La fisica dei sistemi complessi
Complex networks: structure and dynamics

Alessio Cardillo

Department of Engineering Mathematics, University of Bristol
Bristol, United Kingdom

Department of Physics – University of Catania, Catania (Italy)
Thursday 10th January 2019

Who is Alessio Cardillo?

Amarcord


UP THERE
WITH THE BEST
OF THE BEST
A DON SIMPSON / JERRY BRUCKHEIMER PRODUCTION
A TONY SCOTT FILM
TOM CRUISE · KELLY McGILLIS
TOP GUN
PG
PARAMOUNT PICTURES PRESENTS A DON SIMPSON/JERRY BRUCKHEIMER PRODUCTION A TONY SCOTT FILM · TOM CRUISE · TOP GUN
KELLY McGILLIS · VAL KILMER · ANTHONY EDWARDS · TOM SKERRITT · MUSIC SCORE BY HAROLD FALTERMEYER WRITTEN BY JIM CASH & JACK EPPS, JR.
PRODUCED BY DON SIMPSON AND JERRY BRUCKHEIMER · DIRECTED BY TONY SCOTT A PARAMOUNT PICTURE
ORIGINAL MOTION PICTURE SOUNDTRACK ALBUM AVAILABLE ON CBS RECORDS, CASSETTES AND COMPACT DISCS
DOLBY STEREO
READ THE PAPERBACK


ISTITUTO TECNICO AERONAUTICO
A. FERRARIN
CATANIA

Amarcord

Amarcord

Instituto Universitario de Investigación
Biocomputación y Física de Sistemas Complejos
Universidad Zaragoza

Universidad Zaragoza
1542

Amarcord

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Amarcord

IPHES

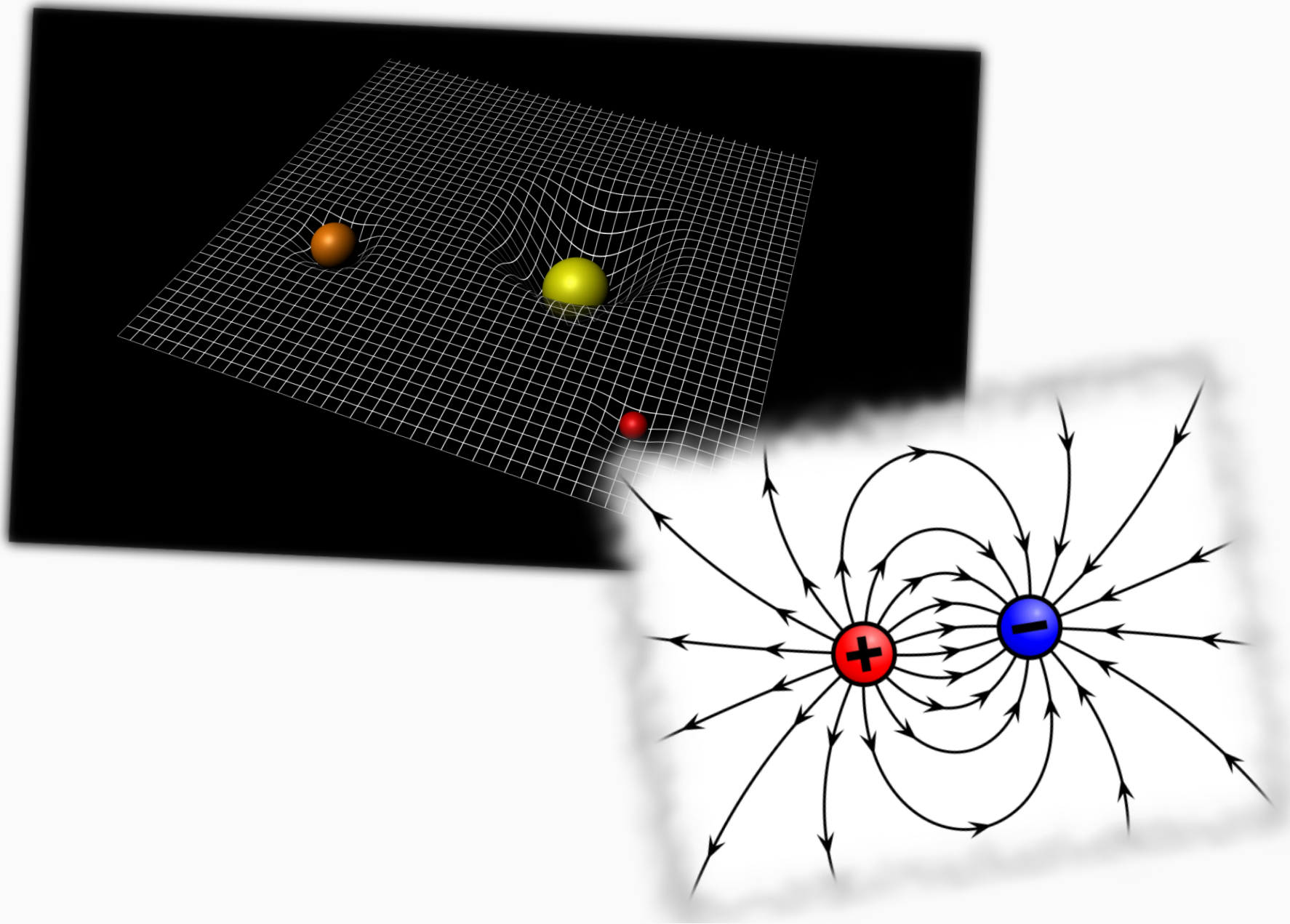
Institut Català de Paleoecologia Humana i Evolució Social

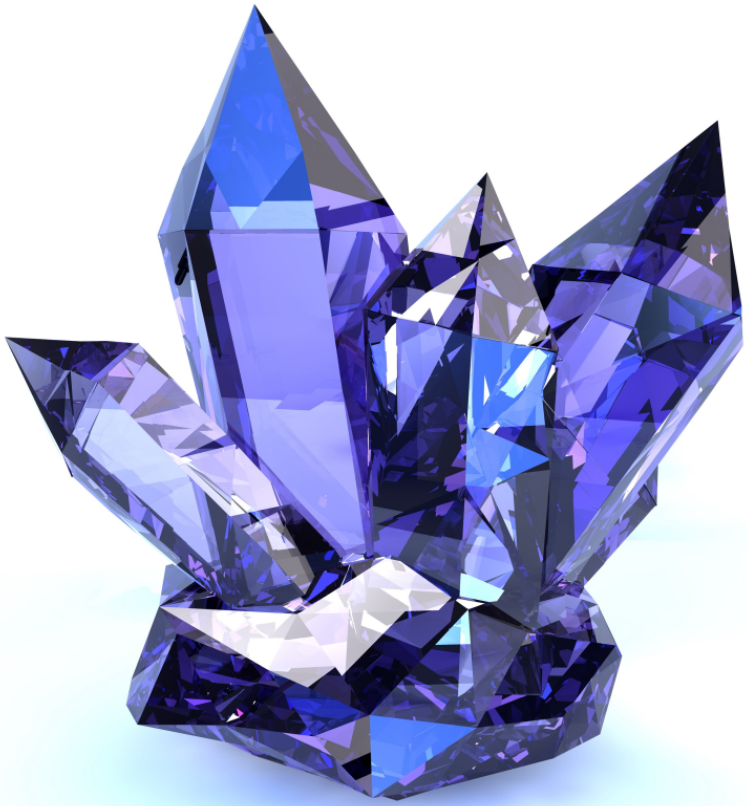
Amarcord

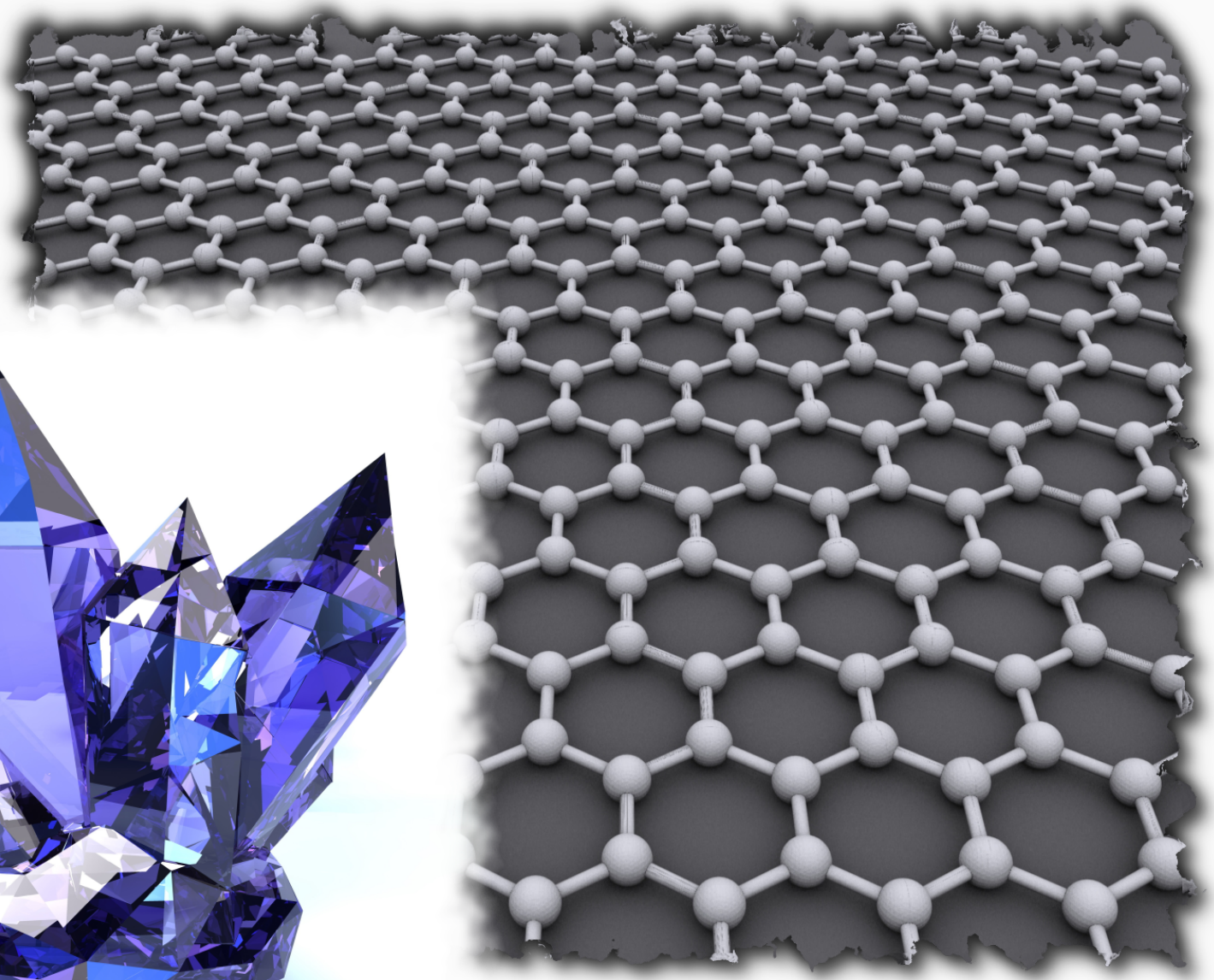
University of BRISTOL

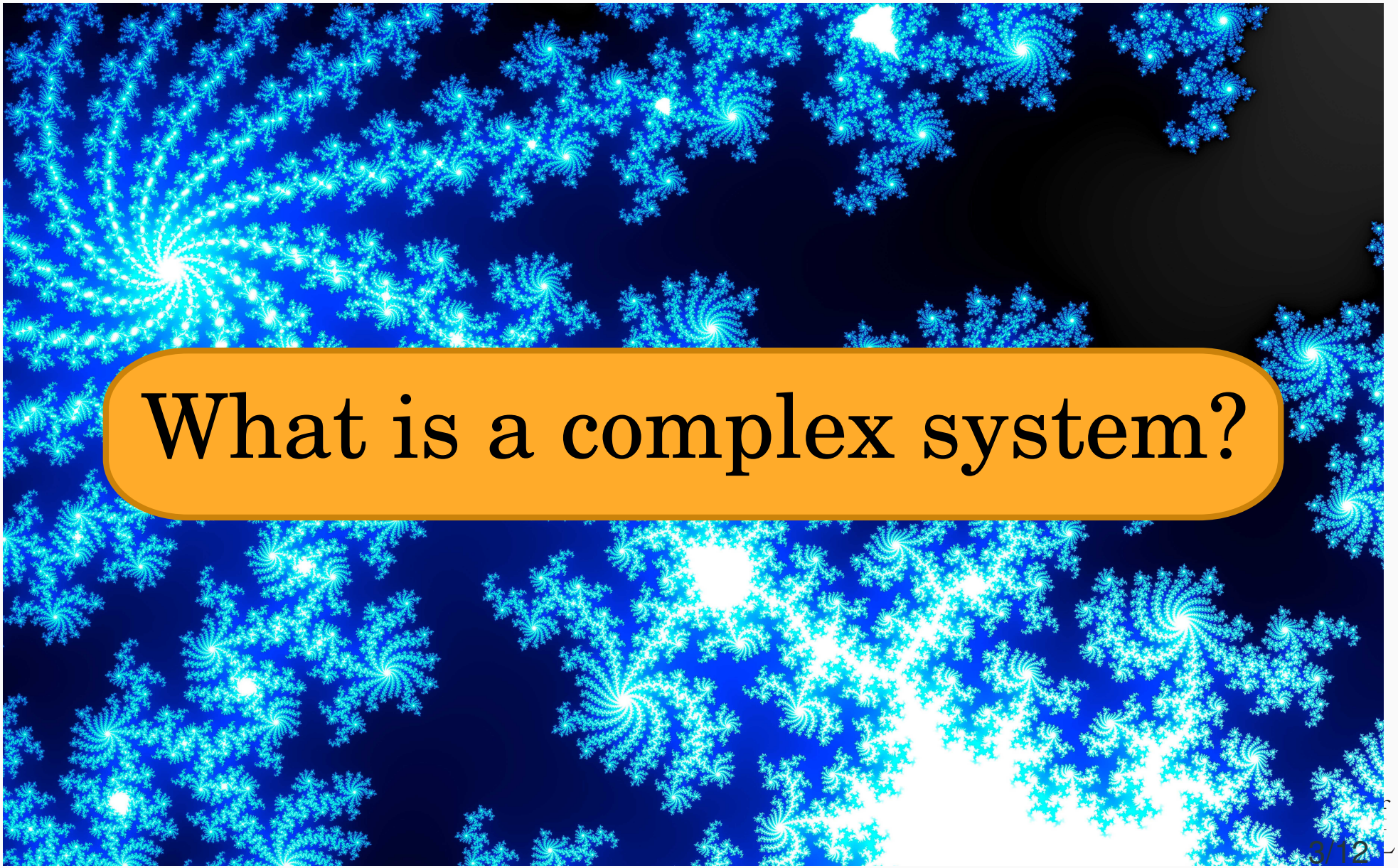
UNIVERSITAT ROVIRA i VIRGILI

Tackling complexity via networks: structure & dynamics








What is a complex system?

Complex systems

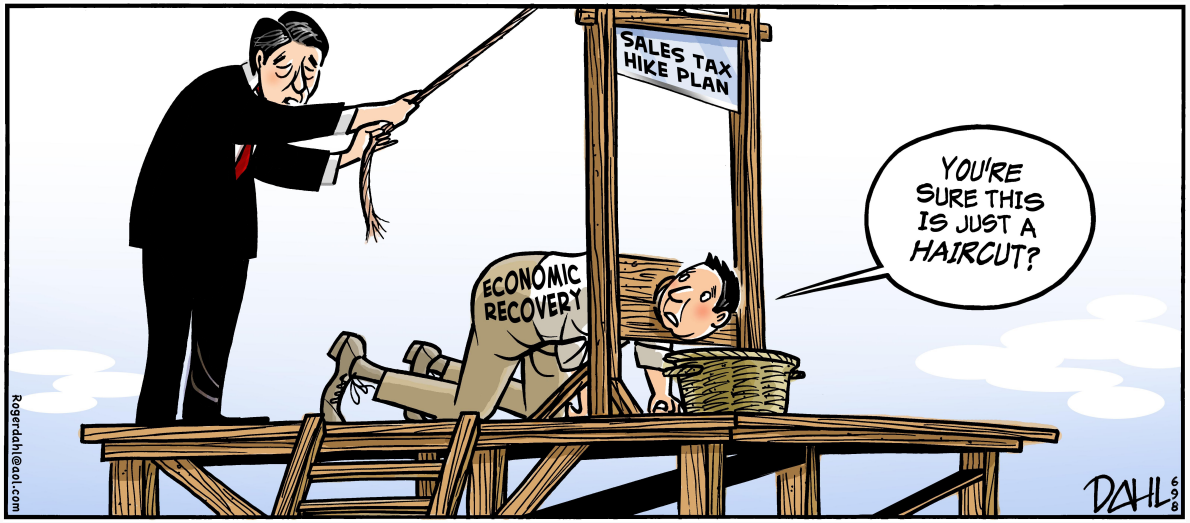
Answers

- Complex systems contain many constituents interacting **non linearly** (*i.e.* non-predictable);

Complex systems

Answers

- Complex systems contain many constituents interacting **non linearly** (*i.e.* non-predictable);
- The constituents of a complex system are **interdependent**;



Complex systems

Answers

- Complex systems contain many constituents interacting **non linearly** (*i.e.* non-predictable);
- The constituents of a complex system are **interdependent**;
- A complex system possesses a structure spanning **several scales**;

Complex systems

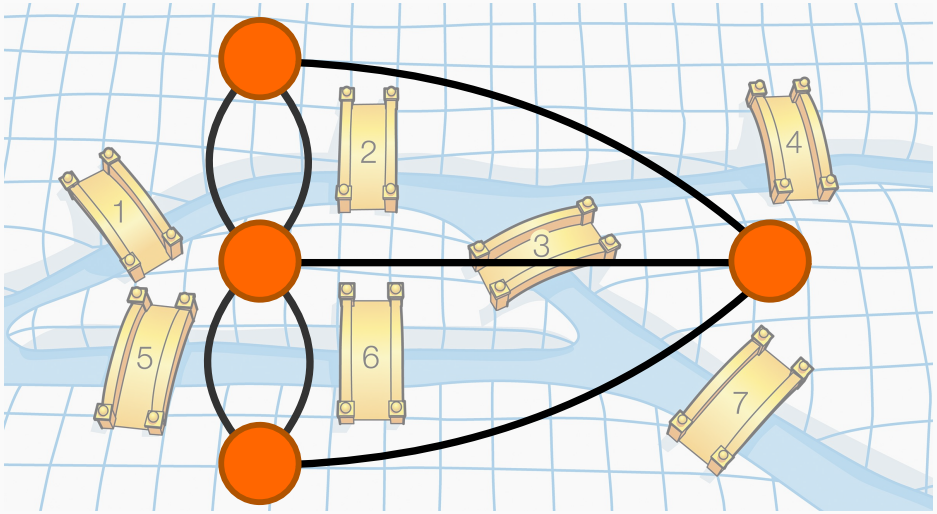
Answers

- Complex systems contain many constituents interacting **non linearly** (*i.e.* non-predictable);
- The constituents of a complex system are **interdependent**;
- A complex system possesses a structure spanning **several scales**;
- A complex system is capable of **emerging behavior**.

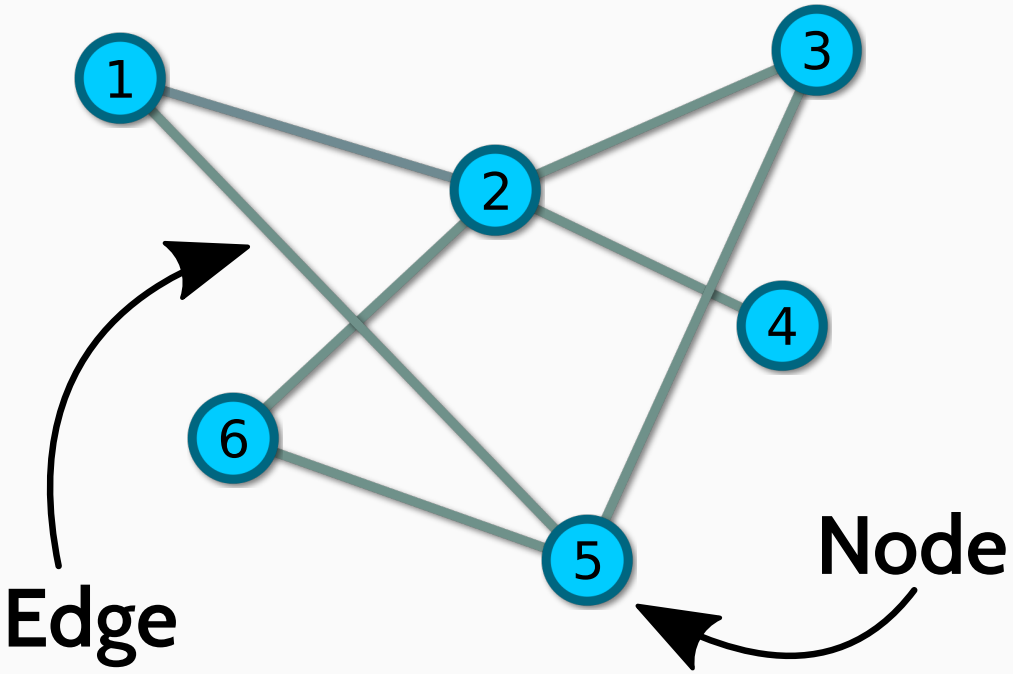
Graph Theory in a nutshell

A bit of history

In 1736 Leonard Euler found the answer to the Königsberg bridge problem, and gave birth to graph theory.



Graph Theory in a nutshell



$N \times N$ Adjacency matrix

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

University of BRISTOL

A world of connections . . .

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

University of BRISTOL

A world of connections . . .

A world of connections . . .

Elements: People

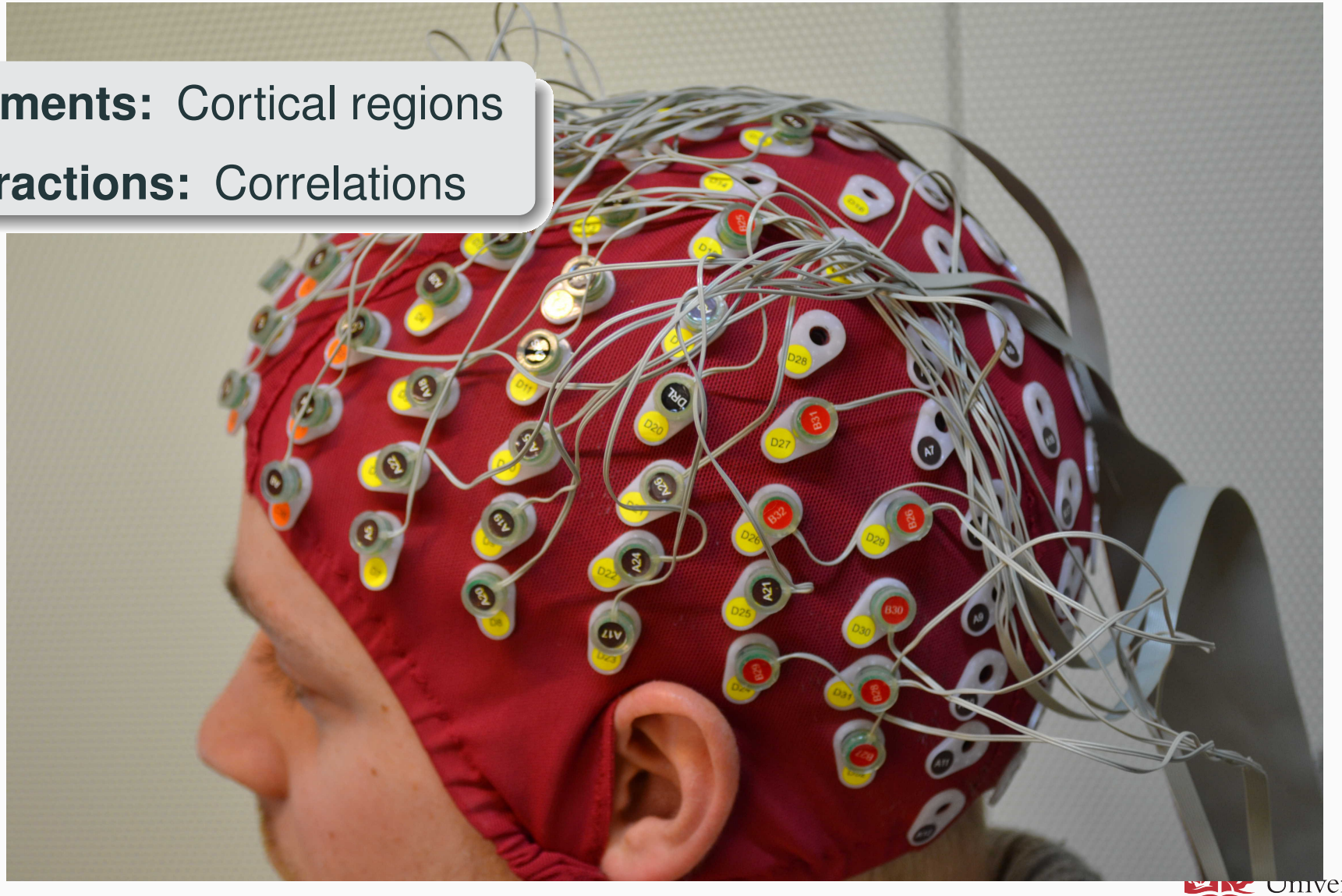
Interactions: Friendship

University of BRISTOL

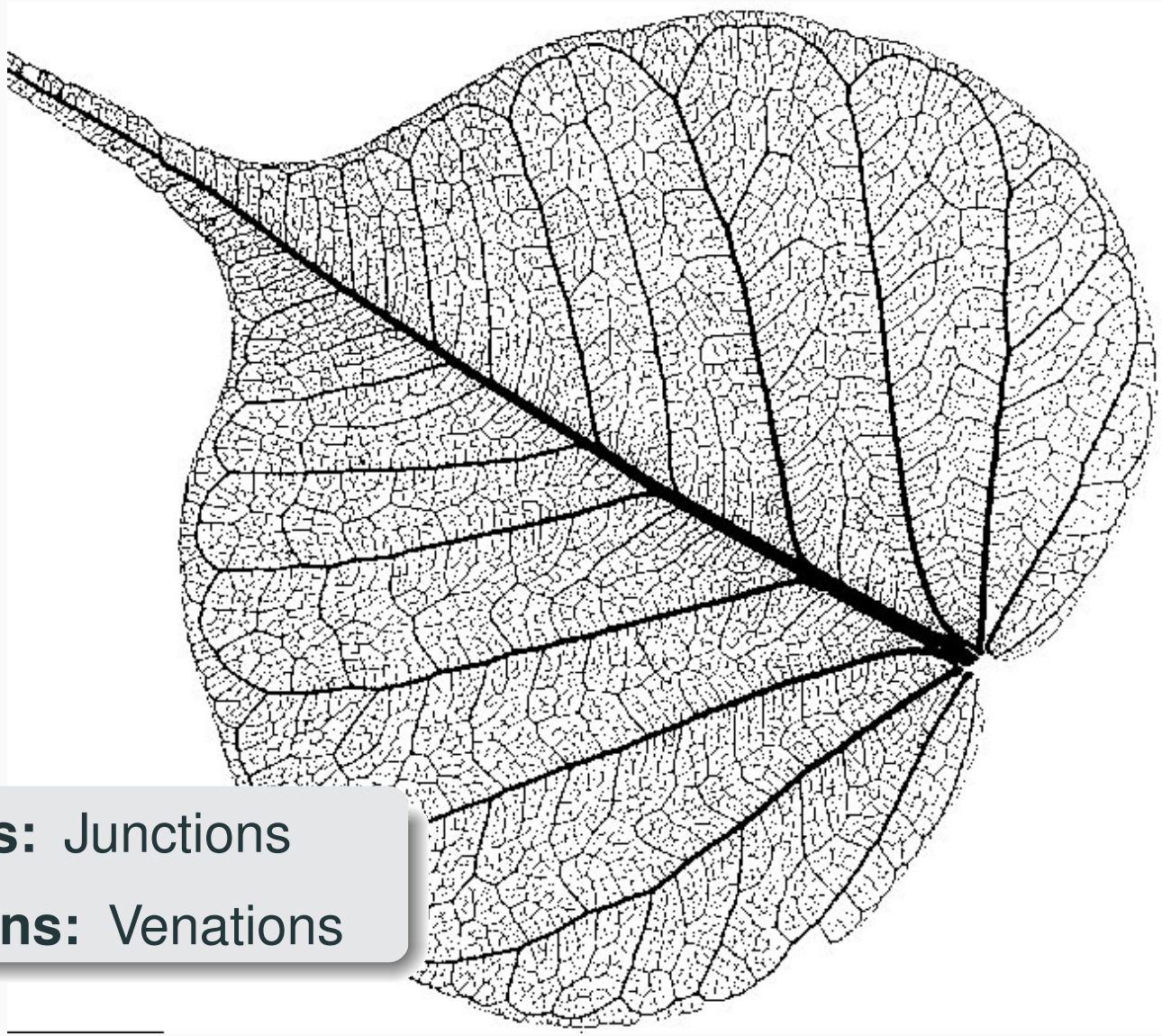
A world of connections . . .

Elements: Cortical regions

Interactions: Correlations



A world of connections . . .



Elements: Junctions

Interactions: Venations

University of BRISTOL

A world of connections . . .

Elements: Crossings (locations)

Interactions: Streets

University of BRISTOL

A world of connections . . .

Dynamics on Networks

Disease spreading

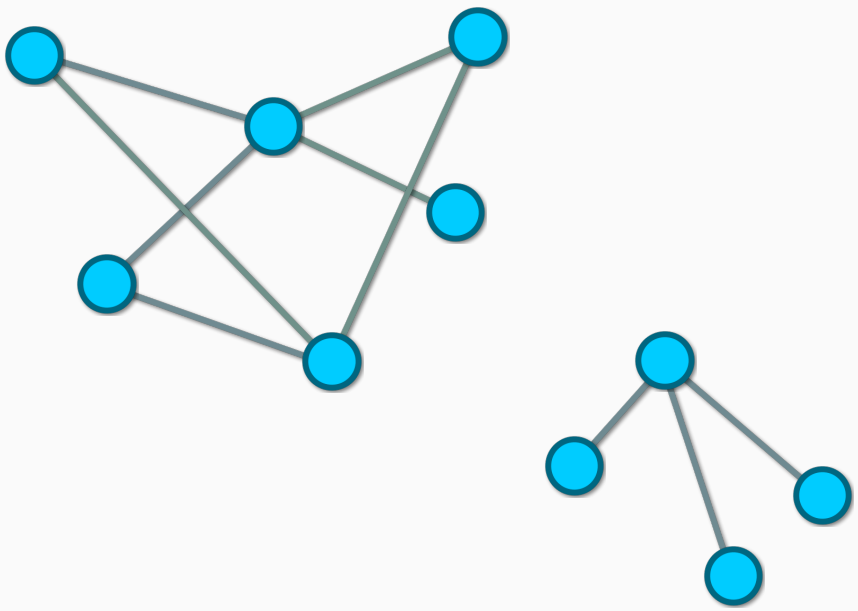
Synchronization

Cooperation

University of BRISTOL

Dynamics on Networks

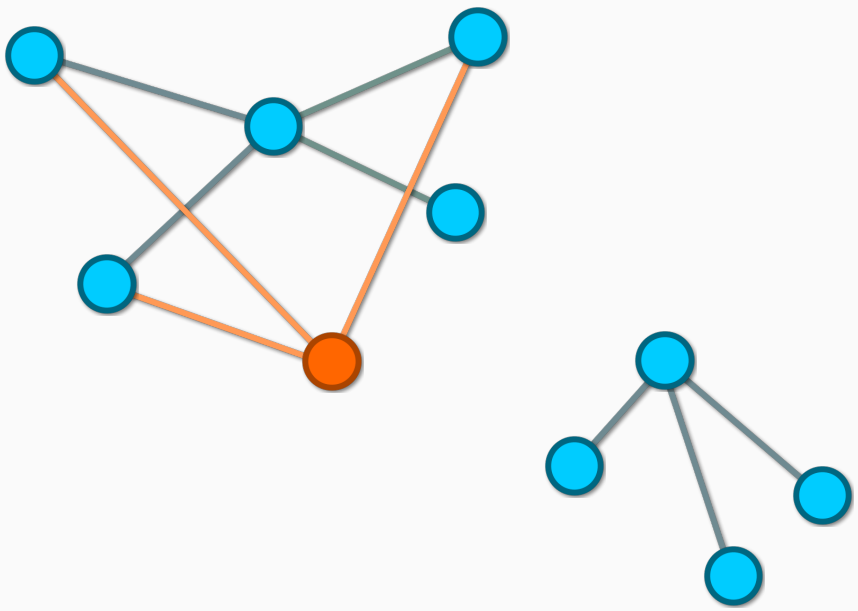
Dynamics on Networks



Percolation in a nutshell

1. Compute the number of nodes (size) of the largest component, $P_\infty(0) = 6$.

- Stauffer, D., & Aharony, A. (1994). Introduction to Percolation Theory (CRC Press). Taylor & Francis.



Percolation in a nutshell

2. With probability p, delete one node.

• Stauffer, D., & Aharony, A. (1994). Introduction to Percolation Theory (CRC Press). Taylor & Francis.

Percolation in a nutshell

3. Repeat the process for all the nodes.

• Stauffer, D., & Aharony, A. (1994). Introduction to Percolation Theory (CRC Press). Taylor & Francis.

Percolation in a nutshell

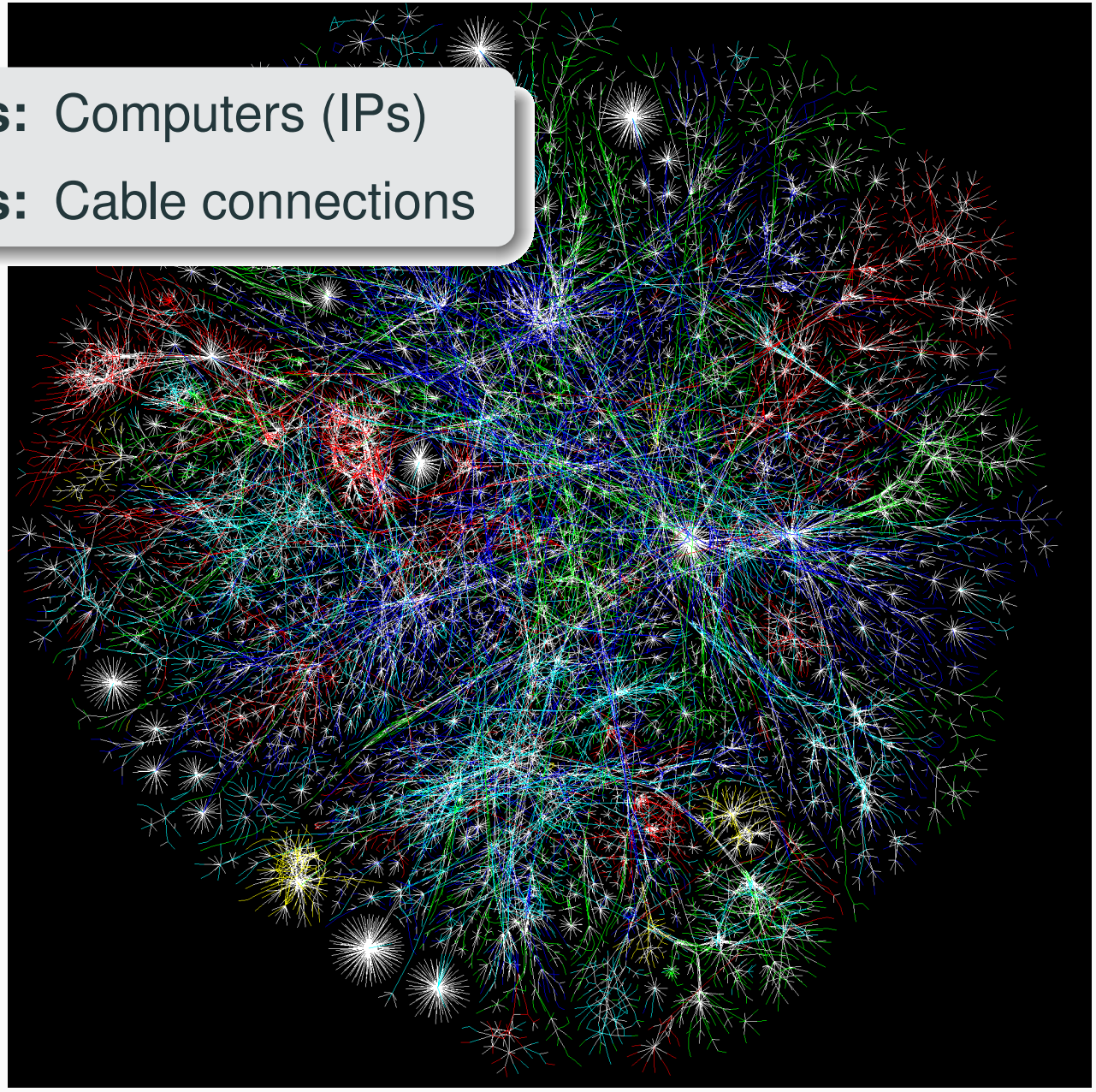
4. Compute again the value of $P_\infty(p) = 5$.

• Stauffer, D., & Aharony, A. (1994). Introduction to Percolation Theory (CRC Press). Taylor & Francis.

Dynamics on Networks

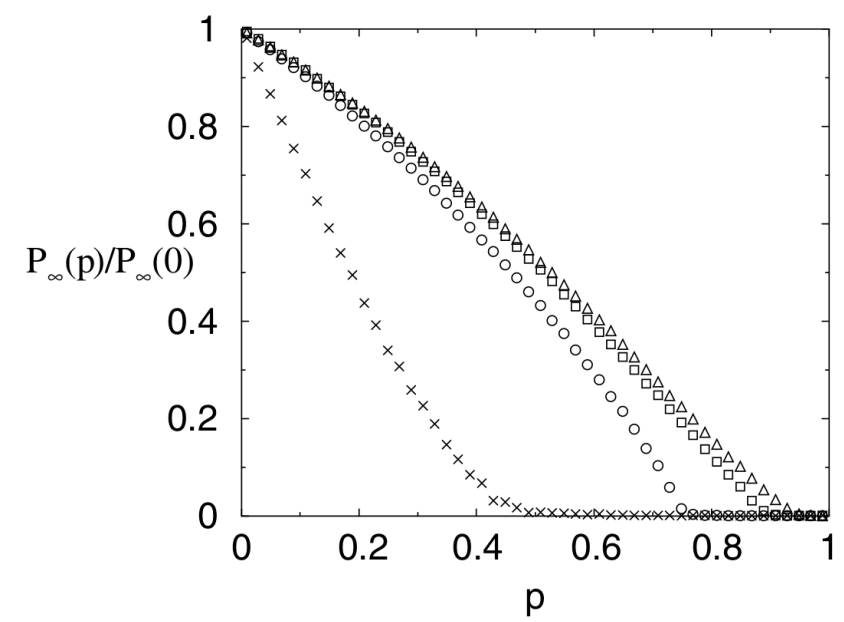
Nodes: Computers (IPs)

Edges: Cable connections



University of BRISTOL

Random attack

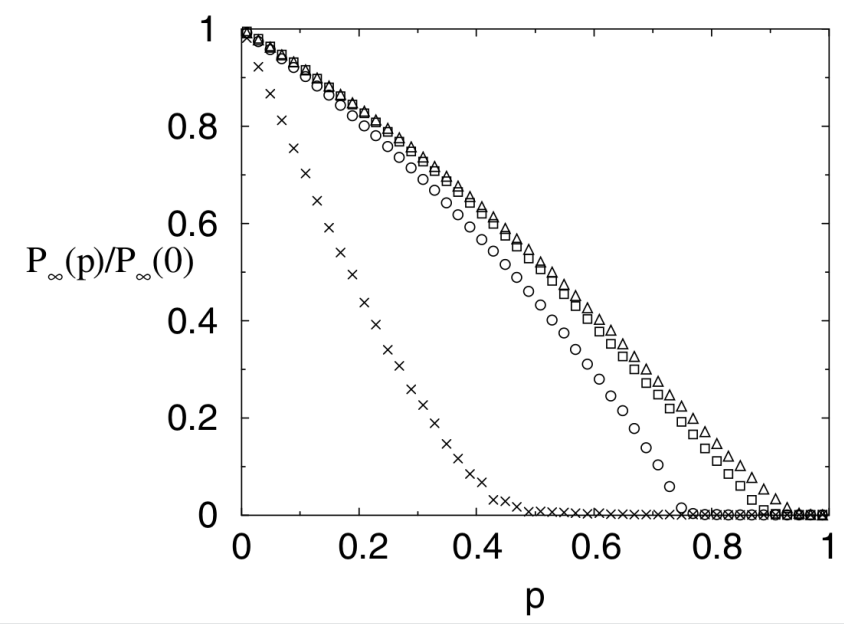


Internet is resilient to random failures.

- R. Cohen *et al.* (2000). Resilience of the Internet to Random Breakdowns. Phys. Rev. Lett., **85**, 4626
- R. Cohen *et al.* (2001). Breakdown of the Internet under Intentional Attack. Phys. Rev. Lett., **86**, 3682

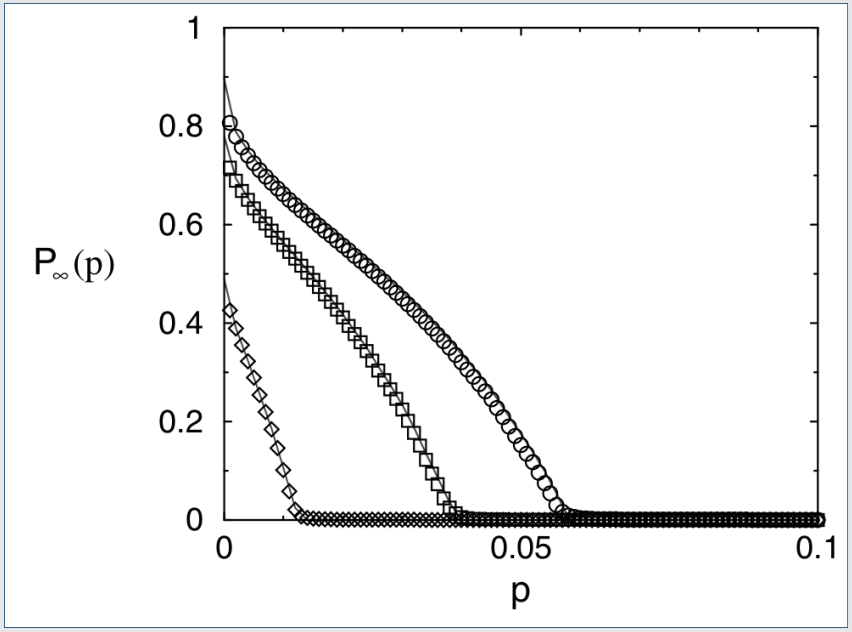
Dynamics on Networks

Random attack



Internet is resilient to random failures.

Targeted attack



Internet is extremely vulnerable to targeted attacks!

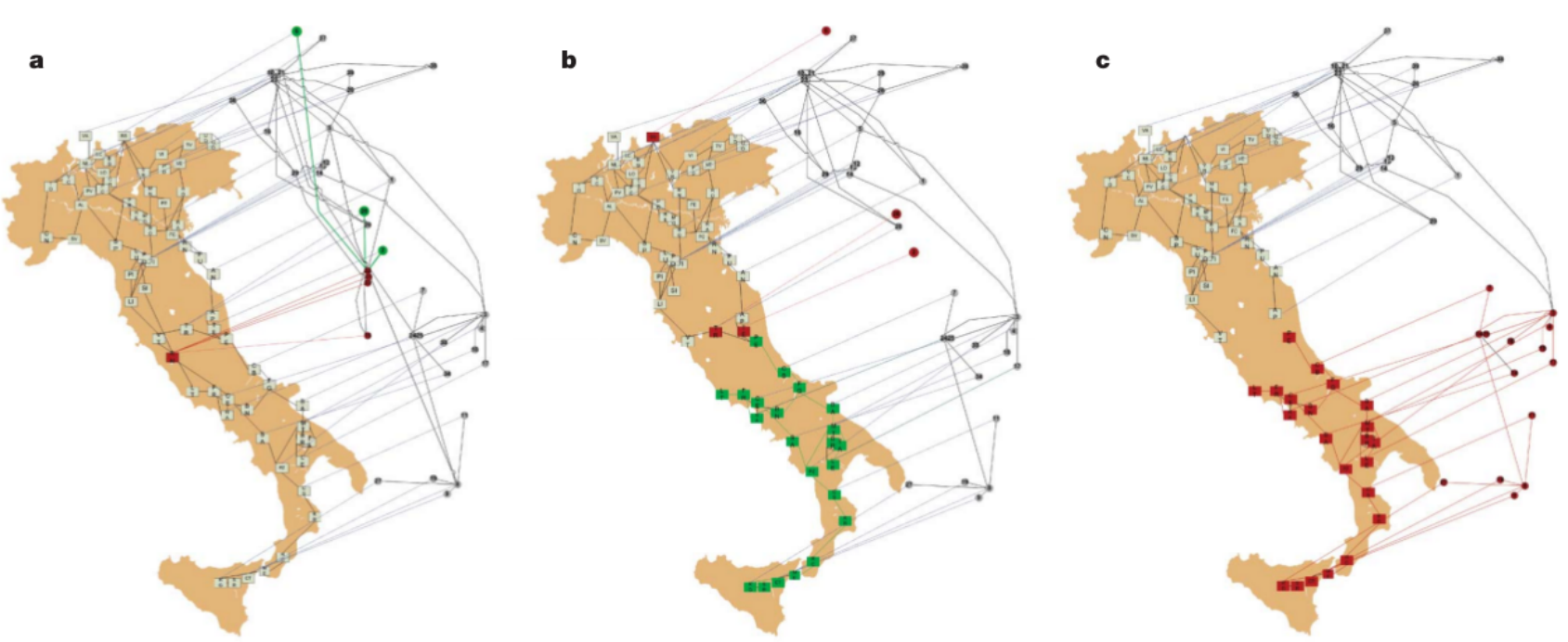
- R. Cohen *et al.* (2000). Resilience of the Internet to Random Breakdowns. Phys. Rev. Lett., **85**, 4626
- R. Cohen *et al.* (2001). Breakdown of the Internet under Intentional Attack. Phys. Rev. Lett., **86**, 3682

A concrete example: Italy 2003 blackout

On the 28th of Sep. 2003 a major blackout affected Italy (except for Sardinia) for 12 hours.

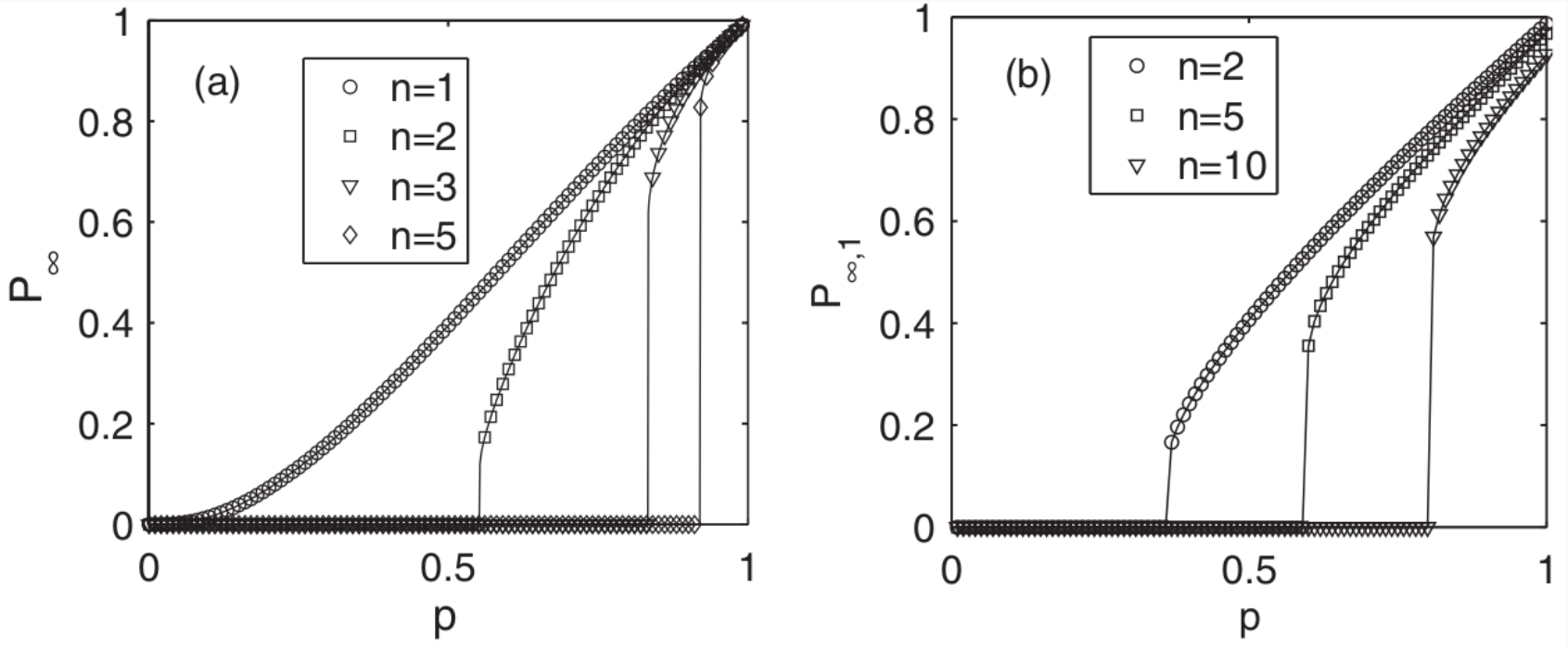
University of BRISTOL

A concrete example: Italy 2003 blackout



- Buldyrev S V, Parshani R, Paul G, Stanley H E, & Havlin S. *Catastrophic cascade of failures in interdependent networks*. Nature, **464**, 1025 (2010).

A concrete example: Italy 2003 blackout



- Gao J, Buldyrev S, Havlin S, & Stanley H E. *Robustness of a Network of Networks*. Phys. Rev. Lett., **107**, 195701 (2011).

Other applications

- Spreading of diseases/news/rumors
- Sociophysics
- Biophysics/Biology/Bioinformatics
- Econophysics
- Transportation
- Synchronization/Control
- Smart Cities
- Science of Science
- Language and Cognition
- Neuroscience
- . . .

Other applications

What about Catania?

Complex systems & DFA @UniCT

Vito Latora

Andrea Rapisarda

Alessandro Pluchino

Complex systems & DFA @UniCT

Roberta Sinatra

Manlio De Domenico

Moreno Bonaventura

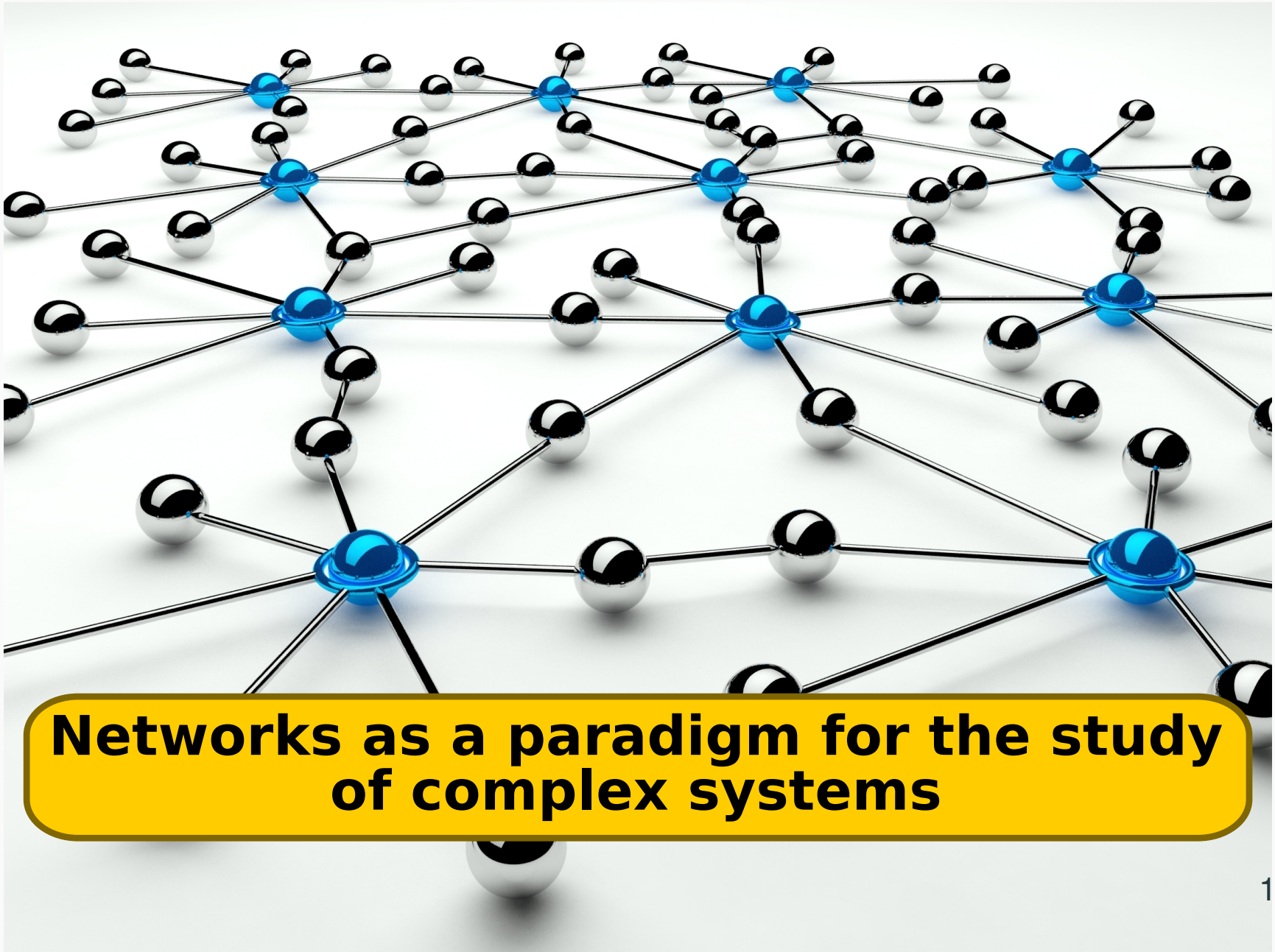
Giovanna Miritello

... and (many) others!

Summing up . . .

Take home messages

Take home messages



Networks as a paradigm for the study of complex systems

Take home messages

Bibliography

- Gleick, James. “Chaos: Making a new science.” Viking, New York, (1987).
- Barabási, Albert-László. “Linked: The New Science of Networks.” Perseus Books Group, (2002).
- Capra, Fritjof. “The Web of Life.” Harper Collins, (1996).
- Strogatz, Steven H. “Sync: The Emerging Science of Spontaneous Order.” Hyperion, New York, (2003).
- Latora V., Nicosia V. & Russo G. “Complex Networks: Principles, Methods and Applications.” Cambridge University Press (2017).
- Strogatz, S. H. “Nonlinear Dynamics And Chaos: With Applications To Physics, Biology, Chemistry And Engineering.” Westview Press, (1994).

Contacts

alessio.cardillo@bristol.ac.uk

http://www.bifi.es/∼cardillo/

@a_cardillo