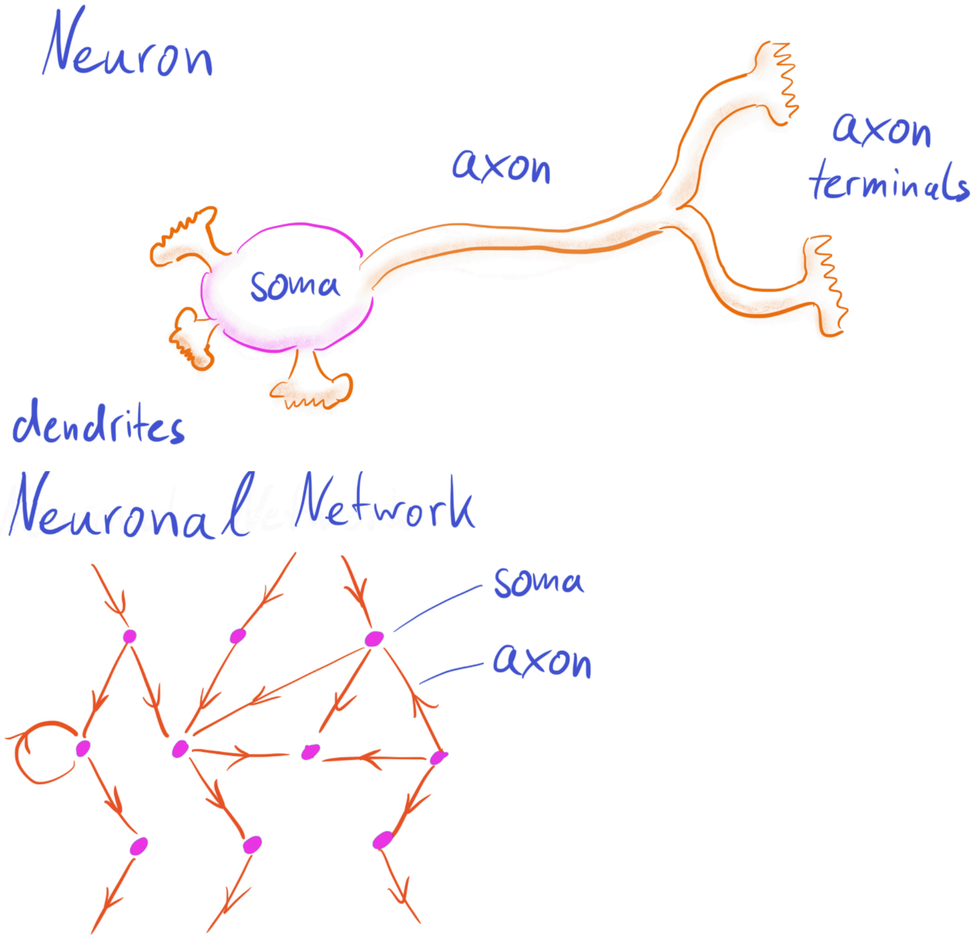
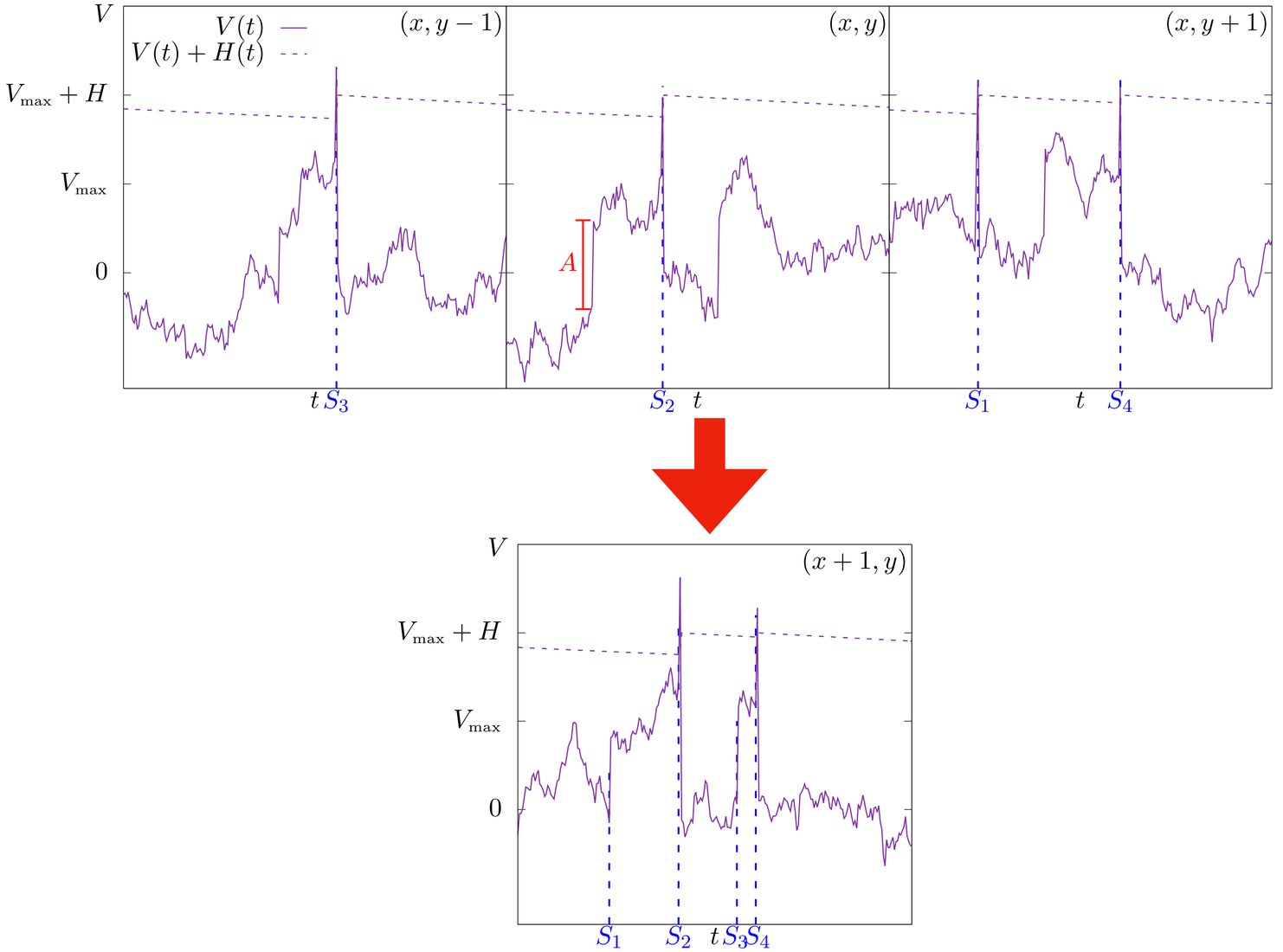
Imperial College London

Complexity Science

Centre for Complexity Science Group Overview 26/1/23

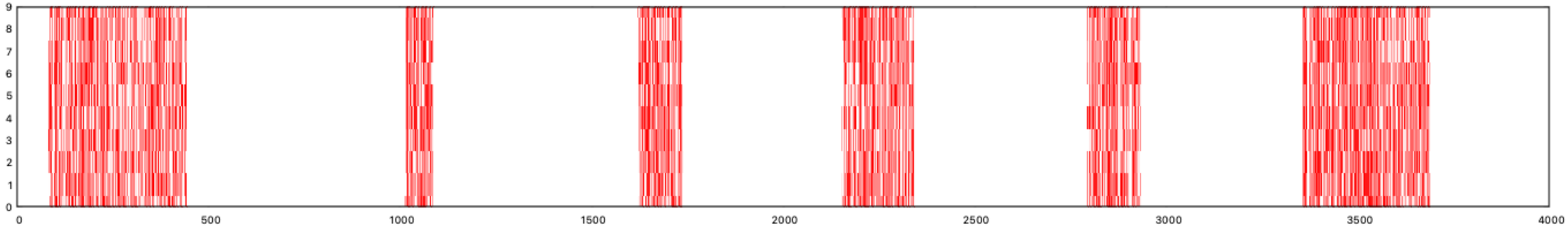
Collective Neuronal Behaviour





Johannes Pausch 26/01/2023

Inhomogeneous network ⇒ Rich phenomenology

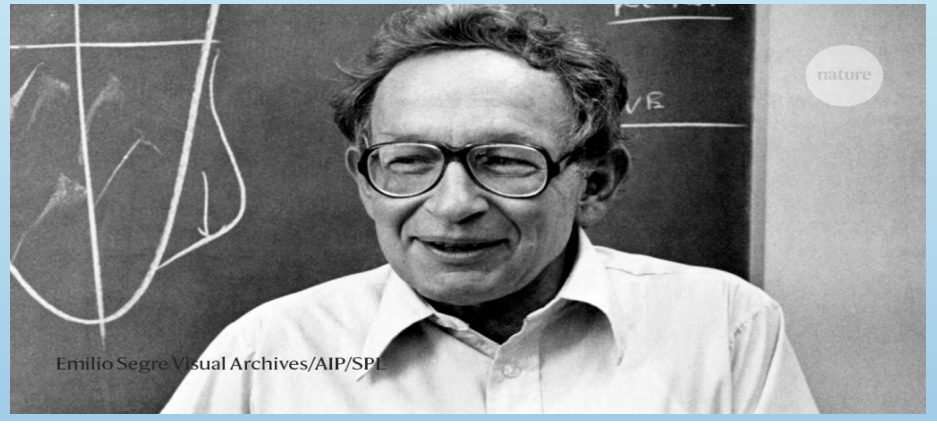


Find out more at Complexity Seminar on Tue 28 Feb

EMERGENCE

Scientists

Collective novel behaviour



Fifty years of 'More is different'

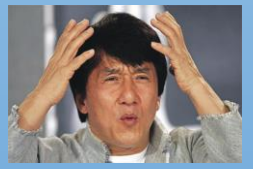
Steven Strogatz, Sara Walker, Julia M. Yeomans, Corina Tarnita, Elsa Arcaute, Manlio De Domenico, Oriol Artime & Kwang-Il Goh

Nature Reviews Physics **4**, 508–510 (2022) | Cite this article

Philosophers

Weak E (complement reduction)

Strong E (contrast reduction)



Irreducible Supervenience?

Nanxin Wei n.wei14@imperial.ac.uk 2023-01-26 ICL Complexity Catch-up Meeting

Only one kind of emergence, in various degrees of complexity (weak to strong).

Or

Weak E

Part -> Whole
Bottom-up
How weak is an emergence relation, is about how little (organization, interaction, etc.) is needed in additional to the parts to generate to whole.

More is Different.

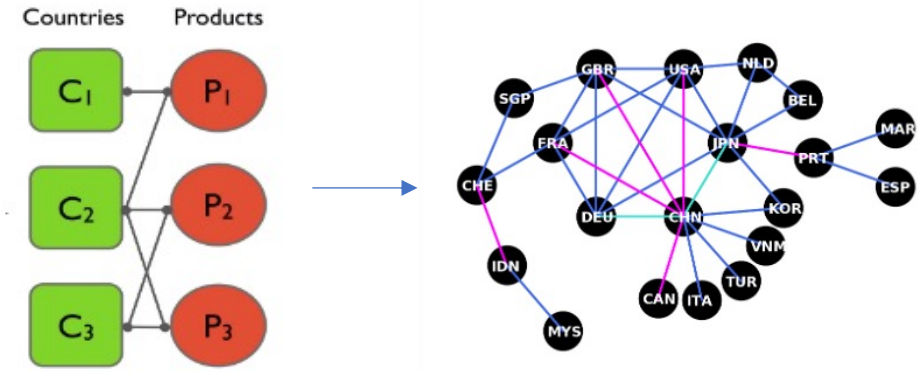
Strong E

Whole -> Part
Top-down
How strong is an emergence relation, is about how much would be lost (e.g., synergistic information, topological order) if the whole is divided into its constituents.

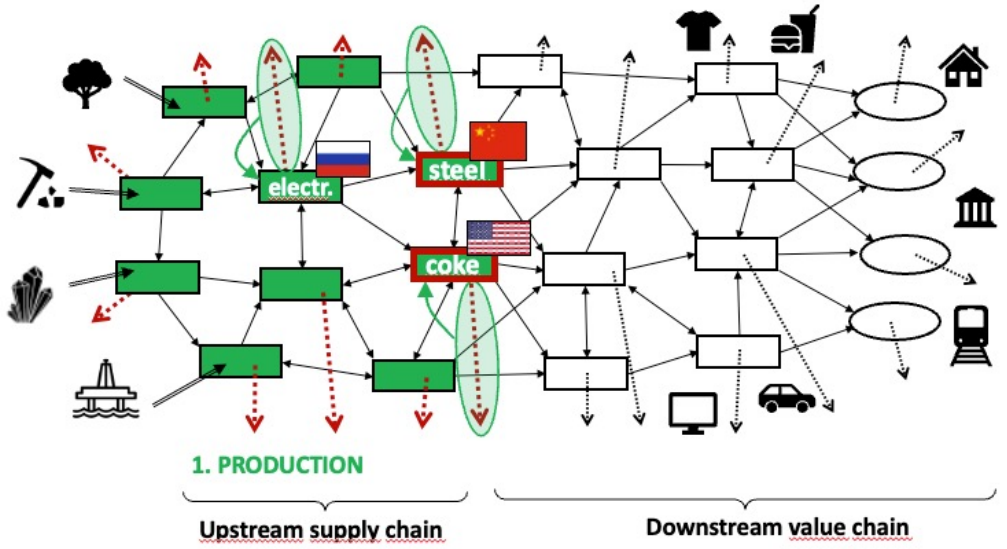
Less if Divided.

Economic Trade Networks

- Mapping Economic Trade Networks and deriving “influence”
- Evolution of production and trade networks

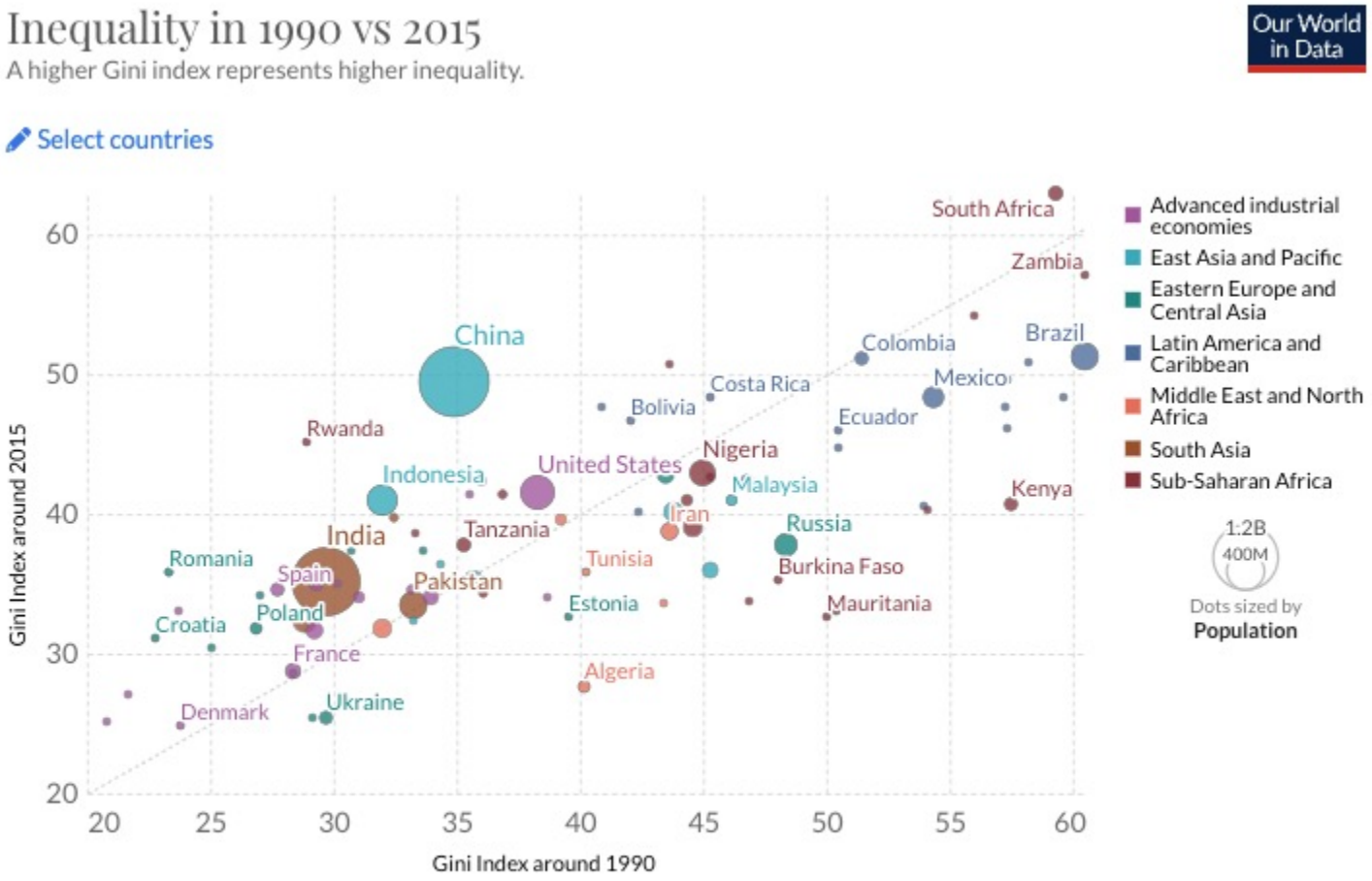


- Mapping Production and trade of carbon-emissions (and climate impacts)



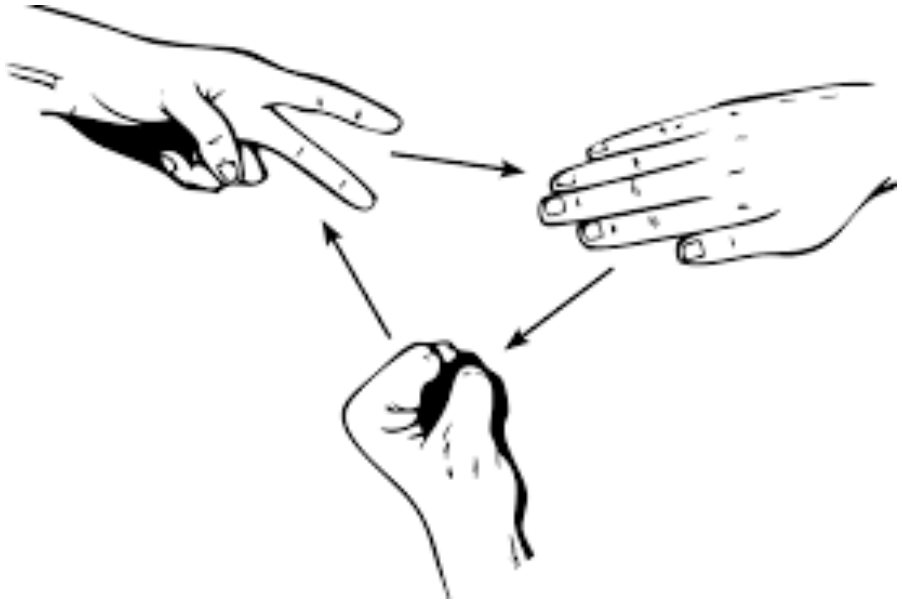
Source: Carbernard (2019)

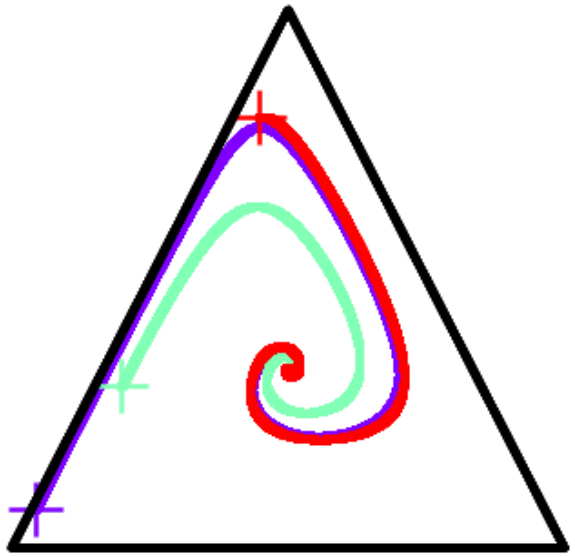
Emergence of Inequality

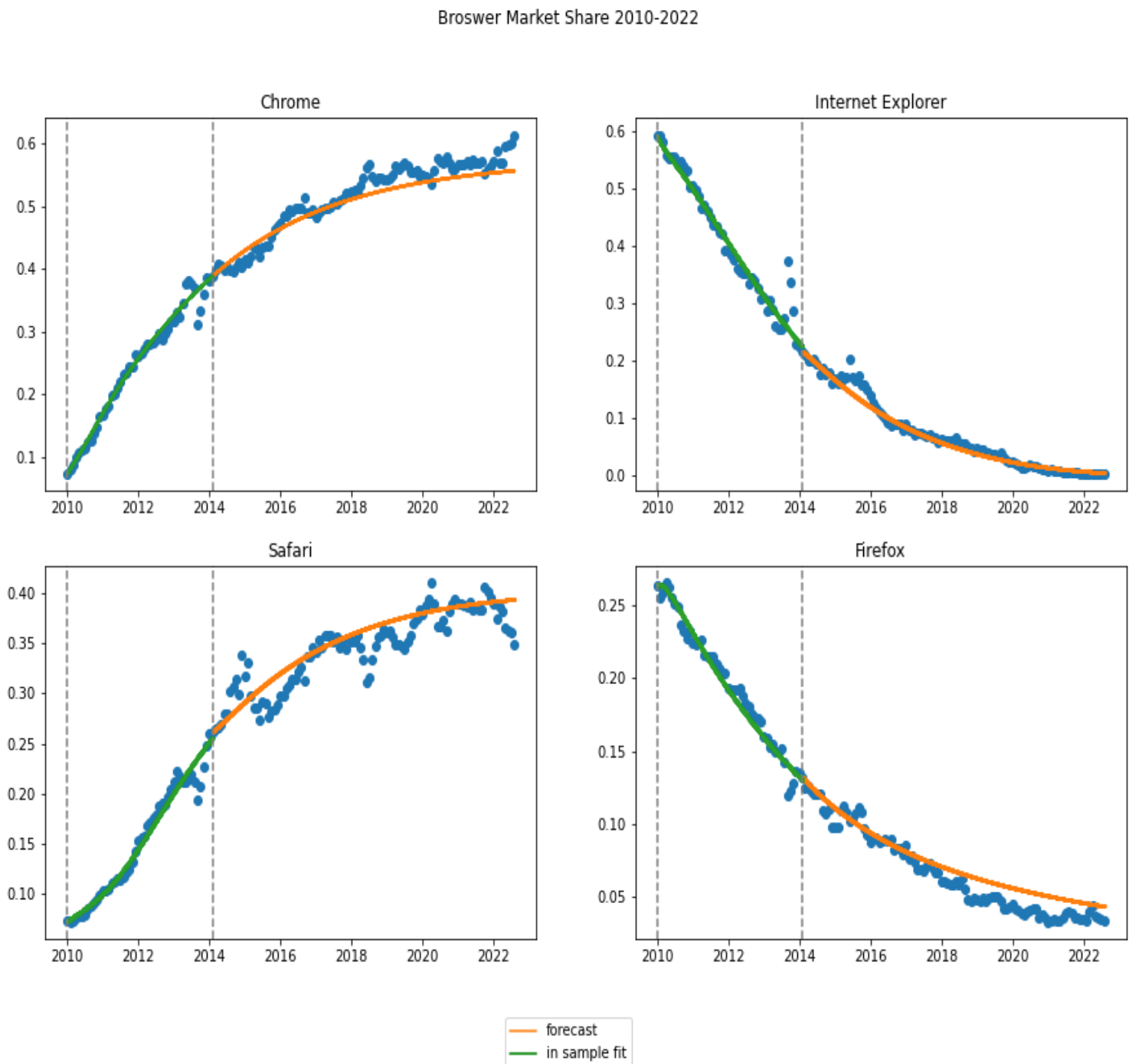


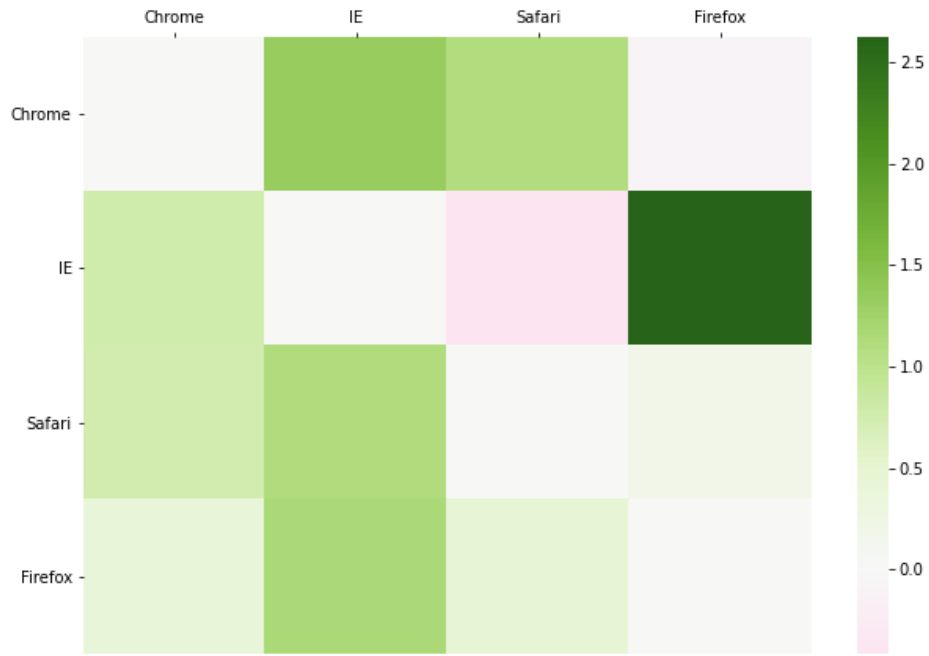
- Trade interactions have impacts on economies
- Traditional “producers” or exporters have grown in inequality over time
- In Complex economic/social networks, when does inequality emerge?

Evolutionary Games

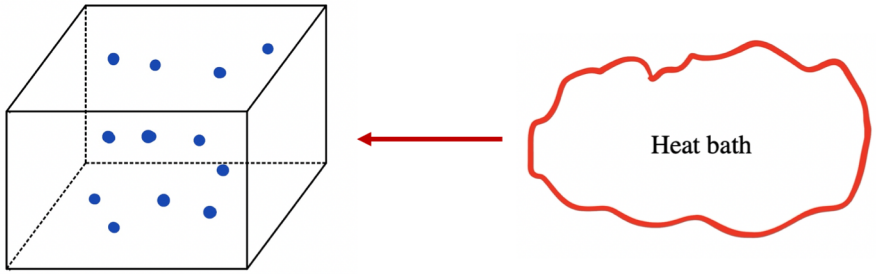


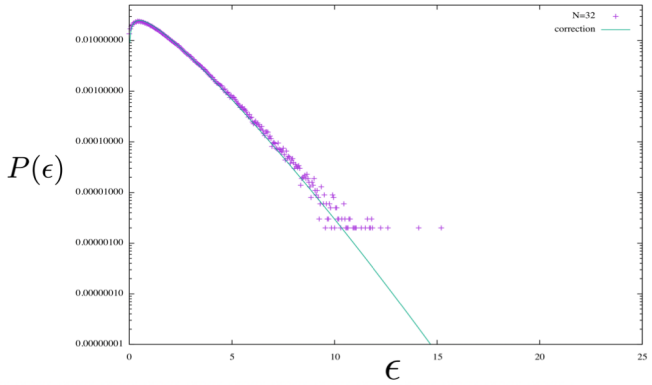



Broswer Market Share 2010-2022
Chrome
Internet Explorer
Safari
Firefox
forecast
in sample fit


Chrome
IE
Safari
Firefox

Thermalization of small (many particles) isolated systems





$$\delta\left[-N\int_0^\infty P(\epsilon)\ln P(\epsilon)d\epsilon-\alpha\left(\int_0^\infty P(\epsilon)d\epsilon-1\right)-\beta\left(N\int_0^\infty P(\epsilon)\epsilon d\epsilon-E\right)-\gamma\left(N\int_0^\infty P(\epsilon)\epsilon^2 d\epsilon-C_1\right)\right]=0$$

$$P(\epsilon)=\frac{e^{-\frac{\epsilon}{T}-\frac{1}{3}\frac{\epsilon^2}{N}}}{\sum_i e^{-\frac{\epsilon_i}{T}-\frac{1}{3}\frac{\epsilon_i^2}{N}}}$$

$$P(n_1\to\epsilon_1)P(n_2\to\epsilon_2)\neq P(n_1\to\epsilon_1,n_2\to\epsilon_2)$$

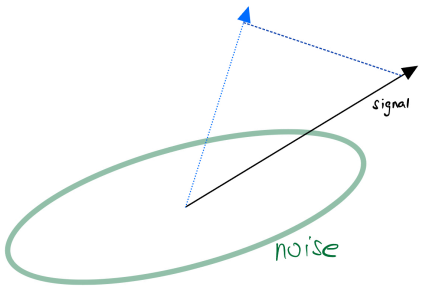
- The energy distribution of small isolated systems is not M-B distribution.
- Mutual information between particles is not zero in a system with finite degrees of freedom.
- Application to systems with finite degrees of freedom: black hole information paradox.
- Other playgrounds: biological systems, miniaturization of devices, heat engine?

Collaborate with Dr. Yuhan Ma.

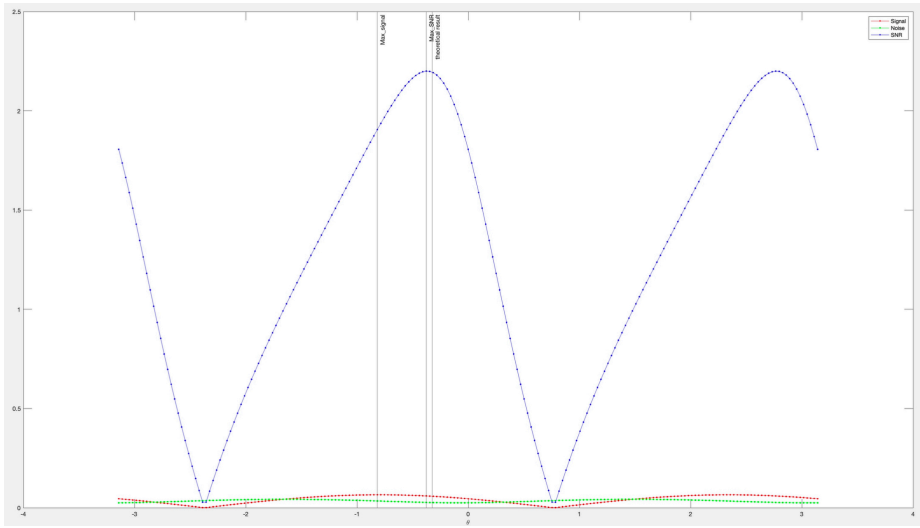
Optimal fingerprints method in a spin system

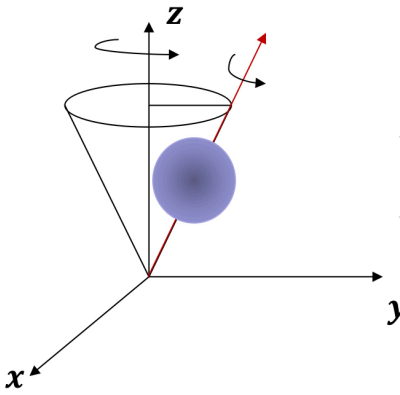
Klaus Hasselmann

……He also developed methods for identifying specific signals, fingerprints, that both natural phenomena and human activities imprint in the climate. His methods have been used to prove that the increased temperature in the atmosphere is due to human emissions of carbon dioxide……



$$\mathbf{Y} = \mathbf{aX} + \mathbf{u}$$





$$\vec{B} = (B_1 \cos\omega t + R(t)\cos\omega t, B_2 \cos\omega t, B_0)$$

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \vec{B} - \hat{\Gamma} \cdot \vec{M} + \Gamma_1 M_0 \hat{e}_z$$

Collaborate with Prof. Changpu Sun.

Imperial College London

Gunnar Pruessner g.pruessner@imperial.ac.uk

Field Theory of Active Matter

Field theory: Many degrees of freedom (position x, orientation φ etc) expressed as field $\chi(x, \varphi, t)$. Like QFT, but better.

Active matter: Interacting particle-like entities, turning external energy supply into mechanical action, such as self-propulsion.

E coli (Di Leonardo et al)

Starling murmuration
(The Atlantic, Menahem Kahana / AFP / Getty)

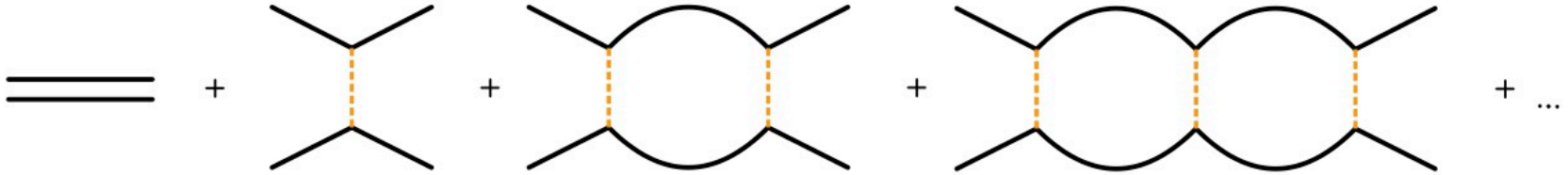
$\approx 37 \cdot 10^{12}$ cells (Gunnar)

Questions and Projects

25% Experiments (collaborators), 25% Numerics, 50% Analytics

- Field theoretic foundations (eg Dana, James, Kaili)
- Mechanics of self-propulsion (eg Jacob)
- Morphogenesis and locomotion (eg Johannes, Marius)
- Flocking and swarming (eg Letian, Connor, Callum, Eloise)
- Rectification (eg Zigan)

Two model cells colliding



Field theory is that of Møller scattering (QFT at low Reynolds number)

What I like doing and will keep doing…

Fernando E. Rosas, PhD

Department of Informatics, University of Sussex

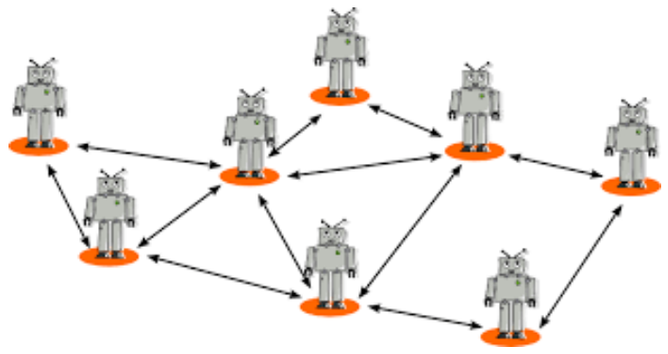
Centre for Complexity Science, Imperial College London

Centre for Psychedelics Research, Department of Brain Sciences, Imperial College London

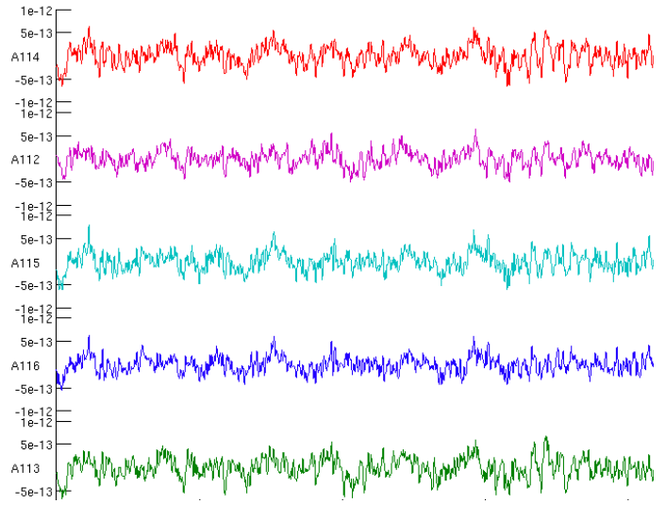
Centre for Eudaimonia and Human Flourishing, University of Oxford

Studying interdependence via time-series analyses

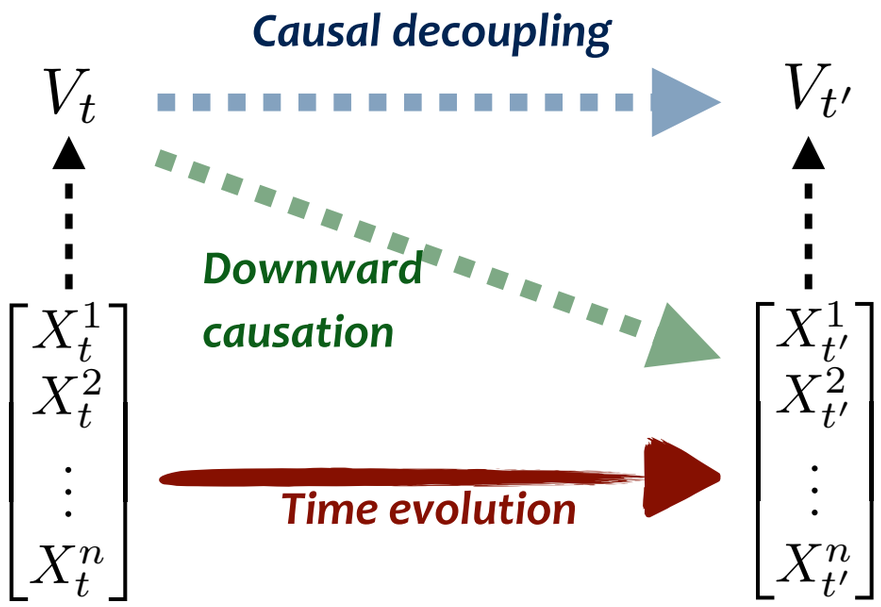
System of interest:

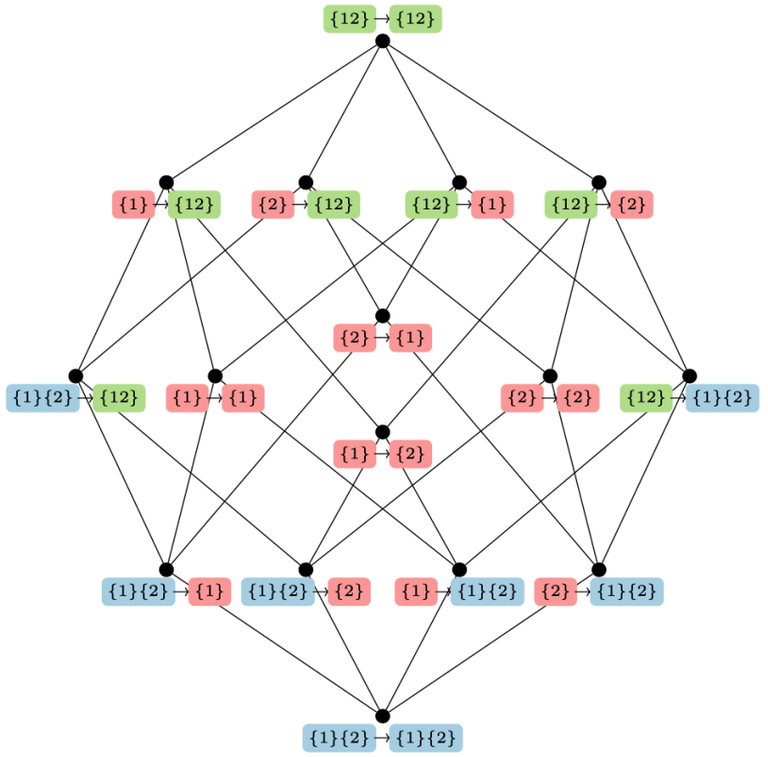


Data:



New analysis frameworks:





Goals

Technical questions:

- How can we operationalise notions of **synergy** and **emergence**.
- How can we build algorithms to **estimate** these from data.
- How can we **optimise** these algorithms to make them **data-efficient**.

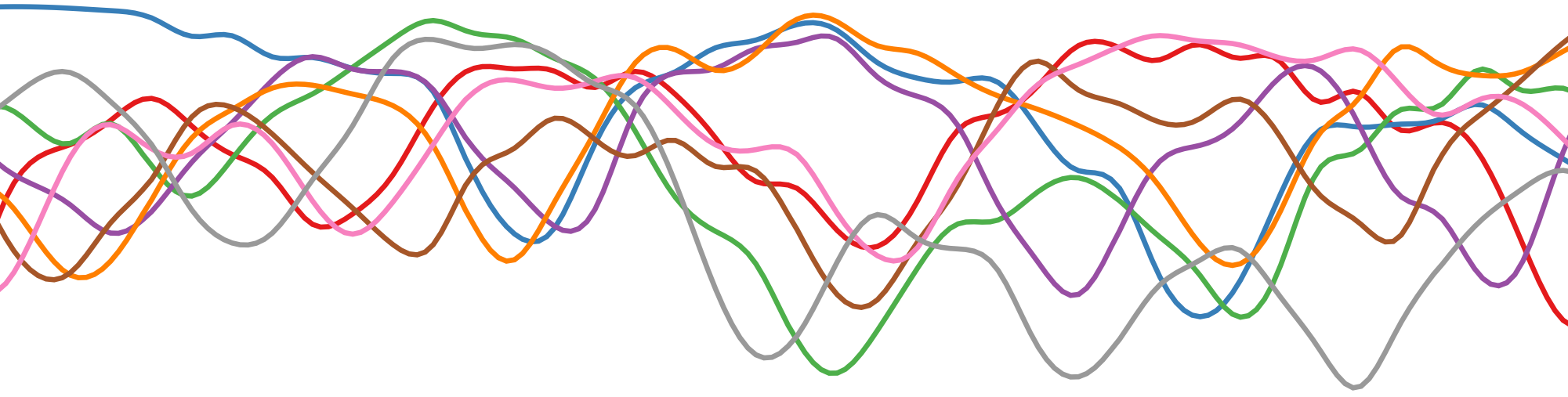
Big picture questions: how can these tools help us to understand **consciousness** and **cognition**, and hence be used to better reason about (i) learning systems and (ii) therapy.

Vision: a “scientific” (i.e. reproducible & naturalised) view of therapy and “spiritual” traditions can have a positive large-scale transformative impact on society. As craftsmanship’s, they

- Cannot be systematised —> implemented at large scale (e.g. in NHS)
- Lack of error-correcting mechanisms —> can degrade in time
- Can be optimised / updated
- Much to win if “validated”

SYNERGY AND INFORMATION IN COMPLEX NEURAL SYSTEMS

LINKING BIOLOGICAL AND ARTIFICIAL INTELLIGENCE



Pedro A.M. Mediano

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Imperial College London

UNIVERSITY OF CAMBRIDGE

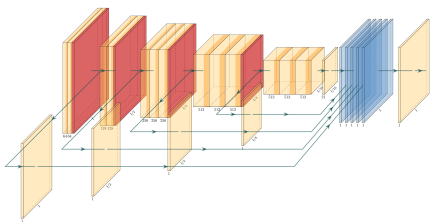
Research goal

Goal:

Discover the principles of *collective intelligence*.

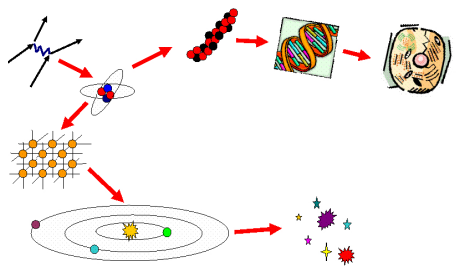
To understand ourselves

To build better systems



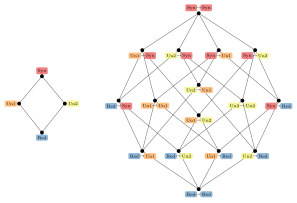
To fix it when it breaks

To understand the world

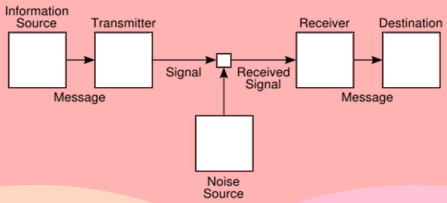


Beyond complexity science

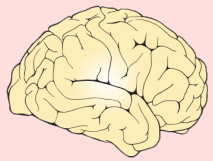
Synergy, information decomposition



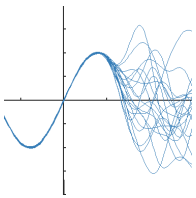
Information theory



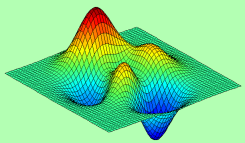
Computational neuroscience



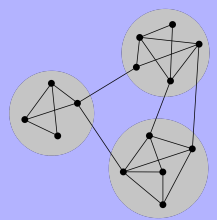
Statistical modelling



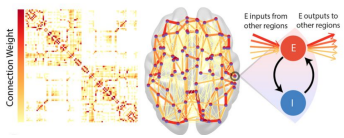
Machine learning



Complex systems



Neural mass models



Criticality and brain health

Critical exponents as biomarkers for brain ageing and health

Siddharth Kackar 26/01/2023

- In a recent paper, Fosque et al. have tried to use the concept of criticality to look for biomarkers of brain health (Fosque et al., 2022).
- They have analysed data from magnetoencephalography (MEG) studies of the human brain.
- They have used the quasicriticality framework (Williams-García et al., 2014), which states that the effective critical exponents for brain function can be considered to lie along a scaling line.
- They hypothesise that the position of the exponents and its change along this scaling line can be used as a biomarker for neurological ageing and health.
- It is our opinion that this reported correlation between ageing and the change in position of the biomarkers along the scaling line cannot be entirely correct. Essentially, they are using the failure of the scaling relation as a measure of distance from criticality.
- However, it is known that the exponents of a scaling relation do not change. Their results may be an artefact due to a lack of precision in their experiments.

.

- In order to consolidate our view, I will aim to first simulate neural activity as a branching process using a random number generator as my starting point.
- Analysing burst activity is a prototypical problem in data science.
- We will consider the neural activity as a memoryless Markov process, with each new state being independent of the previous ones.
- The simulations will be similar to Markov Chain Monte Carlo simulations.
- I will then measure the critical exponents and rationalise the data with respect to known properties of scaling relations.

- References -

Fosque, L. J., Alipour, A., Zare, M., Williams-García, R. v, Beggs, J. M., Ortiz, G., & Ortiz, G. (2022). *Quasicriticality explains variability of human neural dynamics across life span*. https://arxiv.org/abs/2209.02592v1

Williams-García, R. v., Moore, M., Beggs, J. M., & Ortiz, G. (2014). Quasicritical brain dynamics on a nonequilibrium Widom line. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, *90*(6), 062714. https://doi.org/10.1103/PHYSREVE.90.062714/FIGURES/7/MEDIUM

The ψ measure pf emergence

Consider a collection of N degrees of freedom $x_i(t)$

A robust collective variable $R(t) = F[x_1(t), ..., x_N(t)] = \frac{1}{N}\sum_{i=1}^{N} x_i(t)$

The Fernando-Pedro ψ is defined as $\Psi(t) = I[R(t); R(t')] - \mu \sum_i I[x_i(t); R(t)]$

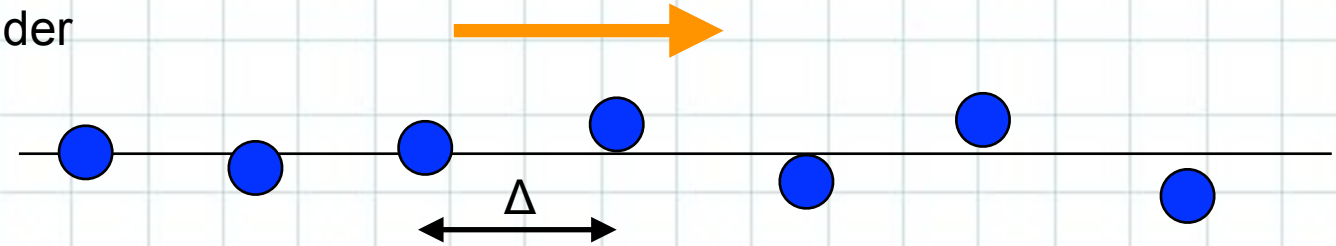
Recall

$$I(A;B) = \sum_a \sum_b P_{AB}(a,b) \log \frac{P_{AB}(a,b)}{P_A(a) P_B(b)}$$

Question: should μ = 1 or should μ = 1/N

I.e. should we compare to the average information transfer of the individual d.o.f. to the collective degree ?

Consider



$$x_i(t) = x_i^0 + t\Delta + \sum_{\tilde{t}=1}^{N} \eta_i(\tilde{t})$$

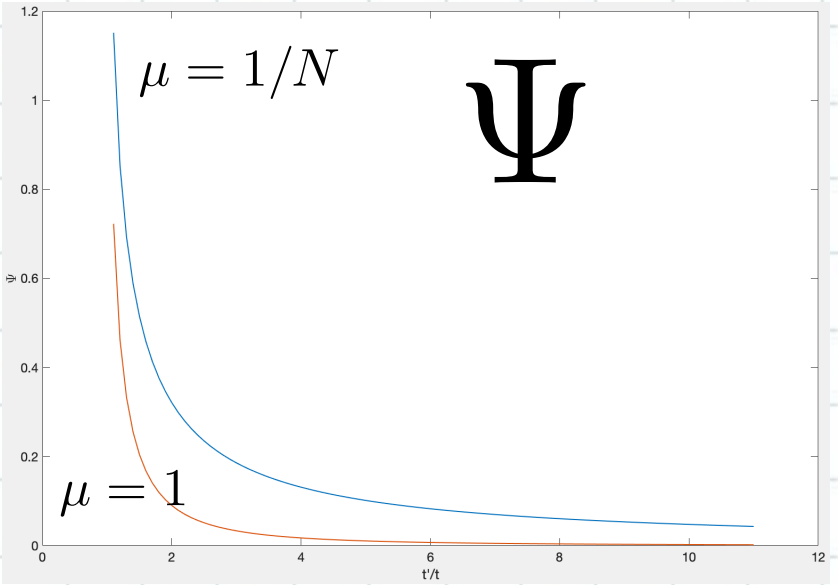
assume $\eta_i(t) \sim \mathcal{N}(o, \sigma^2)$

I and Ψ

$$I[R(t); R(t')] = \frac{1}{2} \log \frac{t'/t}{t'/t - 1}$$

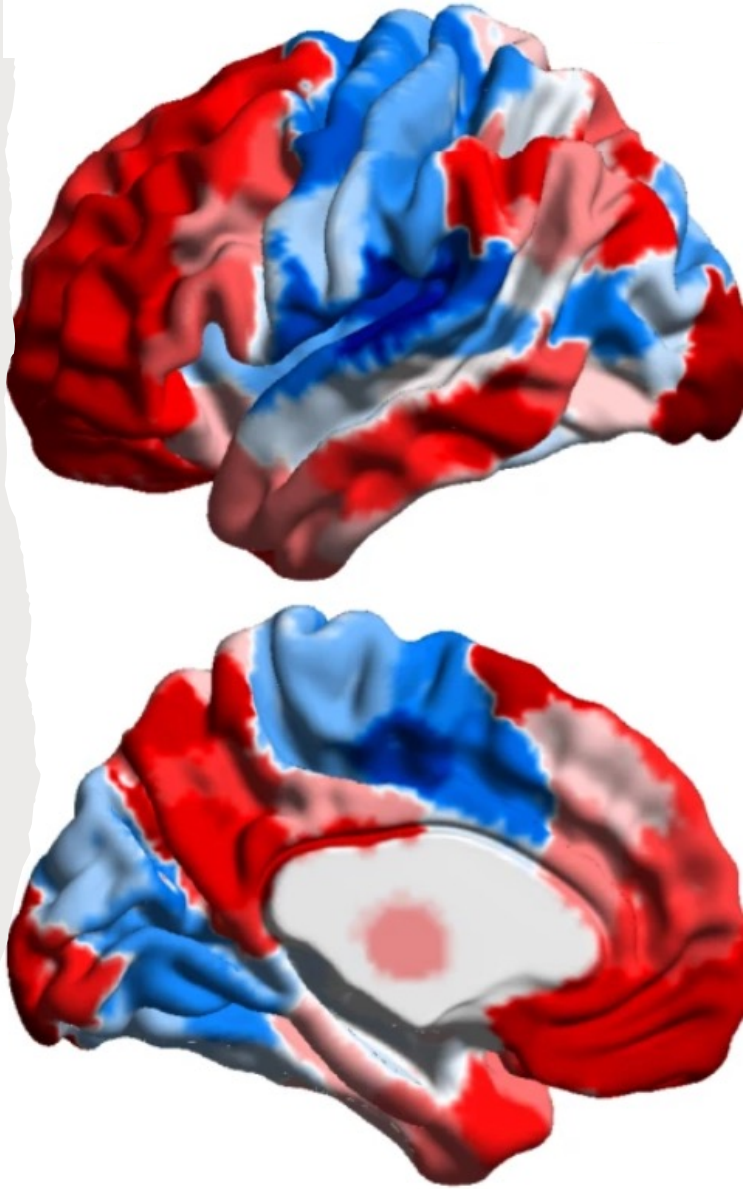
$$I[x_i(t); R(t')] = \frac{1}{2} \log \frac{Nt'/t}{Nt'/t - 1}$$

$$\Psi(t) = I[R(t); R(t')] - \mu \sum_i I[x_i(t); R(t)]$$



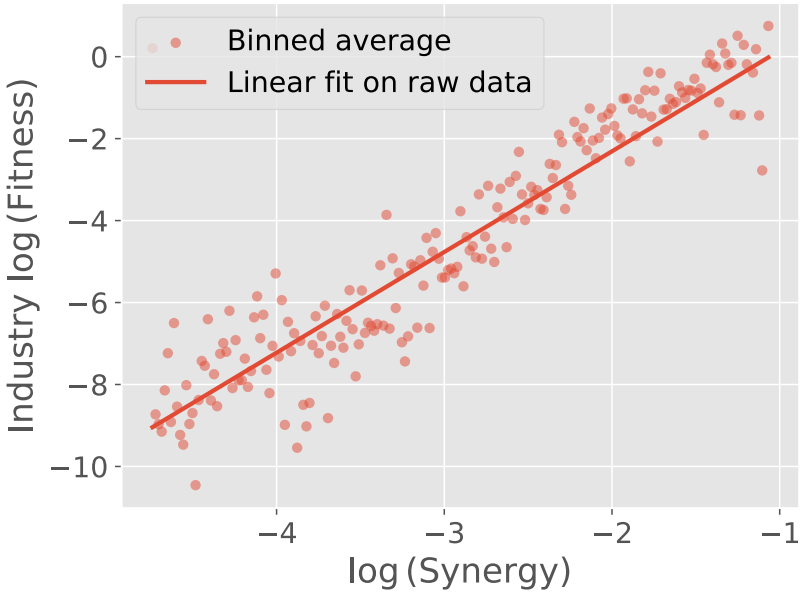
The Economic Brain

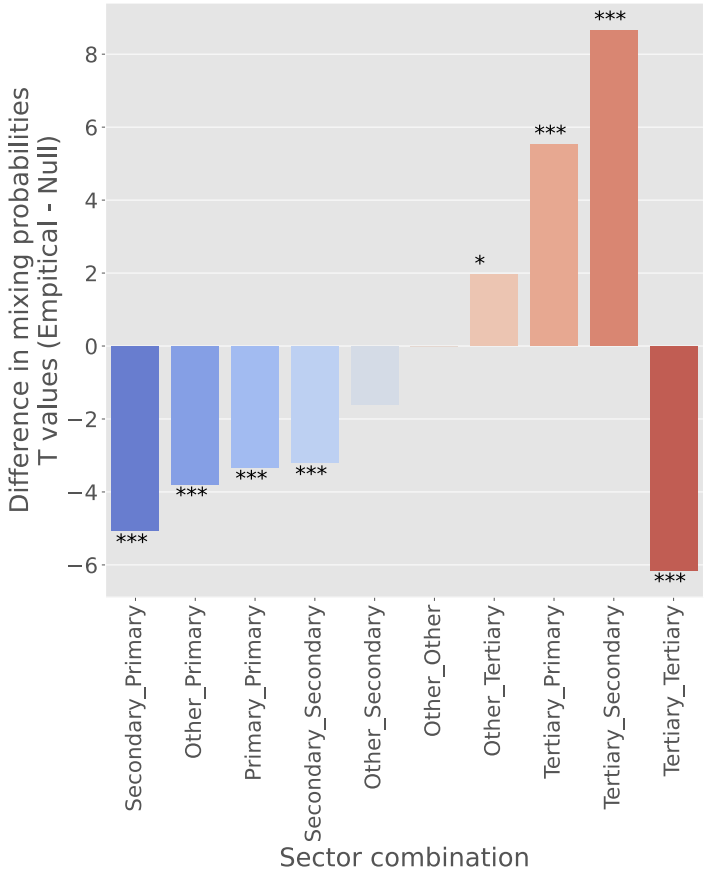
- Economic systems integrate various inputs, manipulate them and, in the process, produce novelty.
- They respond to shocks, demands and are highly differentiated to problem solve in a specialized way.
- Brains do that too!
- And information-theory helps us quantify, visualize and interpret these properties of the brain.
- Understand the ideal and aberrant behaviors of the economy.

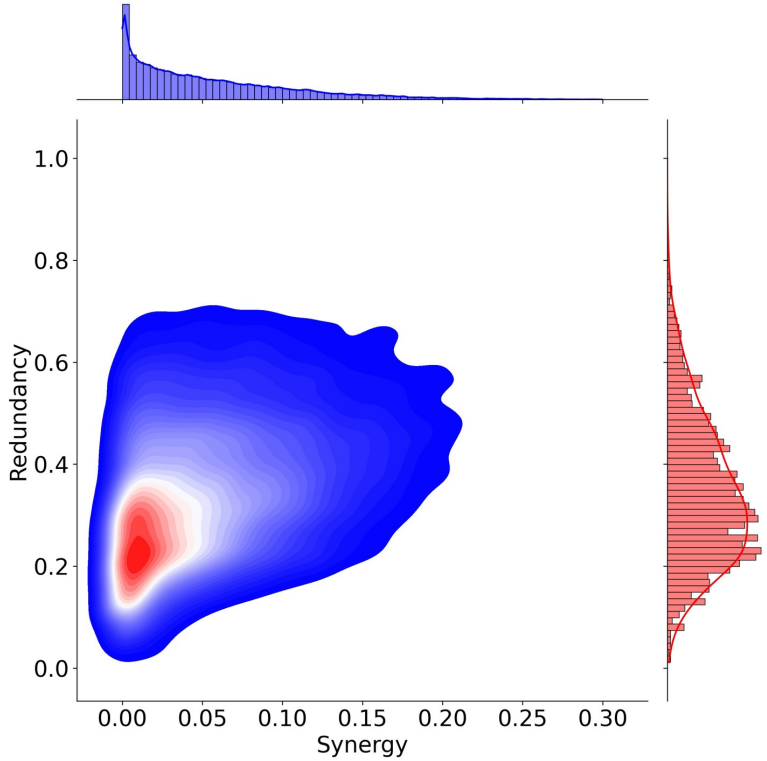


The Informational Economy

- Synergy among inputs of an industry, is strongly correlated to economic complexity indices.
- Tertiary sector of the economy facilitates synergistic interactions in the economy.
- Redundancy although correlated with synergy is a pre-requisite for more synergistic interactions in the economy.







Rajpal, H. and Guerrero, O.A., 2023. Quantifying the Technological Foundations of Economic Complexity. *arXiv preprint arXiv:2301.04579*.

Tim Evans

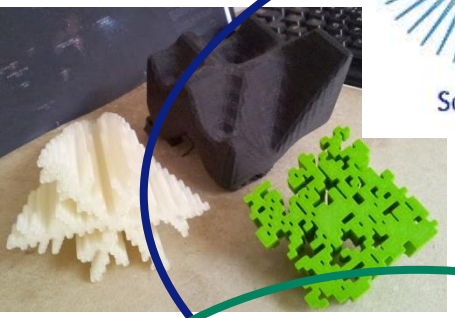
Particle Physics

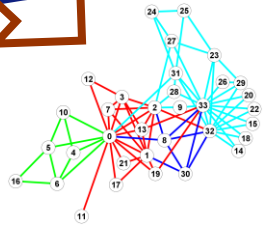
Condensed Matter Physics

Statistical Physics

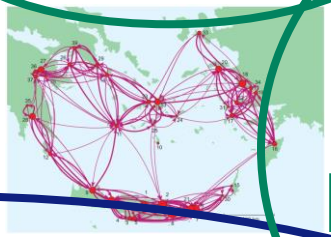
Complexity

Science

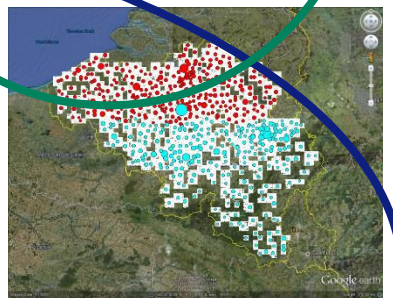




Archaeology

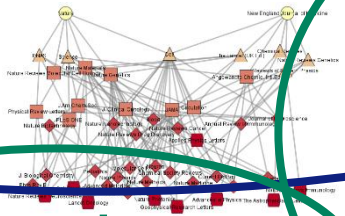


Spatial Networks



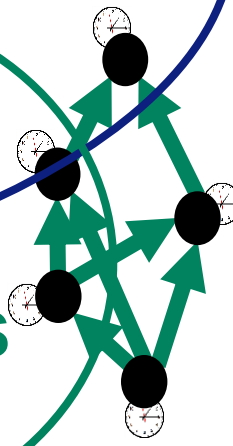
Complexity & Networks

Evolution of Complex Systems



Innovation, Bibliometrics

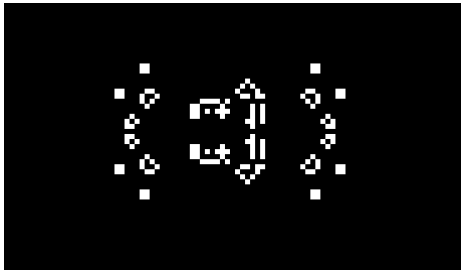
Temporal Networks

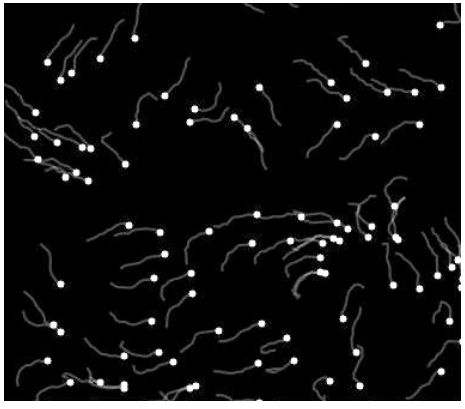


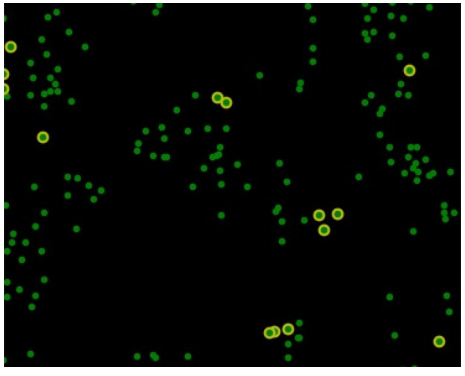
Year	Title of Recent TSE Paper	CoAuth	C/N	Th/App	Type	Historical
2022	Cycle analysis of directed acyclic graphs	+PhD +PD	network	theory	time	
2021	Higher-order temporal network effects through triplet evolution	+KC +2xPhD	network	th/appl	general	
2020	How do we avoid imposing the present on the past when modelling spatial interactions?	+RJR	network	theory	spatial	historical
2020	Predictive limitations of spatial interaction models	+2xUG	network	th/appl	spatial	
2020	Longest path in the Price model	+PhD +UG	network	theory	time	
2020	Identifying time dependence in network growth	+KC +PhD +Tokyo	network	theory	general	
2020	Understanding the transition from paroxysmal to persistent atrial fibrillation	+KC +2xPhD +Staff	complexity	th/appl	bio	
2019	The Wikipedia Network of Mathematicians	+PhD +UG	network	applied	social	historical

Collective Behaviour

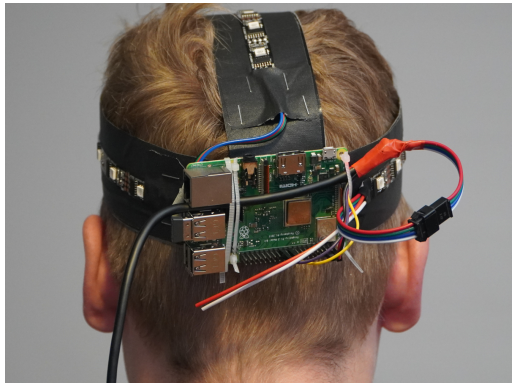
Models

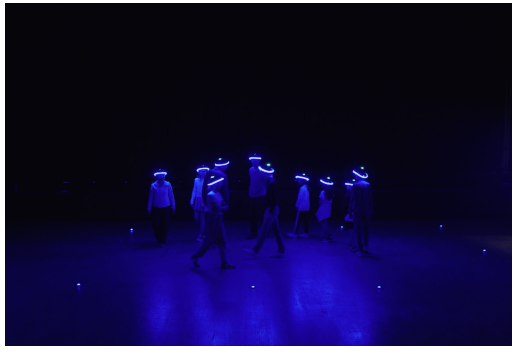




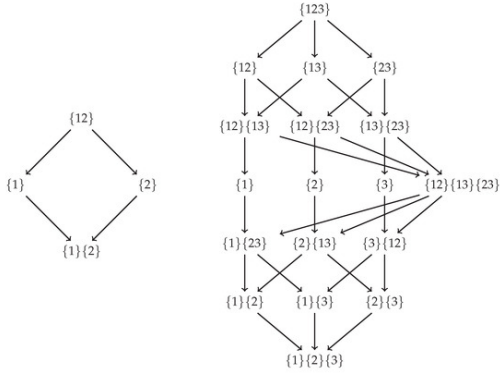


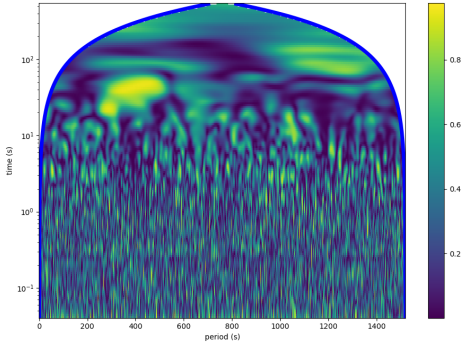
Experiments



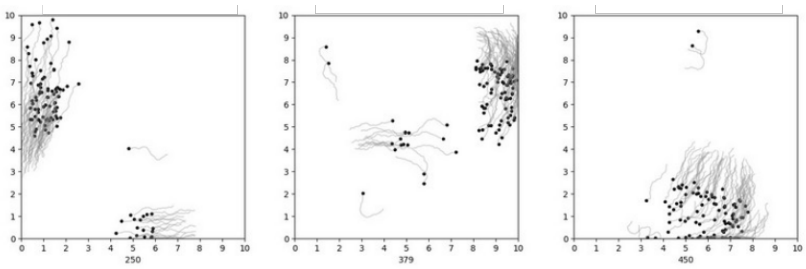


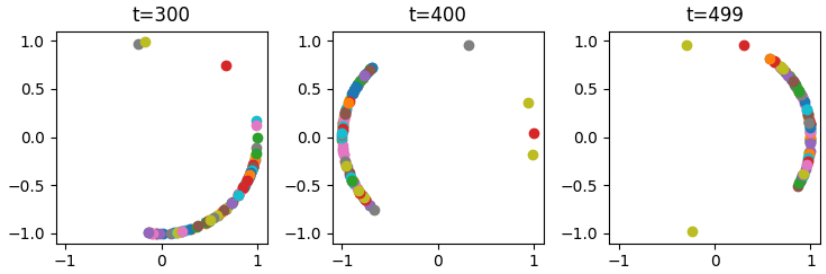
Methods



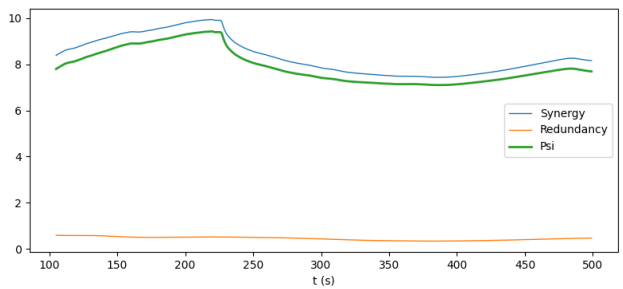


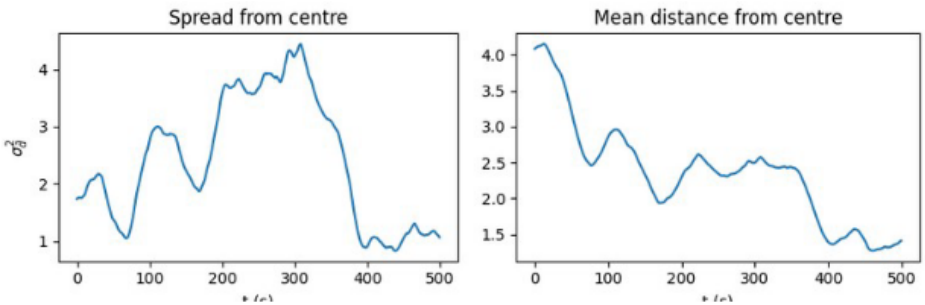
Emergence in finite flocks

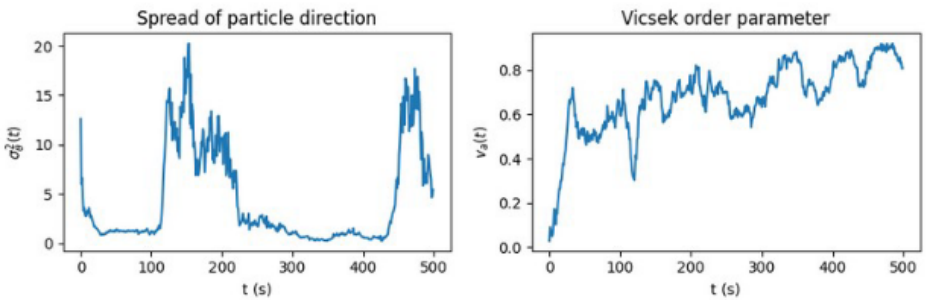


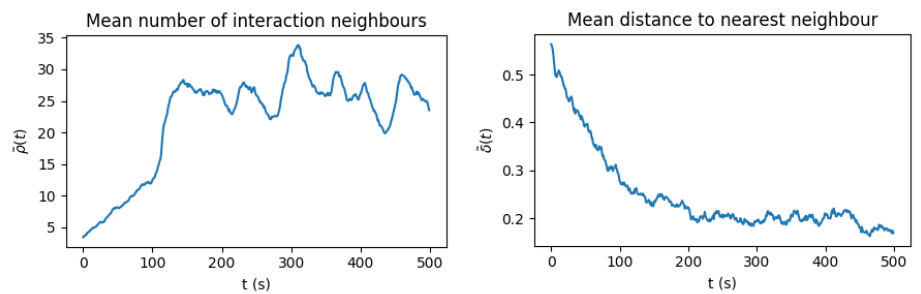


$$\Psi^{(1)}_{t,t'}(V) := I(V_t; V_{t'}) - \sum_j I(X^j_t; V_{t'})$$









- other order parameters as system features
- correcting for redundancy
- S-info and O-info

Neuron-Inspired Models of Financial Markets- David Meine


"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CXXXVII.... No. 47,258 NEW YORK, TUESDAY, OCTOBER 20, 1987 50 CENTS

STOCKS PLUNGE 508 POINTS, A DROP OF 22.6%; 604 MILLION VOLUME NEARLY DOUBLES RECORD

U.S. Ships Shell Iran Installation In Gulf Reprisal

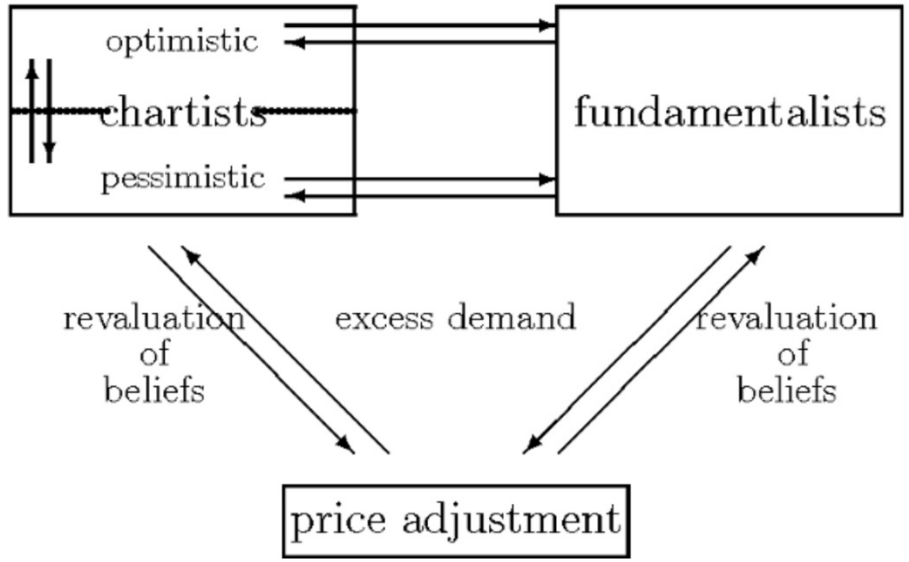
Offshore Target Termed a Base for Gunboats

A Huge Blow to the Five-Year Bull Market

Dow's Record Fall

WORLDWIDE IMPACT

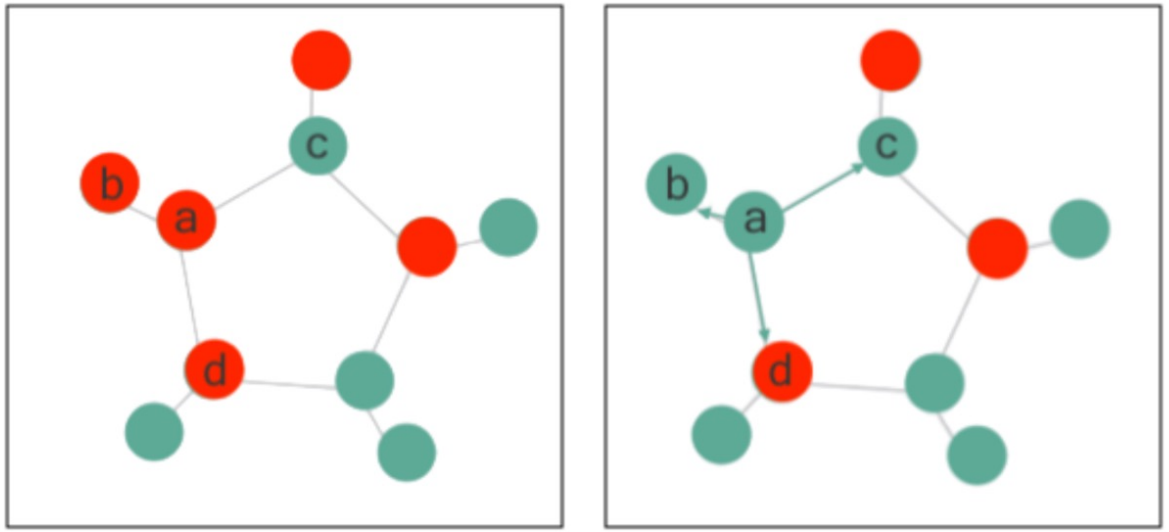
Frenzied Trading Raises Fears of Recession — Tape 2 Hours Late



Humans: Collect Information

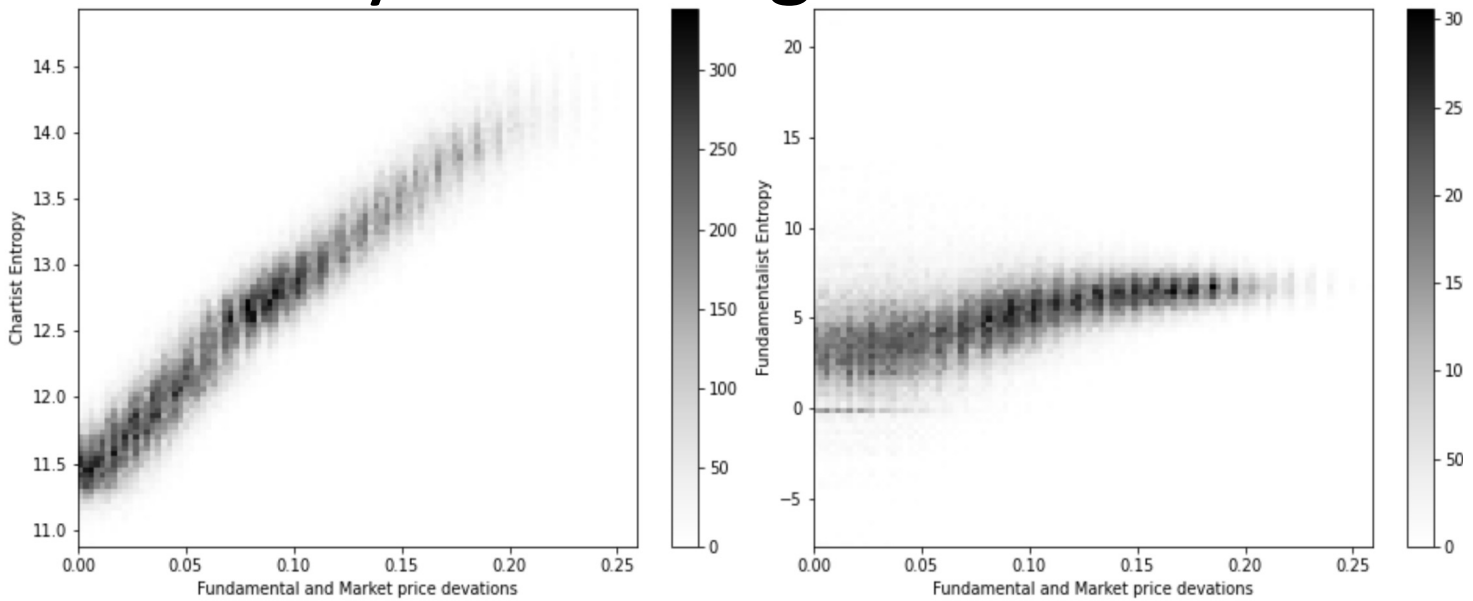
Enough Information: Decide!

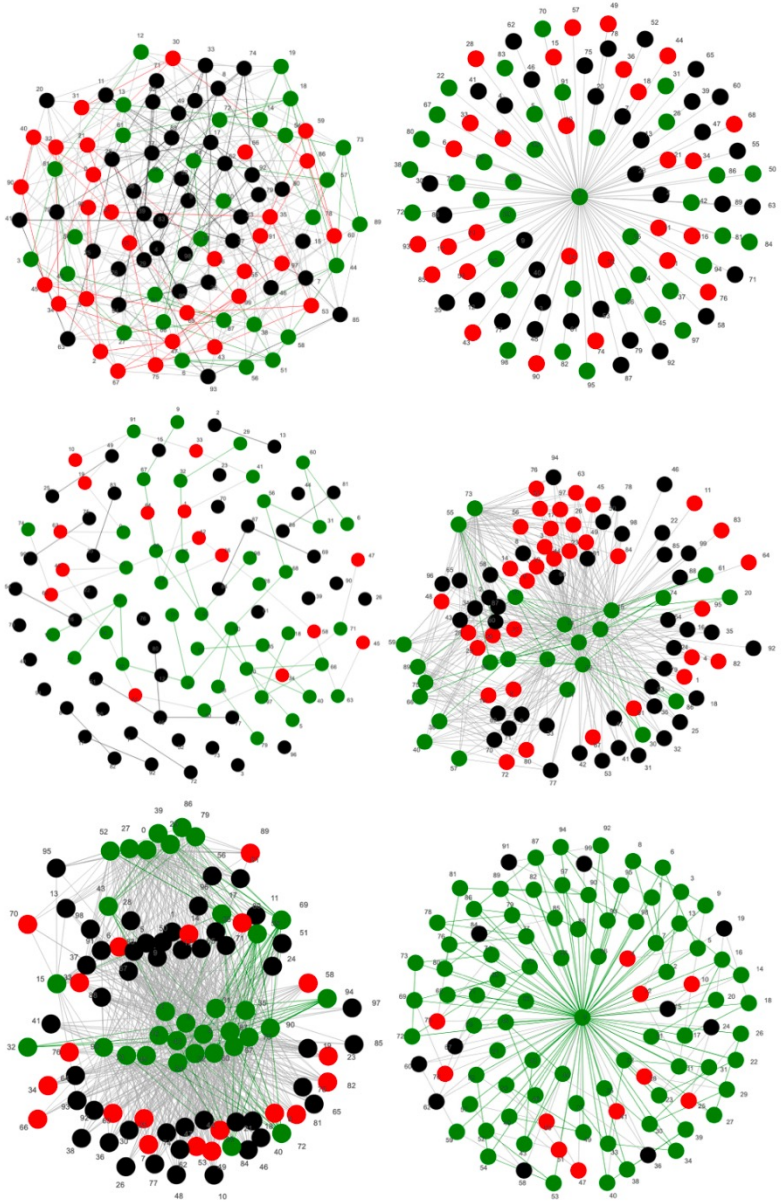
Neurons: Integrate and Fire!



Model Reproduces many Features of Stock Markets!

Fat-tailed Price Distributions
Financial Bubbles and Crashes
Mean-reversion
Volatility Clustering

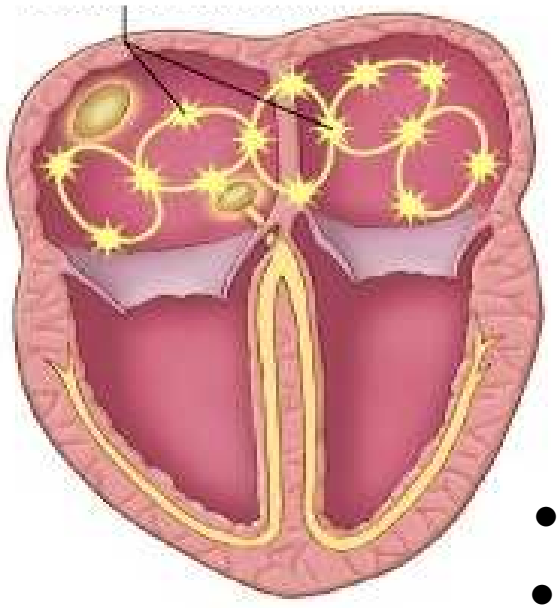




Personalised physics-based models of the human heart

- Atrial Fibrillation (AF): Arrhythmia – abnormal wave propagation in the atria.
  - Affects 35M people. Risk increases with age. Single biggest cause of stoke.
  - Objective: Understand what triggers AF.

Chaotic & irregular conduction



Atrial Fibrillation

2D Model: Level of transversal coupling $\rightarrow +$

- Gain better mechanistic understanding of AF
- Applying information theory to assess fibrillation dynamics
- Applying neural networks to measure action potential
- Applying ABM on heart muscle fiber networks

References: Christensen, Manani and Peters, PRL **114**, 028104 (2015); Philip Ball, Physics **8**, 5 (2015).
Manani, Christensen and Peters, PRE **94**, 042401 (2016).
Falkenberg, Ford, Li, Ciacci, Peters and Christensen, PRE **100**, 062406 (2019).

Dynamics of social interactions on networks

nature physics

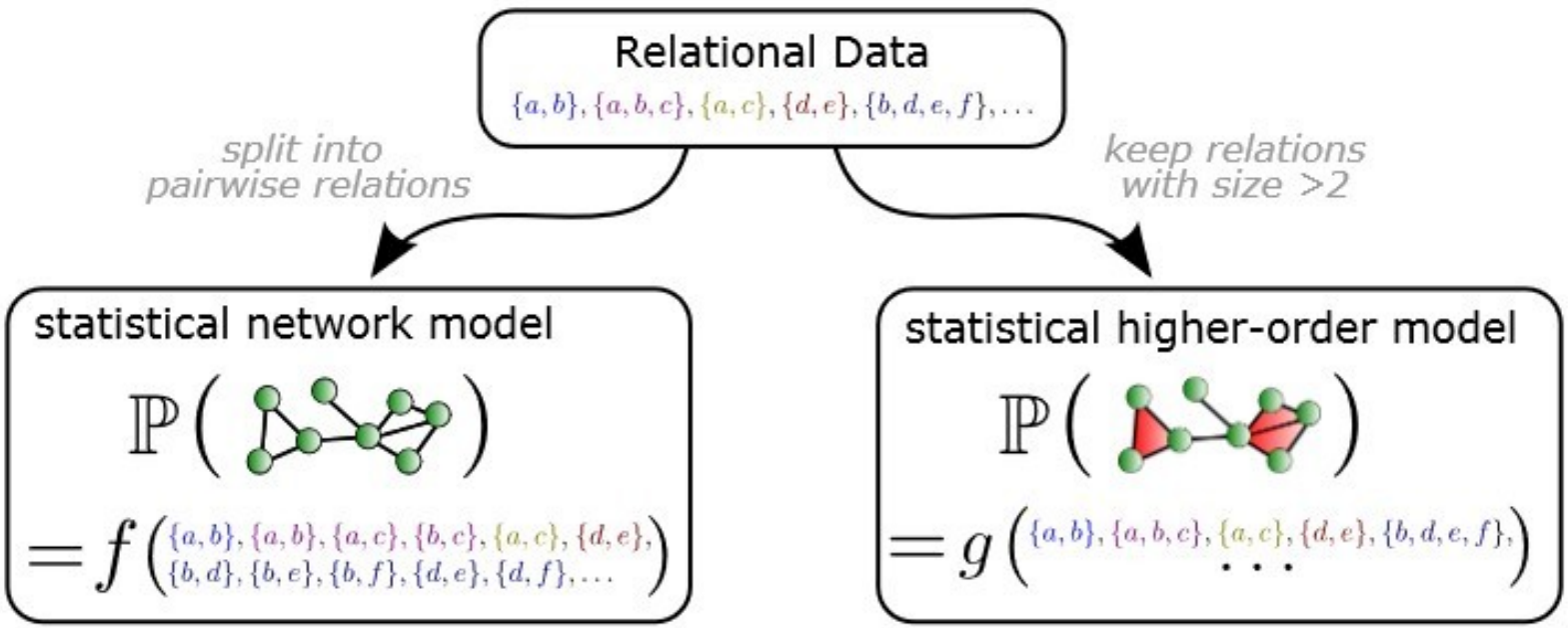
PERSPECTIVE

https://doi.org/10.1038/s41567-021-01371-4

Check for updates

The physics of higher-order interactions in complex systems

Federico Battiston[1]✉, Enrico Amico[2,3], Alain Barrat[4,5], Ginestra Bianconi[6,7], Guilherme Ferraz de Arruda[8], Benedetta Franceschiello[9,10], Iacopo Iacopini[1], Sonia Kéfi[11,12], Vito Latora[6,13,14,15], Yamir Moreno[8,15,16,17], Micah M. Murray[9,10,18], Tiago P. Peixoto[1,19], Francesco Vaccarino[20] and Giovanni Petri[8,21]✉



Reference: Battiston *et al.*, Nature Physics **17**, 1093 (2021).

Current Works and Projects

Current Research Areas	Internal Collaborators	External Collaborators	Status
International Trade and Economic Development	Nishanth Henrik		
Environmental Impact and Economic Development	Nishanth Henrik	Toyota (Likely)	
UK (Economic) Geospatial Structure	Tim Meghdad Henrik	Sussex (Potential) Liverpool (Potential)	
Japanese Interfirm Trading (Geography)		Tokyo Tech / TDB Tel-Aviv	
Banking Competition in Japanese Markets	Henrik	Tokyo Tech / TDB	
Evolutionary Dynamics and Game Theory (Theoretical)	Santiago Henrik		
Dynamics of Bankruptcy in Japan		Tokyo Tech / TDB	
Population Dynamics of Gut Bacteria	Santiago Henrik	Tokyo Tech	
Historical development of UK railways and building societies		Liverpool	

Recent Presentations:

- The Emergence of New Business Models and Technologies within Financial Markets (UCL)
- Towards an Evolutionary Theory for the Development of Resilient and Sustainable Economic and Financial Systems (Surrey)

Recent Influences:

- John Quiggin (Rates and Markets)
- Simon Conway Morris (Evolution)
- David Haig (Evolution)
- Nick Bostrom (Philosophy)

The “Dream” Projects

Hogsmill River

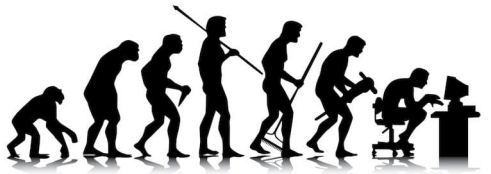
To develop time-serie methods to analyse data gathered from different procedures: Ecoacustics, Imaging, Water Composition, Scpecies countings, etc. Obtain data from various points throughout the river flow.

Issue: Cost, Uncertain Technology

Historical Evolution of the UK and US cities and infrastructure

To gather long term historical data from various sources, in particular from the National Archives, to measure evolution and co-dependency of advancements

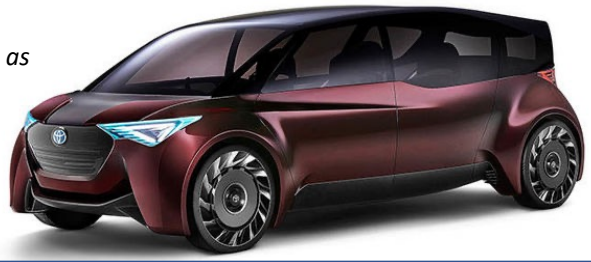
Issue: Time



Maximizing Friendliness of Supply Chain and Product Sale Distribution

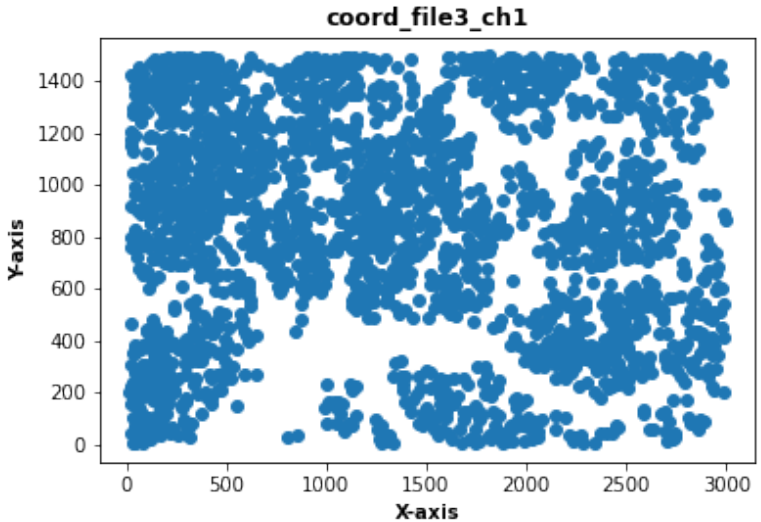
Working with Toyota research on a better understanding of the environmental impact of supply chain as well as the use of Toyota products.

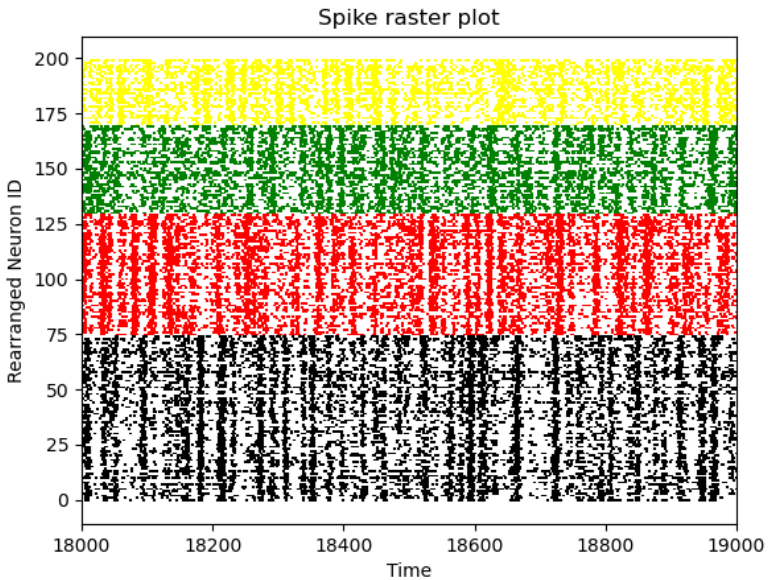
Issue: Cost, Third Party Dependency, Contractual Formalism



Collaborating in the theoritical part of project “Statistical Physics of Cognition“

- Working on the data recorded in Lab of Professor Simon Schultz
- Ca2+ imaging of head-fix mice



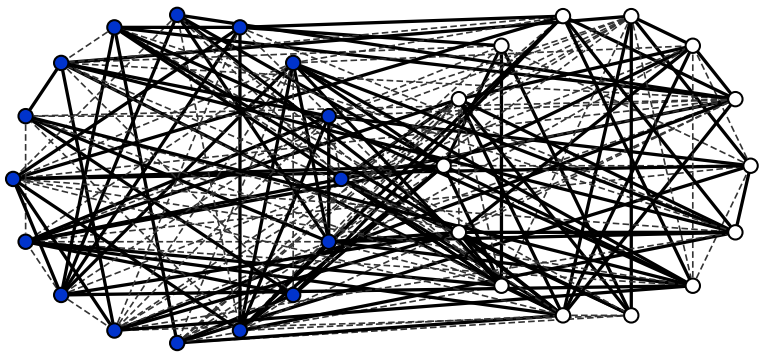


- Invesitgating the functinal and structral nework of Brain
- Investigating the Criticality of the brain
- Connection of the networks of the brain and the criticality

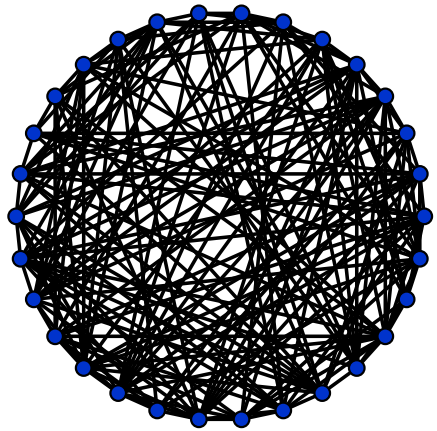
What type/feature/calss of network cause to emarge the cognition

Emergence of Public Polarization and Sustainability of Socio-Ecological Systems

- Public Polarization is more stable than Public Consensus
- Public polarization might keep the socio-ecological system sustainable



(a)



(b)