Palaeontology of complex systems: Complex Networks

Alessio Cardillo

Department of Condensed Matter Physics and UBICS – Universitat de Barcelona, Barcelona (Spain)

Seminars RSEF-UB for students
Tuesday, March 10th 2026

UNIVERSITAT DE BARCELONA

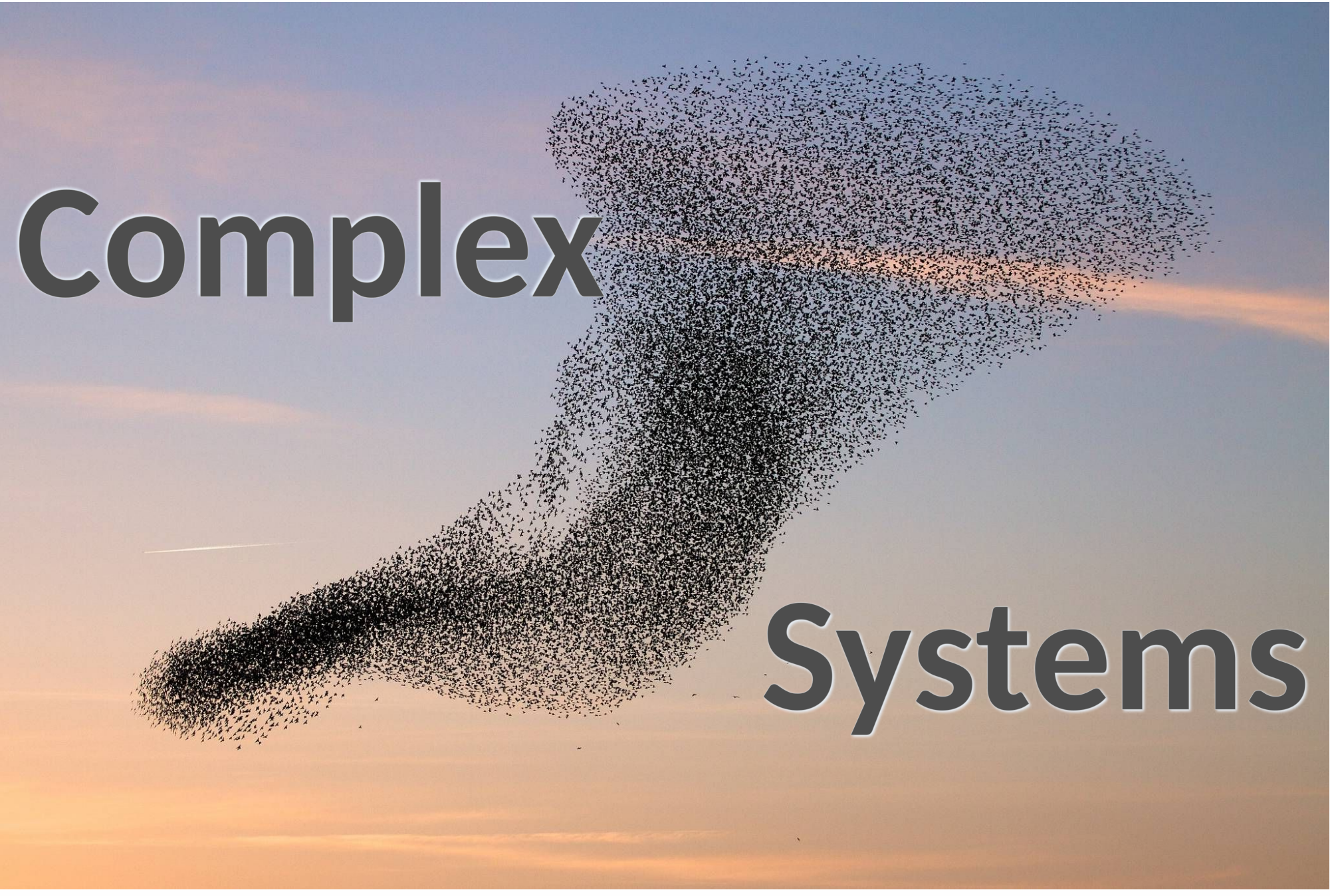
Who is Alessio Cardillo?

Who is Alessio Cardillo?

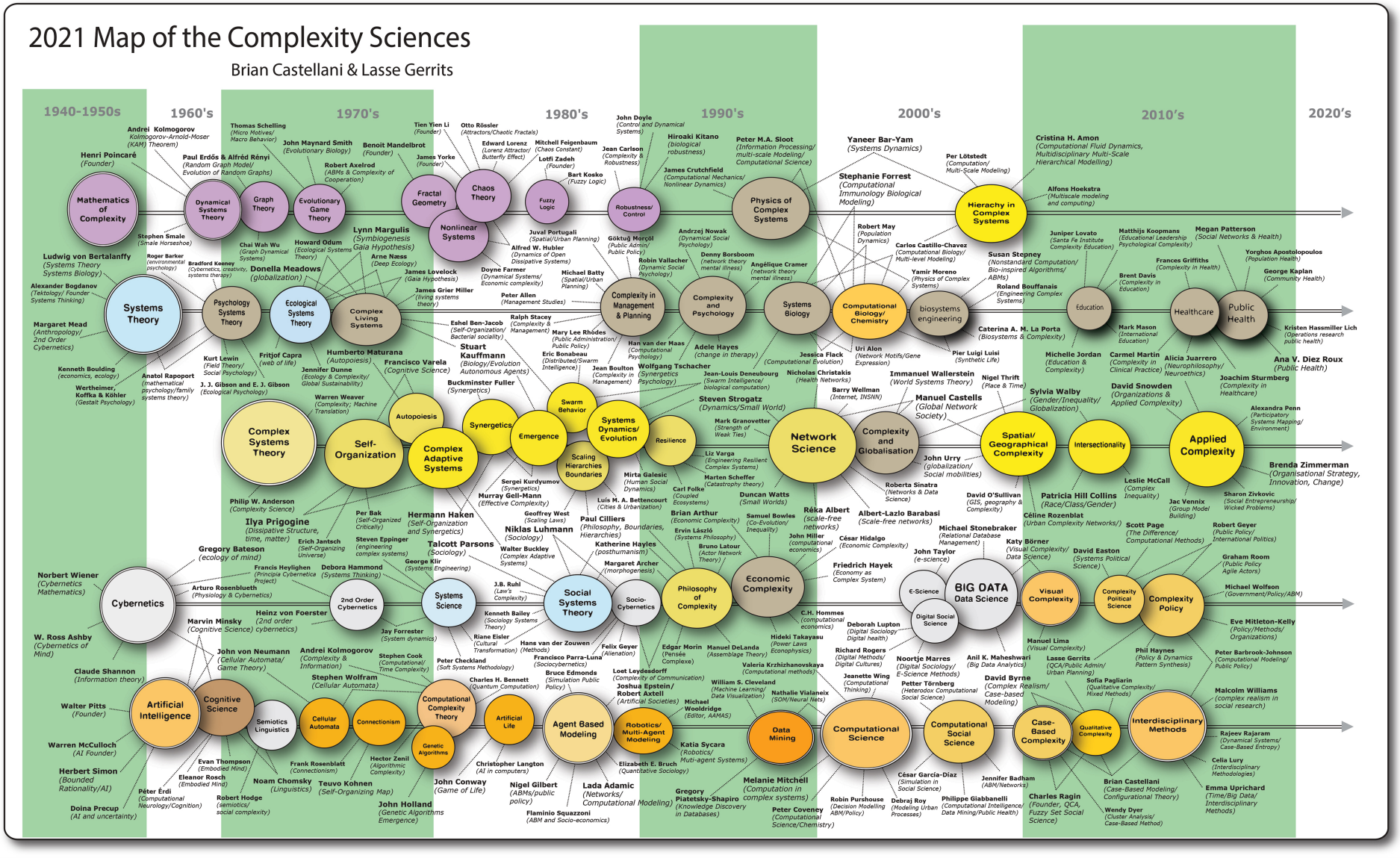
- Born *a long time ago* in a city (Catania, Italy) far far away . . .
- Trained as a *confused* physicist (MSc and PhD in physics).
- Ramon y Cajal fellow at FMC-UB **since 2025**.
- Expert in complex systems, network science, nonlinear dynamics, applications of statistical physics.

Who is Alessio Cardillo?

- **Very broad range of research topics**: linguistics, archaeology, mobility, humanities, ecology, collective behaviors (vaccination, cooperation, synchronization), etc..
- Working in **highly multidisciplinary** teams.


Complex
Systems

Complex systems



- https://www.art-sciencefactory.com/complexity-map_feb09.html

Complex systems

The Nobel Prize in Physics 2021

Syukuro Manabe
Klaus Hasselmann
Giorgio Parisi

Share this

Giorgio Parisi
Facts

© Nobel Prize Outreach.
Photo: Stefan Bladh

Giorgio Parisi
The Nobel Prize in Physics 2021

Born: 4 August 1948, Rome, Italy

Affiliation at the time of the award: Sapienza University of Rome, Rome, Italy

Prize motivation: "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales"

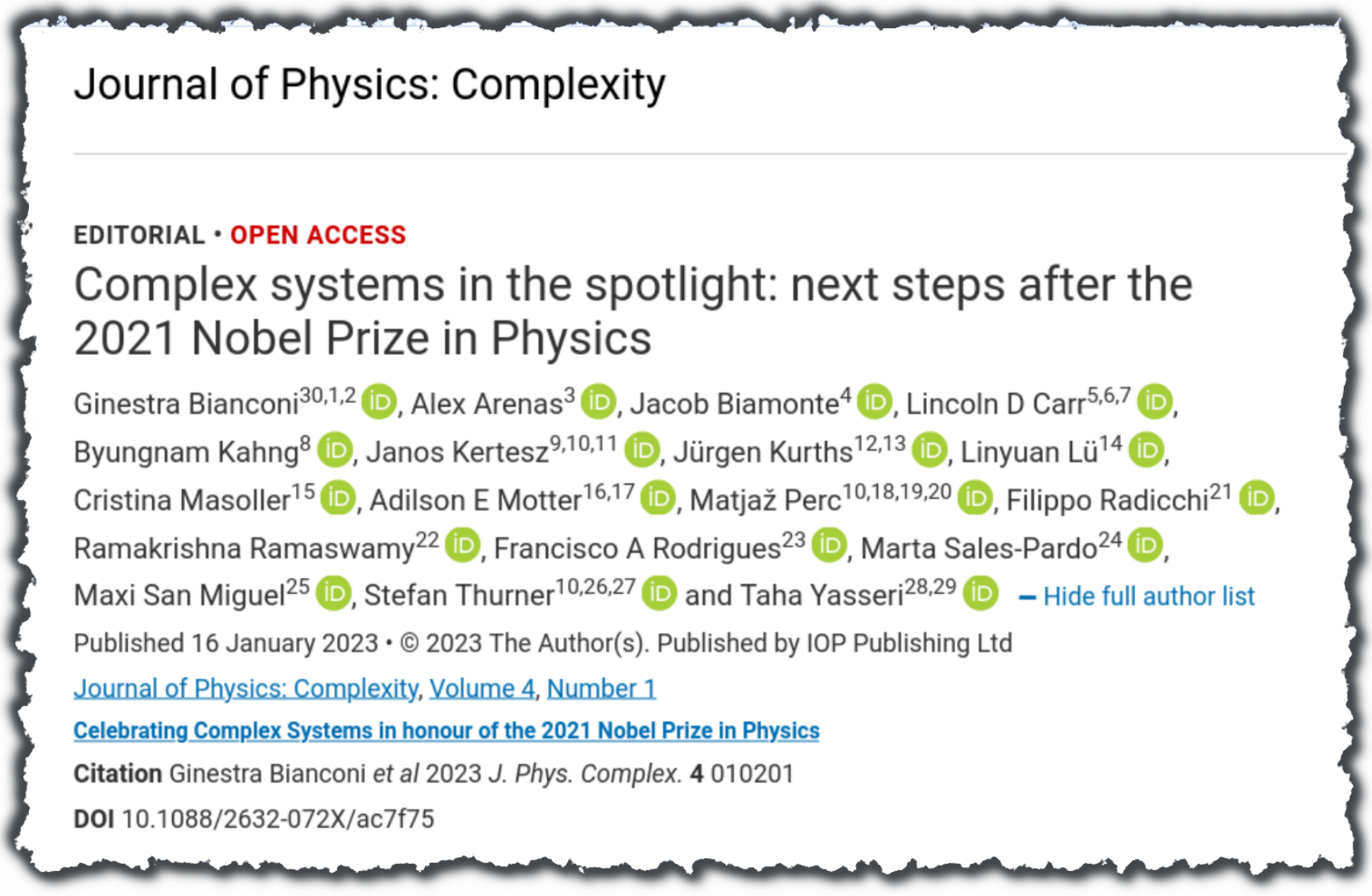
Prize share: 1/2

- https://www.nobelprize.org/prizes/physics/2021/parisi/facts/

Complex systems

Complex systems

Complex systems



Journal of Physics: Complexity

EDITORIAL • OPEN ACCESS

Complex systems in the spotlight: next steps after the 2021 Nobel Prize in Physics

Ginestra Bianconi[30,1,2], Alex Arenas[3], Jacob Biamonte[4], Lincoln D Carr[5,6,7], Byungnam Kahng[8], Janos Kertesz[9,10,11], Jürgen Kurths[12,13], Linyuan Lü[14], Cristina Masoller[15], Adilson E Motter[16,17], Matjaž Perc[10,18,19,20], Filippo Radicchi[21], Ramakrishna Ramaswamy[22], Francisco A Rodrigues[23], Marta Sales-Pardo[24], Maxi San Miguel[25], Stefan Thurner[10,26,27] and Taha Yasseri[28,29] – Hide full author list

Published 16 January 2023 • © 2023 The Author(s). Published by IOP Publishing Ltd

Journal of Physics: Complexity, Volume 4, Number 1

Celebrating Complex Systems in honour of the 2021 Nobel Prize in Physics

Citation Ginestra Bianconi *et al* 2023 *J. Phys. Complex.* **4** 010201

DOI 10.1088/2632-072X/ac7f75

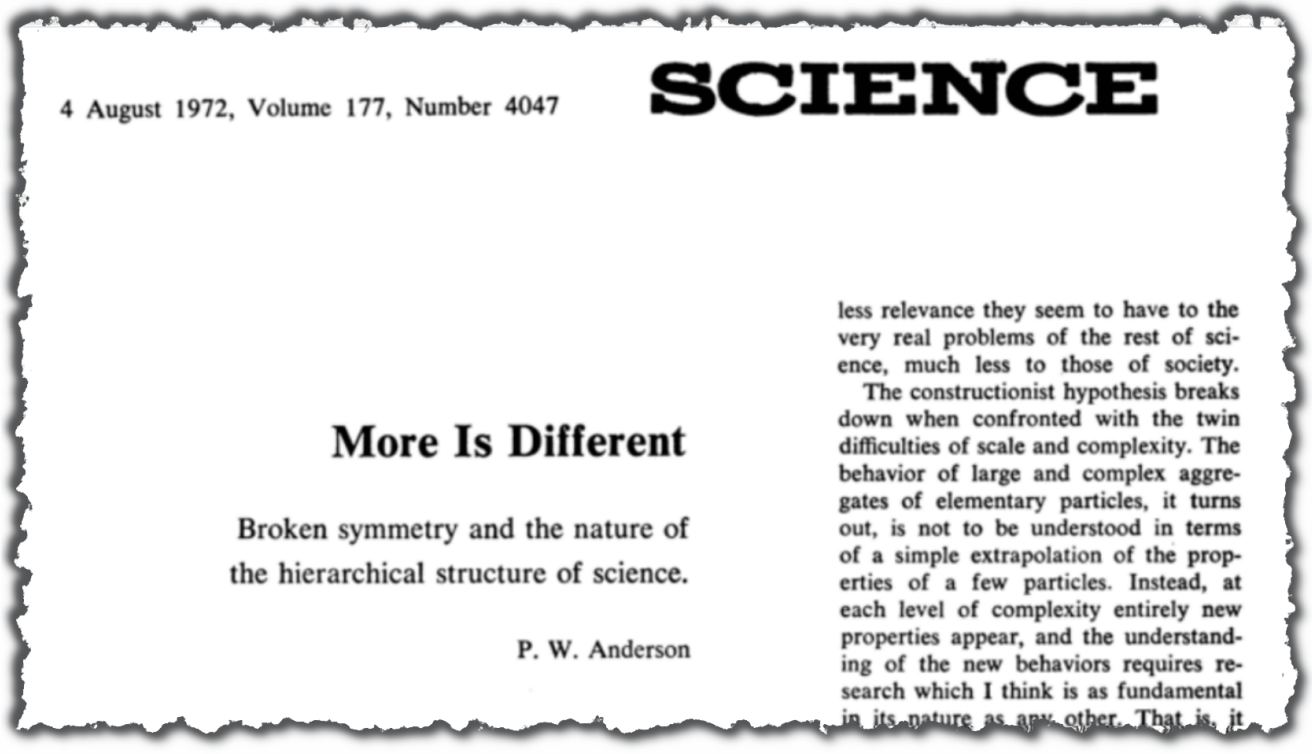
- G. Bianconi *et al.*, J. Phys. Complex., **4** 010201 (2023). DOI: `10.1088/2632-072X/ac7f75`

Complex systems

"*. . . any system consisting of many interconnected parts which, as a whole, display properties that are not trivial aggregates of those of its constituents*"

Complex systems

"*. . . any system consisting of many interconnected parts which, as a whole, display properties that are not trivial aggregates of those of its constituents*"



4 August 1972, Volume 177, Number 4047

SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

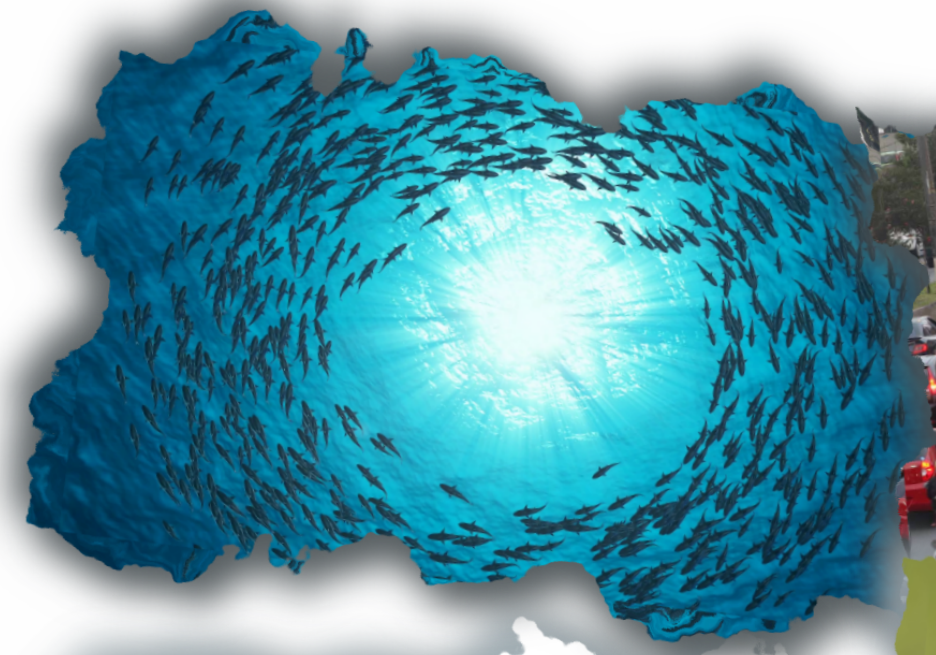
The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

- P.W. Anderson. Science **177**(4047), 393-396 (1972). DOI: 10.1126/science.177.4047.393

Complex systems

"*any system consisting of many* ***interconnected parts*** *which, as a whole, display* ***properties that are not trivial aggregates of those of its constituents***"

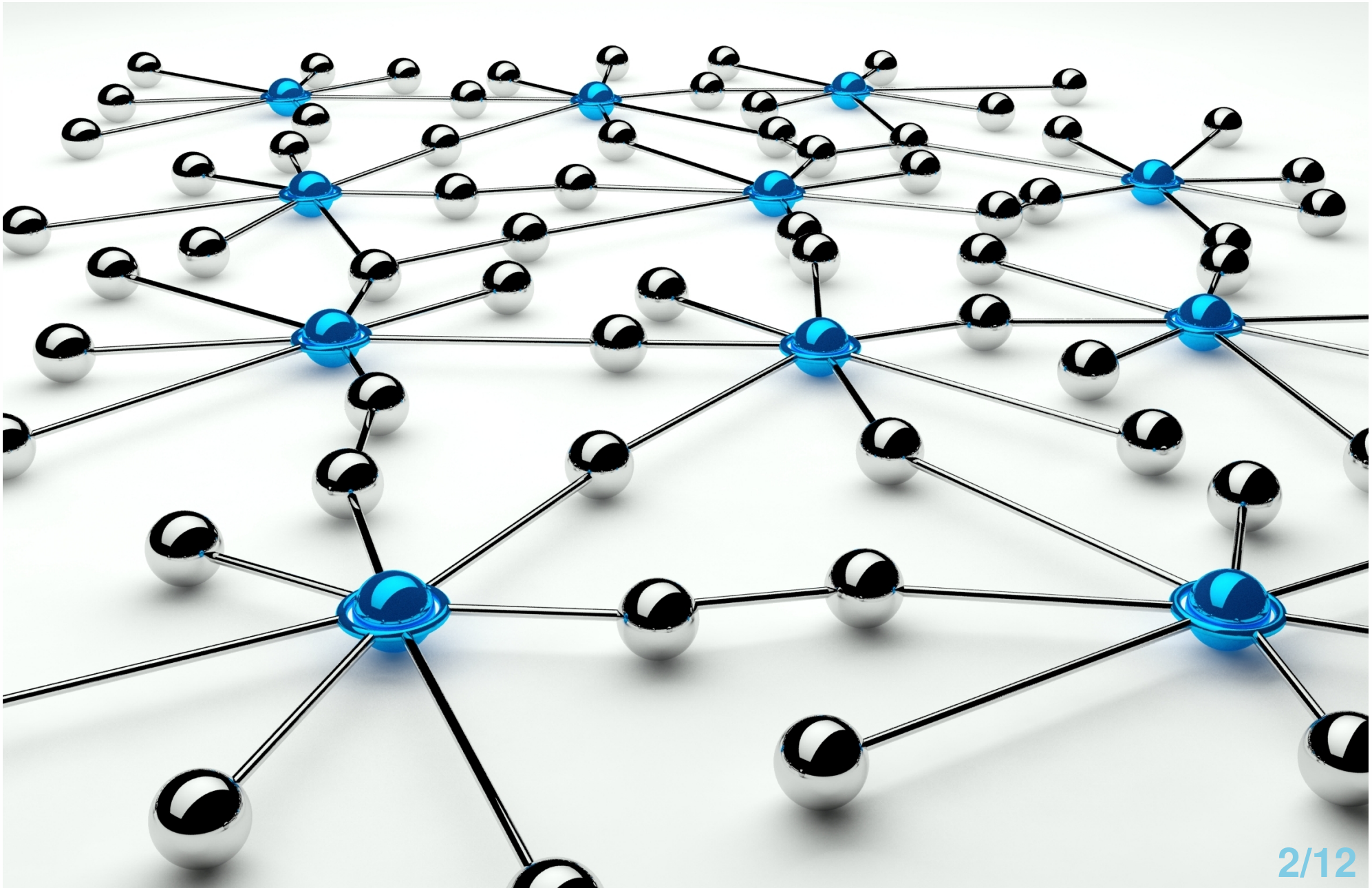
Complex systems

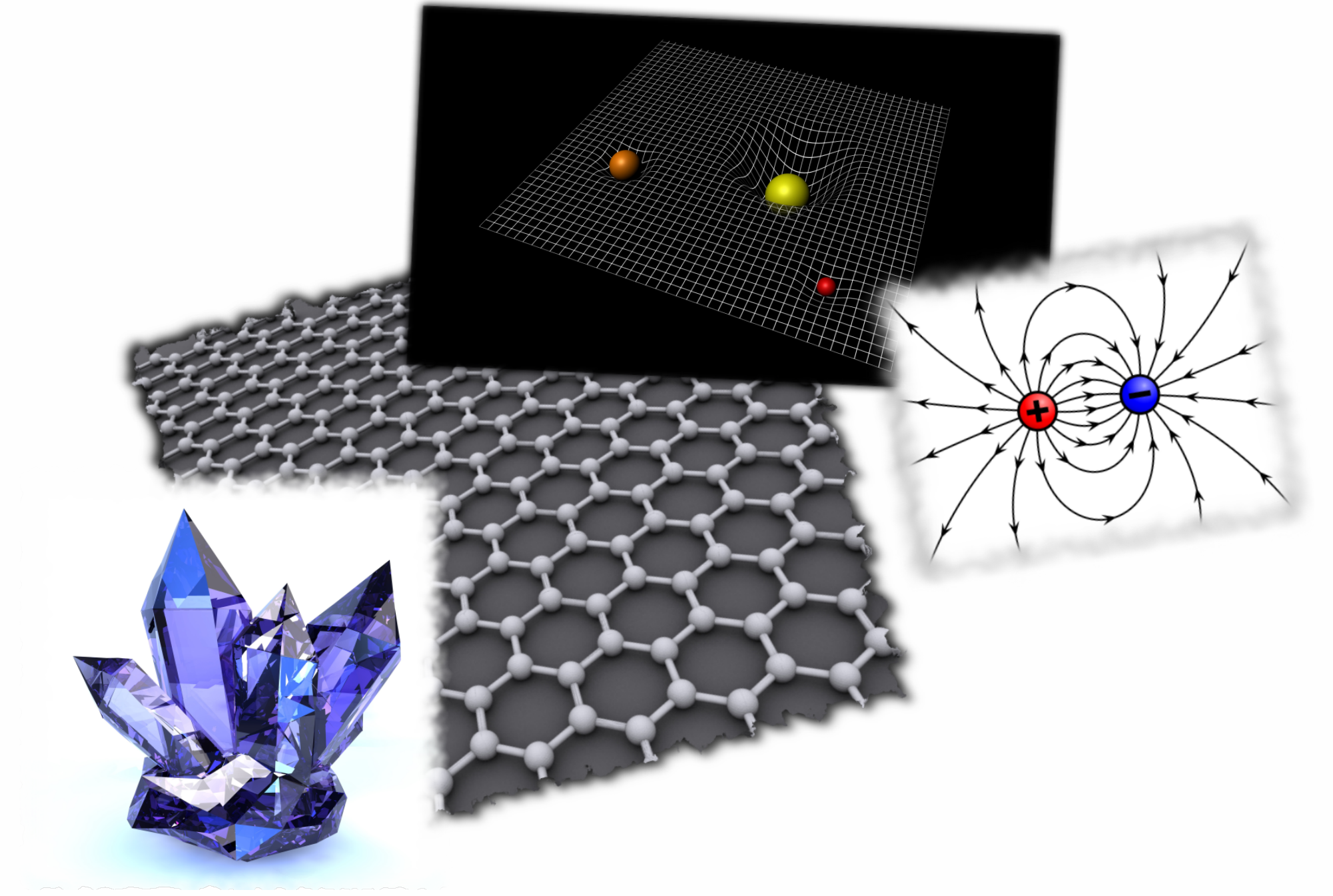


Complex systems

"*any system consisting of many* ***interconnected parts*** *which, as a whole, display* ***properties that are not trivial aggregates of those of its constituents***"

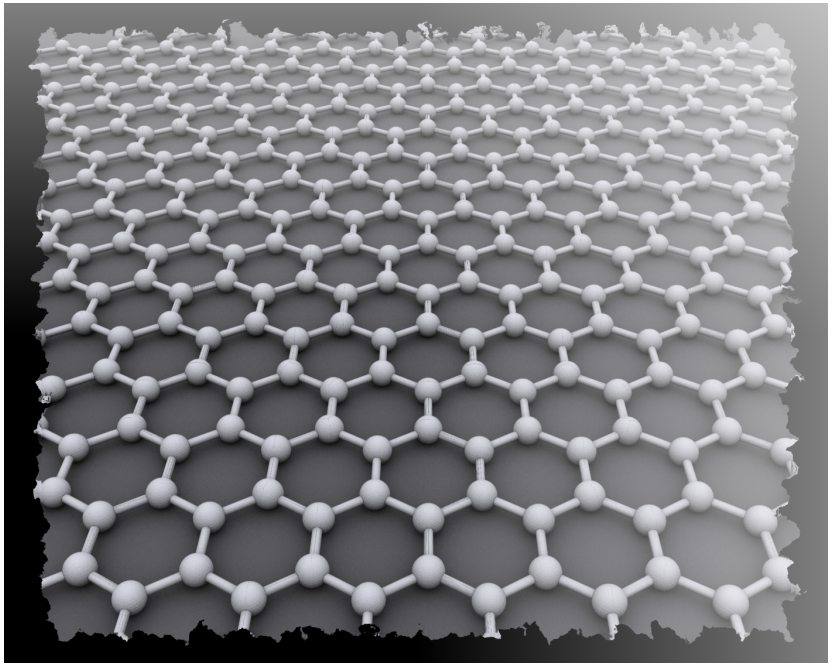
Complex systems

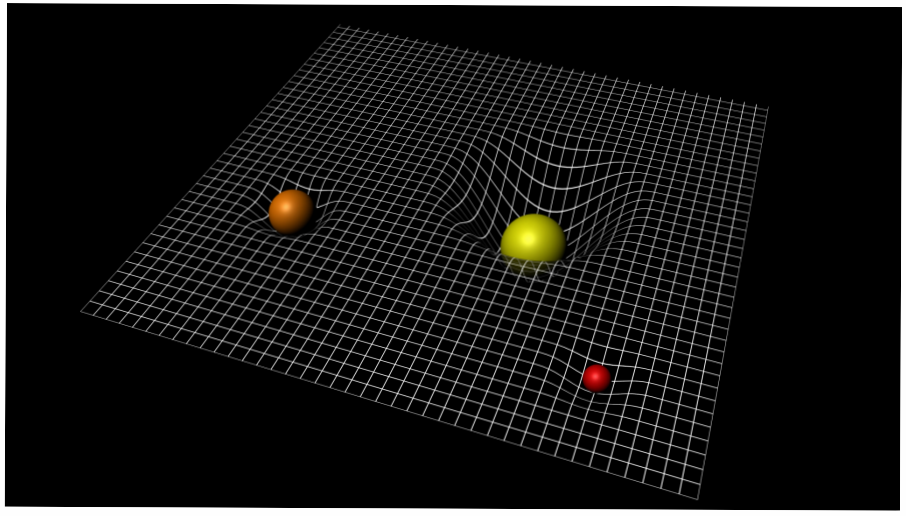




lattice / random

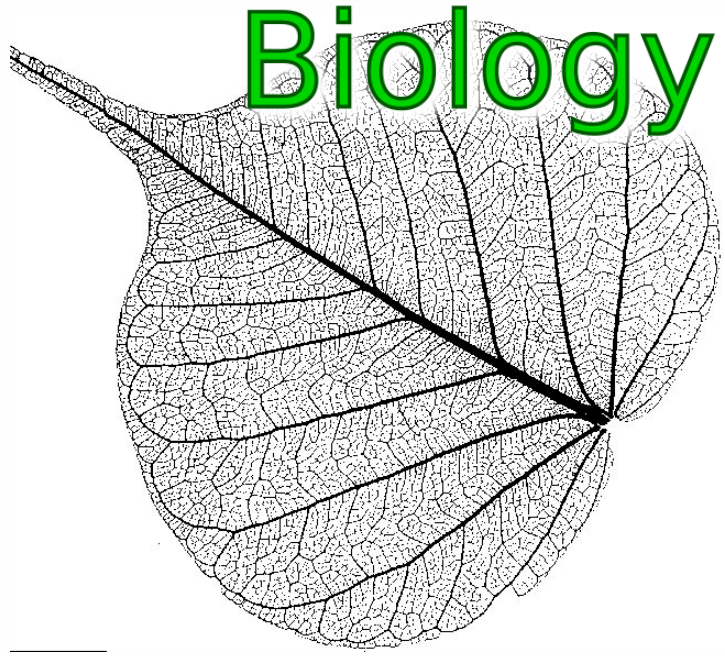
continuum





Complex systems

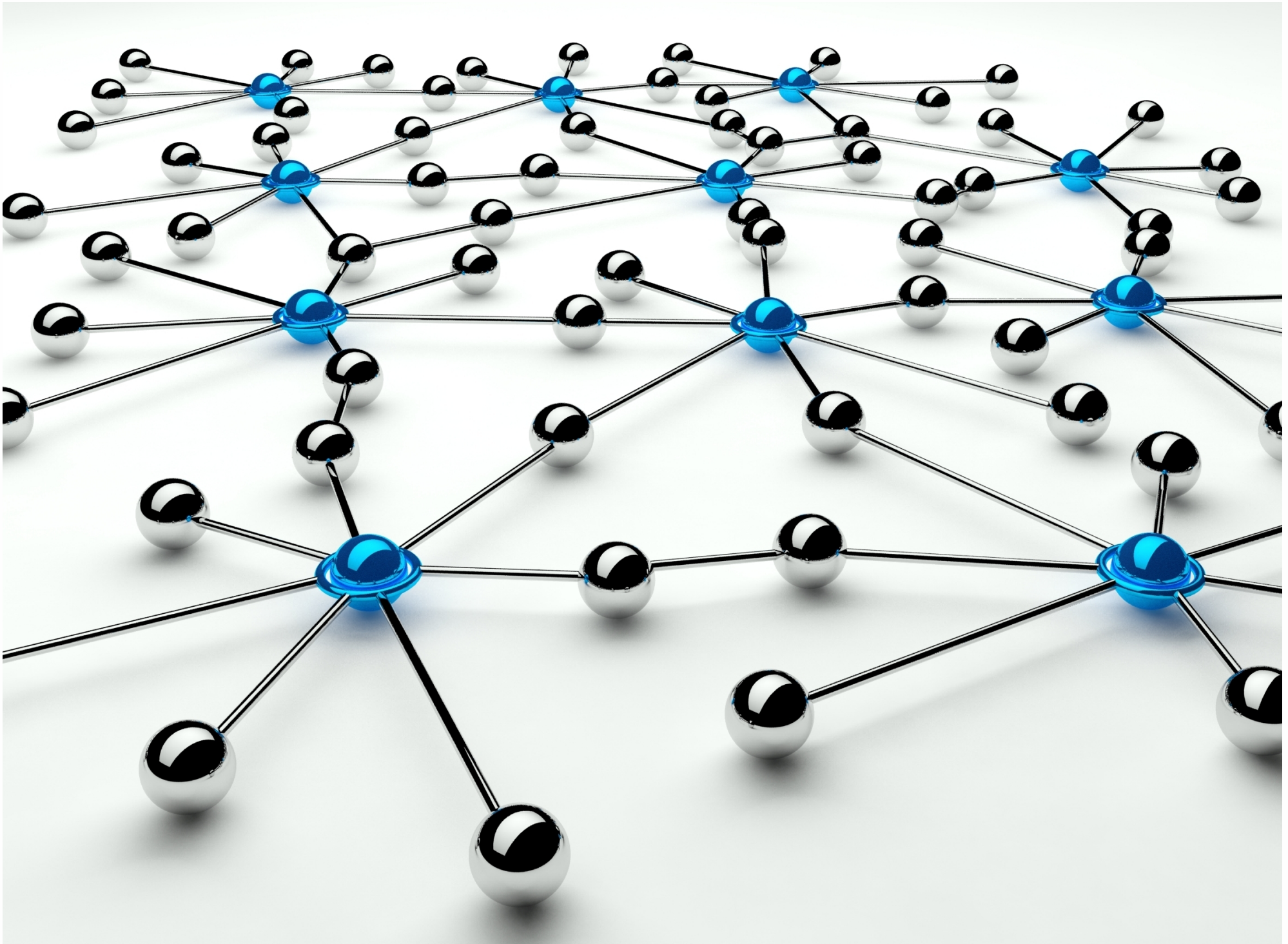
Social Science

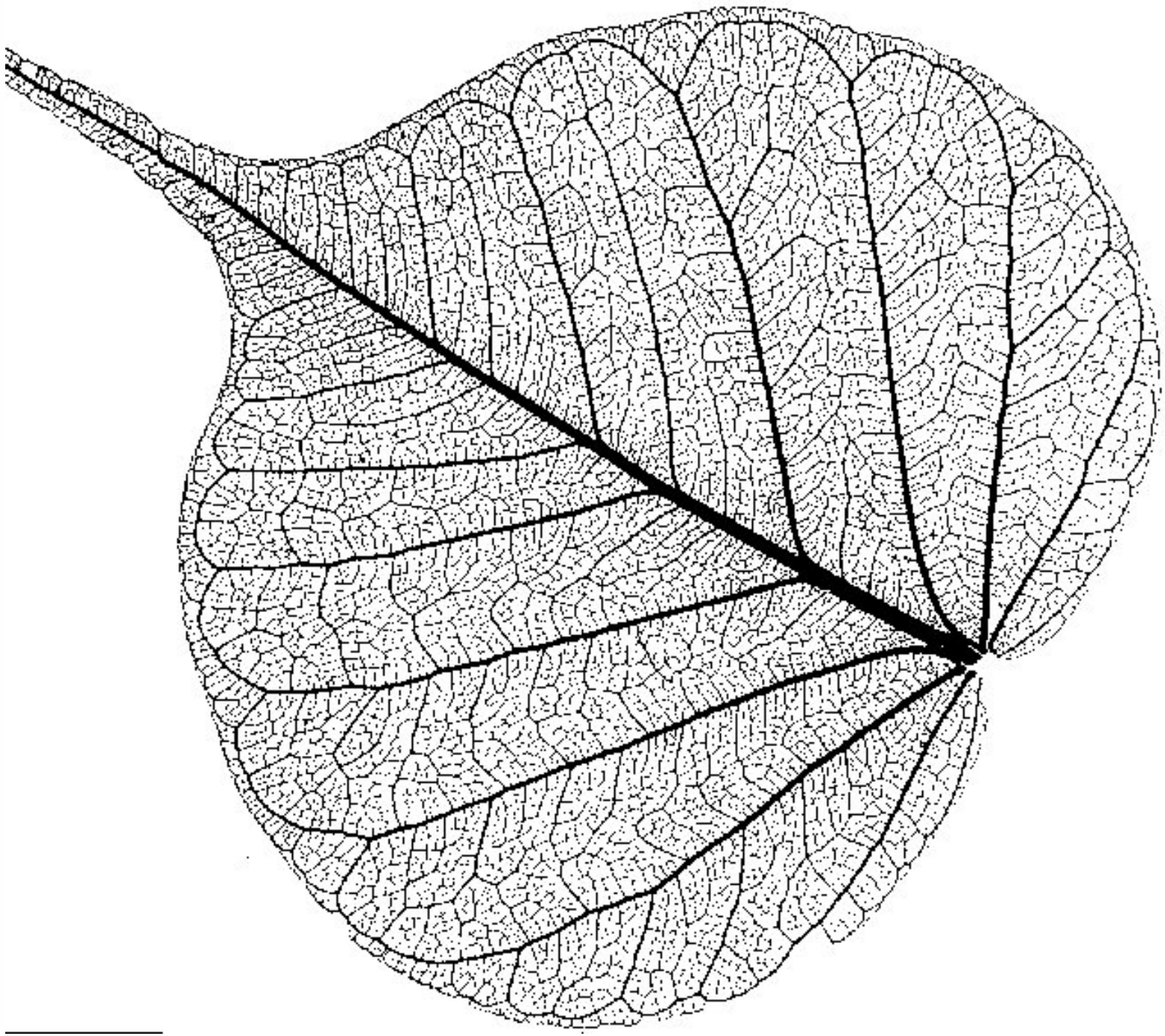


Biology

Neuroscience

Transportation





Disease spreading

Synchronization

Cooperation

Using networks to study complex systems is like paleontology ...

Graph theory/network science in a nutshell

A bit of theory

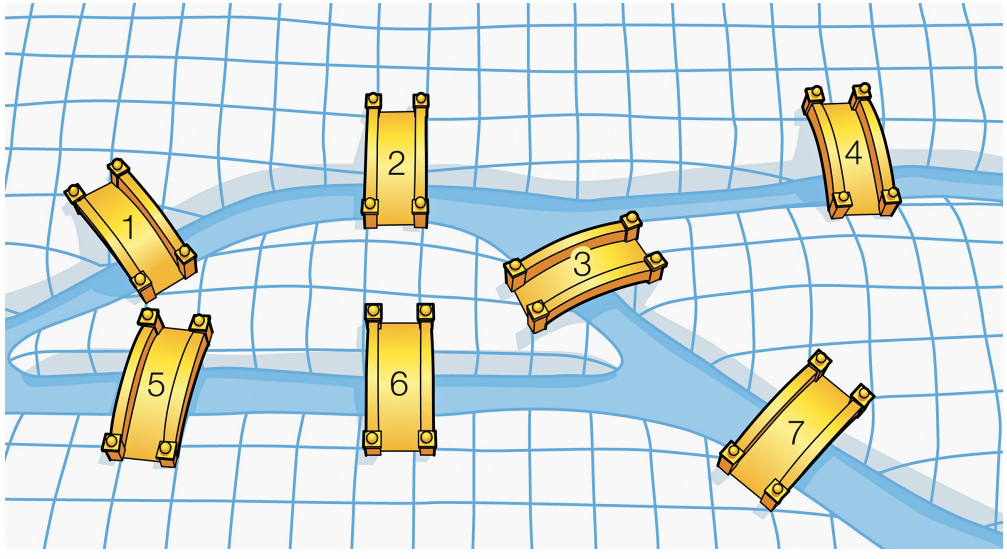
Once upon a time . . .

In 173x a mathematical puzzle based on the city of Königsberg was posed.

A bit of theory

Once upon a time . . .

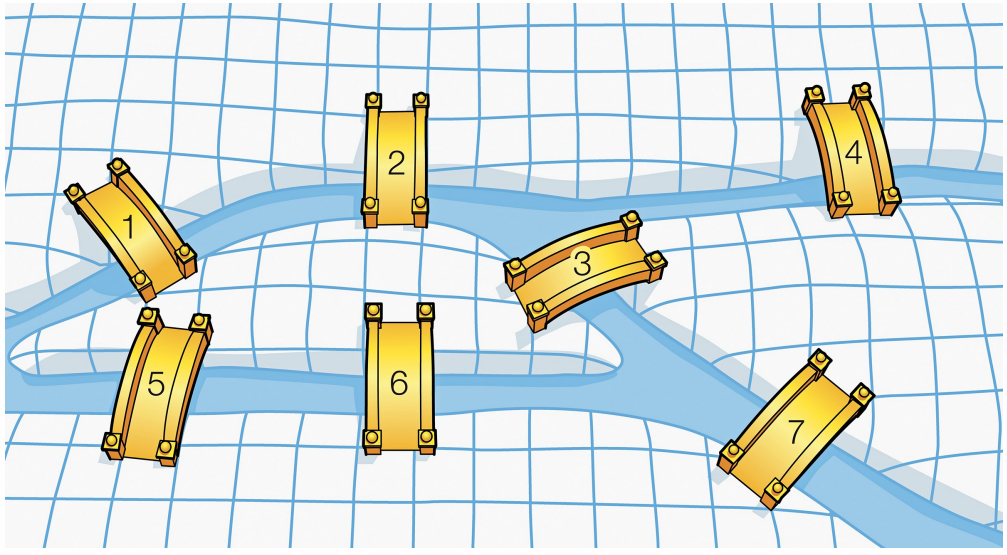
In 173x a mathematical puzzle based on the city of Königsberg was posed.



A bit of theory

The puzzle

Can we find a path that makes us explore the city passing ***from each bridge just once****?*

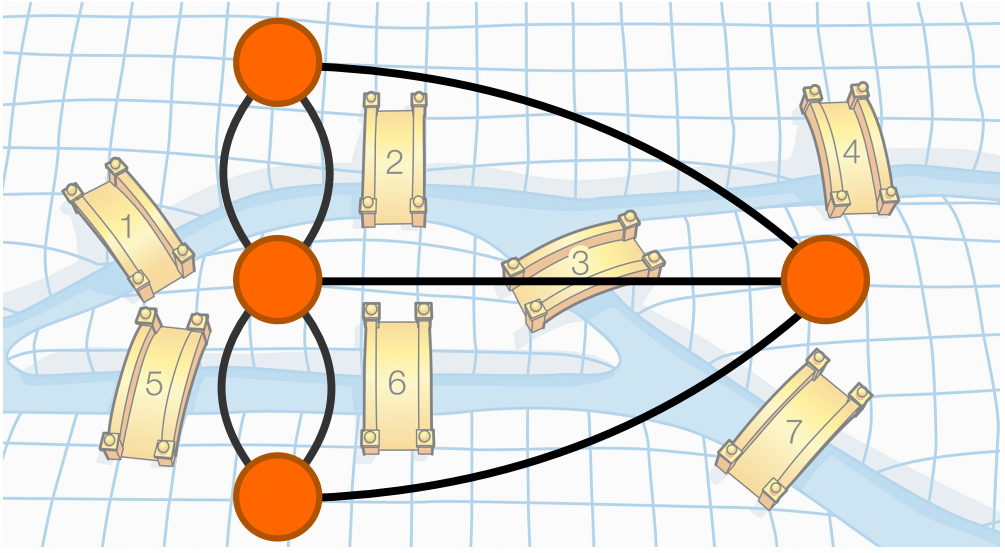


- https://en.wikipedia.org/wiki/Seven_Bridges_of_K%C3%B6nigsberg

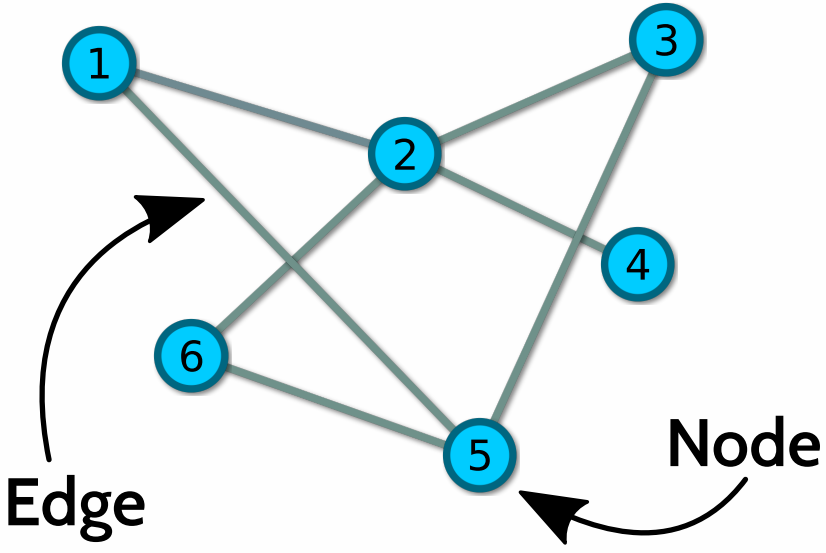
A bit of theory

The solution

In 1736 Leonard Euler found the answer and gave birth to **graph theory**.



A bit of theory



$N \times N$ Adjacency matrix

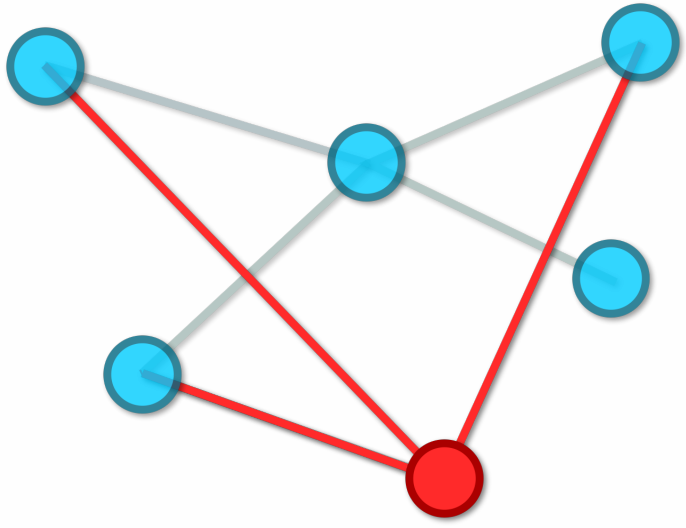
$$\mathcal{A} = \begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

A bit of theory

Advantages

- Easy mathematical formalism.
- Ability to go beyond visual inspection.
- Possibility to adopt many techniques from statistical physics/nonlinear dynamics.

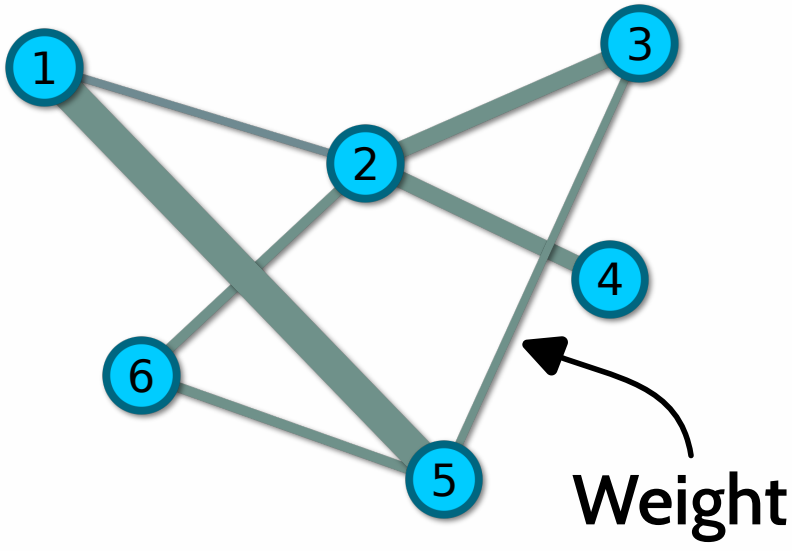
A bit of theory



Degree

$$k_i = \sum_j a_{ij} \, .$$

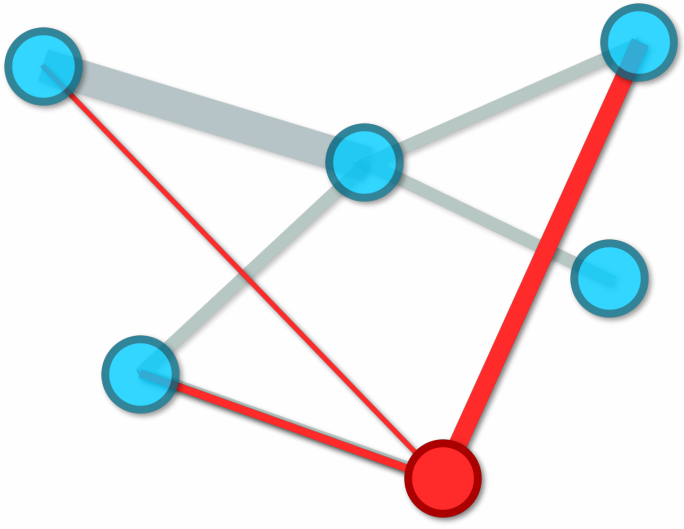
A bit of theory



$N \times N$ Weight matrix

$$\mathcal{W} = \begin{pmatrix} 0 & 2 & 0 & 0 & 7 & 0 \\ 2 & 0 & 3 & 1 & 0 & 1 \\ 0 & 3 & 0 & 0 & 5 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 7 & 0 & 5 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

A bit of theory



Strength

$$s_i = \sum_j w_{ij} \, .$$

A bit of theory

Network science's flavors

- Spatial networks
- Networks of networks
- Time-varying networks
- Multiple interactions (multilayer/multiplex)
- High-order networks
- . . .

My research interests in a nutshell

Structure

Dynamics

My research interests in a nutshell

Structure

- Spatial Networks
  - Cities
  - Geomarketing
  - Transportation (Multiplex)
  - Mobility (gender/socio)★
- Semantic Networks
  - Computational Linguistics
- Network filtering ★
- Social Networks
  - Co-Authorship
  - Mesoscopic structure
  - Historical networks & Digital humanities★
  - Homophily★
- Palaeocological Networks★

Dynamics

My research interests in a nutshell

Structure

- Spatial Networks
  - Cities
  - Geomarketing
  - Transportation (Multiplex)
  - Mobility (gender/socio)★
- Semantic Networks
  - Computational Linguistics
- Network filtering ★
- Social Networks
  - Co-Authorship
  - Mesoscopic structure
  - Historical networks & Digital humanities★
  - Homophily★
- Palaeocological Networks★

Dynamics

- Synchronization
  - Remote synchronization
- Emergence of cooperation
  - Time-varying interactions
  - Zealotry
- Coevolutionary dynamics
  - Spontaneous vaccination (spreading + games)
  - Evolutionary synchronization (synchro + games)
  - Evolutionary spreading (spreading + games)
- Context-dependent dynamics★

My research interests in a nutshell

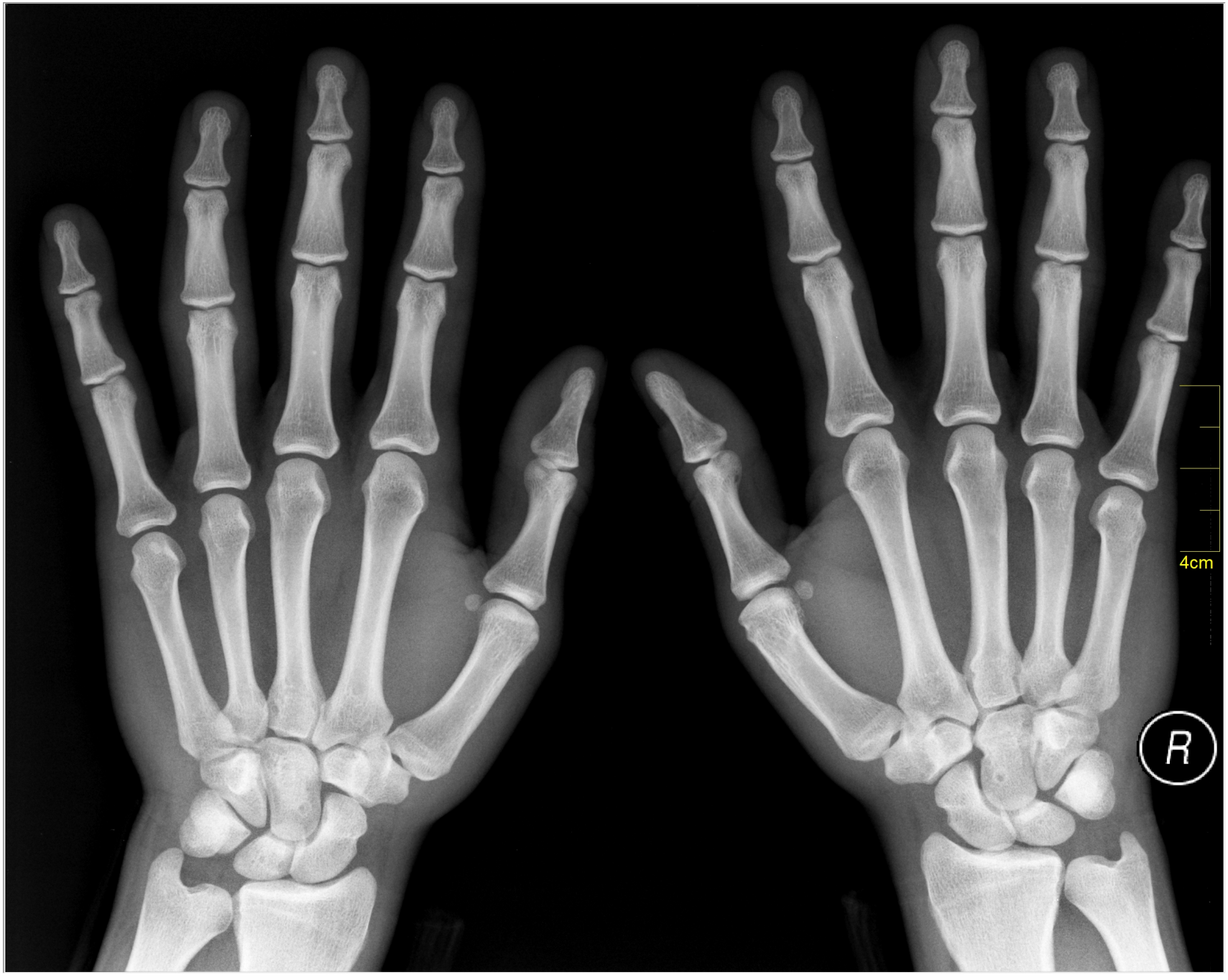
Structure

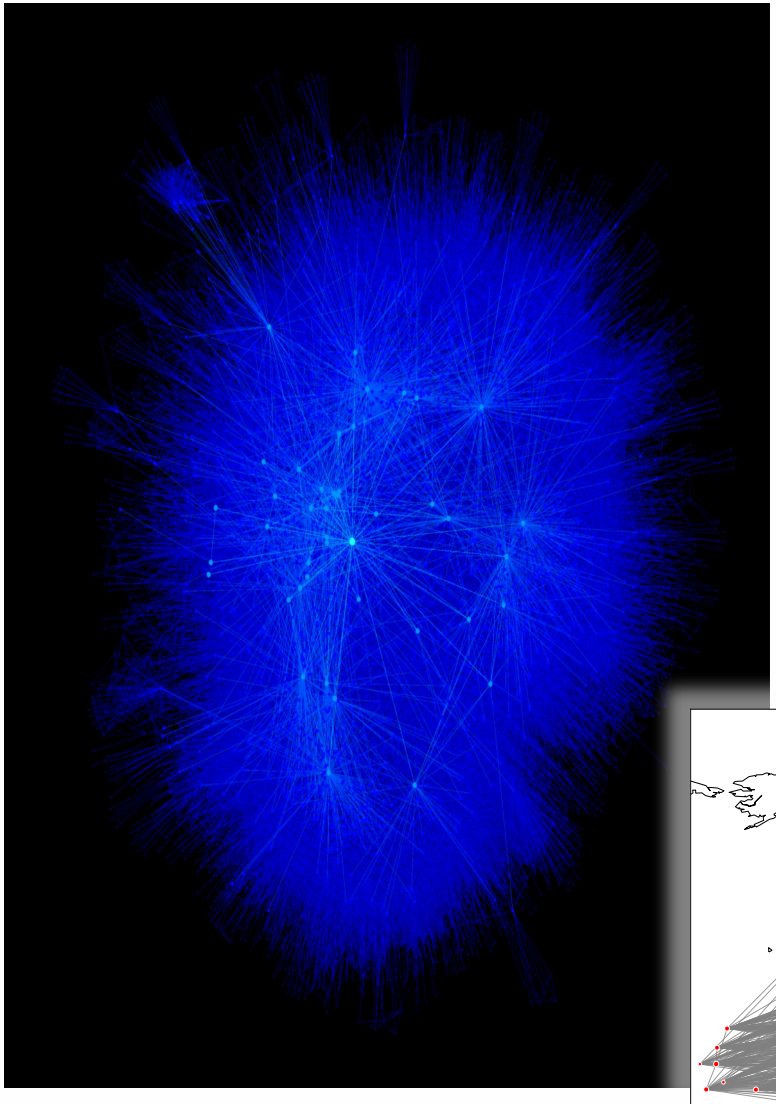
- Spatial Networks
  - Cities
  - Geomarketing
  - Transportation (Multiplex)
  - Mobility (gender/socio)★
- Semantic Networks
  - Computational Linguistics
- Network filtering ★
- Social Networks
  - Co-Authorship
  - Mesoscopic structure
  - Historical networks & Digital humanities★
  - Homophily★
- Palaeocological Networks★

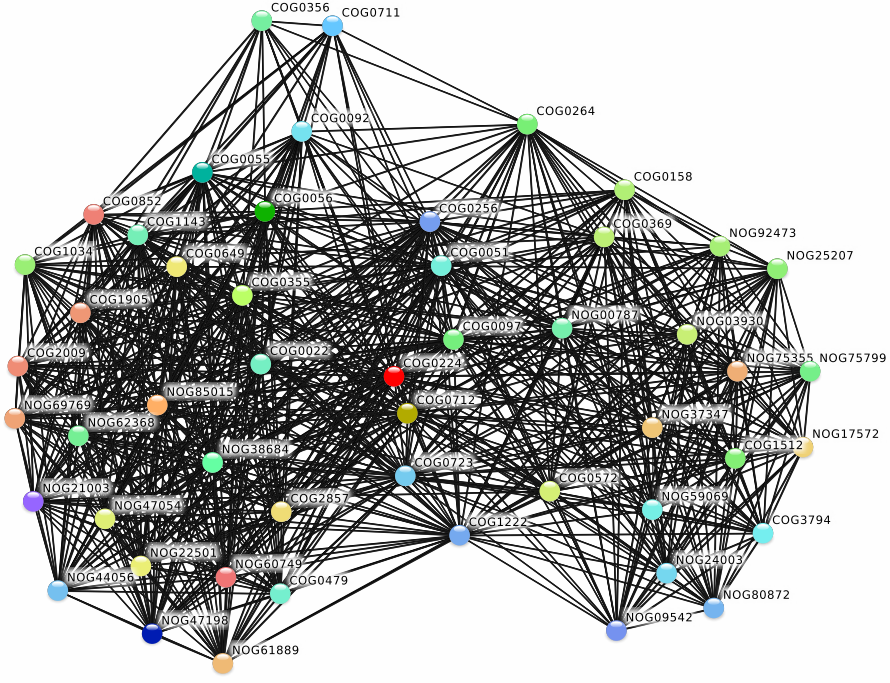
Dynamics

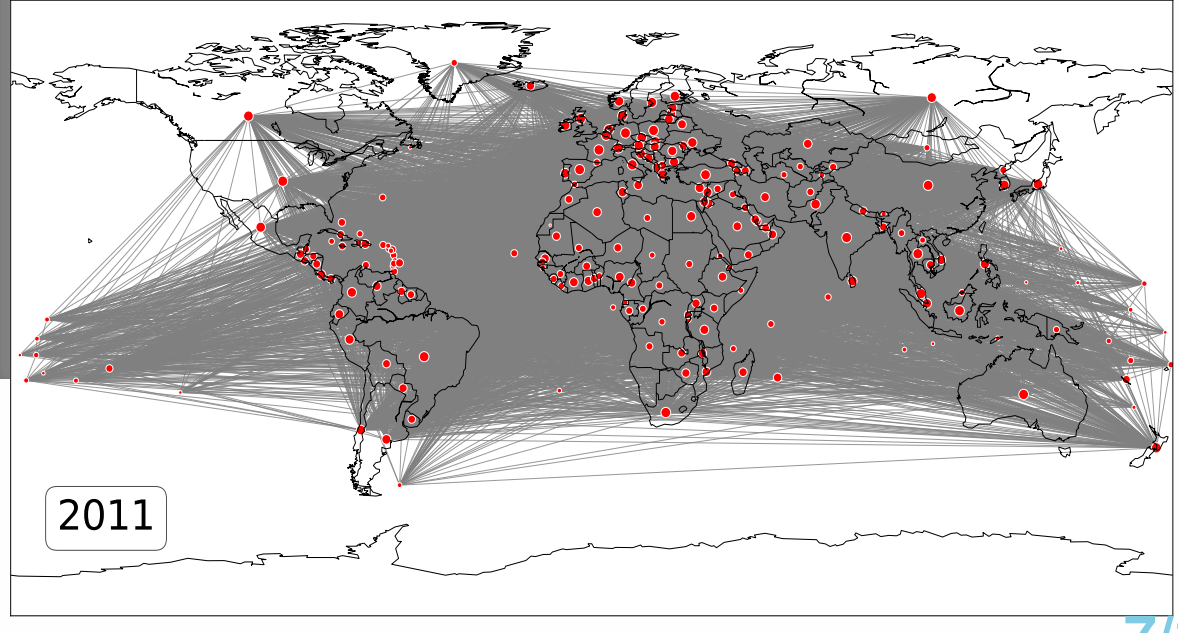
- Synchronization
  - Remote synchronization
- Emergence of cooperation
  - Time-varying interactions
  - Zealotry
- Coevolutionary dynamics
  - Spontaneous vaccination (spreading + games)
  - Evolutionary synchronization (synchro + games)
  - Evolutionary spreading (spreading + games)
- Context-dependent dynamics★

Network filtering

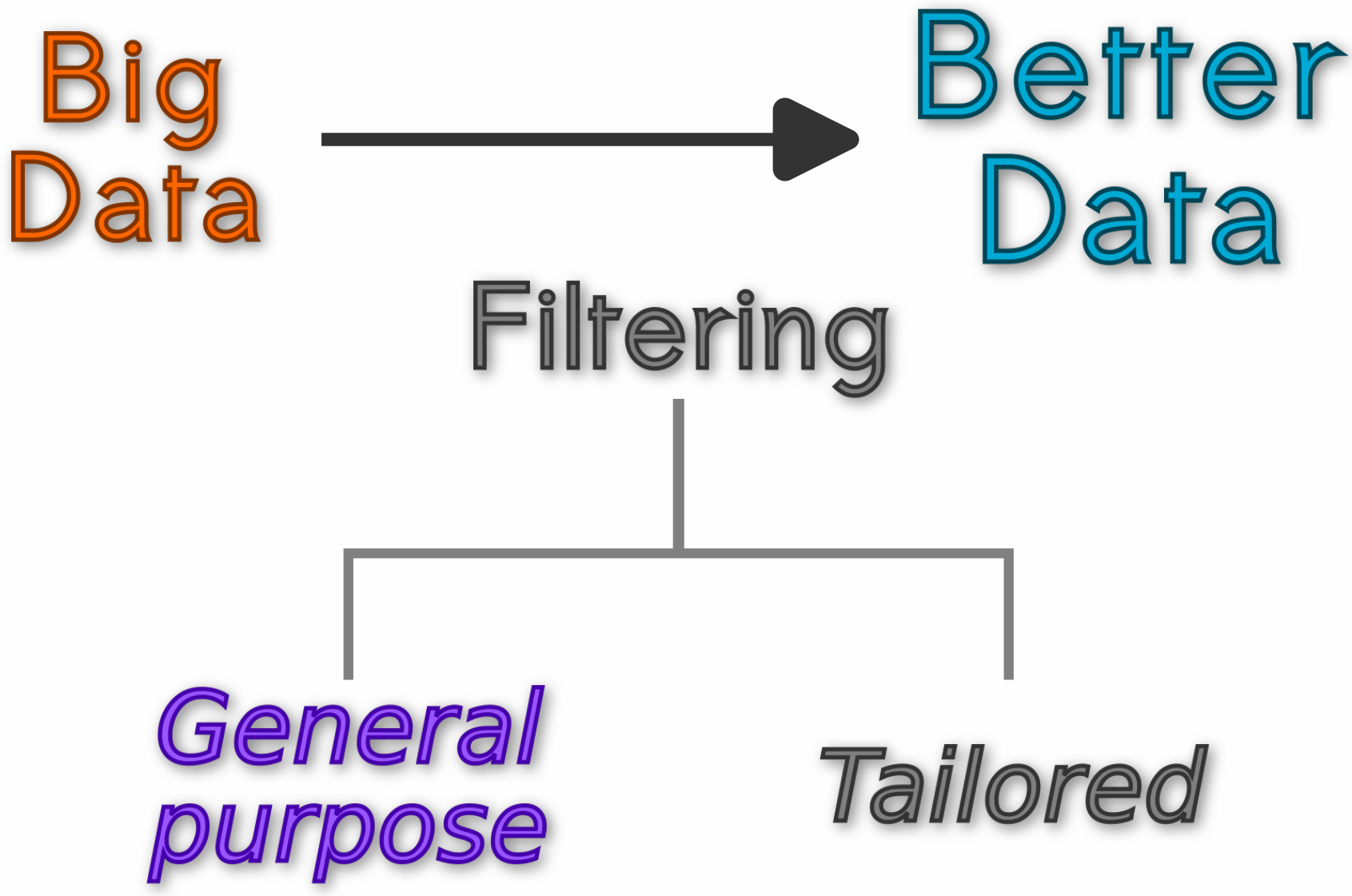

4cm
R



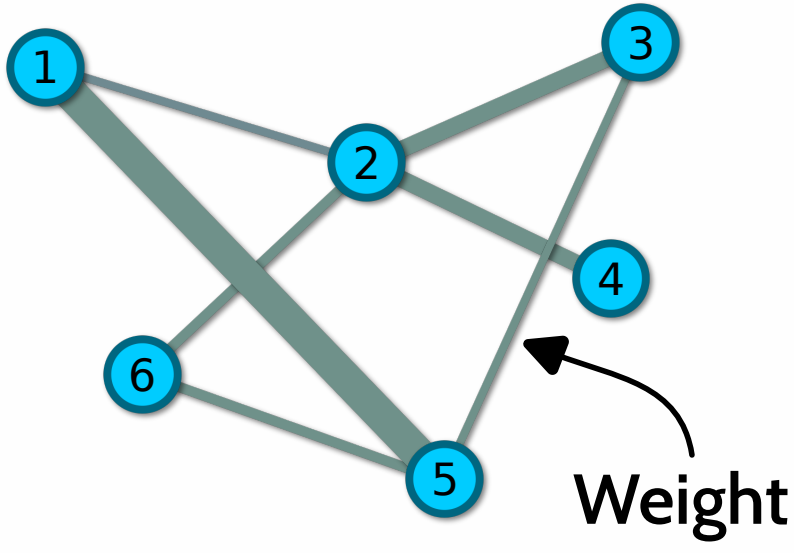

COG0356
COG0711
COG0264
COG0092
COG0055
COG0158
COG0852
COG0056
COG0256
COG1143
COG0369
NOG92473
COG1034
COG0649
COG0051
NOG25207
COG0355
COG1905
NOG0078
NOG03930
COG0097
COG2009
COG0022
COG0224
NOG75355
NOG75799
NOG85015
NOG69769
COG0712
NOG62368
NOG37347
NOG17572
NOG38684
COG0723
COG1512
NOG21003
COG0572
NOG47054
COG2857
NOG59069
COG3794
COG1222
NOG22501
NOG24003
NOG60749
NOG44056
COG0479
NOG80872
NOG47198
NOG09542
NOG61889


2011


The Economist
Obama the warrior
Misgoverning Argentina
The economic shift from West to East
Genetically modified crops blossom
The right to eat cats and dogs
FEBRUARY 27TH–MARCH 5TH 2010
Economist.com
The data deluge
AND HOW TO HANDLE IT: A 14-PAGE SPECIAL REPORT


Big Data
Better Data
Filtering
General purpose
Tailored

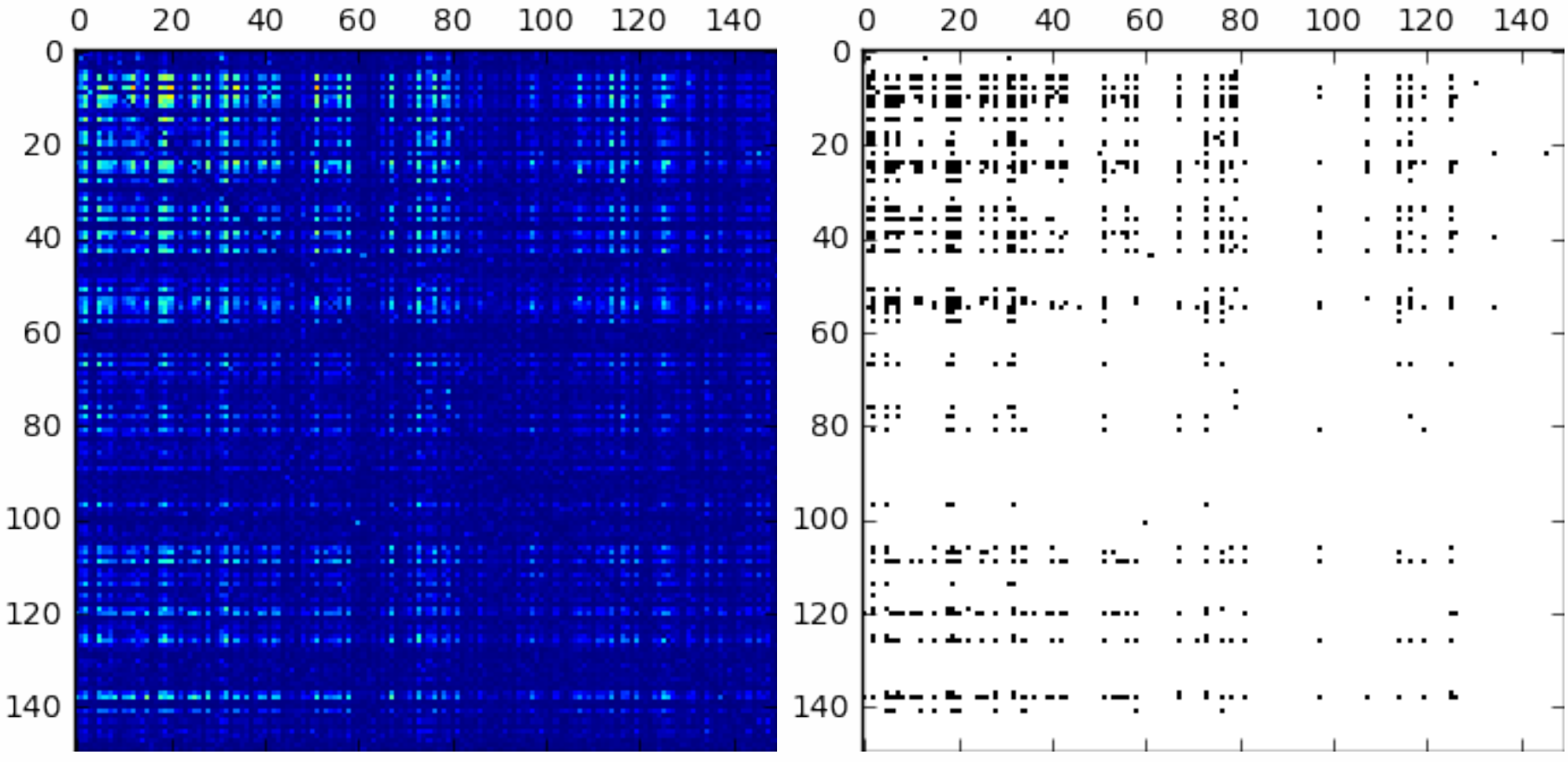

BRACE YOURSELVES
FILTERING IS COMING
imgflip.com



$N \times N$ Weight matrix

$$\mathcal{W} = \begin{pmatrix} 0 & 2 & 0 & 0 & 7 & 0 \\ 2 & 0 & 3 & 1 & 0 & 1 \\ 0 & 3 & 0 & 0 & 5 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 7 & 0 & 5 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Thresholding



Thresholding

PNAS

Proceedings of the
National Academy of Sciences
of the United States of America

Keyword, Author

Home | Articles | Front Matter | News | Podcasts | Authors

NEW RESEARCH IN Physical Sciences Social Sciences

A tool for filtering information in complex systems

M. Tumminello, T. Aste, T. Di Matteo, and R. N. Mantegna

PNAS July 26, 2005 102 (30) 10421-10426; https://doi.org/10.1073/pnas.0500298102

Edited by H. Eugene Stanley, Boston University, Boston, MA (received for review January 13, 2005)

- M. Tumminello, *et al.* Proc. Nat. Acad. Sci. USA, **102**, 10421–10426 (2005).

DOI: 10.1073/pnas.0500298102

Thresholding

PLOS COMPUTATIONAL BIOLOGY

BROWSE PUBLISH ABC

OPEN ACCESS PEER-REVIEWED

RESEARCH ARTICLE

A Topological Criterion for Filtering Information in Complex Brain Networks

Fabrizio De Vico Fallani, Vito Latora, Mario Chavez

Version 2

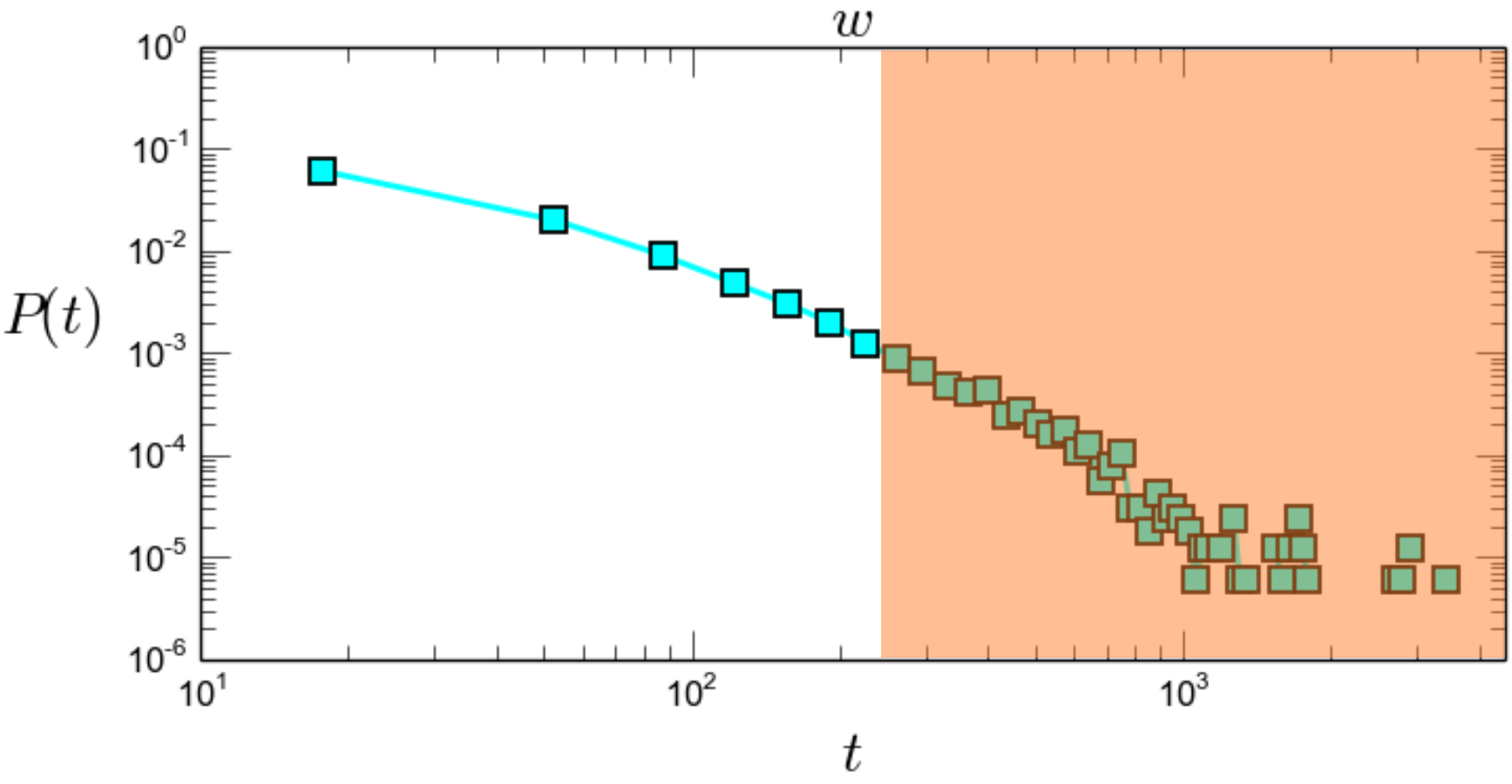
Published: January 11, 2017 • https://doi.org/10.1371/journal.pcbi.1005305

- F. De Vico Fallani, *et al.* PLoS Comp. Bio. **13** e1005305 (2017). DOI: `10.1371/journal.pcbi.1005305`

Thresholding

- X. Yan, *et al.* Phys. Rev. E **98**, 042304 (2018). DOI: 10.1103/PhysRevE.98.042304

Thresholding



• M. S. Granovetter, *The Strength of Weak Ties*. Am. Jour. Soc., **78**, 1360 (1973). DOI: 10.1086/225469

The ECM-filter

The ECM-filter

Main Features

1. Based on the comparison between the ***observed network*** and one generated via a ***null model***.

- R. Mastrandrea, *et al.* New Jour. Phys., **16**, 043022. (2014). DOI: 10.1088/1367-2630/16/4/043022
- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Main Features

1. Based on the comparison between the ***observed network*** and one generated via a ***null model***.
2. Null model: maximum-entropy canonical ensemble of networks satisfying given constraints.

- R. Mastrandrea, *et al.* New Jour. Phys., **16**, 043022. (2014). DOI: 10.1088/1367-2630/16/4/043022
- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Main Features

1. Based on the comparison between the ***observed network*** and one generated via a ***null model***.
2. Null model: maximum-entropy canonical ensemble of networks satisfying given constraints.
3. Constraints: $\{k_i\}$ and $\{s_i\}$ preserved (on average).

- R. Mastrandrea, *et al.* New Jour. Phys., **16**, 043022. (2014). DOI: 10.1088/1367-2630/16/4/043022
- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Main Features

1. Based on the comparison between the ***observed network*** and one generated via a ***null model***.
2. Null model: maximum-entropy canonical ensemble of networks satisfying given constraints.
3. Constraints: $\{k_i\}$ and $\{s_i\}$ preserved (on average).
4. Two versions: **local** (focus on links) and **global** (focus on entire networks).

- R. Mastrandrea, *et al.* New Jour. Phys., **16**, 043022. (2014). DOI: 10.1088/1367-2630/16/4/043022
- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Local filter

- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Local filter

1. Generate the null model networks' ensemble and compute:

$$q_{ij}(w) \equiv \frac{\left(x_i x_j\right)^{\Theta(w_{ij})} \left(y_i y_j\right)^{w_{ij}} \left(1 - y_i y_j\right)}{1 - y_i y_j + x_i x_j y_i y_j} \, .$$

- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Local filter

1. Generate the null model networks' ensemble and compute:

$$q_{ij}(w) \equiv \frac{\left(x_i x_j\right)^{\Theta(w_{ij})} \left(y_i y_j\right)^{w_{ij}} \left(1 - y_i y_j\right)}{1 - y_i y_j + x_i x_j y_i y_j} \, .$$

2. Compute the probability:

$$p_{ij}(w^\star) = 1 - \sum_{w=0}^{w^\star - 1} q_{ij}(w) \, .$$

- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Local filter

1. Generate the null model networks' ensemble and compute:

$$q_{ij}(w) \equiv \frac{\left(x_i x_j\right)^{\Theta(w_{ij})} \left(y_i y_j\right)^{w_{ij}} \left(1 - y_i y_j\right)}{1 - y_i y_j + x_i x_j y_i y_j} \, .$$

2. Compute the probability:

$$p_{ij}(w^\star) = 1 - \sum_{w=0}^{w^\star - 1} q_{ij}(w) \, .$$

3. Associate for each link a p-value, γ, such that $P(w_{ij} > w_{ij}^\star)$.

• V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Local filter

1. Generate the null model networks' ensemble and compute:

$$q_{ij}(w) \equiv \frac{\left(x_i x_j\right)^{\Theta(w_{ij})} \left(y_i y_j\right)^{w_{ij}} \left(1 - y_i y_j\right)}{1 - y_i y_j + x_i x_j y_i y_j} \, .$$

2. Compute the probability:

$$p_{ij}(w^\star) = 1 - \sum_{w=0}^{w^\star - 1} q_{ij}(w) \, .$$

3. Associate for each link a p-value, γ, such that $P(w_{ij} > w_{ij}^\star)$.
4. Select a threshold $\widetilde{\gamma}$ and remove all the links with $\gamma_{ij} > \widetilde{\gamma}$.

• V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Global filter

- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Global filter

1. Find the subgraph Σ with L' links minimizing the **likelihood** of being generated by chance.

- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Global filter

1. Find the subgraph Σ with L' links minimizing the **likelihood** of being generated by chance.
2. Minimize the function:

$$P(\Sigma) = \prod_{i<j} \left[q_{ij}(w_{ij})\right]^{a_{ij}} \ .$$

- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: 10.48550/arXiv.1706.00230

The ECM-filter

Global filter

1. Find the subgraph Σ with L' links minimizing the **likelihood** of being generated by chance.
2. Minimize the function:

$$P(\Sigma) = \prod_{i<j} \left[q_{ij}(w_{ij}) \right]^{a_{ij}} .$$

3. Rank edges upon their $q_{ij}(w)$. and then add the first L' smallest ones.

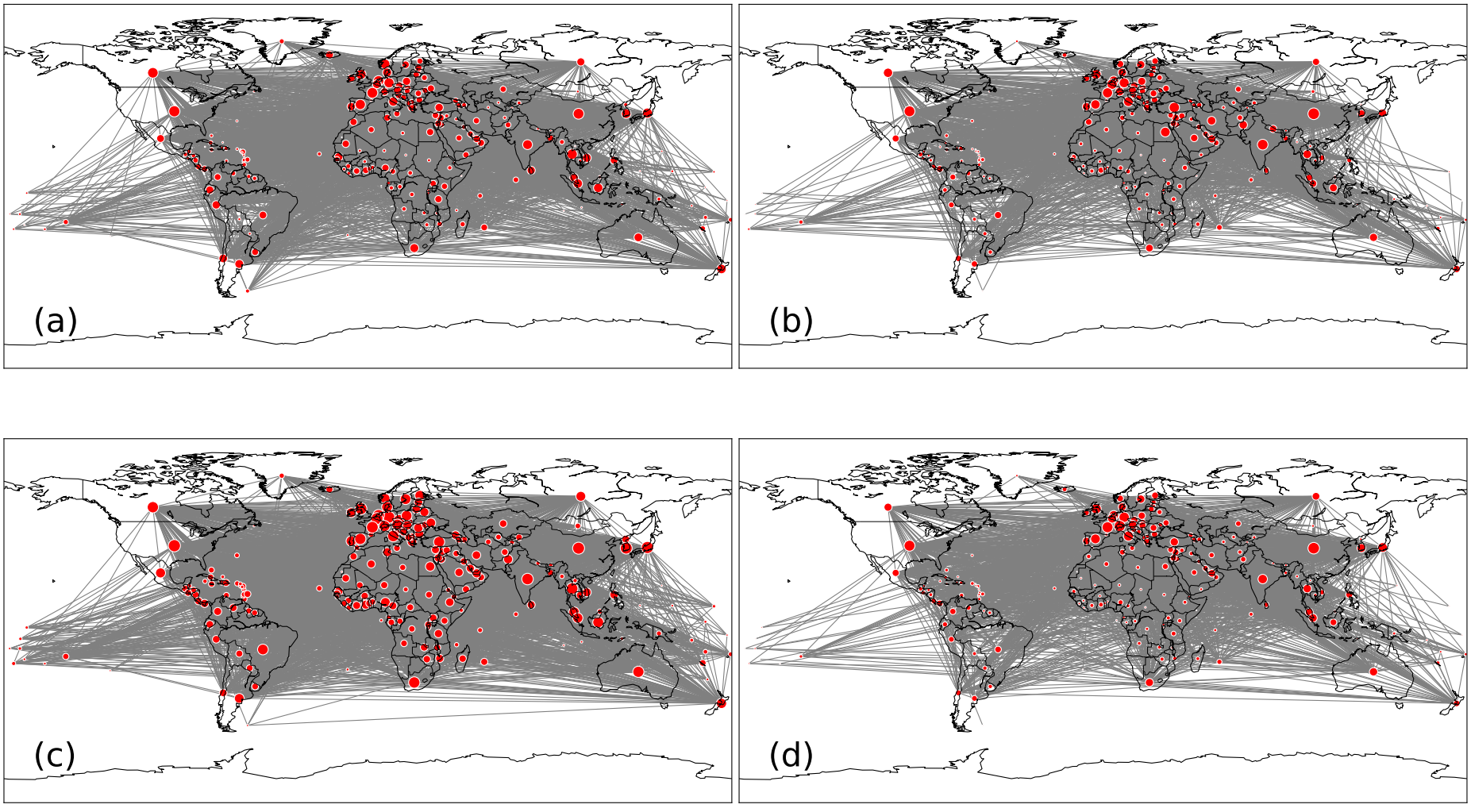
- V. Gemmetto, *et al.* arXiv, 1705-00230 (2017). DOI: `10.48550/arXiv.1706.00230`

ECM-filter in action

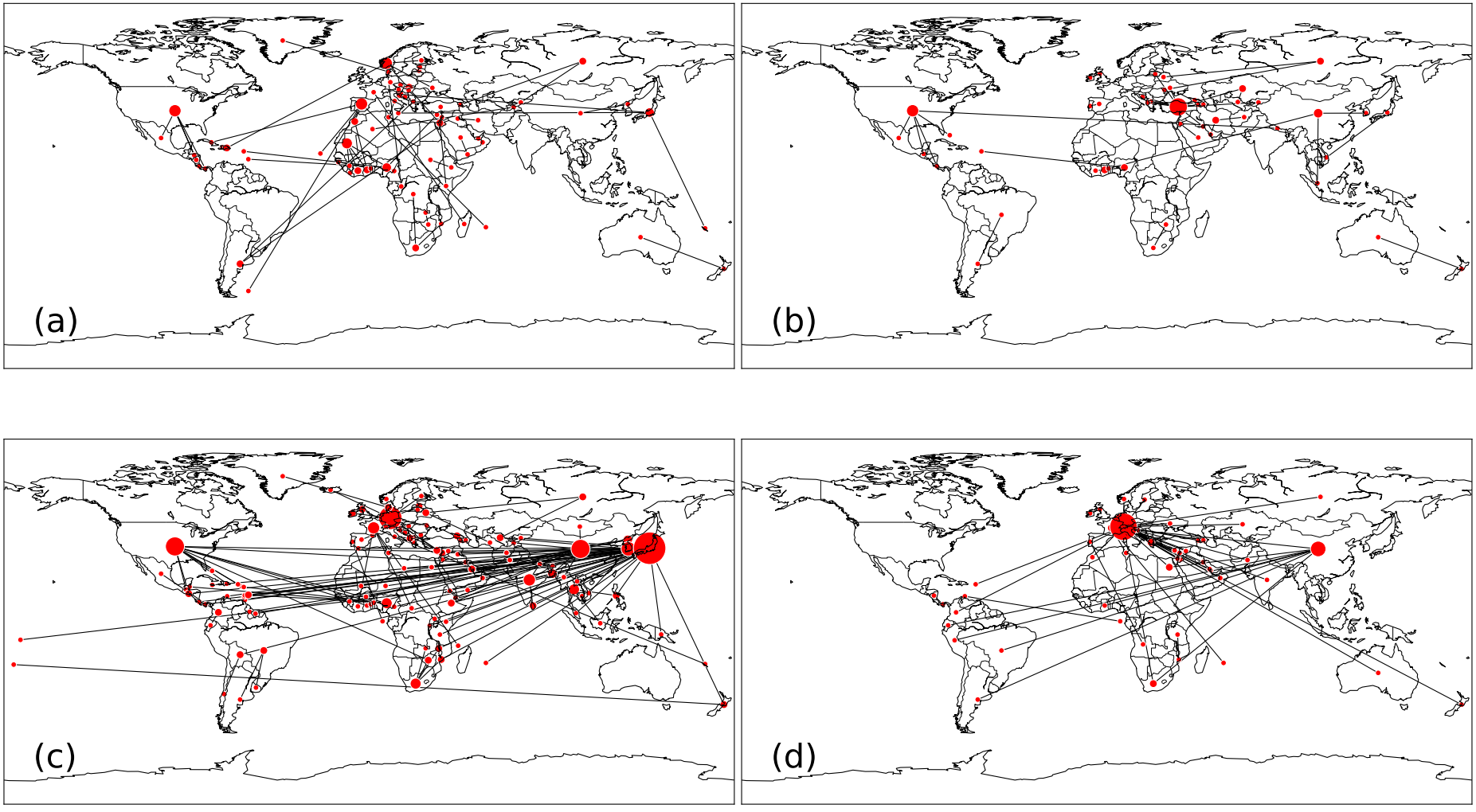
ECM-filter in action

ECM-filter in action

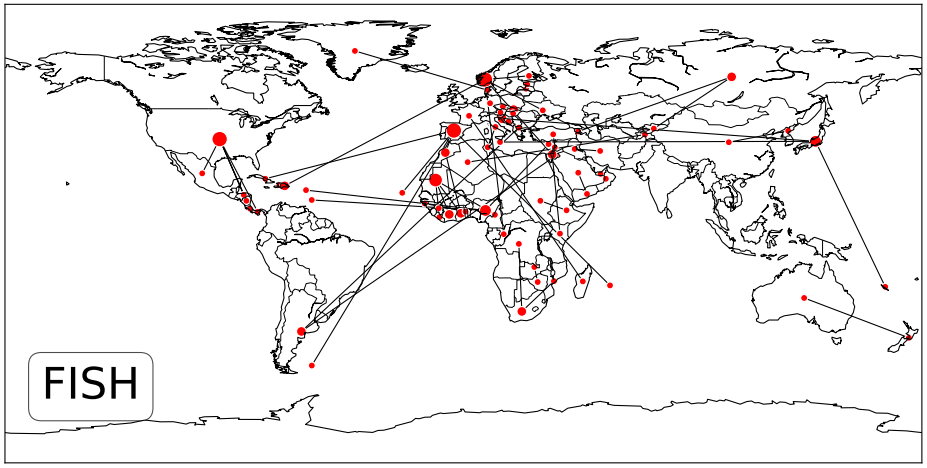
ECM-filter in action

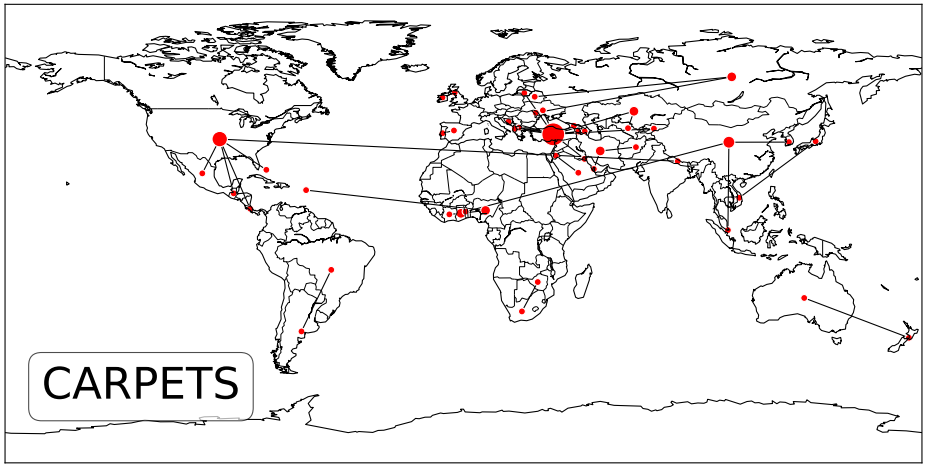


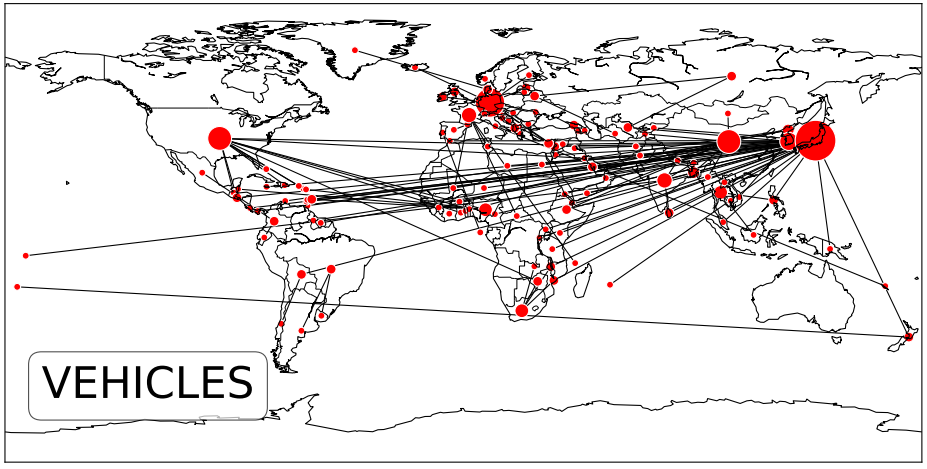
ECM-filter in action

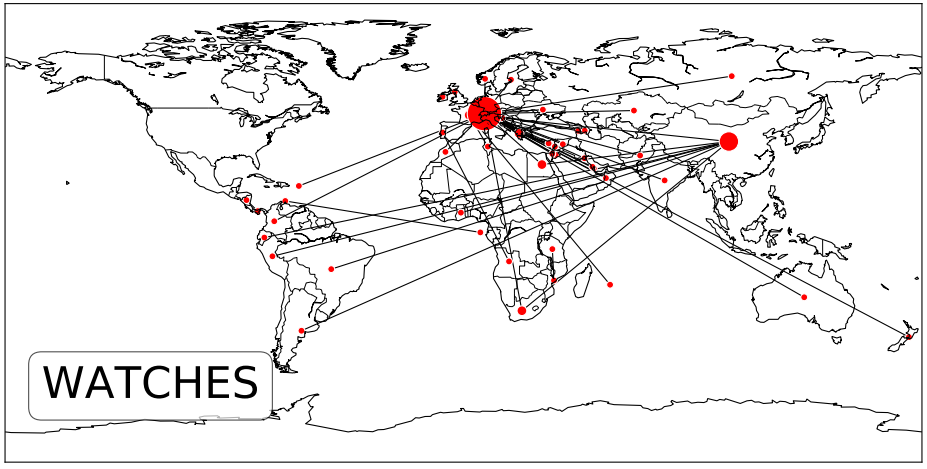


ECM-filter in action



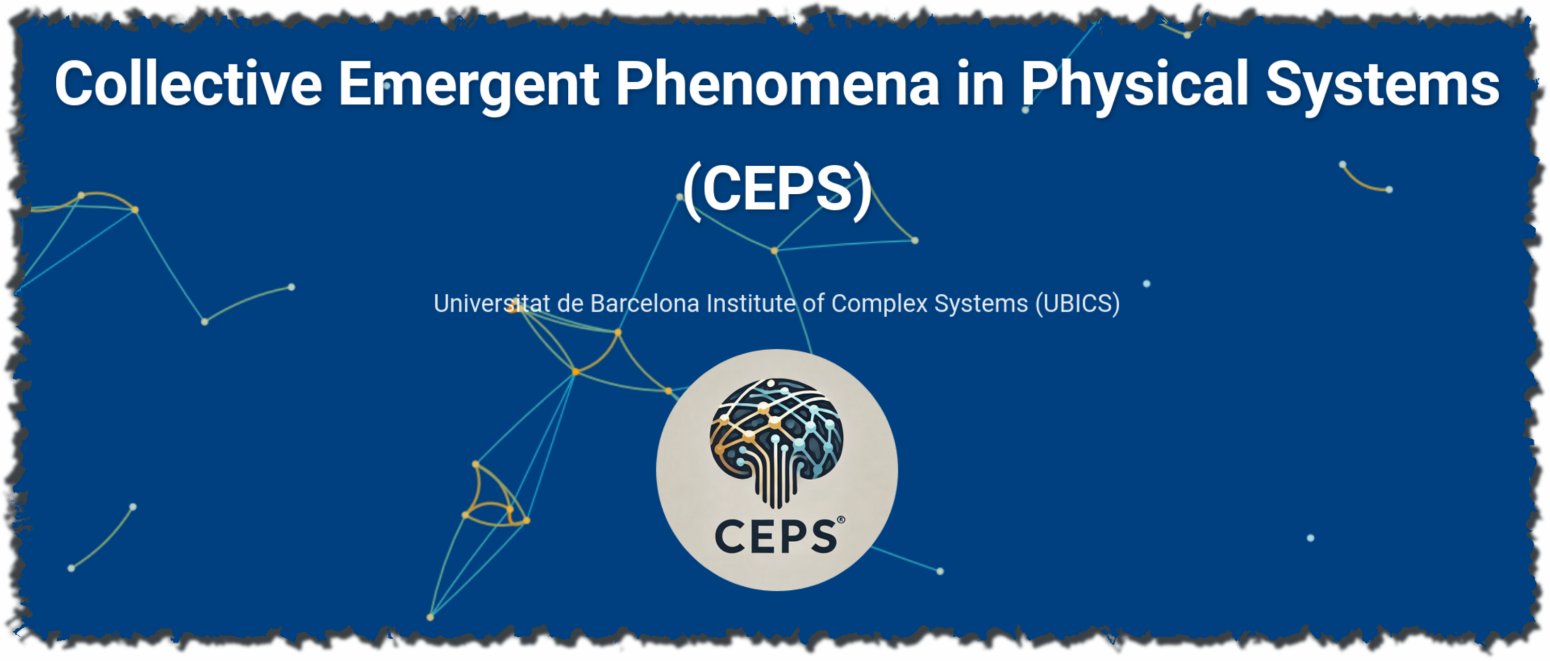






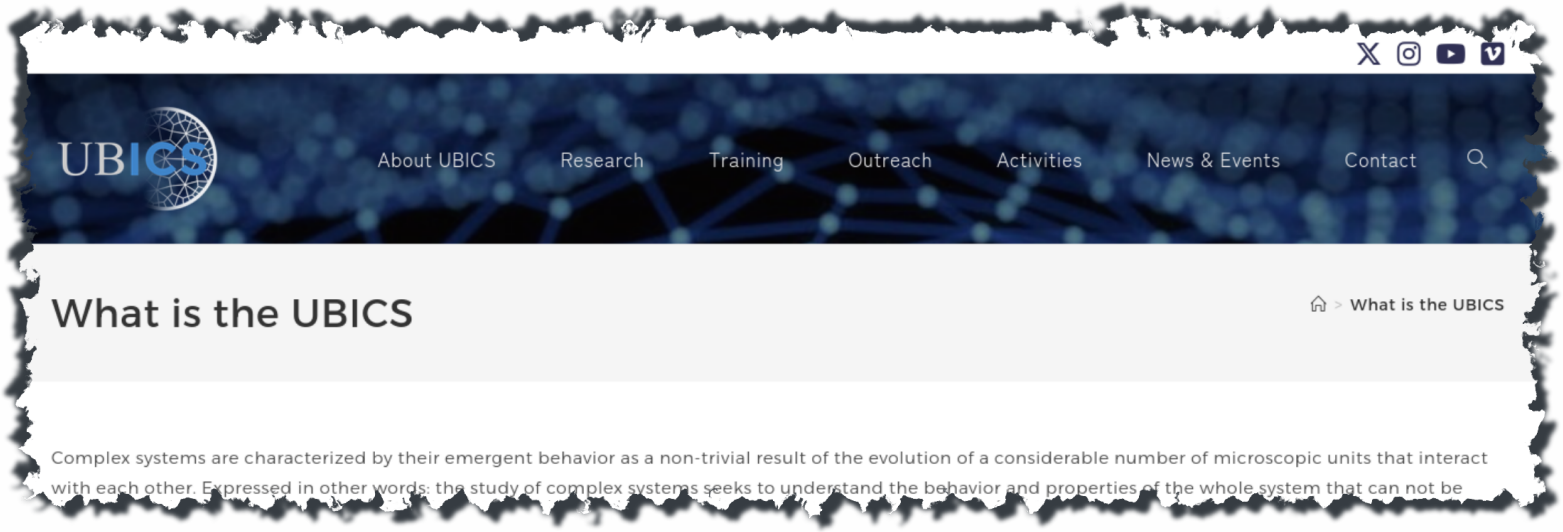
Wanna know more?

Networks & Physics at UB



- https://www.ub.edu/ceps/

Networks & Physics at UB

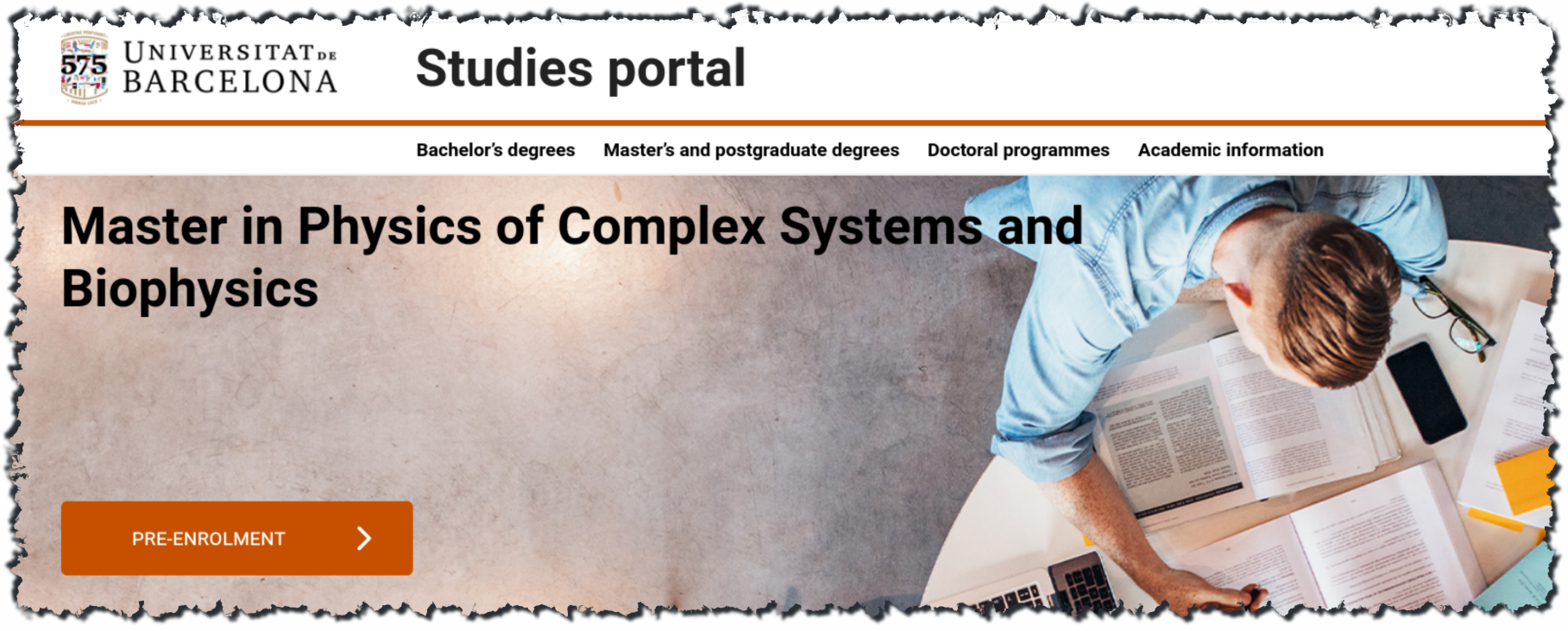


- https://ubics.ub.edu/

Networks & Physics at UB

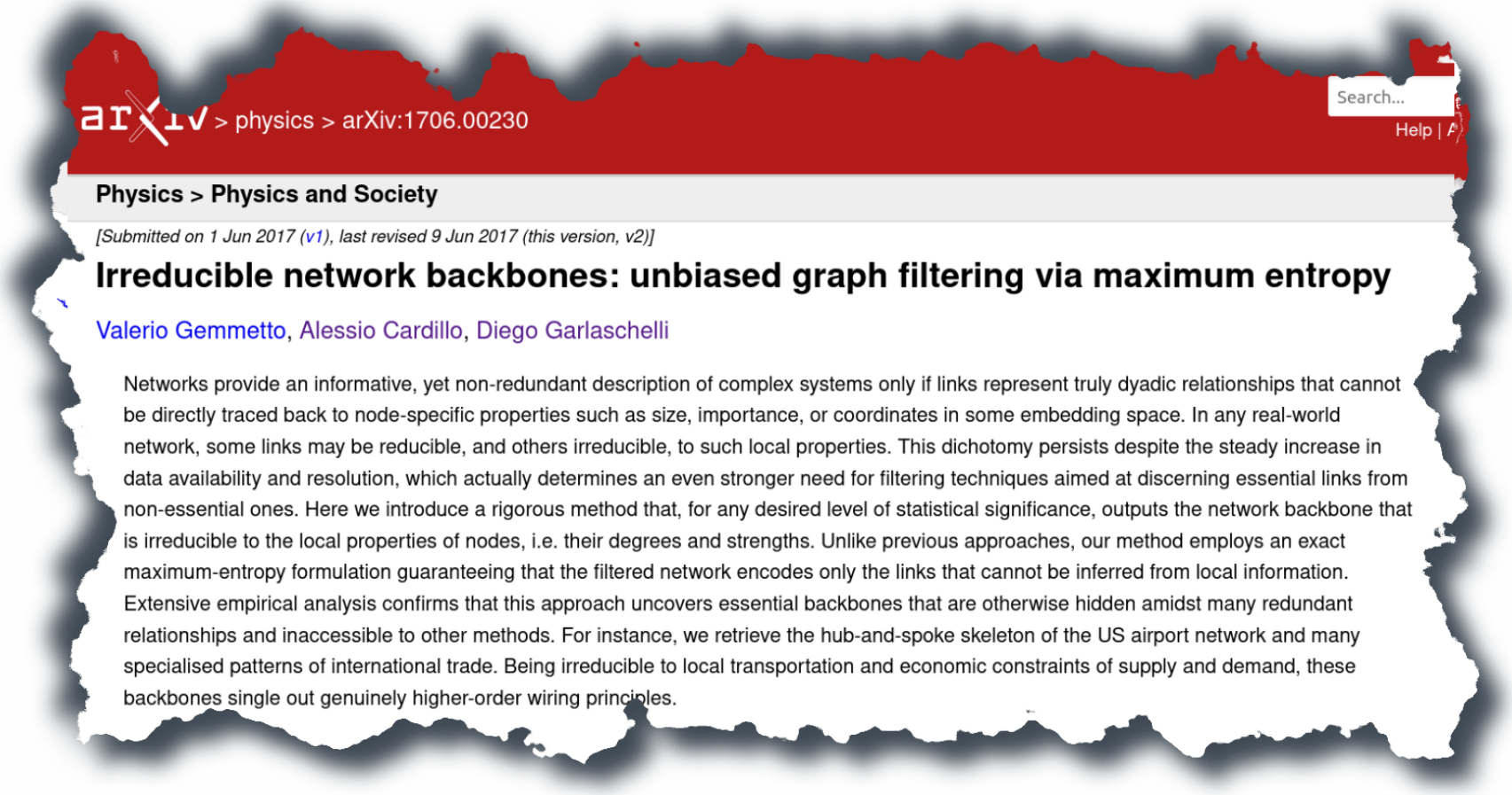
- Albert Diaz-Guilera
- Conrad Perez-Vicente
- Emanuele Cozzo
- Oriol Artime
- Mariangeles Serrano
- Marian Boguñá
- Jordi Soriano
- Mari Carmen Miguel
- . . .

Networks & Physics at UB



- https://web.ub.edu/en/web/estudis/w/masterdegree-md70c

Acknowledgements



arXiv > physics > arXiv:1706.00230

Search...

Help | A

Physics > Physics and Society

[Submitted on 1 Jun 2017 (v1), last revised 9 Jun 2017 (this version, v2)]

Irreducible network backbones: unbiased graph filtering via maximum entropy

Valerio Gemmetto, Alessio Cardillo, Diego Garlaschelli

Networks provide an informative, yet non-redundant description of complex systems only if links represent truly dyadic relationships that cannot be directly traced back to node-specific properties such as size, importance, or coordinates in some embedding space. In any real-world network, some links may be reducible, and others irreducible, to such local properties. This dichotomy persists despite the steady increase in data availability and resolution, which actually determines an even stronger need for filtering techniques aimed at discerning essential links from non-essential ones. Here we introduce a rigorous method that, for any desired level of statistical significance, outputs the network backbone that is irreducible to the local properties of nodes, i.e. their degrees and strengths. Unlike previous approaches, our method employs an exact maximum-entropy formulation guaranteeing that the filtered network encodes only the links that cannot be inferred from local information. Extensive empirical analysis confirms that this approach uncovers essential backbones that are otherwise hidden amidst many redundant relationships and inaccessible to other methods. For instance, we retrieve the hub-and-spoke skeleton of the US airport network and many specialised patterns of international trade. Being irreducible to local transportation and economic constraints of supply and demand, these backbones single out genuinely higher-order wiring principles.

https://doi.org/10.48550/arXiv.1706.00230

Acknowledgements

Diego Garlaschelli

Leiden University & IMT Lucca

Valerio Gemmetto

Leiden University

Shanti Ramoneda

University of Barcelona

Acknowledgements

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN

RYC2023-044587-I
PID2024-158120NB-C22

alessio.cardillo@ub.edu

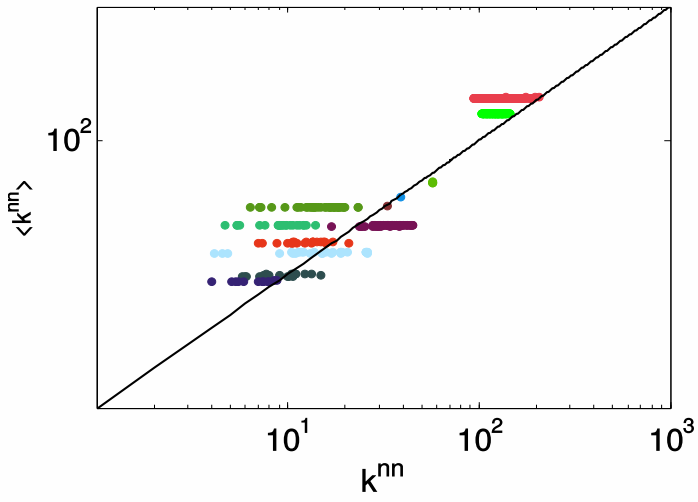
https://cardillo.web.bifi.es/

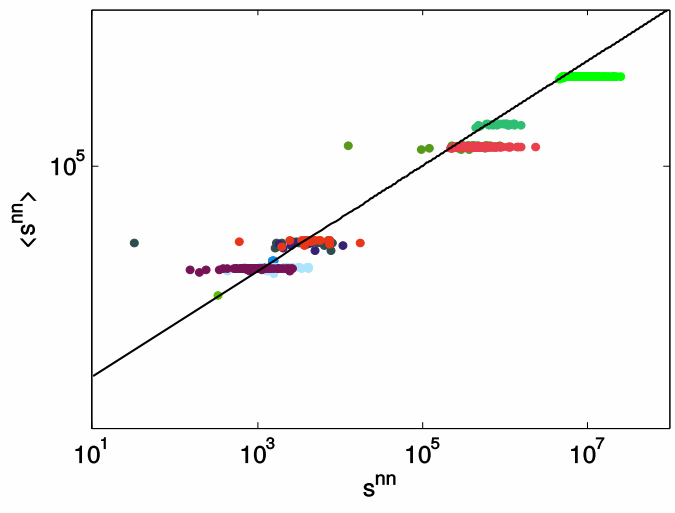
@acardillo.bsky.social

Extra slides

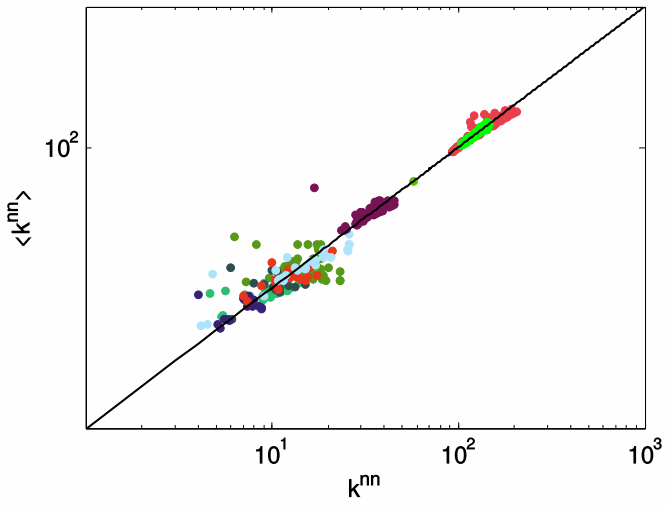
The Enhanced Configuration Model (ECM)

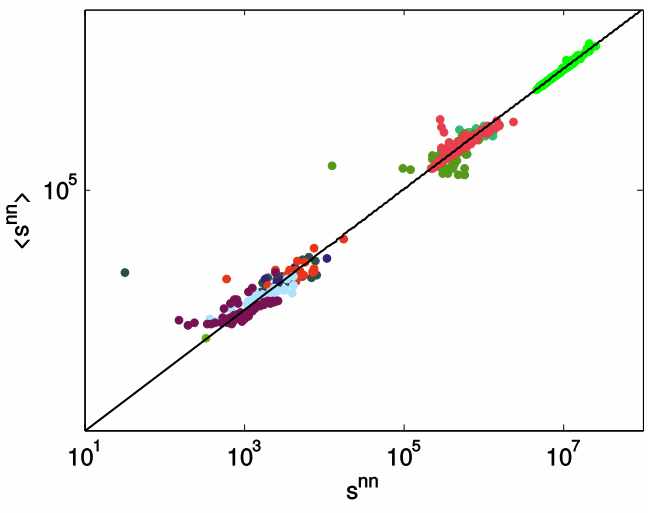
degree OR strength





degree AND strength





- R. Mastrandrea, *et al.* New Jour. Phys., **16**, 043022. (2014). DOI: 10.1088/1367-2630/16/4/043022