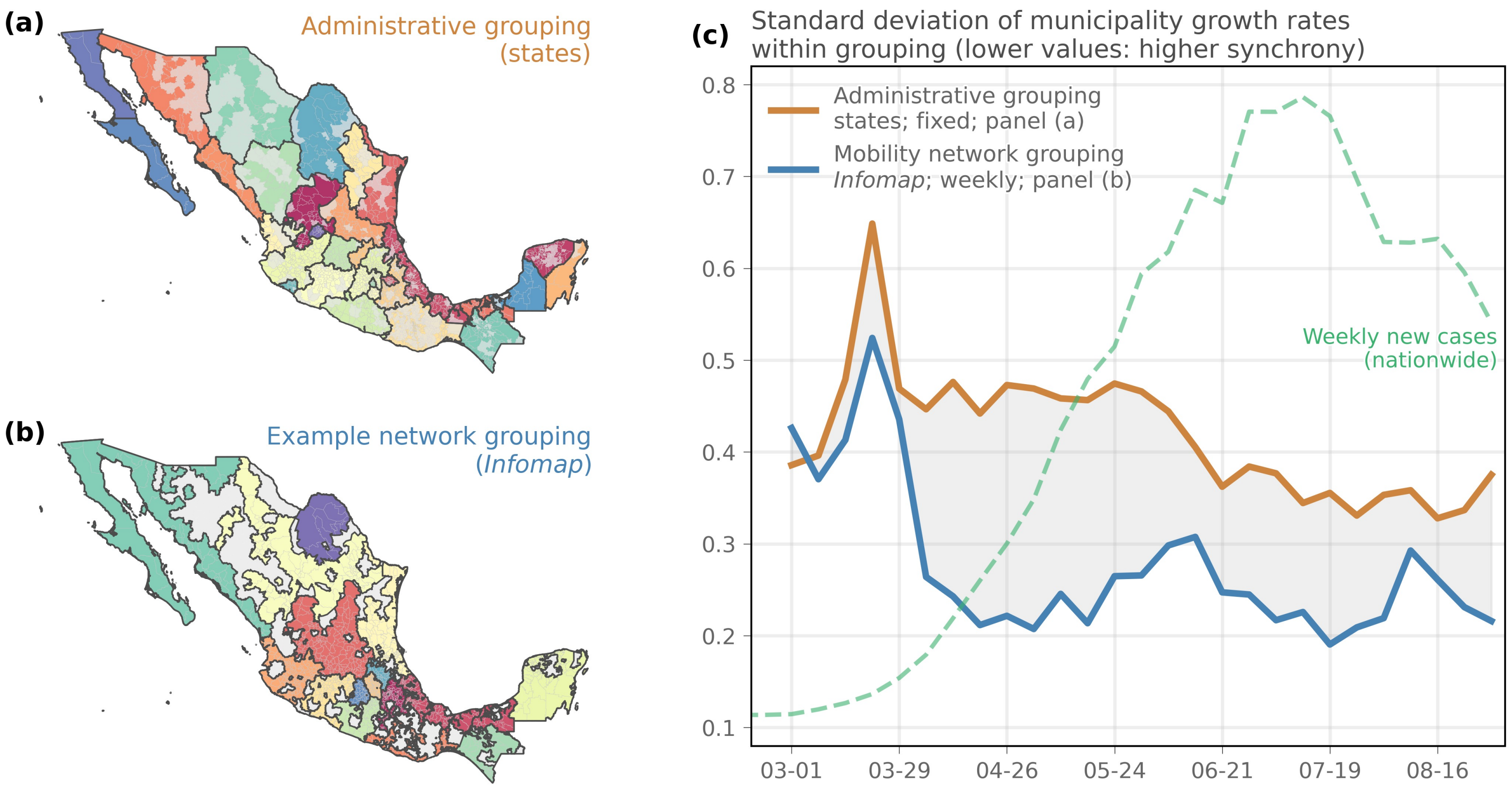
Policy operates on this scale
(administrative)



People interact at this scale
(network)

Klein, Hartle, Shrestha, Zenteno, ... Scarpino, & Kraemer
(2023). Spatial scales of COVID-19 transmission in Mexico. under review, *PNAS*.

Networks, scale, and disease dynamics



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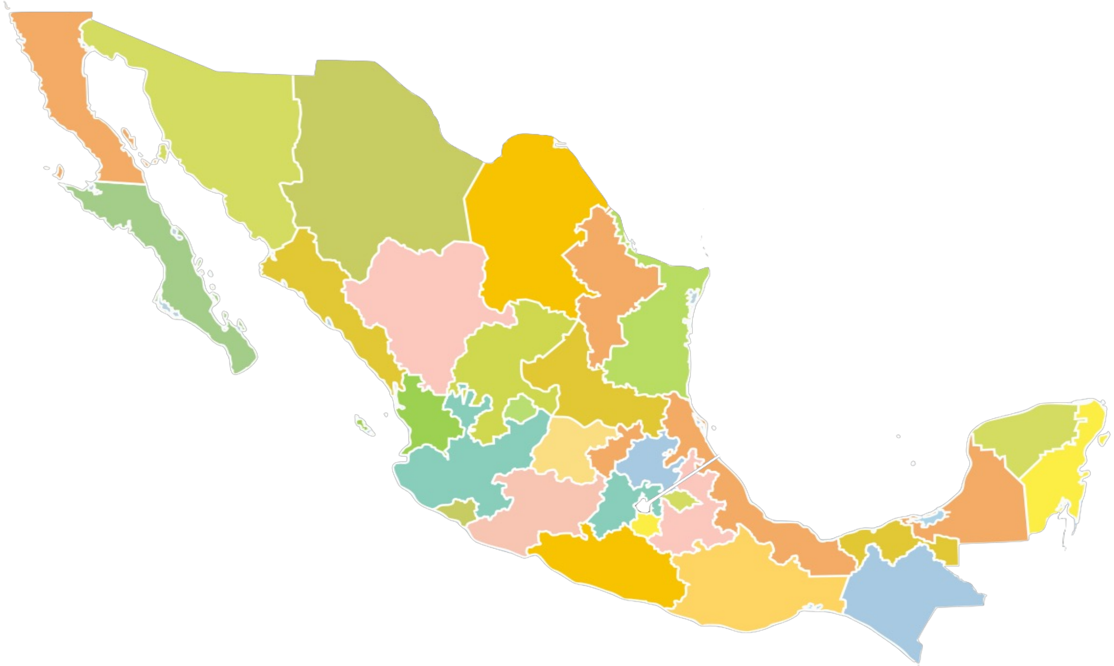
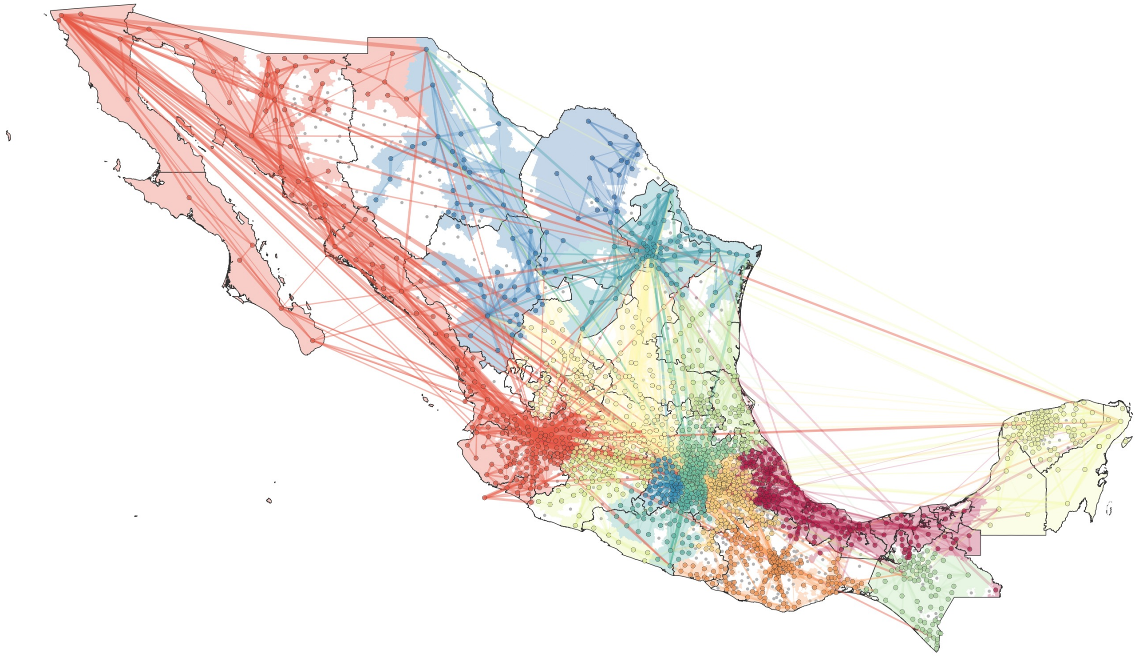
Networks, scale, and disease dynamics



Higher within-community variance
of infection growth rates



More *synchronized*
outbreaks

Klein, Hartle, Shrestha, Zenteno, ... Scarpino, & Kraemer
(2023). Spatial scales of COVID-19 transmission in Mexico. under review, *PNAS*.

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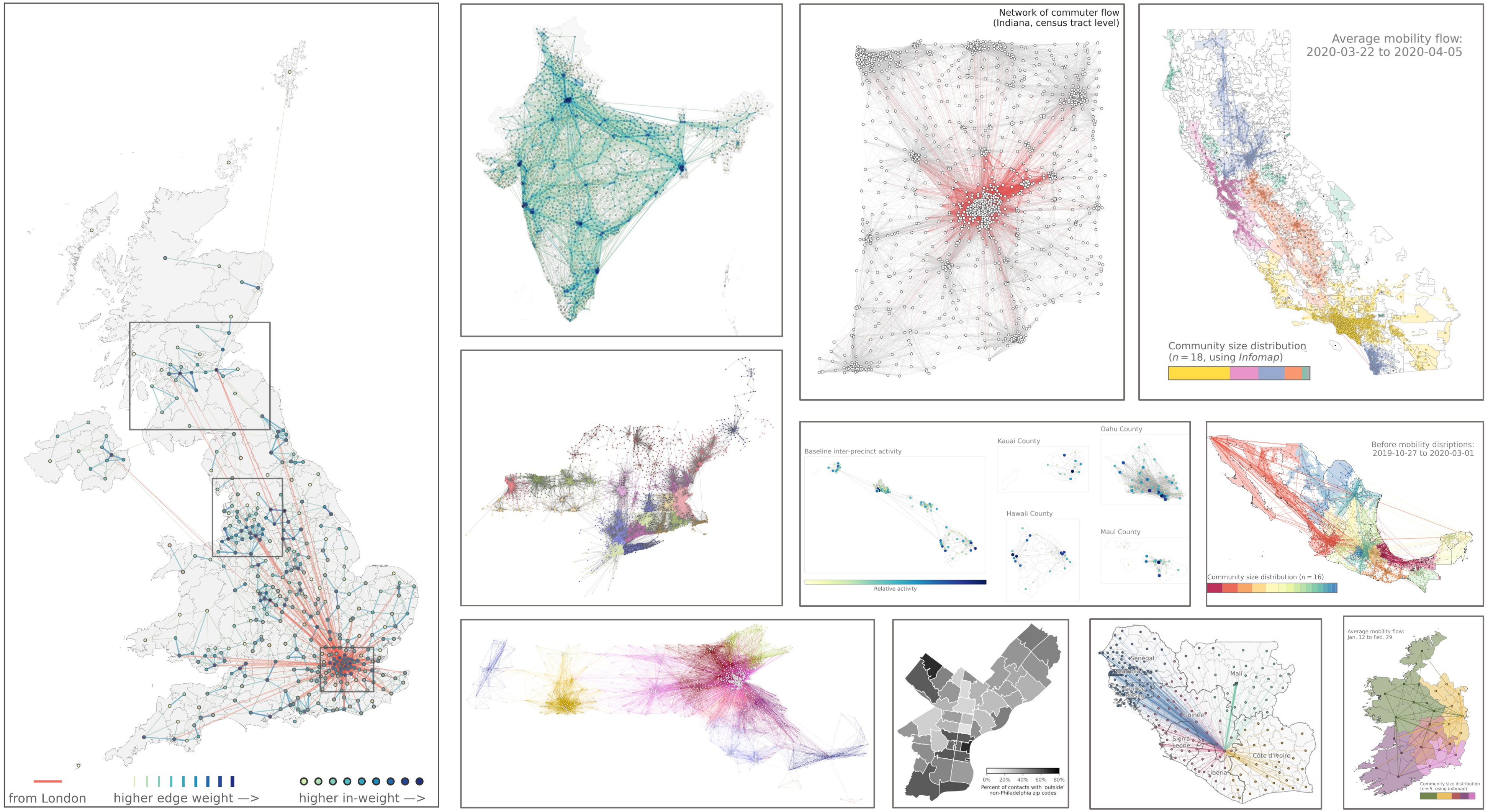
(The right) network data can improve modeling



But we don’t always *need* networks…

RESEARCH

CORONAVIRUS

The effect of human mobility and control measures on the COVID-19 epidemic in China

Moritz U. G. Kraemer[1,2,3]*, Chia-Hung Yang[4], Bernardo Gutierrez[1,5], Chieh-Hsi Wu[6], Brennan Klein[4], David M. Pigott[7], Open COVID-19 Data Working Group†, Louis du Plessis[1], Nuno R. Faria[1], Ruoran Li[8], William P. Hanage[8], John S. Brownstein[2,3], Maylis Layan[9,10], Alessandro Vespignani[4,11], Huaiyu Tian[12], Christopher Dye[1], Oliver G. Pybus[1,13]*, Samuel V. Scarpino[4]*

RESEARCH

CORONAVIRUS

Spatiotemporal invasion dynamics of SARS-CoV-2 lineage B.1.1.7 emergence

Moritz U. G. Kraemer[1]*†, Verity Hill[2]†, Christopher Ruis[3]†, Simon Dellicour[4,5]†, Sumali Bajaj[1]†, John T. McCrone[2], Guy Baele[5], Kris V. Parag[6], Anya Lindström Battle[7], Bernardo Gutierrez[1], Ben Jackson[2], Rachel Colquhoun[2], Áine O'Toole[2], Brennan Klein[8], Alessandro Vespignani[8], COVID-19 Genomics UK (COG-UK) Consortium‡, Erik Volz[6], Nuno R. Faria[1,6,9], David M. Aanensen[10,11], Nicholas J. Loman[12], Louis du Plessis[1], Simon Cauchemez[13], Andrew Rambaut[2]*, Samuel V. Scarpino[8,14,15]*, Oliver G. Pybus[1,16]*

ARTICLE

https://doi.org/10.1038/s41467-021-22521-5 OPEN

Check for updates

The effect of eviction moratoria on the transmission of SARS-CoV-2

Anjalika Nande[1,7], Justin Sheen[2,7], Emma L. Walters[3], Brennan Klein[4,5], Matteo Chinazzi[4,5], Andrei H. Gheorghe[1], Ben Adlam[1], Julianna Shinnick[2], Maria Florencia Tejeda[2], Samuel V. Scarpino[4], Alessandro Vespignani[4,5], Andrew J. Greenlee[3], Daniel Schneider[3], Michael Z. Levy[2,8]✉ & Alison L. Hill[1,6,8]✉

communications medicine

nature > communications medicine > articles > article

Article | Open Access | Published: 14 February 2023

Forecasting hospital-level COVID-19 admissions using real-time mobility data

Brennan Klein ✉, Ana C. Zenteno ✉, Daisha Joseph, Mohammadmehdi Zahedi, Michael Hu, Martin S. Copenhaver, Moritz U. G. Kraemer, Matteo Chinazzi, Michael Klompas, Alessandro Vespignani, Samuel V. Scarpino ✉ & Hojjat Salmasian ✉

Clinical Infectious Diseases

CORRECTED PROOF

Examining the Robustness of 3 Versus 6 Feet of Physical Distancing in Schools: A Reanalysis of van den Berg et al FREE

Brennan Klein ✉, Daniel A Harris

PLOS DIGITAL HEALTH

RESEARCH ARTICLE

Higher education responses to COVID-19 in the United States: Evidence for the impacts of university policy

Brennan Klein[1,2]*, Nicholas Generous[1,2,3], Matteo Chinazzi[1,2], Zarana Bhadricha[1,4], Rishab Gunashekar[1,4], Preeti Kori[1,4], Bodian Li[1,5], Stefan McCabe[1], Jon Green[1,6], David Lazer[1], Christopher R. Marsicano[7,8], Samuel V. Scarpino[1,9,10], Alessandro Vespignani[1,2]*

nature

nature > articles > article

Article | Open Access | Published: 19 April 2023

COVID-19 amplified racial disparities in the US criminal legal system

Brennan Klein ✉, C. Brandon Ogbunugafor ✉, Benjamin J. Schafer, Zarana Bhadricha, Preeti Kori, Jim Sheldon, Nitish Kaza, Arush Sharma, Emily A. Wang, Tina Eliassi-Rad, Samuel V. Scarpino ✉ & Elizabeth Hinton ✉

under review (*PNAS*)

Spatial scales of COVID-19 transmission in Mexico

Brennan Klein*[1,2], Harrison Hartle[1], Munik Shrestha[1], Ana Cecilia Zenteno[3], David Barros Sierra Cordera[4], José R. Nicolas-Carlock[5], Ana I. Bento[6], Benjamin M. Althouse[7,8], Bernardo Gutierrez[9,10,11], Marina Escalera-Zamudio[9,11], Arturo Reyes-Sandoval[12,13], Oliver G. Pybus[9,14,18], Alessandro Vespignani[1,2], Alberto Diaz Quiñonez*†[15], Samuel V. Scarpino*‡[1,16,17], and Moritz U.G. Kraemer*§[9,18]

revision (*PLOS Digital Health*)

Characterizing collective physical distancing in the U.S. during the first nine months of the COVID-19 pandemic

Brennan Klein*[1], Timothy LaRock*[1], Stefan McCabe*[1], Leo Torres*[1], Lisa Friedland*[1], Maciej Kos*[1], Filippo Privitera[4], Brennan Lake[4], Moritz U.G. Kraemer[5], John S. Brownstein[6,7], Richard Gonzalez[8], David Lazer[1], Tina Eliassi-Rad[1], Samuel V. Scarpino[1,9,10], Alessandro Vespignani[1,3], and Matteo Chinazzi§[1,2]

But we don’t always *need* networks…

- Modeling collective physical distancing during the pandemic
  - Klein et al. (2020); Klein et al. (2020); Klein et al. (2022).
- Predicting hospital admissions 21 days out
  - Klein, Zenteno, Joseph, et al. (2023).
- Estimating the impact of eviction moratoria on COVID-19
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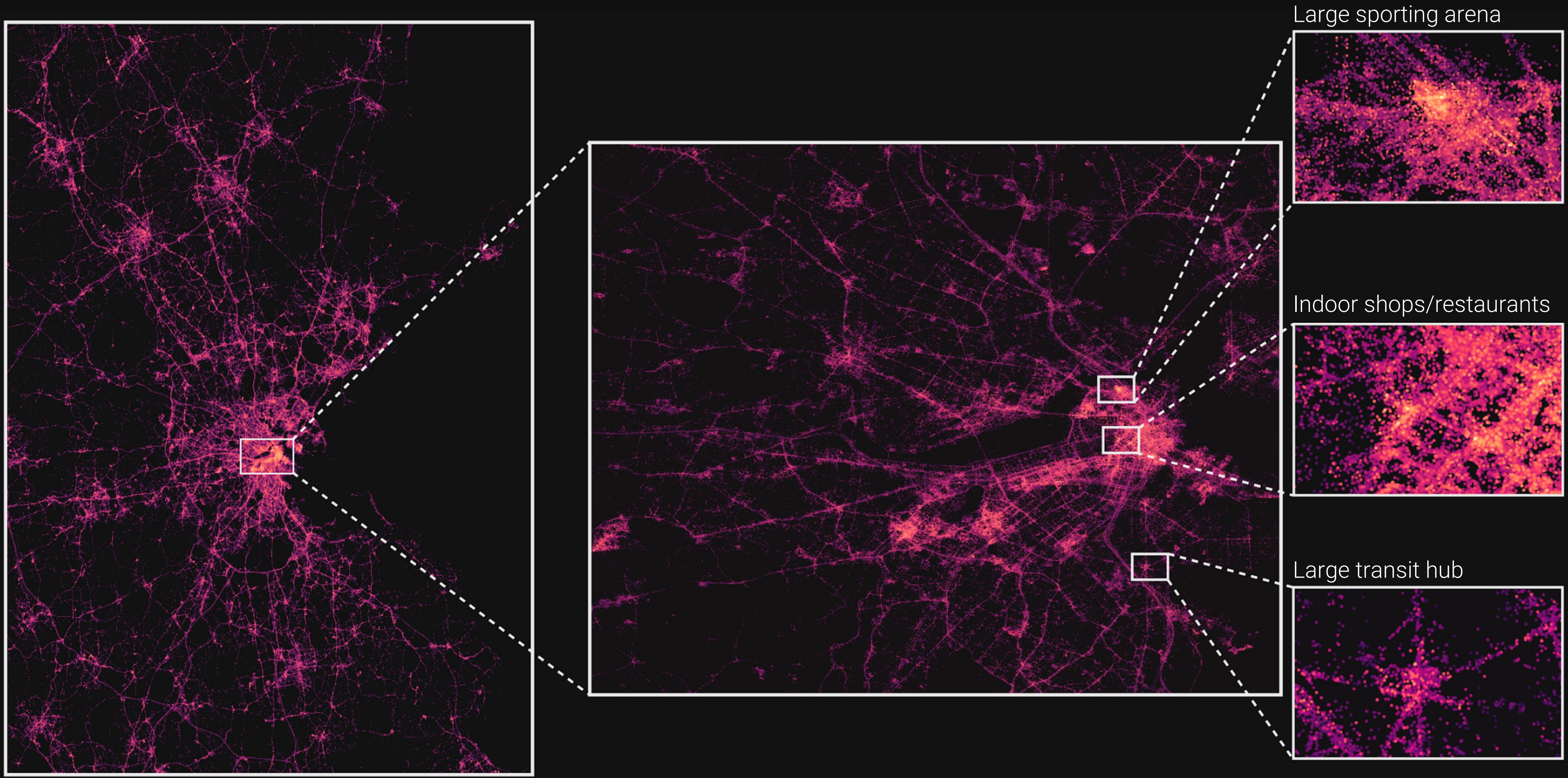
Data from Cuebiq Inc.

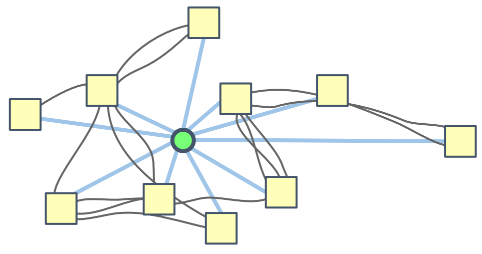
Through its Data for Good program, Cuebiq Inc. provides access to privacy-enhanced mobility data for academic / humanitarian initiatives.

- Opt-in, first-party GPS data
- Obscured personal areas (home and work)
  - Up-leveled to the census block group
- Data from 40+ million total users
  - We select a panel of users from this
- High temporal and spatial resolution.
  - Heavy-tailed location accuracy


Large sporting arena
Indoor shops/restaurants
Large transit hub

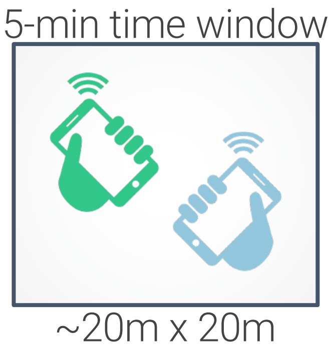
What can Cuebiq data tell us?

- Mobility behavior of users:
  - Measured through the radius of gyration[1]



- Commuting patterns of users:
  - If one user visits their two (up-leveled) "personal areas" in a given 24hr period

- Estimated contact between users:
  - If users are close to each other within the same 5-minute time window (and thus, present an opportunity for transmission)



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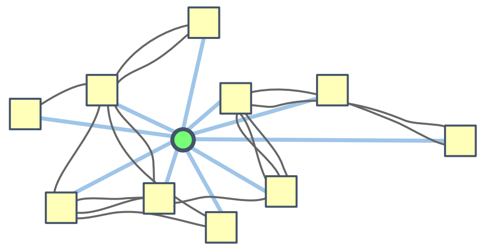
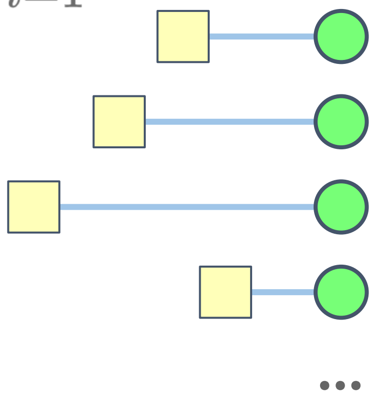


- Mobility behavior of users:
  - Measured through the radius of gyration[1]

$$r = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \|\vec{r}_i - \vec{r}_{cm}\|^2}$$



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[1] González, Hidalgo, & Barabási. Understanding individual human mobility patterns. *Nature* 453, 779–782 (2008).

What can Cuebiq data tell us?

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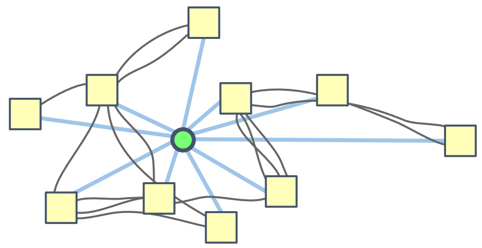

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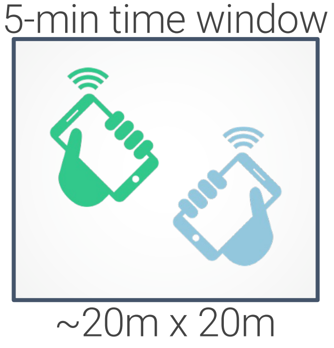
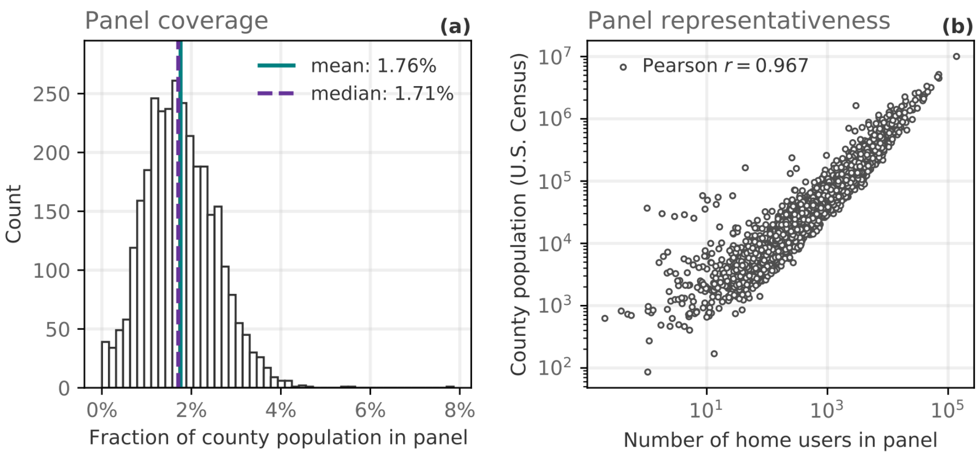
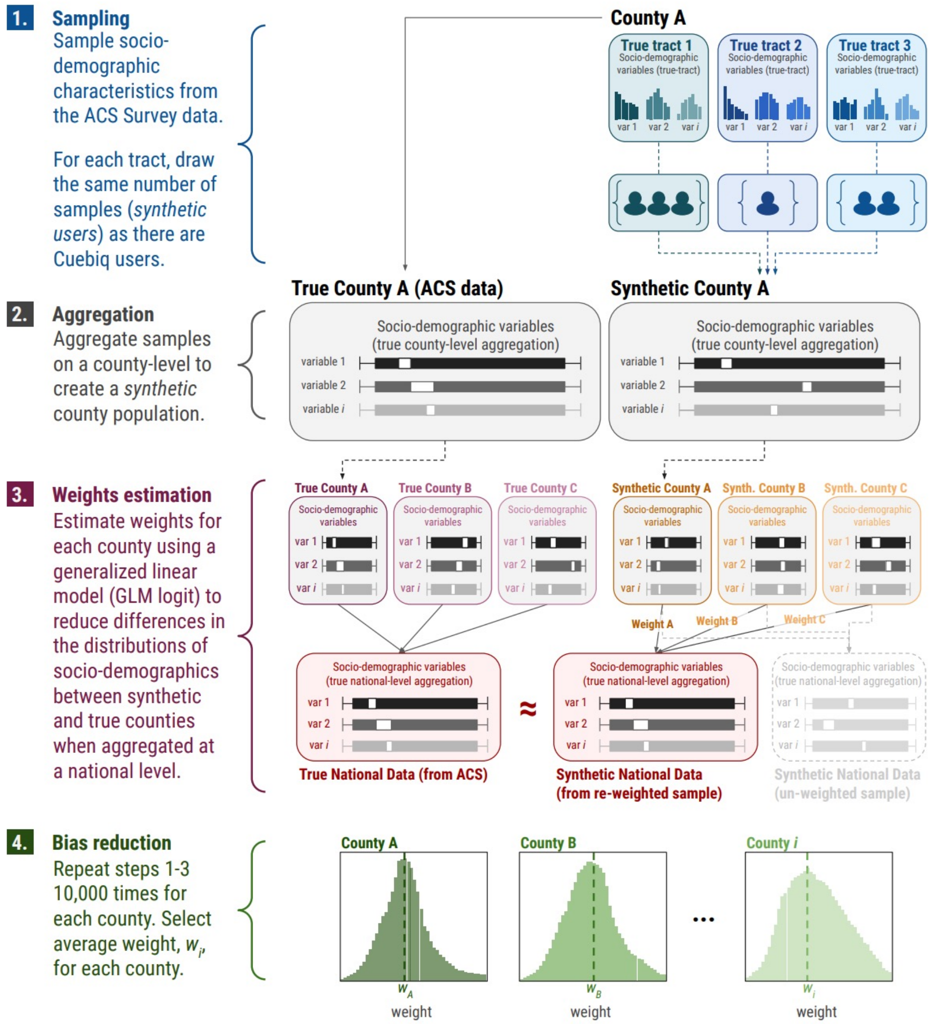


What can Cuebiq data tell us?

But! We can’t just take all 40+ million users and compute measures based on their data.

We need rigorous statistical controls to account for potential over/under sampling.





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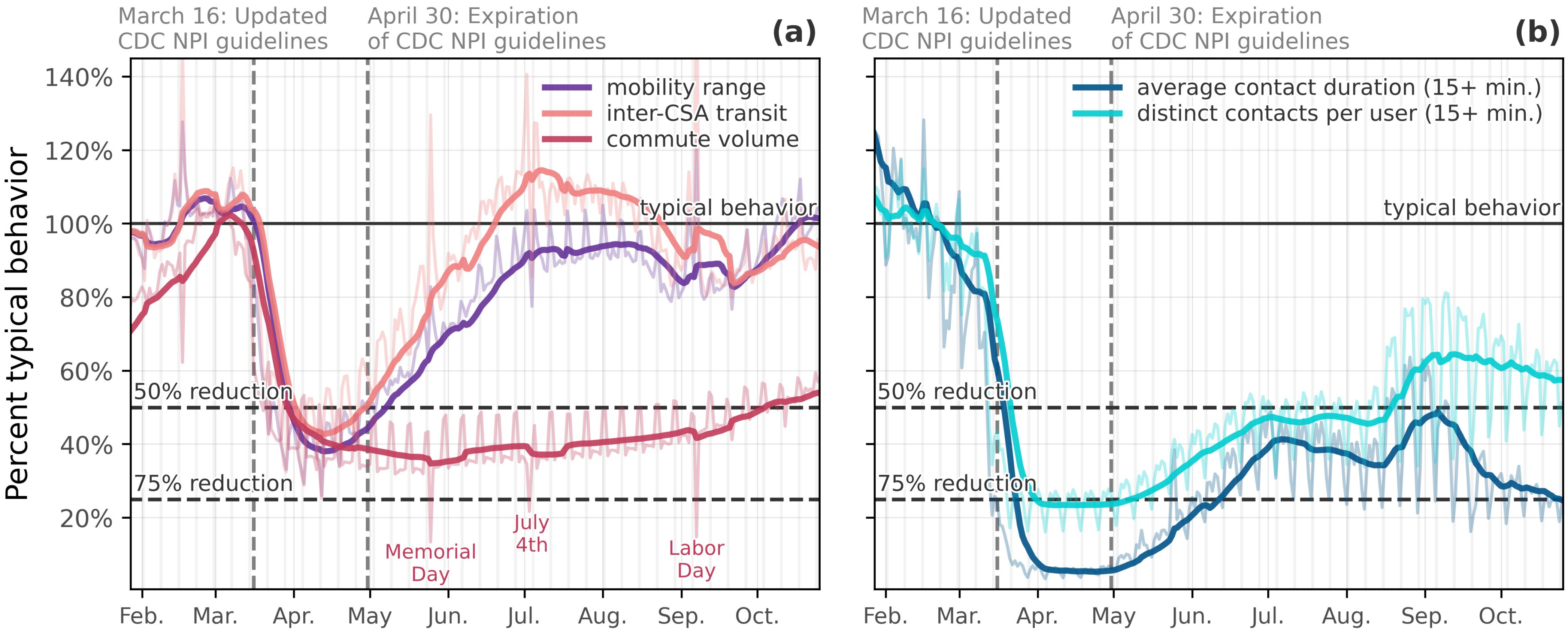

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Forecasting primary COVID-19 admissions

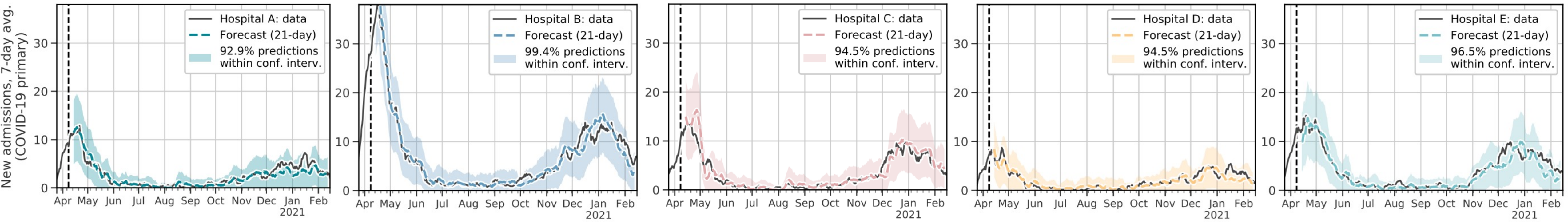
- Large healthcare network in Massachusetts approached us:
  - “We have pretty good in-house forecast accuracy for individual-hospital admissions **14 days out**.”
  - “What about <u>21 days out</u>?”
- Our approach: combine exogenous mobility data with current admissions data in a *k-step ahead nonlinear autoregressive forecasting model.*

$$y(t+k) = f\Big(y(t), y(t-1), ..., y(t-p-1), \mathbf{X}(t), \mathbf{X}(t-1), ..., \mathbf{X}(t-p-1)\Big) + \epsilon(t)$$

k-days ahead forecast

Target time series, *y(t)*

Exogenous (mobility) variables, ***X***(*t*)



Klein, Zenteno et al. (2023). Forecasting hospital-level COVID-19 admissions using real-time mobility data. *Communications Medicine*. 3, 25.

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Sloppy data, sloppy policy

Effectiveness of 3 Versus 6 ft of Physical Distancing for Controlling Spread of Coronavirus Disease 2019 Among Primary and Secondary Students and Staff: A Retrospective, Statewide Cohort Study FREE

Polly van den Berg, Elissa M Schechter-Perkins, Rebecca S Jack, Isabella Epshtein, Richard Nelson, Emily Oster, Westyn Branch-Elliman ✉

Clinical Infectious Diseases, Volume 73, Issue 10, 15 November 2021, Pages 1871–1878, https://doi.org/10.1093/cid/ciab230

Published: 10 March 2021 **Article history ▾**

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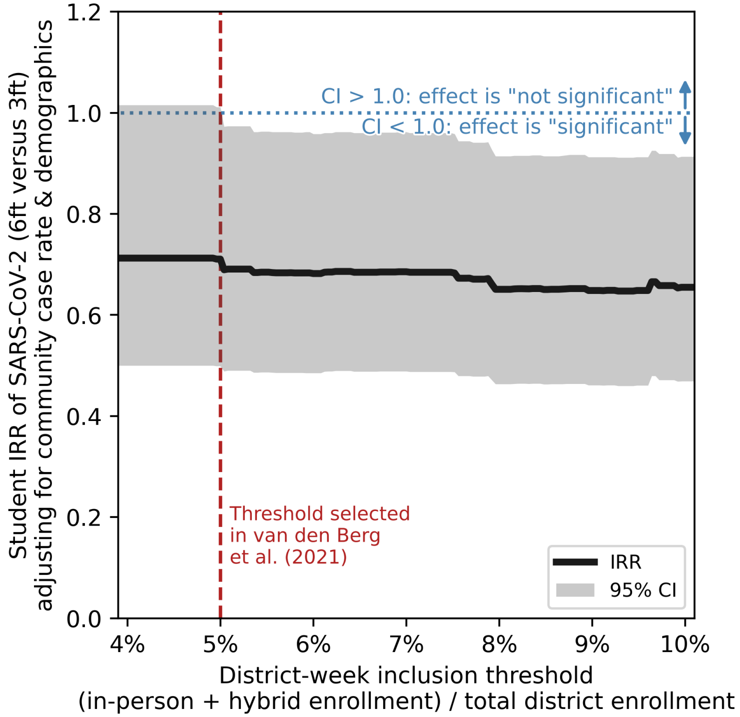
Published: 10 March 2021
Corrected and typeset: 27 April 2021

A correction has been published: *Clinical Infectious Diseases*, ciab1049, https://doi.org/10.1093/cid/ciab1049



Clinical Infectious Diseases

CORRECTED PROOF

Examining the Robustness of 3 Versus 6 Feet of Physical Distancing in Schools: A Reanalysis of van den Berg et al FREE

Brennan Klein ✉, Daniel A Harris

Clinical Infectious Diseases, ciac187, https://doi.org/10.1093/cid/ciac187
Published: 05 March 2022 **Article history ▾**

Klein & Harris (2022). Examining the Robustness of 3 Versus 6 Feet of Physical Distancing... *Clinical Infectious Diseases*, Volume 75, Issue 1, e310–e311.

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- Predicting hospital admissions 21 days out
  - Klein, Zenteno, Joseph, et al. (2023).
- Estimating the impact of eviction moratoria on COVID-19
  - Nande, Sheen, Walters, Klein, et al. (2021).
- Uncovering large-scale data errors in COVID + K-12 data
  - Klein & Harris (2022).
- Evaluating the effect of campus COVID-19 policy on surrounding area
  - Klein, Generous, Chinazzi, et al. (2022).

But we don't always *need* networks…

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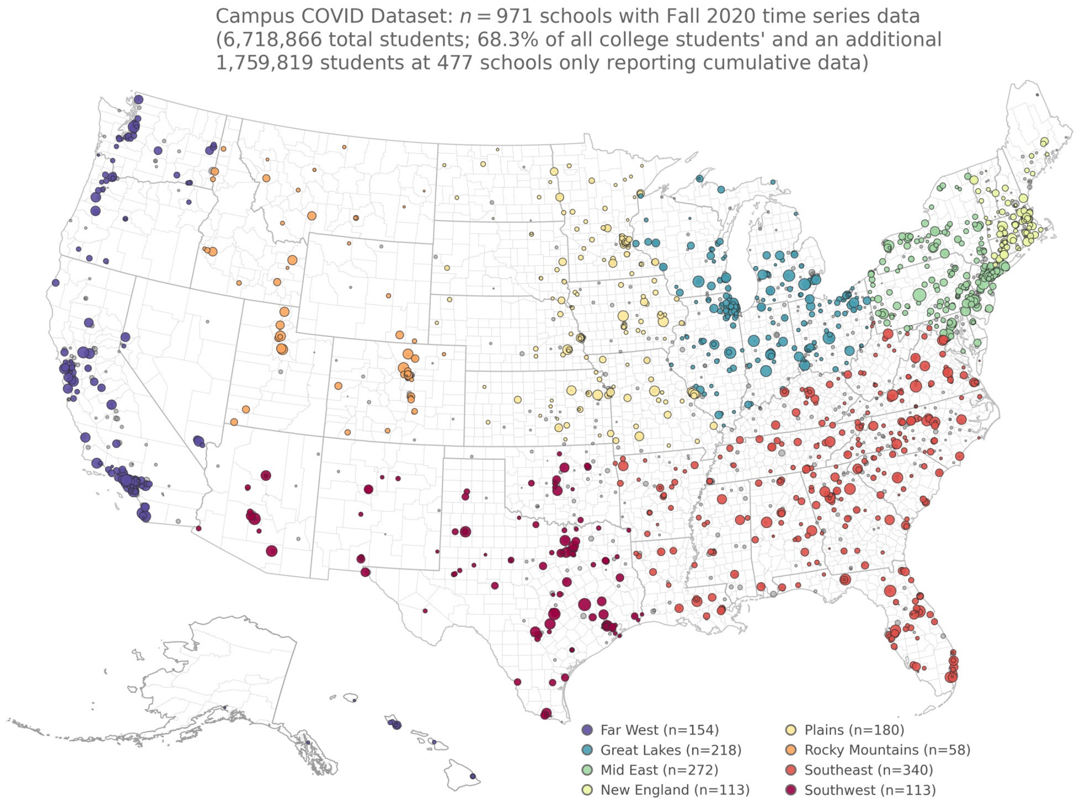
Higher education COVID-19 policy

- Gather the largest dataset of reported tests and cases at institutes of higher education (IHE) for Fall 2020.

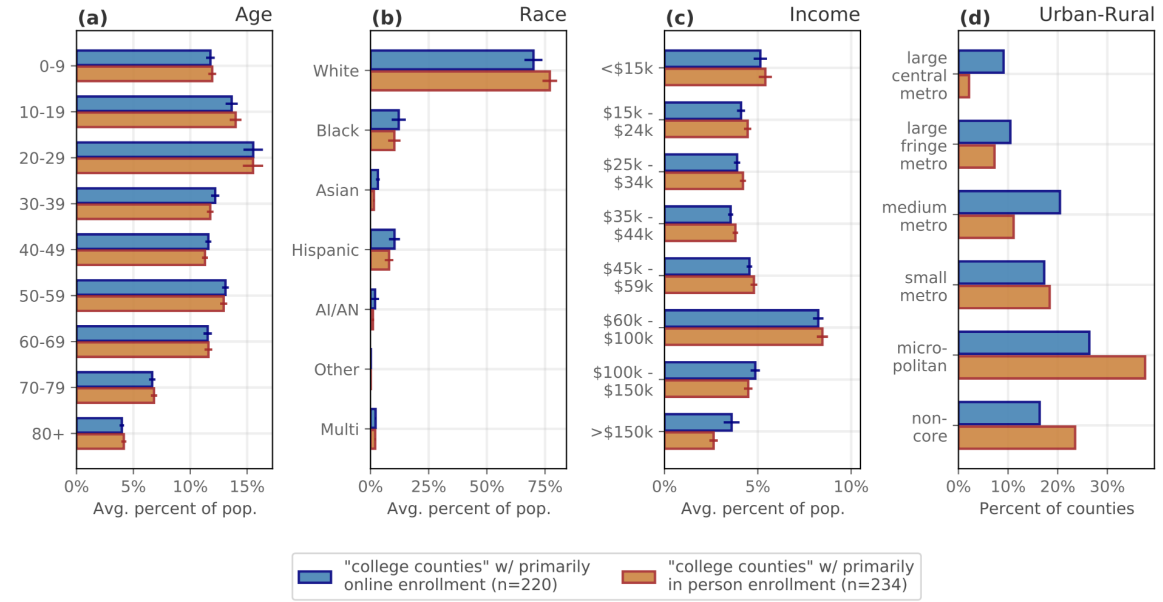
All data available on github
https://github.com/jkbren/campus-covid/



Klein*, Generous, et al. (2022) Higher education responses to COVID-19 in the United States: Evidence for the impacts of university policy. *PLOS Digital Health* 1(6).

Higher education COVID-19 policy

- Gather the largest dataset of reported tests and cases at institutes of higher education (IHE) for Fall 2020.
- Ask whether IHE policy (on-campus testing, online/in-person) has benefits for the surrounding community.
  - Create statistically-matched groups of college counties and compare reported cases / deaths at the county level.



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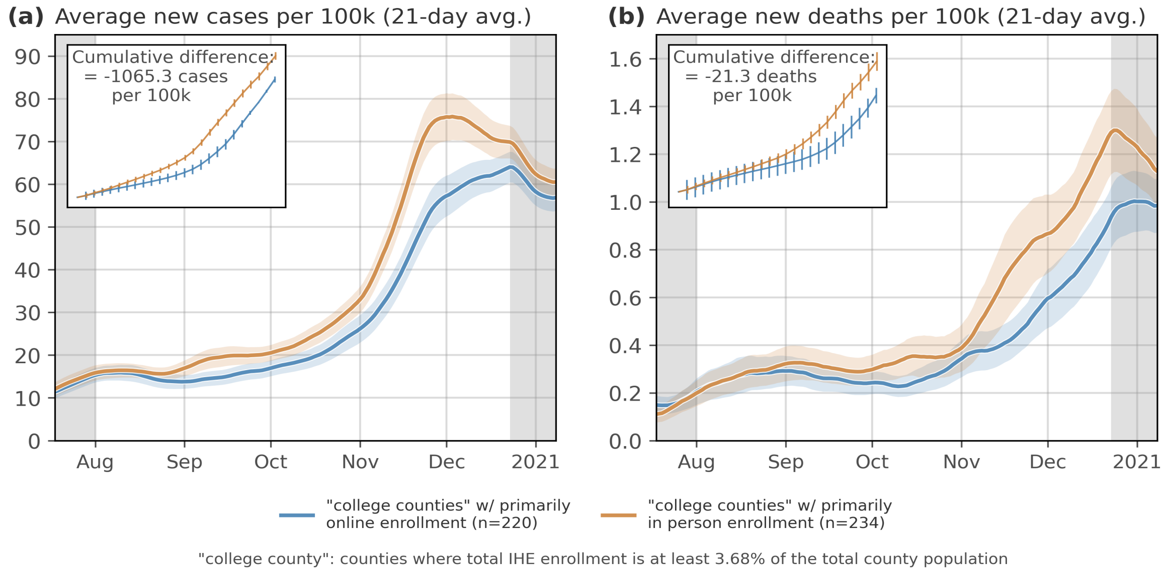
Higher education COVID-19 policy

- Gather the largest dataset of reported tests and cases at institutes of higher education (IHE) for Fall 2020.
- Ask whether IHE policy (on-campus testing, online/in-person) has benefits for the surrounding community.
  - Create statistically-matched groups of college counties and compare reported cases / deaths at the county level.
- Prudent campus policy has a positive impact on the surrounding county.



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Today

1. Introduction
2. Complexity
   i. *Reconstruction & comparison*
   ii. *Informative network scales & representation*
3. Society
   i. *Mobile device data for disease modeling*
   ii. *Assorted COVID-19 projects*
4. Research vision and outlook

Today

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4. **Problems that excite me lately**

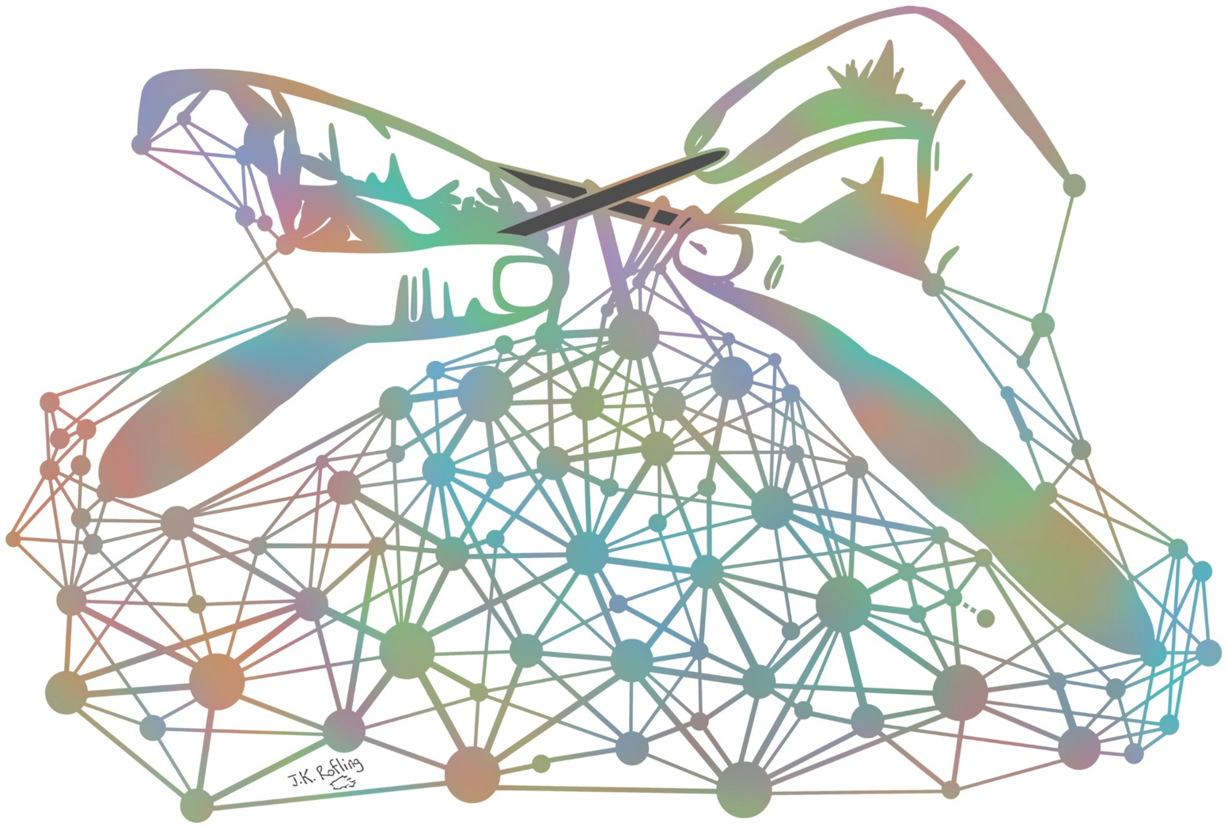
Someday (soon)

1. Higher-order dynamical processes
2. New (principled) graph distances
3. Connectomics of artificial intelligence
4. What is a *typical* graph in model?
5. Individuation and the network science of network mergers
6. The free energy principle and active inference

René Thom

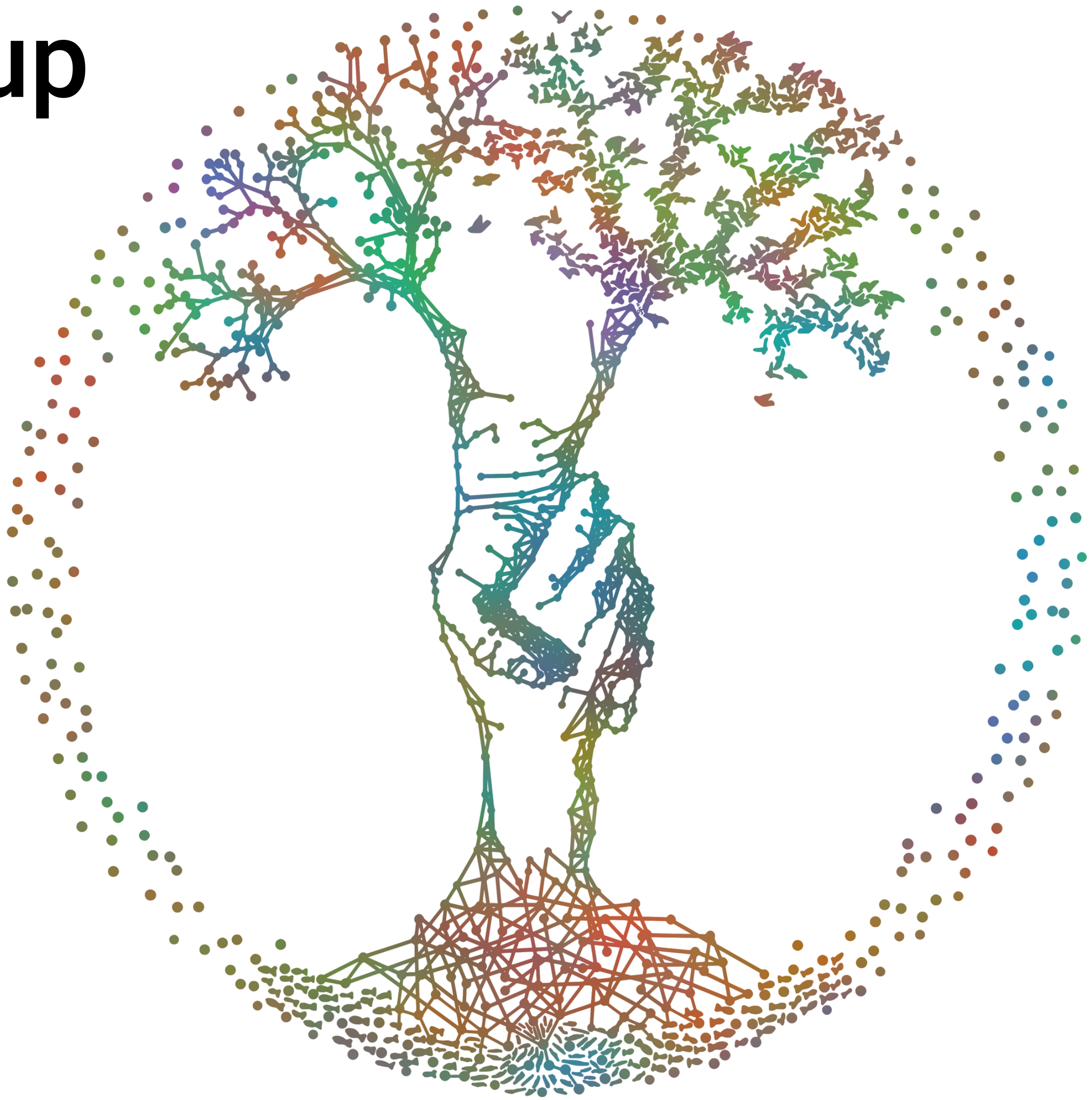
"At a time when so many scholars calculate throughout the world, is it not desirable for some, if they can, to dream?"

— René Thom



Au moment où tant de savants calculent de par le monde, n'est-il pas souhaitable que d'aucuns, s'ils le peuvent, rêvent?

Questions, contact, follow-up



A network science
for complexity & society

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France Regional Conference on Complex Systems
René Thom Young Researcher Award