DEI
DEPARTAMENTO
DE ENGENHARIA INFORMÁTICA
TÉCNICO LISBOA

Network Science

Ciência de Redes Complexas (CRC)

Network Science, 2023/2024

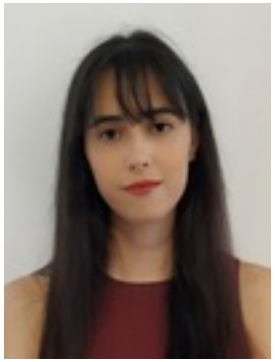
Network Science 2023/24

Francisco C. Santos

franciscocsantos@

Alexandre Francisco

aplf@



Inês Pereira

ines.pereira@

António Fernandes

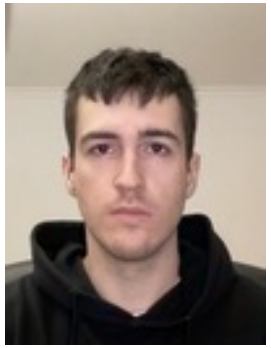
antonio.m.fernandes@

Henrique Fonseca

henrique.c.fonseca@

João T. Aparício

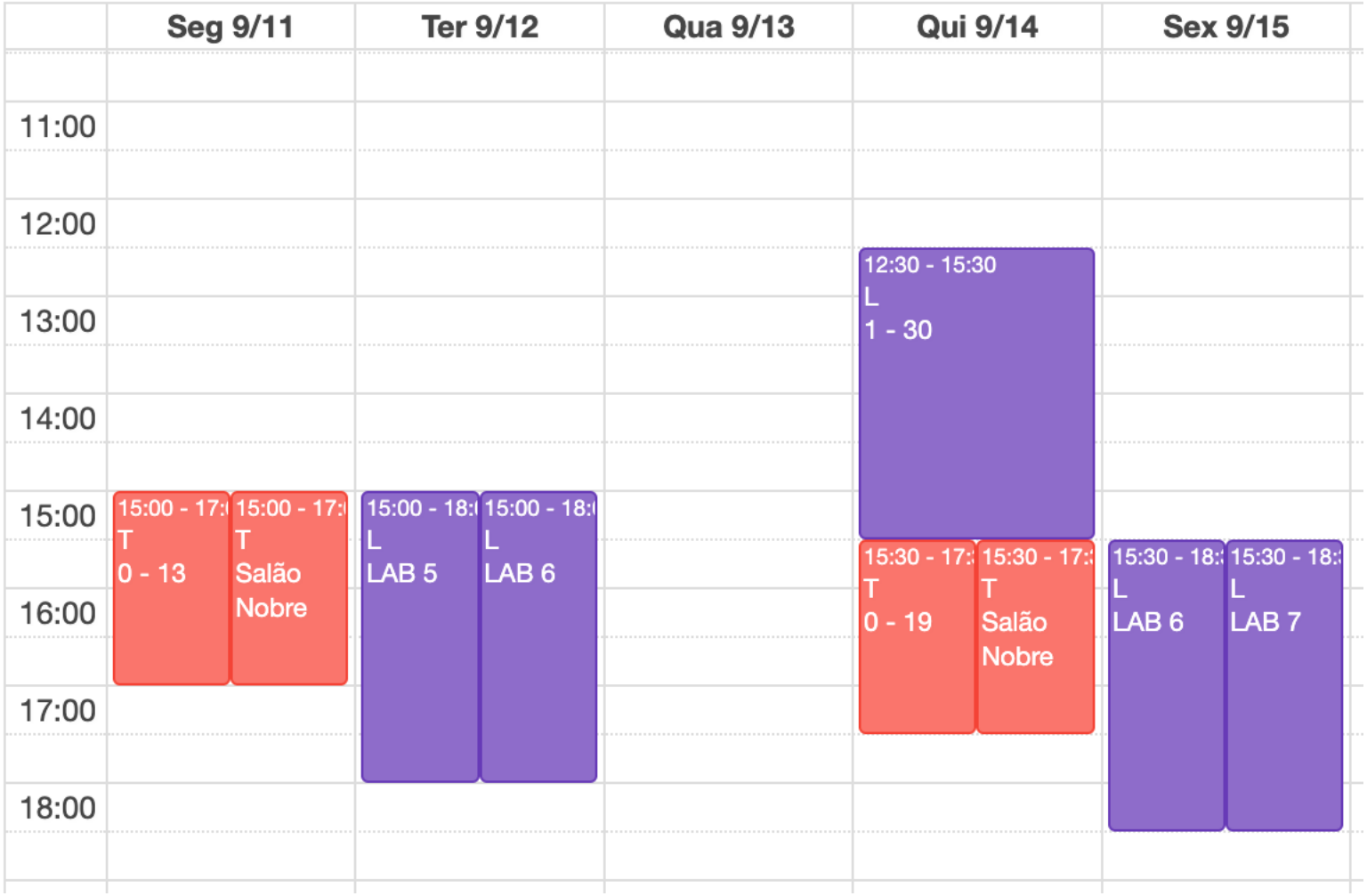
joao.aparicio@



Tomás Almeida

tomas.duarte.almeida@

Network Science 2023/24



Our course in a nutshell

1

Part I: Characterization of networks
Networks observed in nature and society, together with tools capable of characterizing their structure and properties.

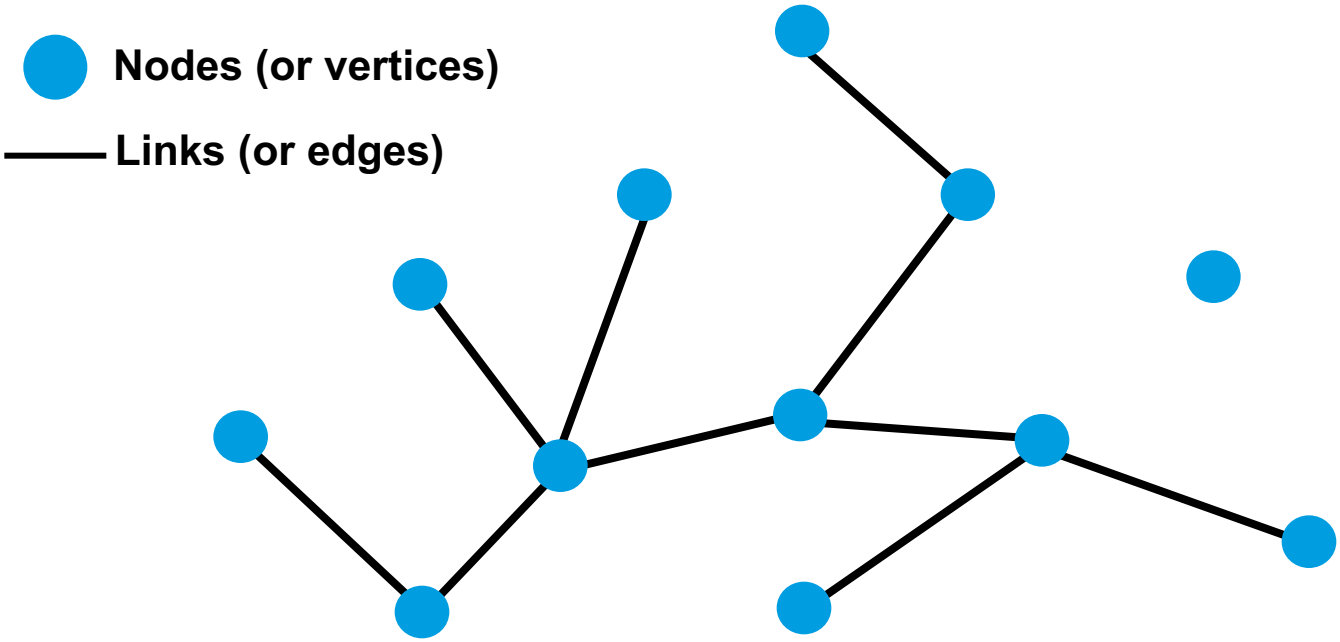
2

Part II: Design principles leading to real-world structures
Network models designed to understand the self-organized nature and time-evolution of empirically observed topologies.

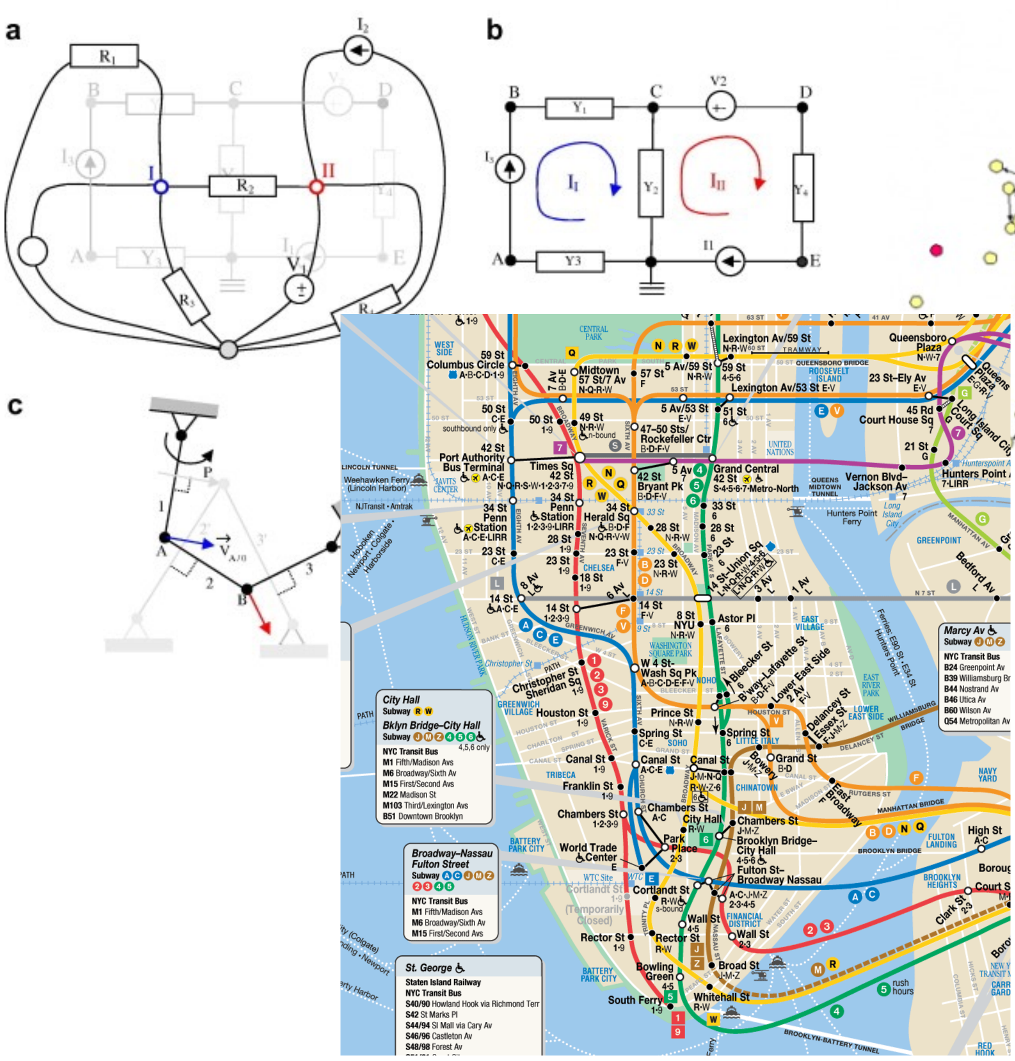
3

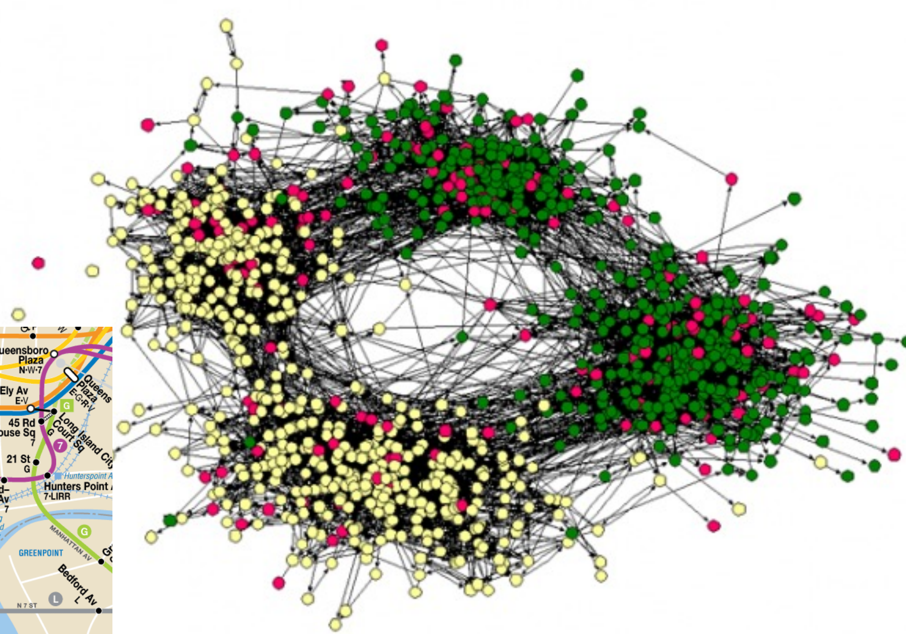
Part III: The impact of these topologies
Dynamical processes taking place on networks: cascading effects, network resilience, opinion dynamics, disease outbreaks, complex social dynamics and strategic decisions, among other examples.

What's a network or a graph?



Examples

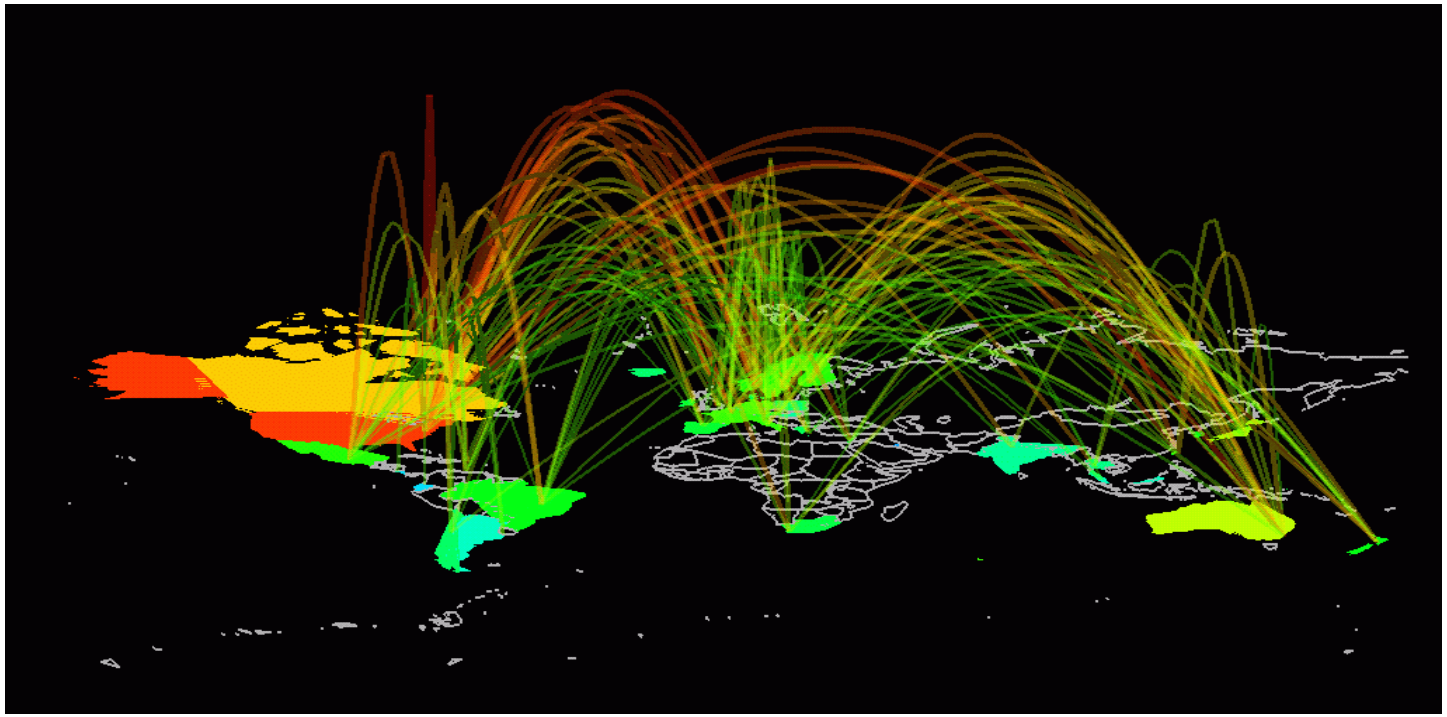

a
b
c
R_1
R_2
I_2
I
II
Y_1
Y_2
Y3
Y_4
V2
I_3
I_I
I_{II}
B
C
D
A
E
P
Columbus Circle
Times Sq
Grand Central
Canal St
Chambers St
South Ferry



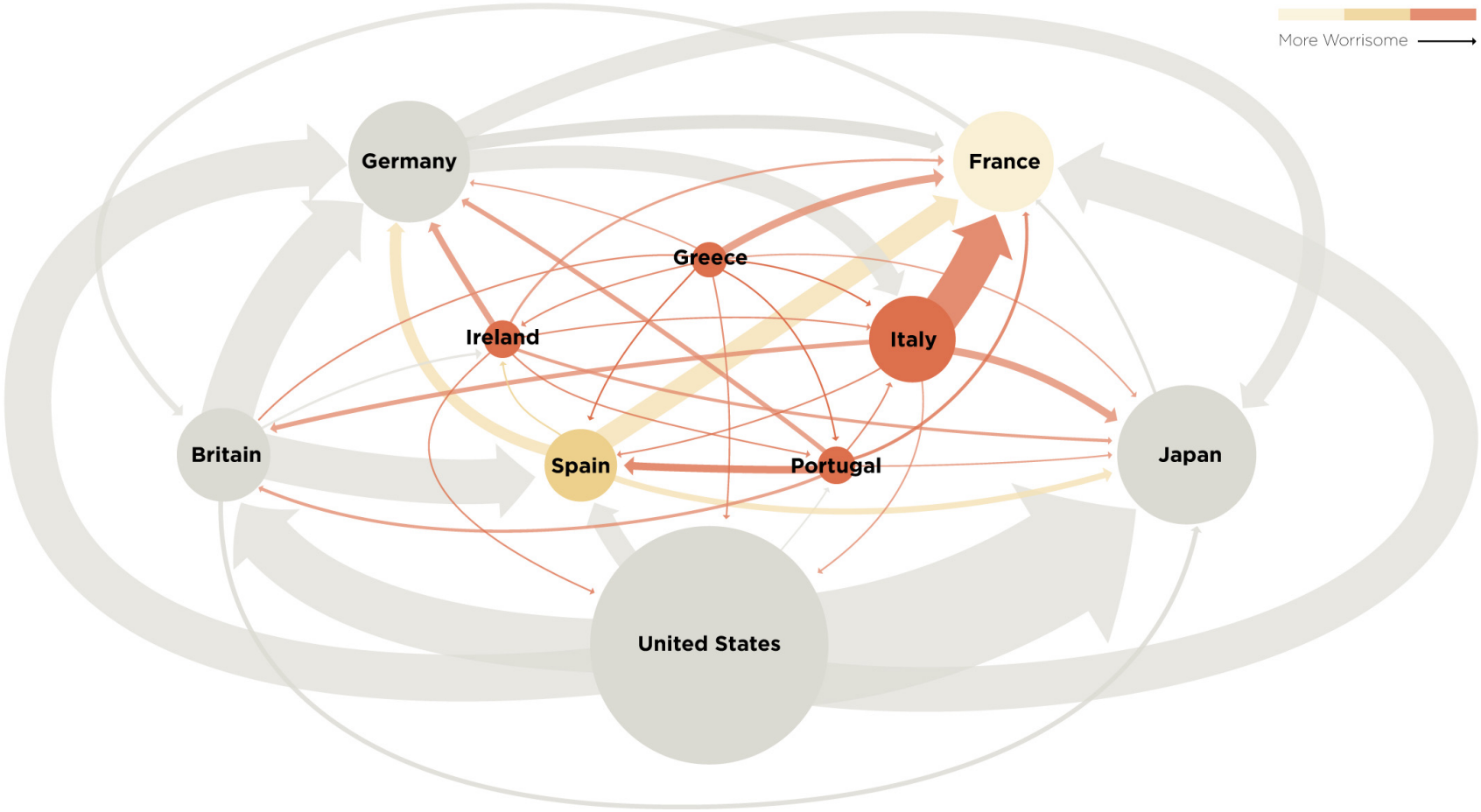
Examples *the nervous system of our planet*

nodes
routers
satellites
Computers, webpages…

links
cables,
electromagnetic waves,
hyperlinks, etc.



Examples *financial networks*



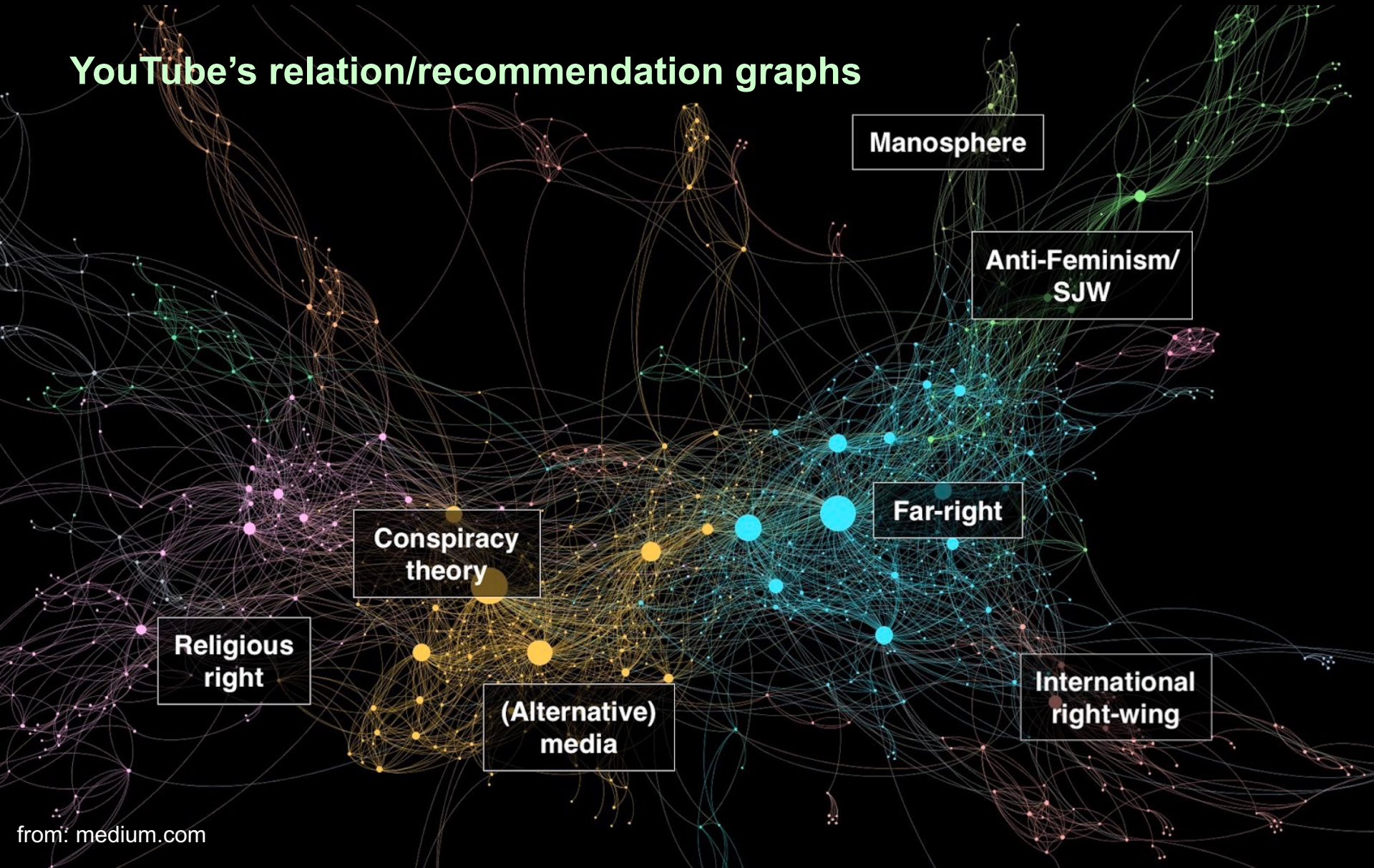
Examples

modern social networks

Examples

graphs underlying such social networks

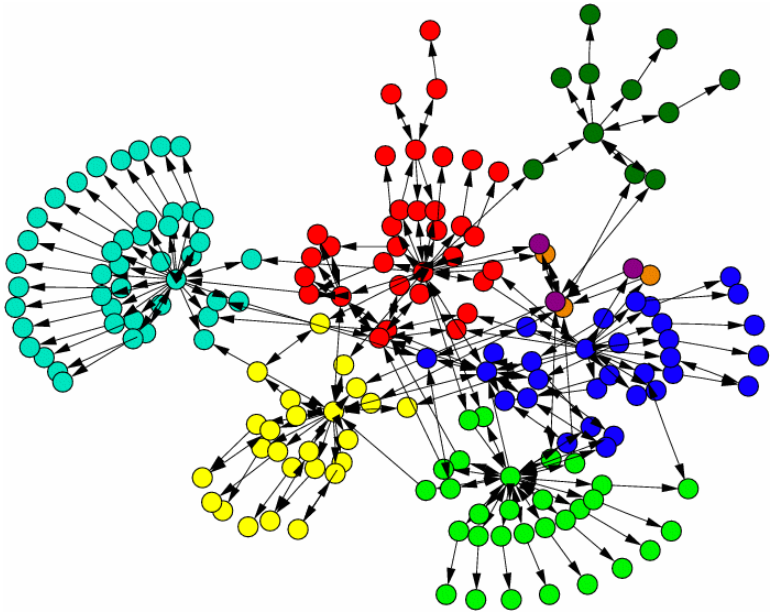
YouTube's relation/recommendation graphs

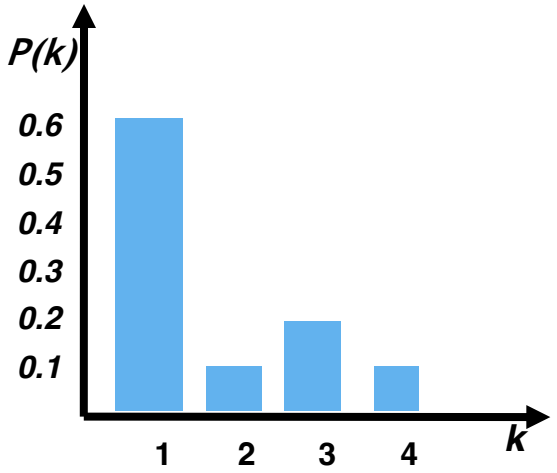


from: medium.com

How can we characterize a network?

Average distances, diameter, shortest paths, clustering, etc, etc.

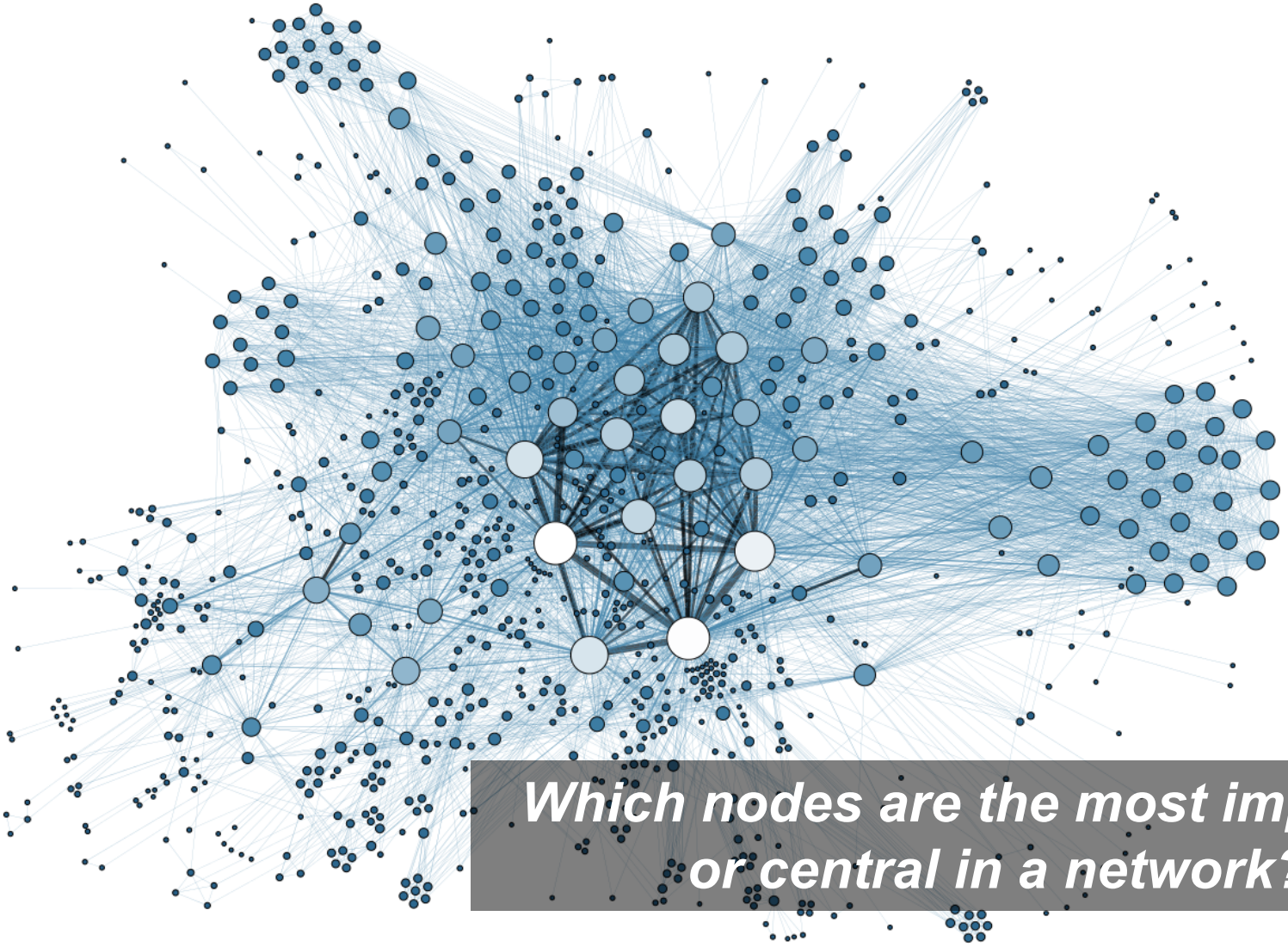




Among those, we start by highlighting three:

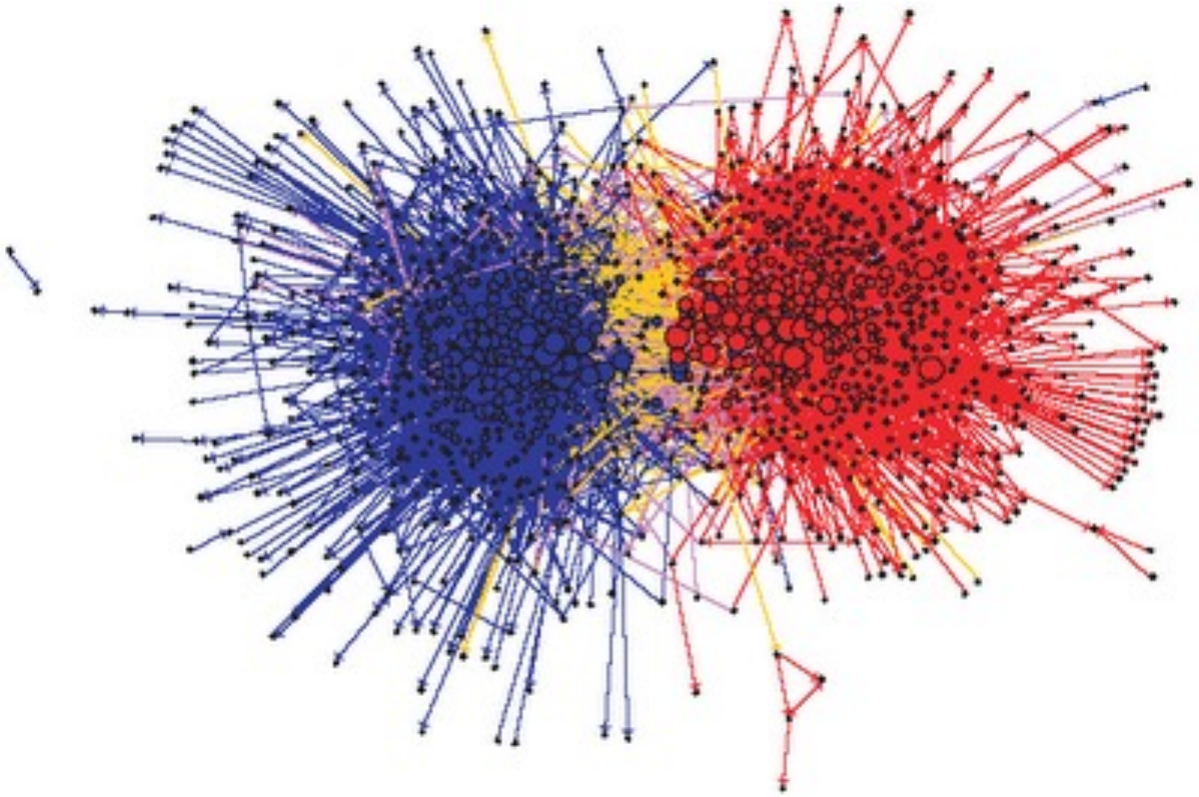
- Degree distribution, *P(k)*
- Average path length, <L>
- Clustering Coefficient, C

How should we characterize a node?



Which nodes are the most important or central in a network?

Modules and communities



Ex: Patterns of citations among democrats and republican US blogs

Gephi

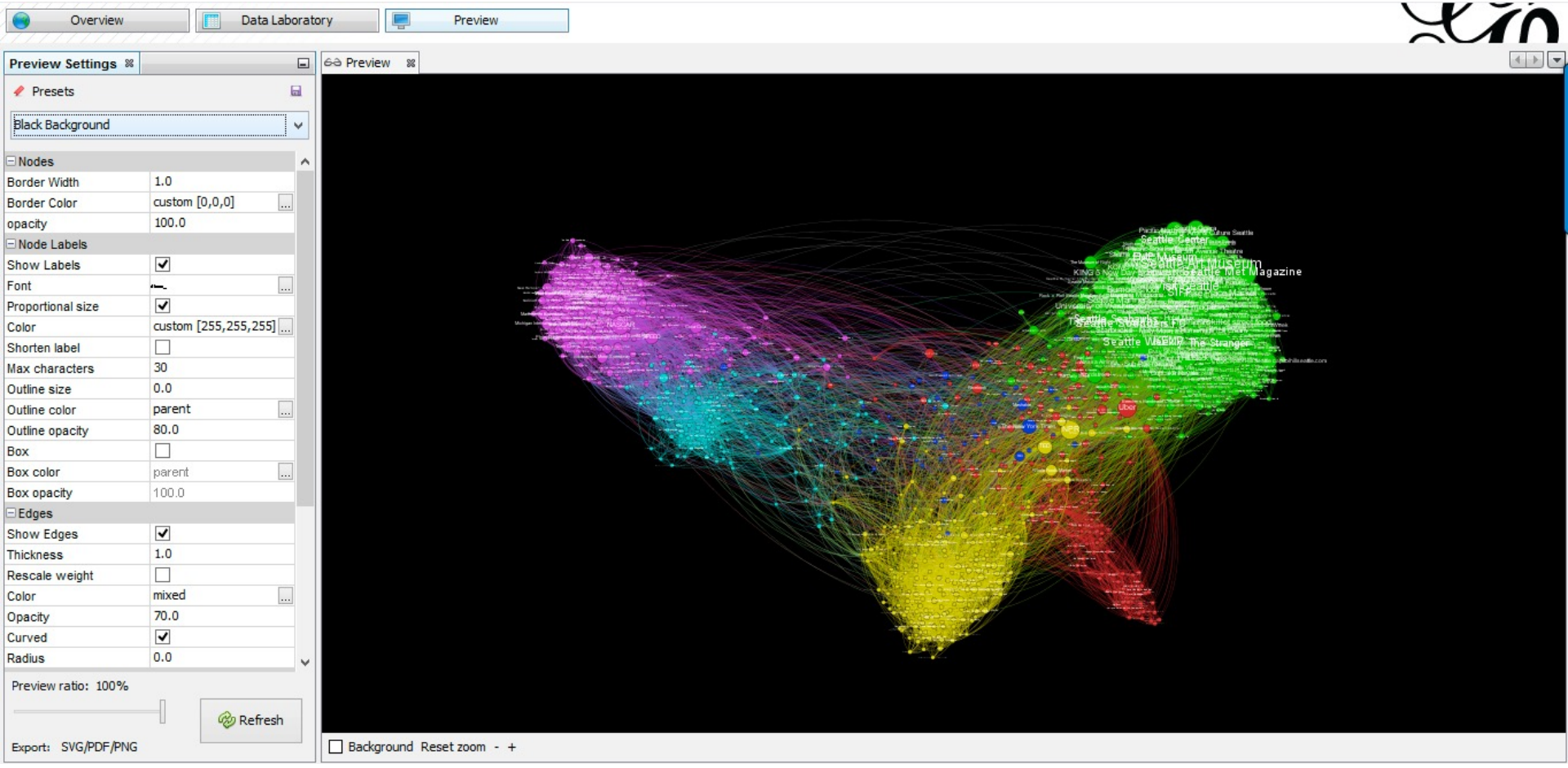
Boost

NetworkX
Network Analysis in Python

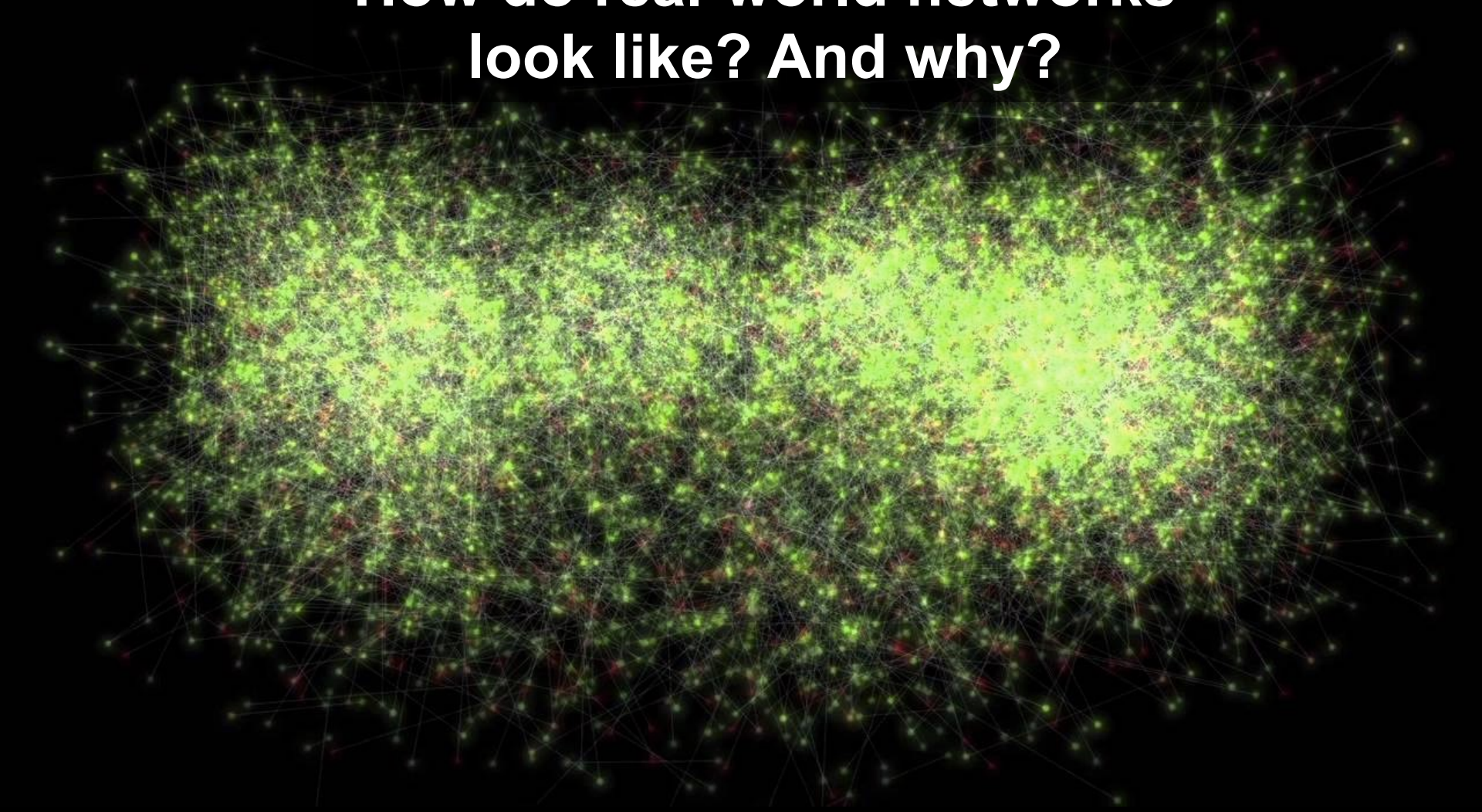
igraph

WebGraph
http://webgraph.di.unimi.it/

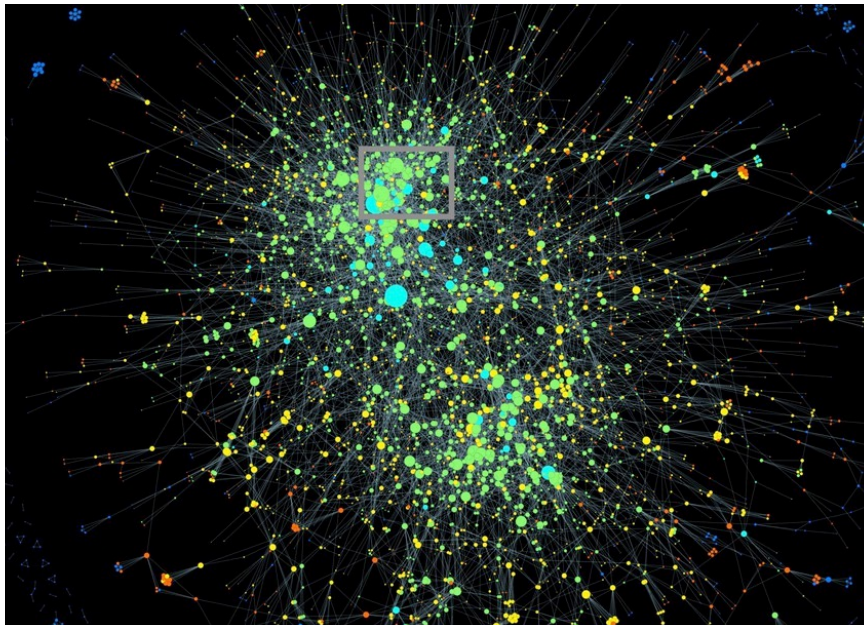
Mathematica



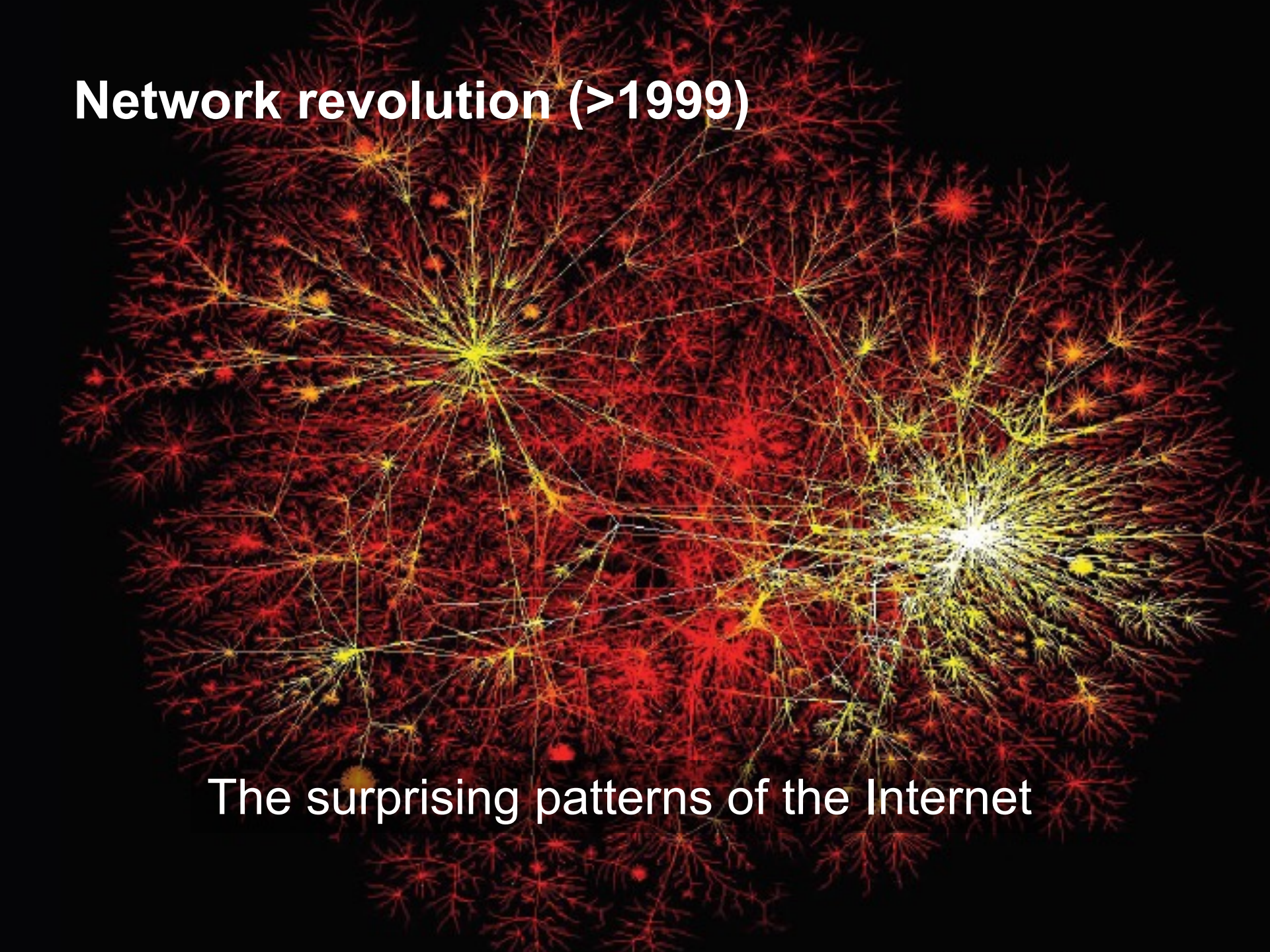
How do real-world networks look like? And why?



Network revolution (>1999)

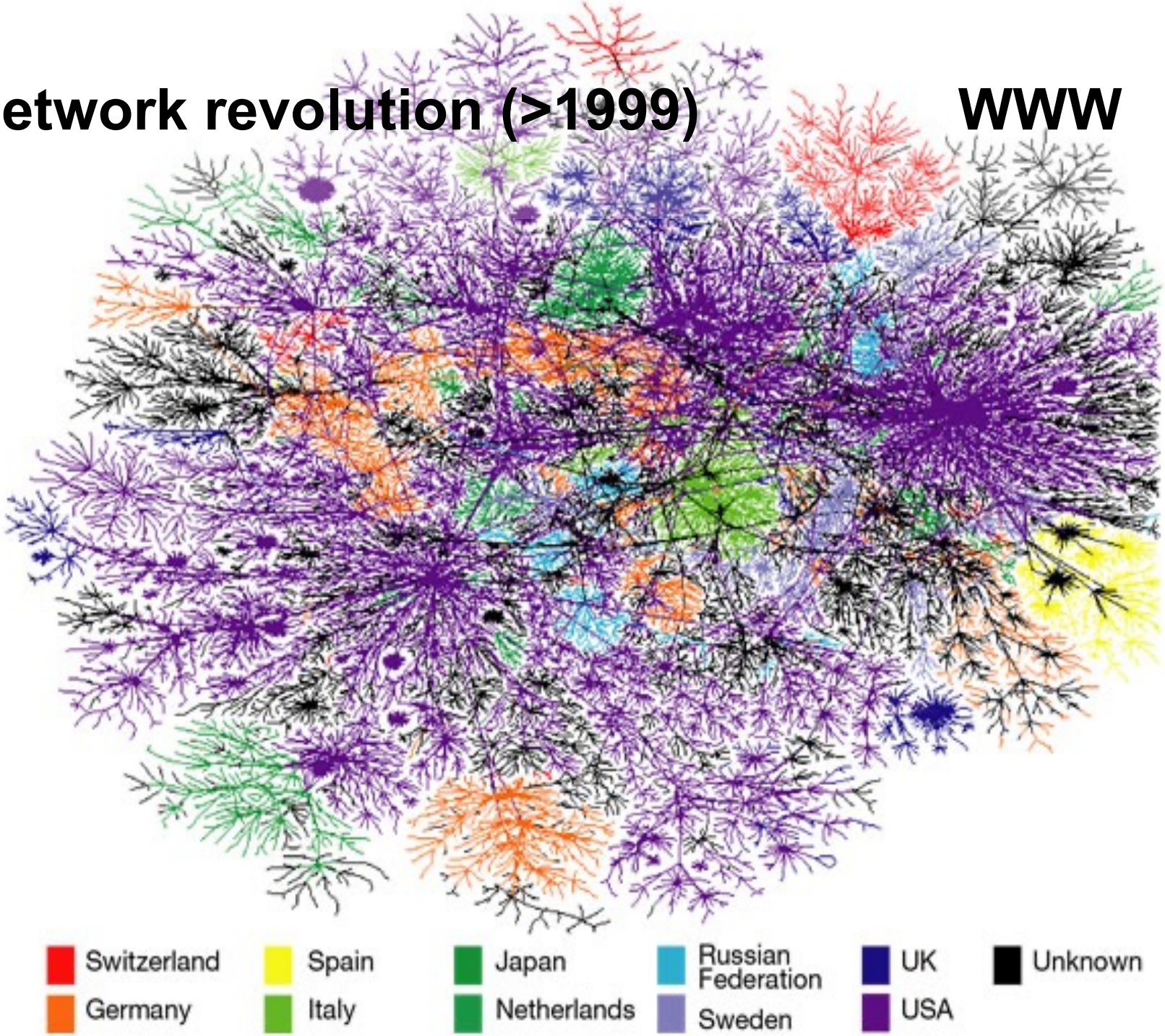


Network revolution (>1999)



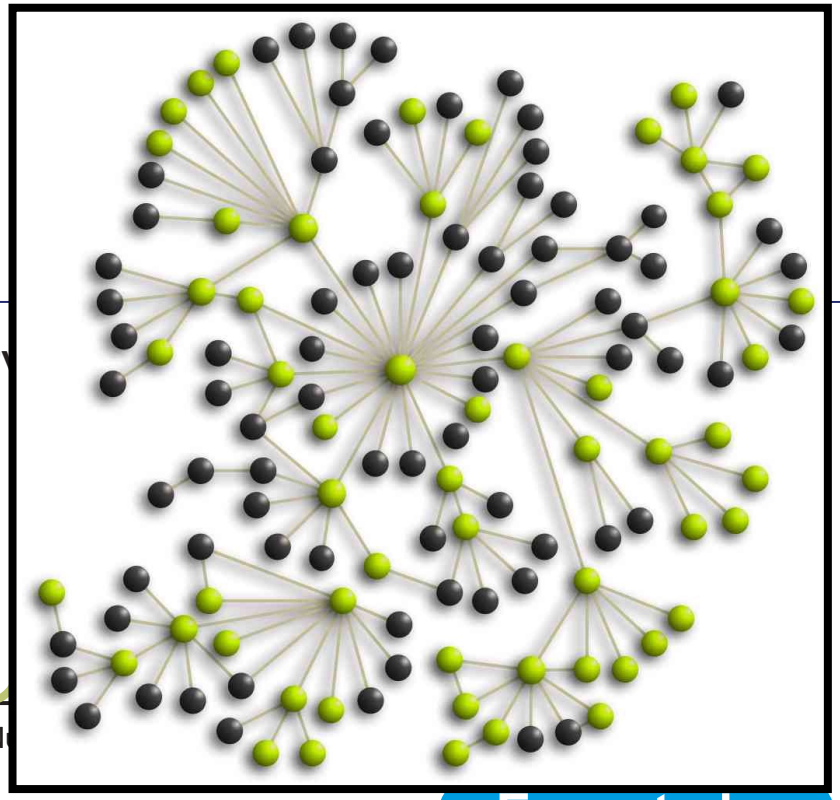
The surprising patterns of the Internet

Network revolution (>1999) WWW



Network revolution (>1999)

- Some nodes have a huge number of connections (hubs)
- A large majority share a small number of connections.



Expected...

...obtained

Bell Curv

Number of Nodes

N

Power Law Distribution of de Linkages

Number of Nodes

Number of Links

Number of Nodes (log scale)

Number of Links (log scale)

After the Internet...

EVERY SAGA HAS A BEGINNING

ACTOR CONNECTIVITIES

nodes: actors
edges: casted jointly

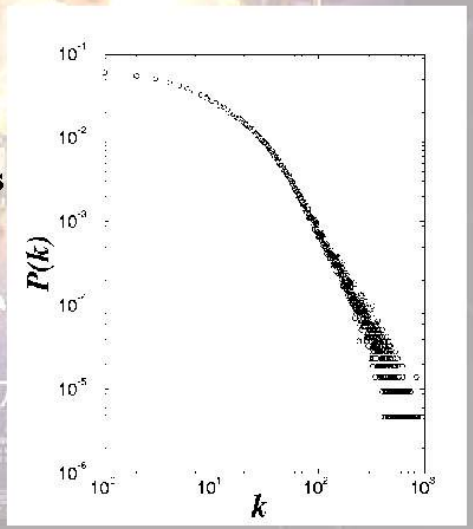
IMDb Internet Movie Database

Days of Thunder (1990)
Far and Away (1992)
Eyes Wide Shut (1999)

N = 212,250 actors
⟨k⟩ = 28.78

$P(k) \sim k^{-\gamma}$

$\gamma = 2.3$

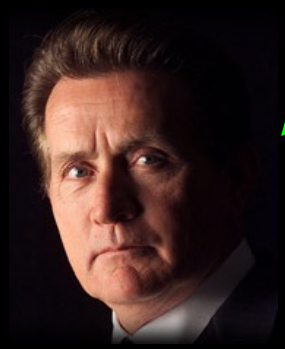


Six degrees of Kevin Bacon

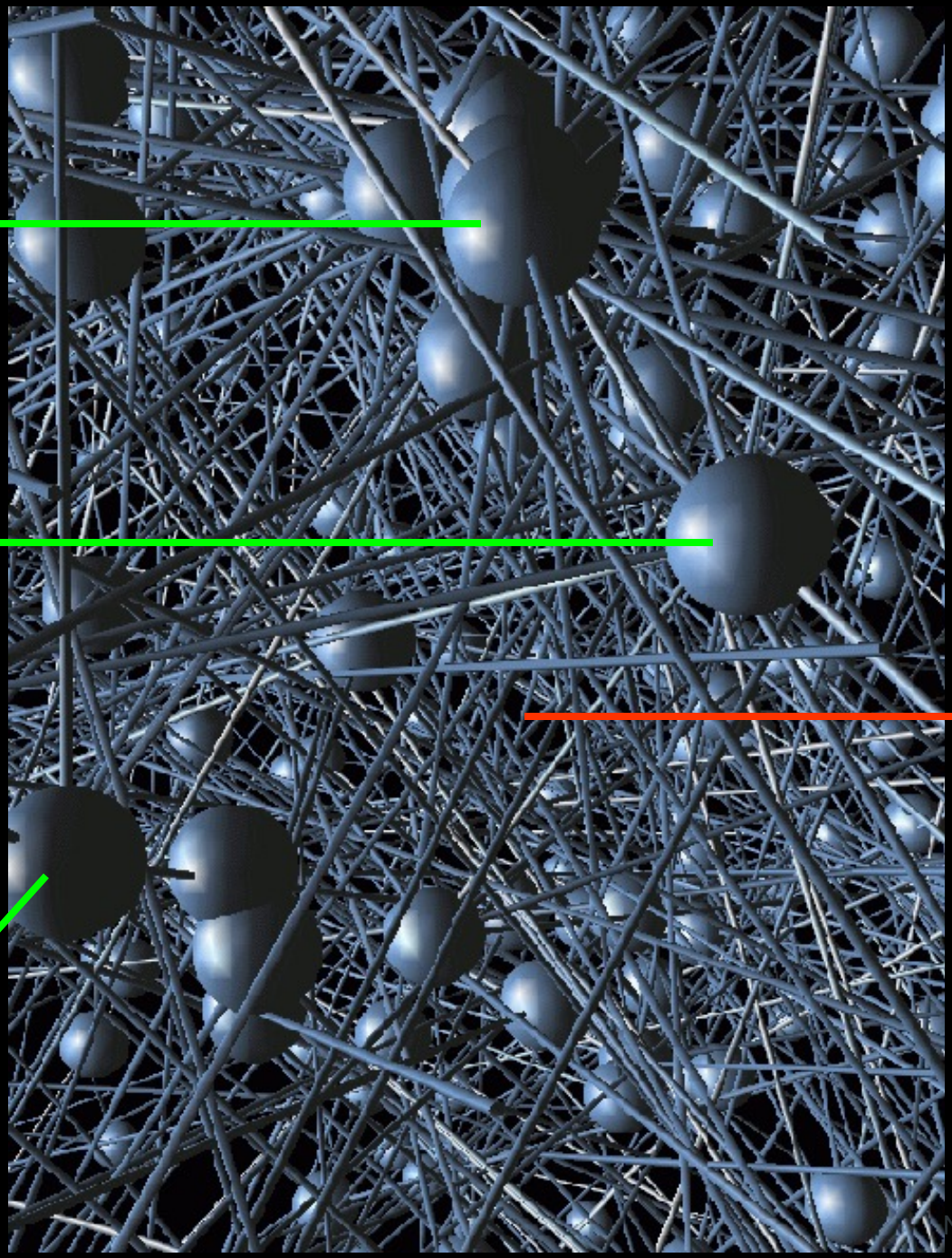
I have worked with everybody in Hollywood or someone who has worked with them.
(K. Bacon 1994)

#1 Rod Steiger

#2 Donald Pleasence



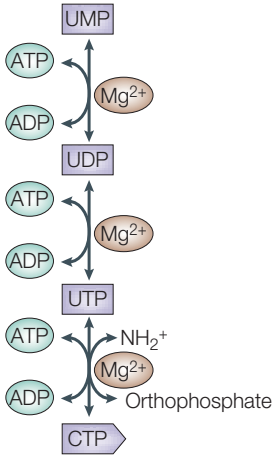
#3 Martin Sheen

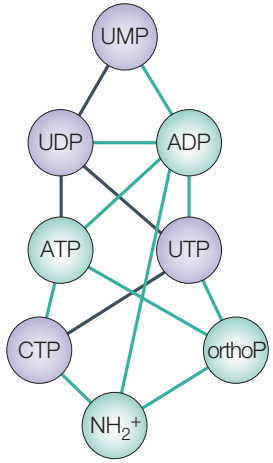


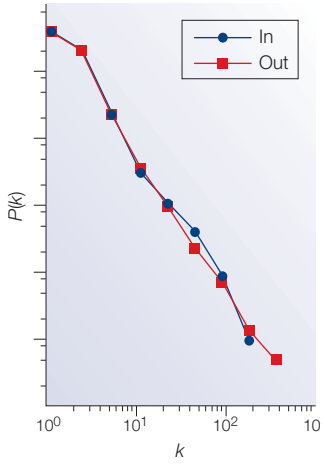
#876

Kevin Bacon

Biological networks

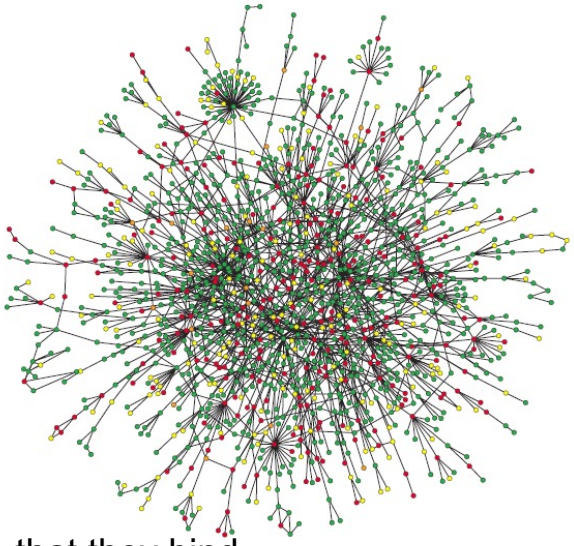






Metabolic networks

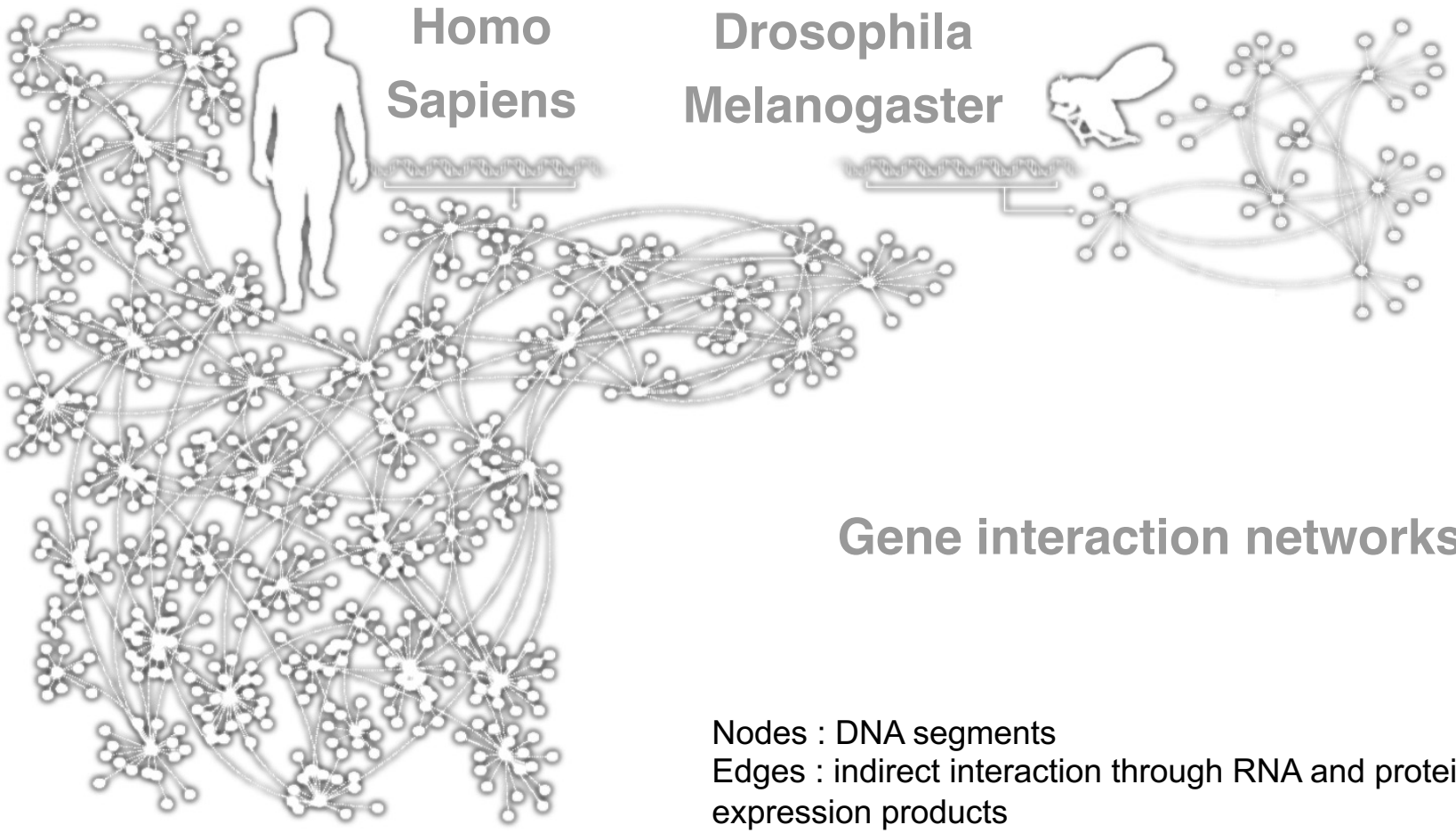
Nodes : metabolites
Edges : enzyme-catalyzed biochemical reactions
(hubs = water, ATP, etc).



Protein interaction networks

Nodes : proteins
Edges : experimental evidence that they bind

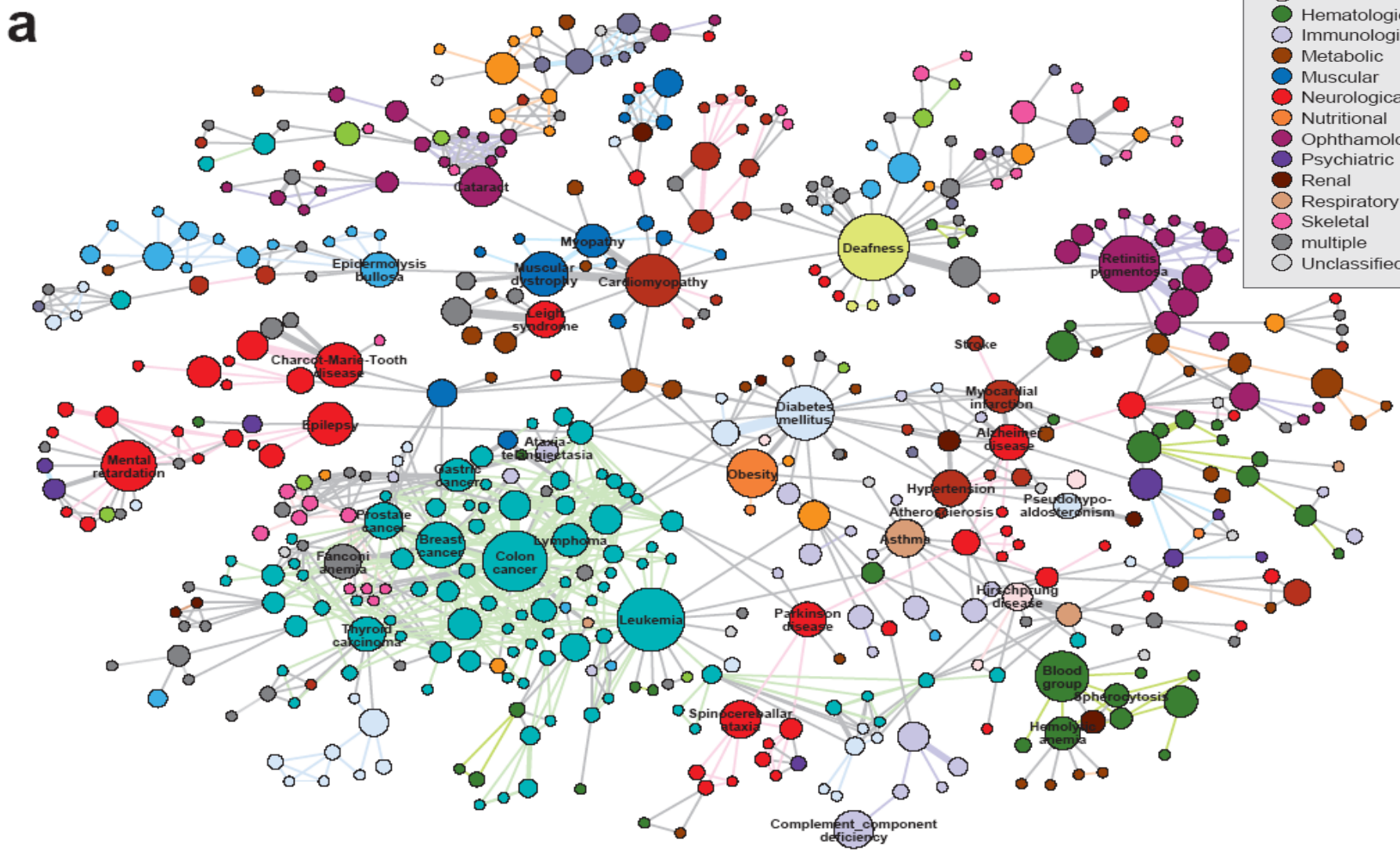
Genetics



Gene interaction networks

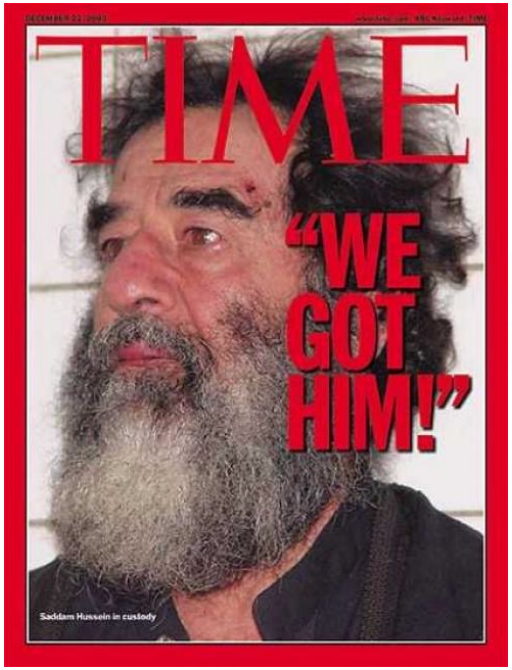
Nodes : DNA segments
Edges : indirect interaction through RNA and protein expression products

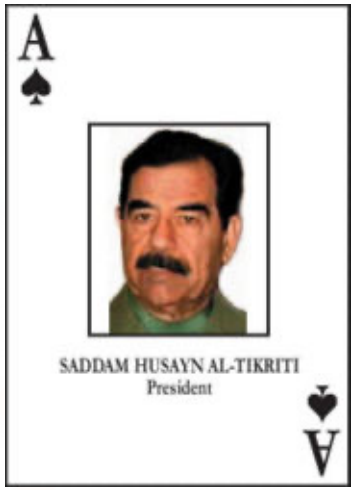
Medicine (human disease networks)

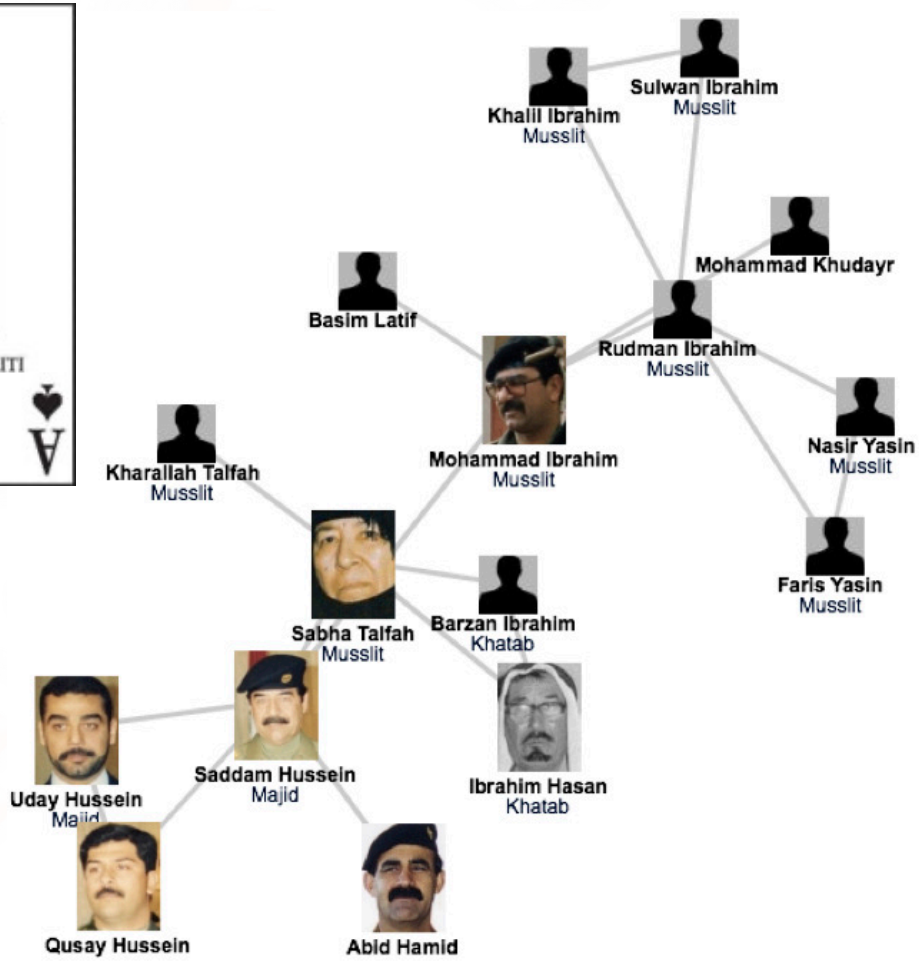


Intelligence services, security & terrorism...

The US Army Research Lab devoted over $300 million
to support network science centers across the US!







C. Wilson. Searching for Saddam: A five-part series on how the US military used social networking to capture the Iraqi dictator. 2010. www. slate.com/id/2245228/.

Social networks: A new Human lab?

Degrees of Separation on Facebook

2008	2011	2016
5.28 hops	4.74 hops	4.57 hops

http://law.di.unimi.it/webdata/fb-current

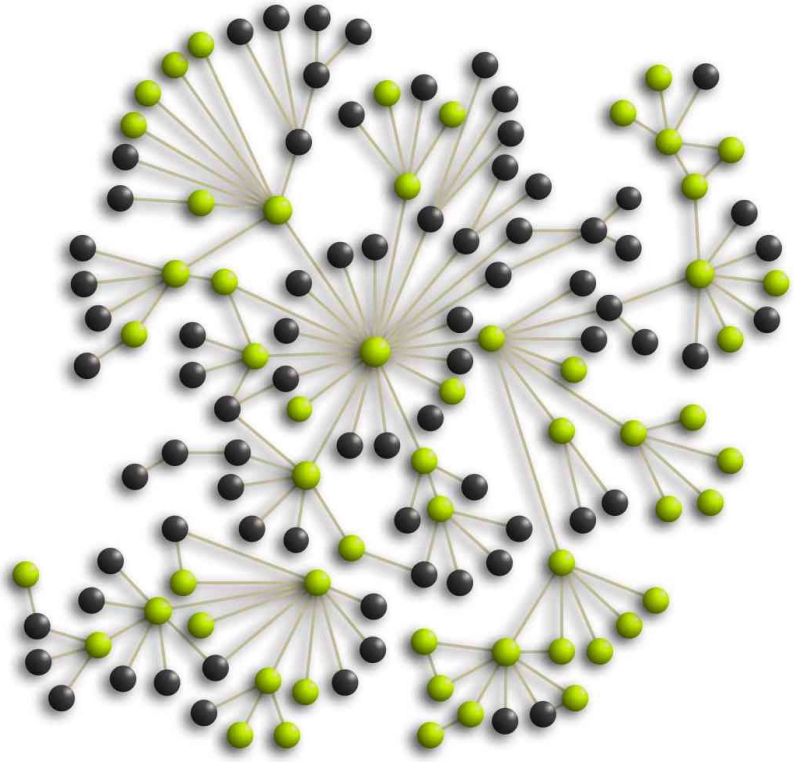
Facebook: 1.6×10^9 users!!!

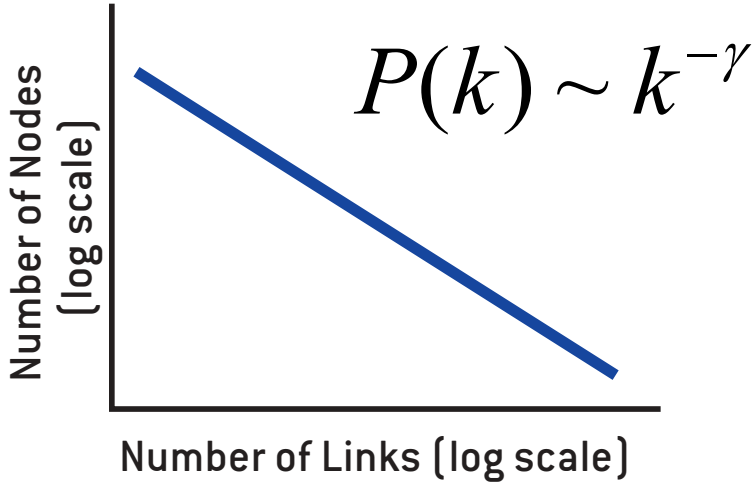
How can we compute this result?

→ Algorithms and data structures for large-scale networks

Universality?

Scale-free properties





WWW	actors	citations	sex	cellular	phones	linguistics
$\gamma = 2.1$	$\gamma = 2.3$	$\gamma = 3$	$\gamma = 3.5$	$\gamma = 2.1$	$\gamma = 2.1$	$\gamma = 2.8$

Universality?

What are the principles underlying the origins of these and other patterns?

Complex systems

Emergence of global patterns, without a central authority, external bias or collective conscience

Complex systems

Ex: Ecology & Theoretical Biology

Microscopic interactions

Emergent collective phenomena / properties

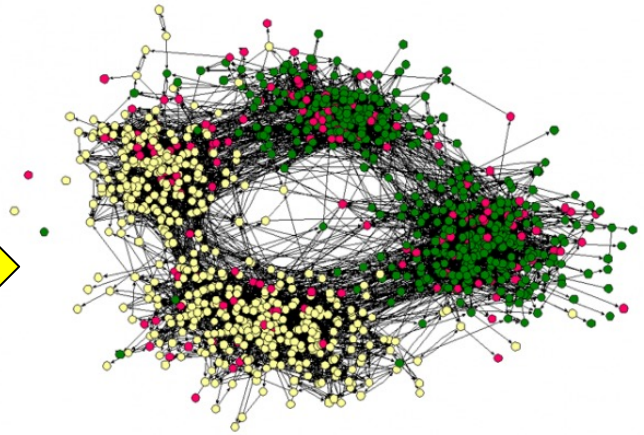
local

global

Complex systems

Ex: Social sciences

Microscopic interactions



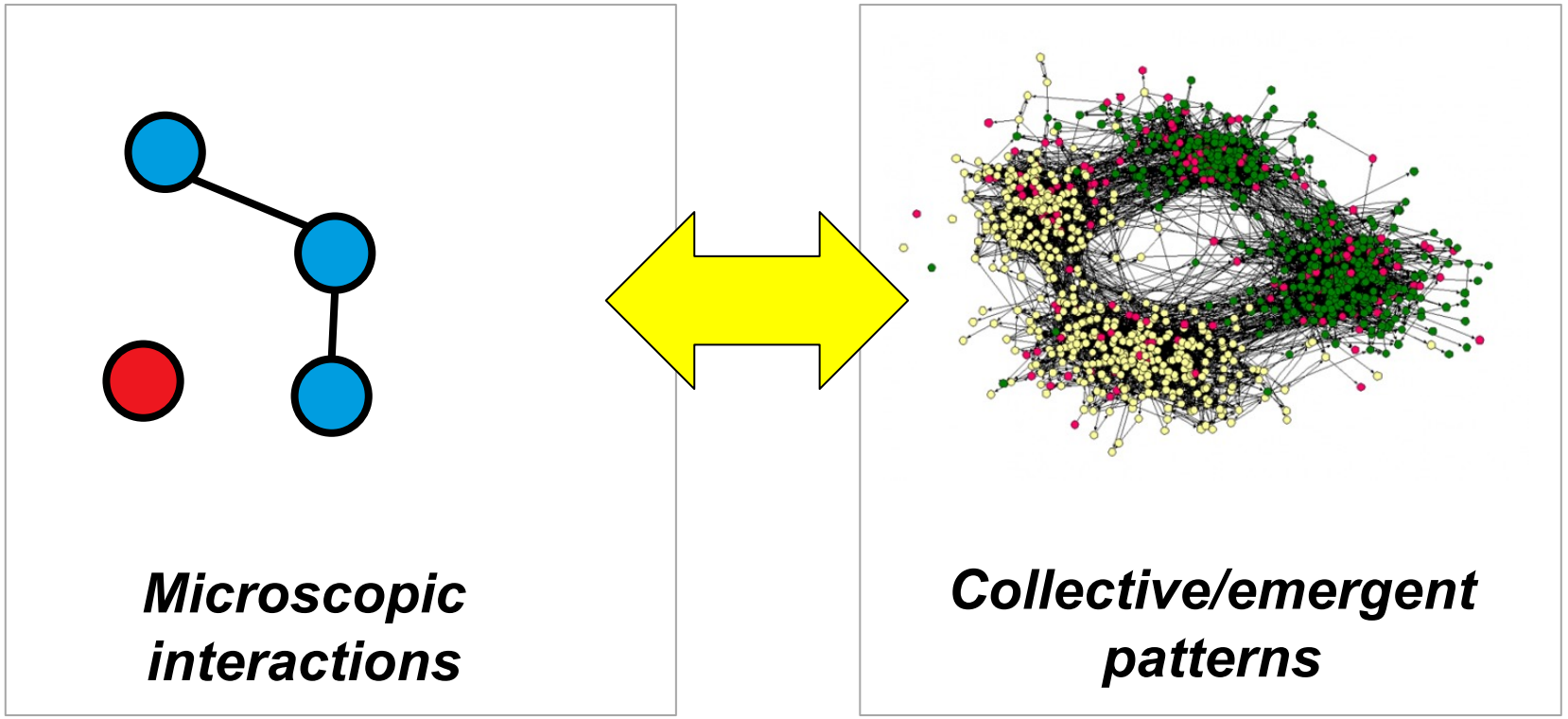
Collective/emergent patterns

local

global

Complex systems

Ex: Social sciences



Microscopic interactions

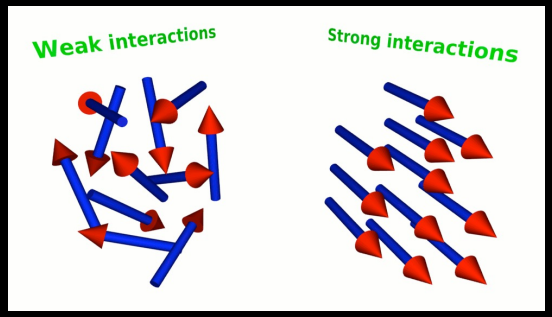
Collective/emergent patterns

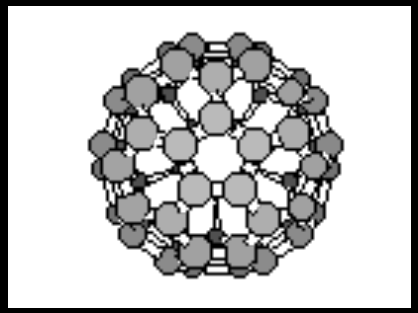
local

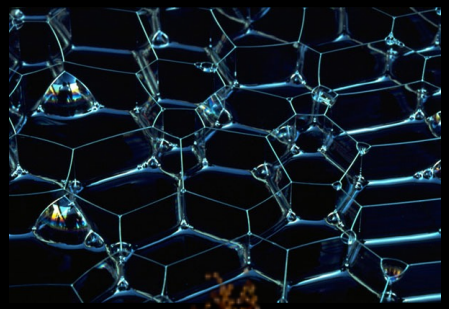
global

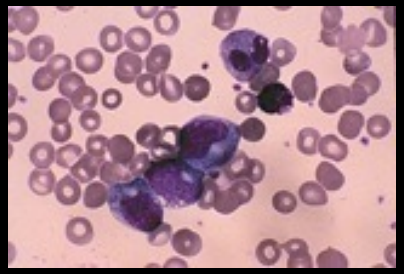
Complex systems

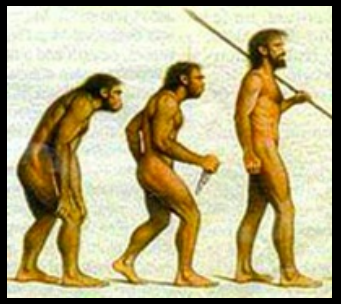
Self-organized systems at all scales



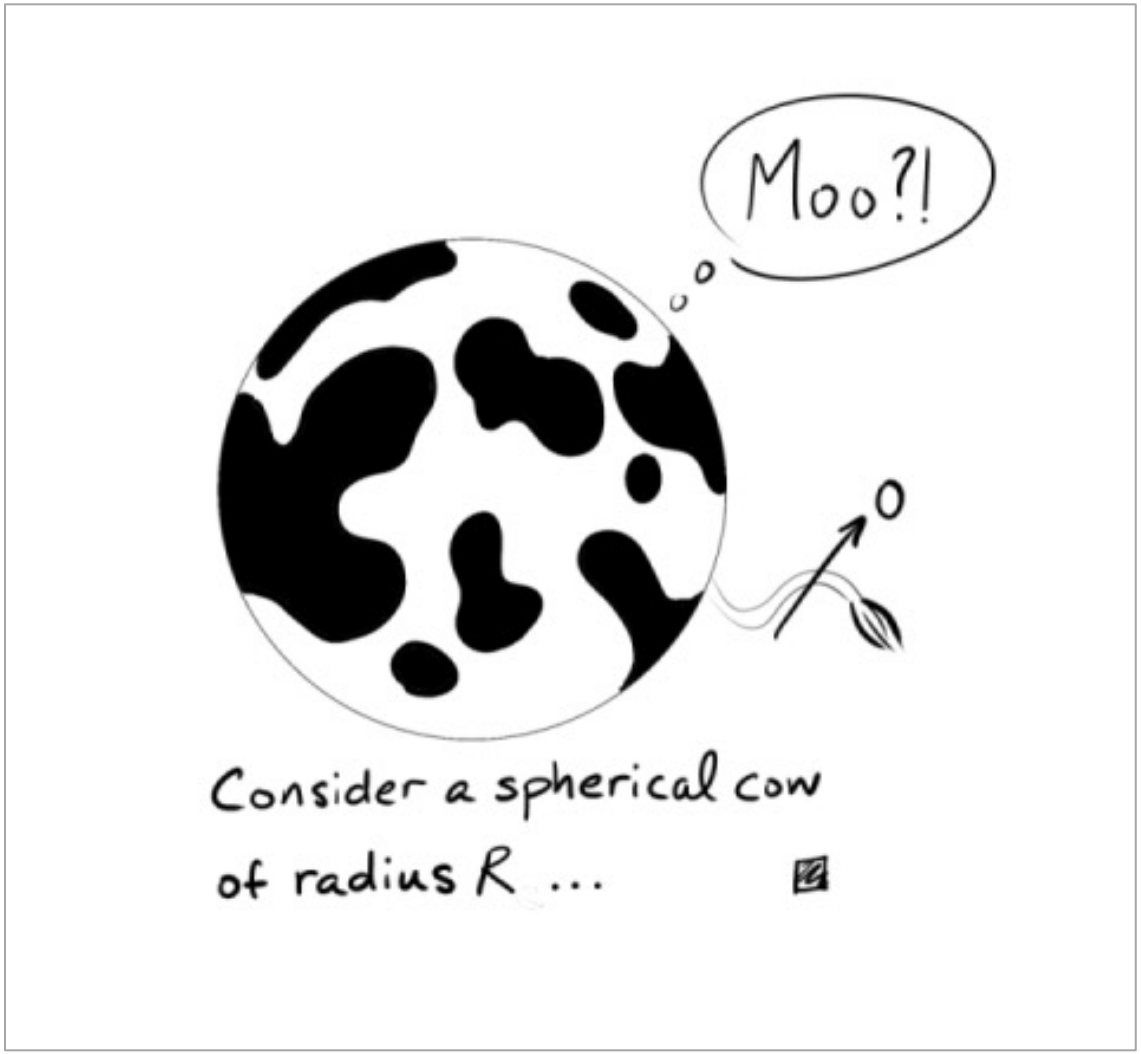






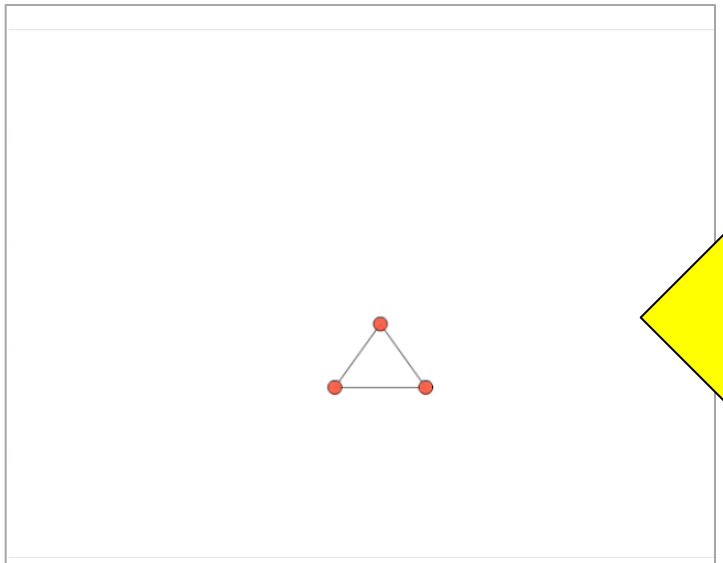


The beauty of modeling core principles

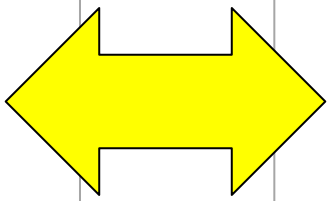


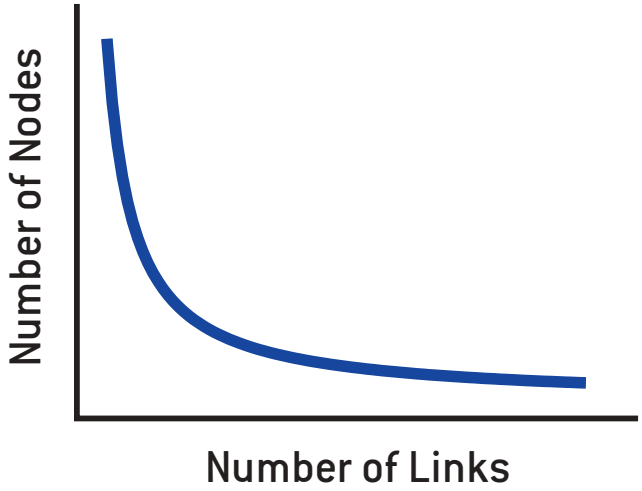
Properties & models of evolving networks

Models:
Barabási-Albert, Mendes-Dorogovtsev-Samukhin, Bianconi, Wagner, etc.



Microscopic interactions





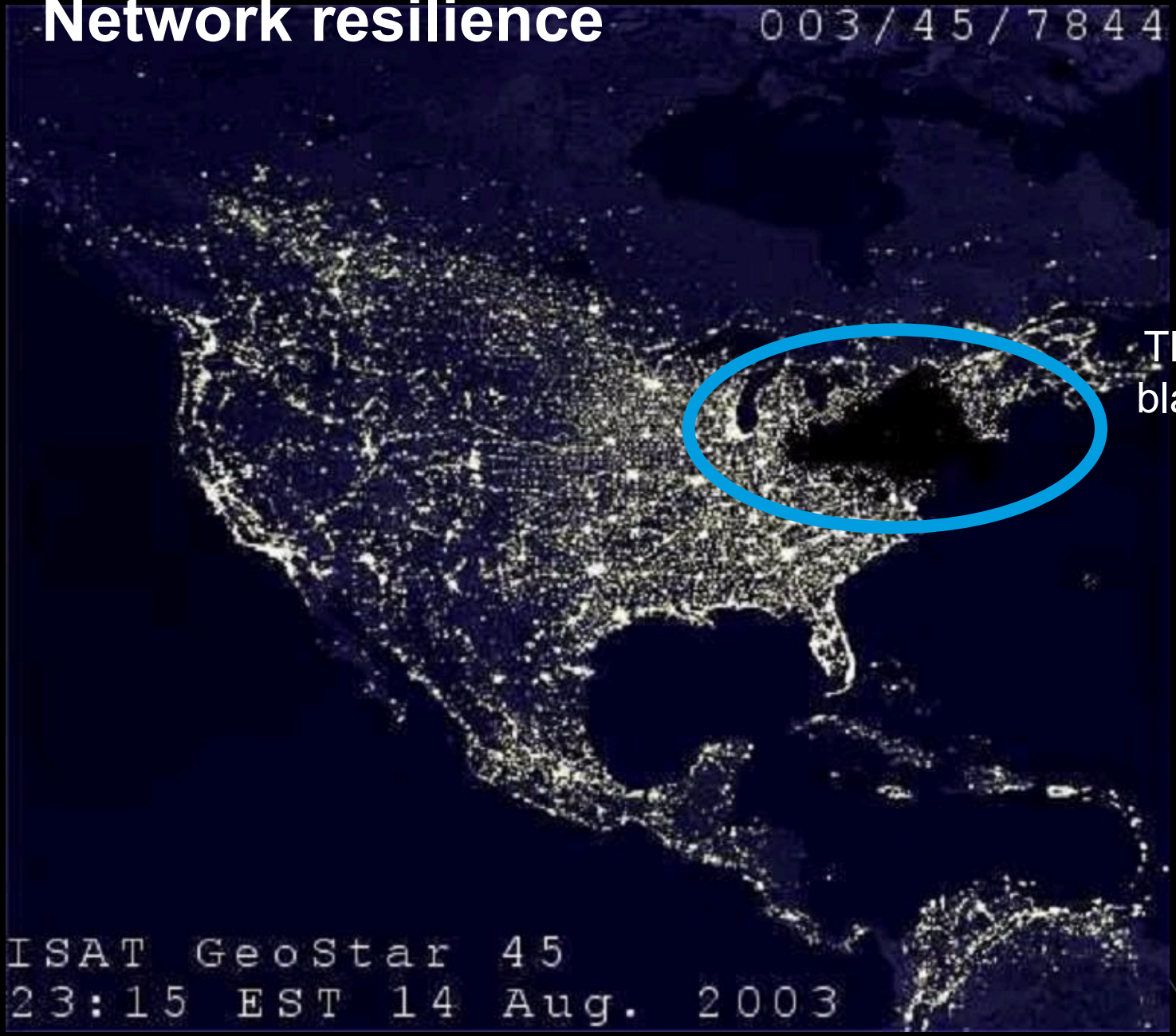
Emergent collective phenomena / properties

local

global

What are the implications of living in such network structures?

Network resilience

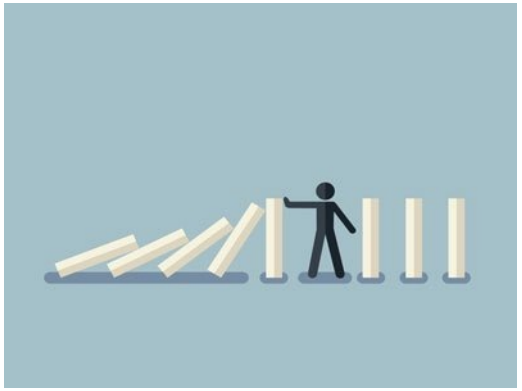


The northeast blackout, 2003

Network resilience

Random failures & attacks

Cascading effects



Building robustness

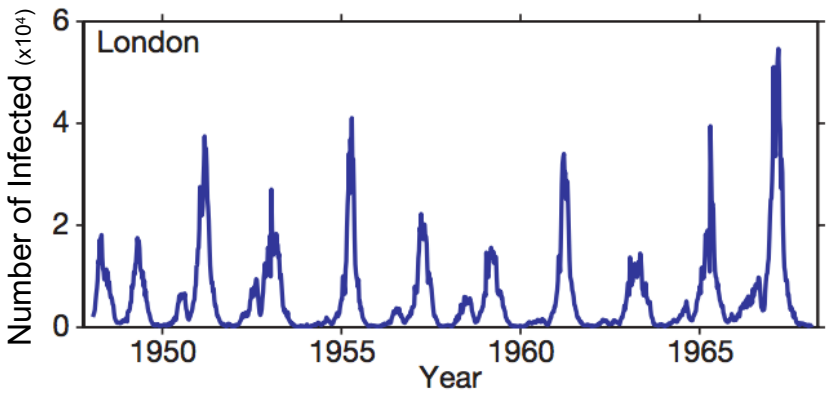
Examples: Airports, Power grids, financial networks, Information cascades in social networks, etc.

Toolkits: percolation theory, computer simulations, etc.

How does the shape of our contact networks influence the spreading of information, diseases, human decisions, etc.?

Microscopic interactions

local

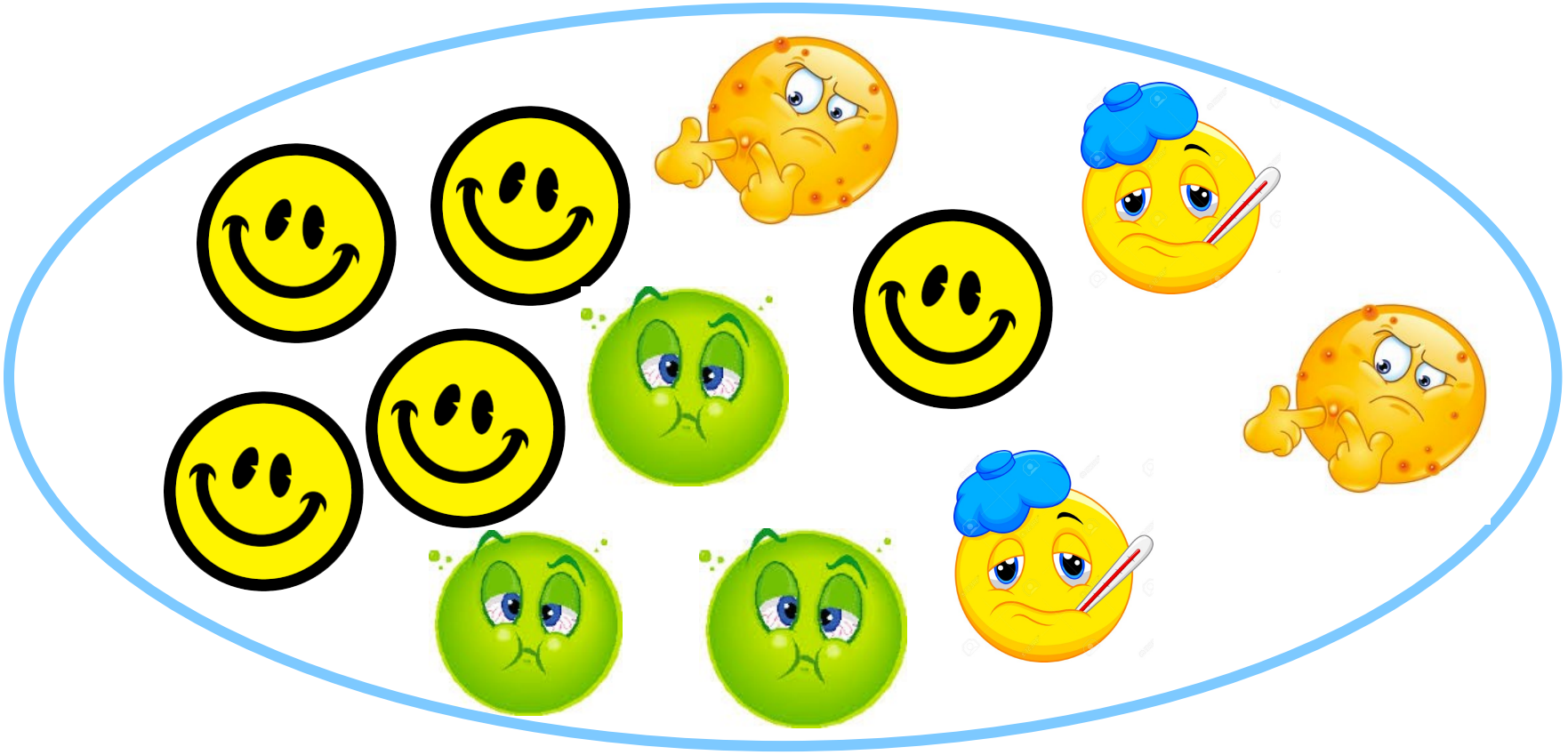


Collective/emergent patterns

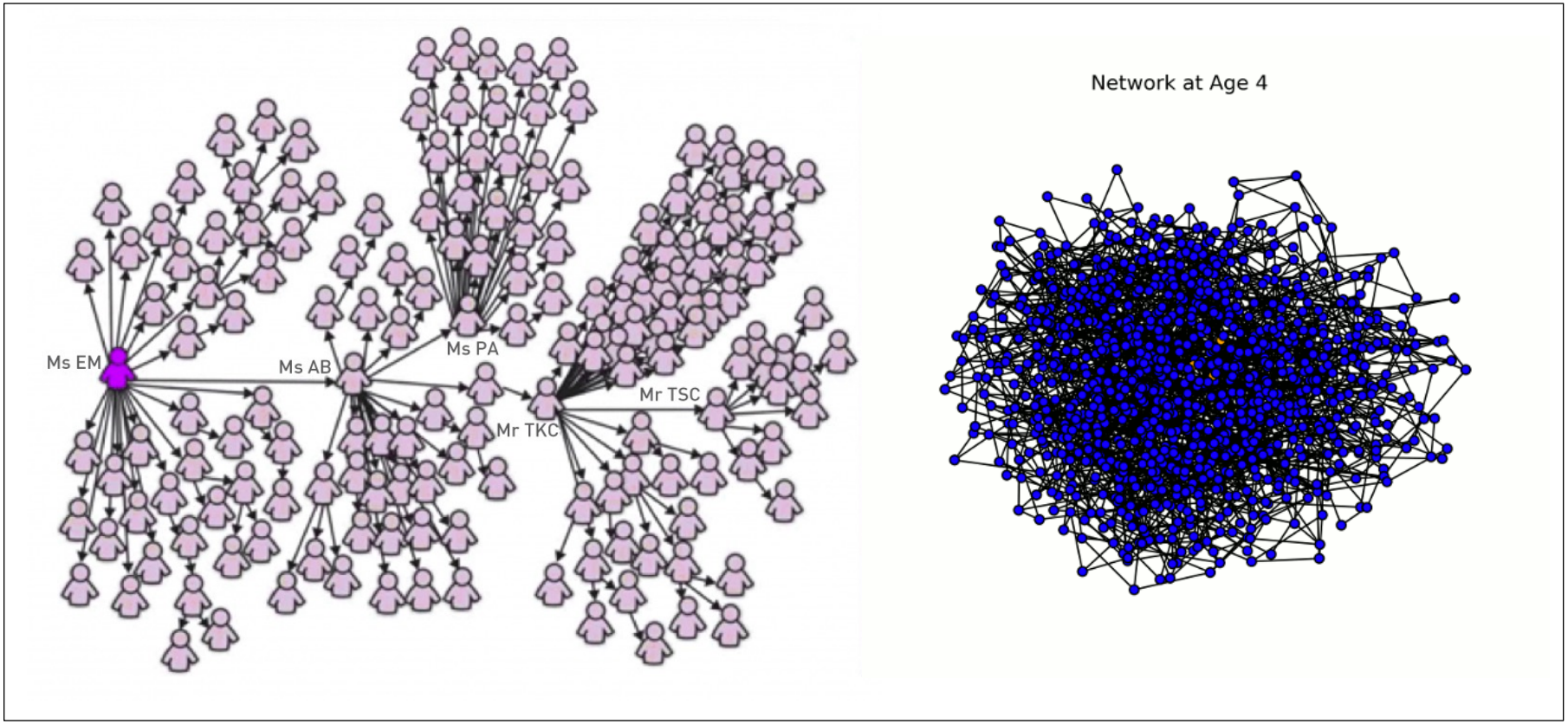
global

We will start from the basics...

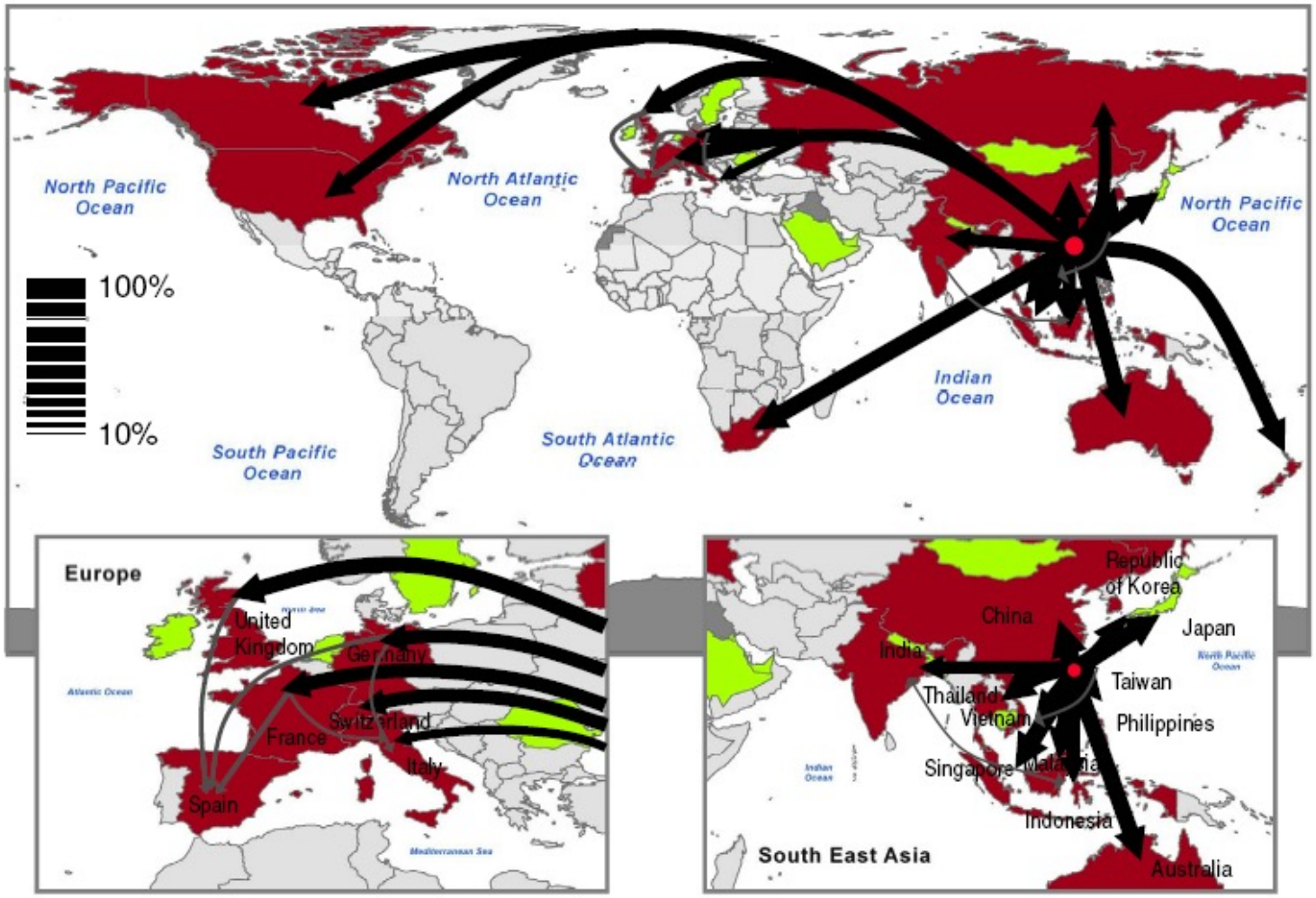
Consider a population where each individual has a disease state



Disease spreading in networked populations, control strategies, adaptive networks, etc.



Computational epidemiology @ global scale



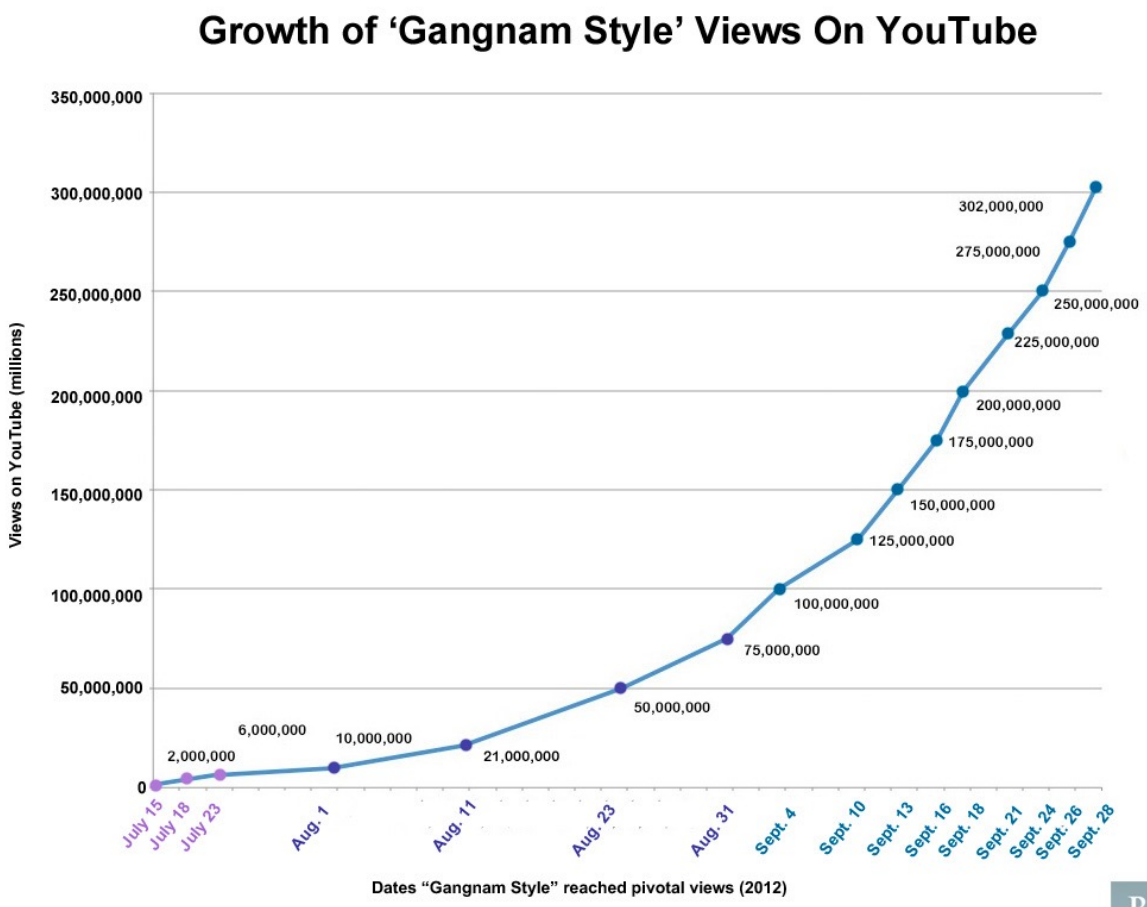
network: air-traffic between airports
weight : #-pass-year-on-route / #-tot-pass

Simulations at a global scale - H1N1 (2009)

Can we resort to contact processes to analyse social dynamics?

Some dynamics can be seen as similar...

Ex: spread of (mis)information



Sources: Yahoo, NY Times, Korea Times, WSJ

BUSINESS INSIDER

MARCELO REBELO DE SOUSA

Encontro do Presidente com *influencers* pretende ser "uma nova forma de fazer política"

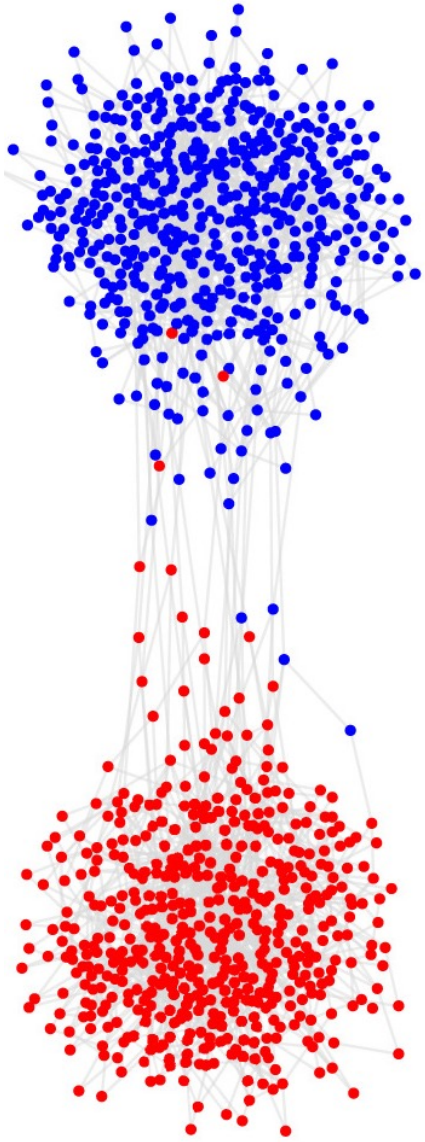
Apesar de estar consciente dos riscos deste encontro, o Presidente da República passou quatro horas com 40 influencers das redes sociais no Palácio de Belém. Ninguém esperava que ficasse em segredo.

Leonete Botelho · 17 de Outubro de 2019, 15:31

In english:

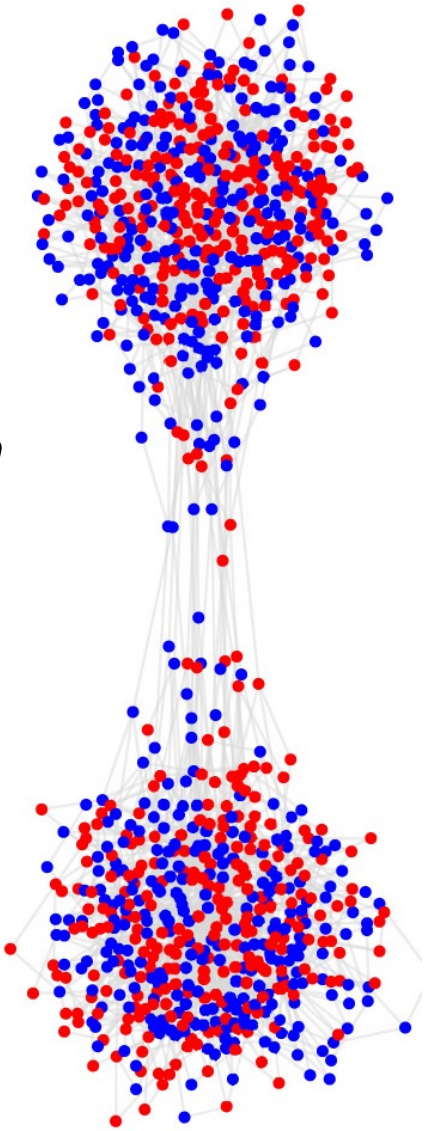
The President's meeting with *influencers* aims to be "a new way of doing politics"

...social dynamics can also be very different



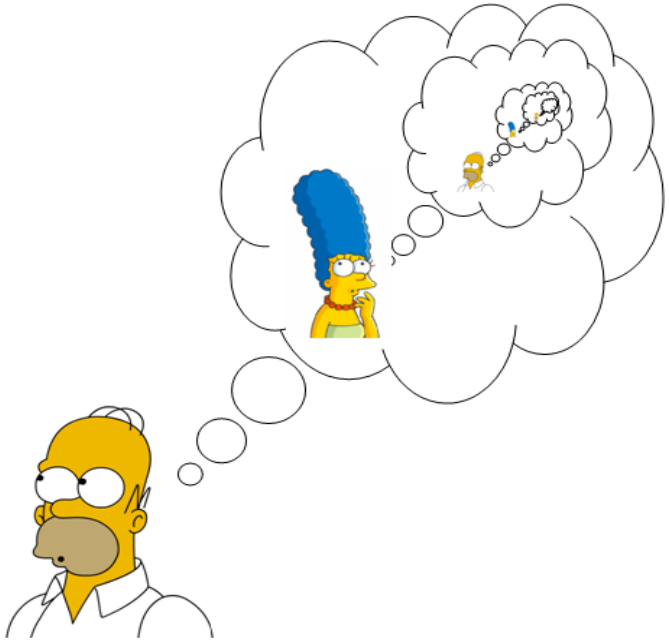
Beyond dyadic interactions

ex: Complex vs Simple contagion in social networks



...and much more complex

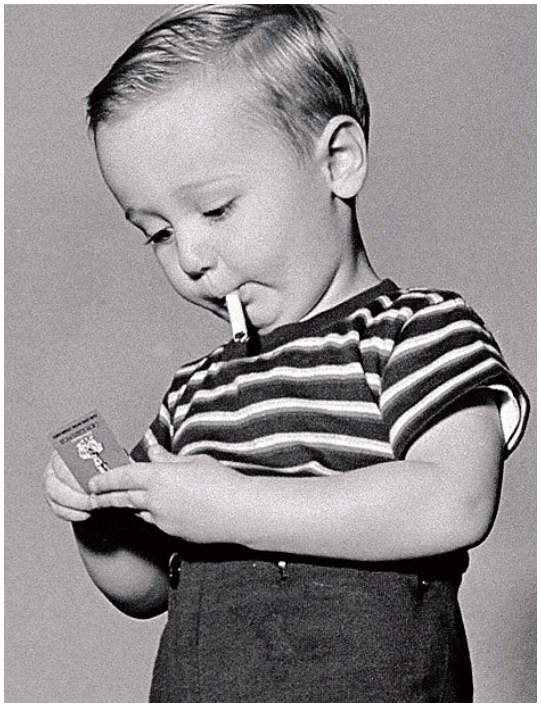
(beyond contact processes)



Strategic decisions

Game theoretical models

Do networks matter?

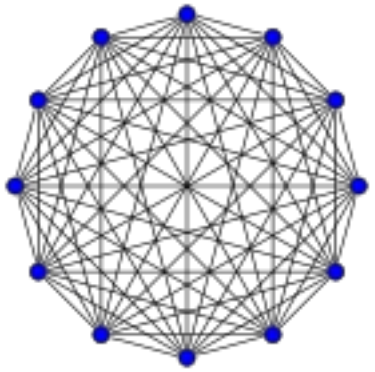


Why do we cooperate?

How do we test hypothesis on the origins of collective patterns?

Large-scale simulations of networked populations

We will start from the basics...



Resorting to well-mixed analysis
(without networks)

- Decision making: game theory and evolutionary game theory
- Ecological dynamics and frequency dependent selection.
- Repeated games & reputation dynamics
- Public goods problems

Etc.

Before addressing all these problems and models from a network perspective.

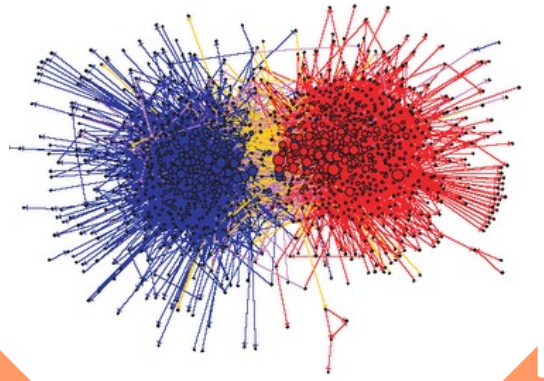
Self-organization is not just a description of how we got here. It can also be a tool kit for improving how we live today and shape our future.

How can we resort to such models to “engineer” a better world? Example: Climate change negotiations.

“Computational science” as a new language of interdisciplinary research?

empirical data

theory



Data wrangling: Methods of data acquisition, storage, manipulation, curation, and visualization.

Uncover complex patterns and correlations through graph-based statistical techniques

Understand and engineer complex systems, beyond black boxes.

Network Science

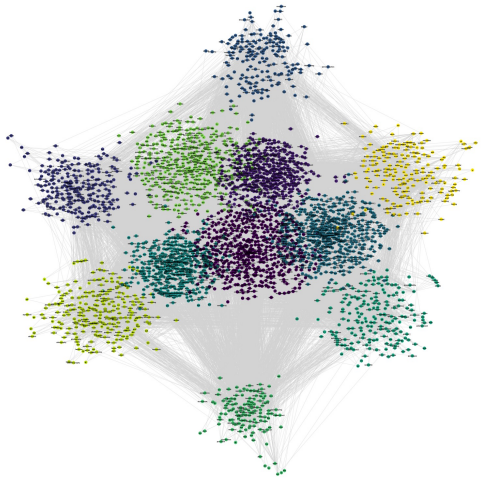
At the end...

You will learn:

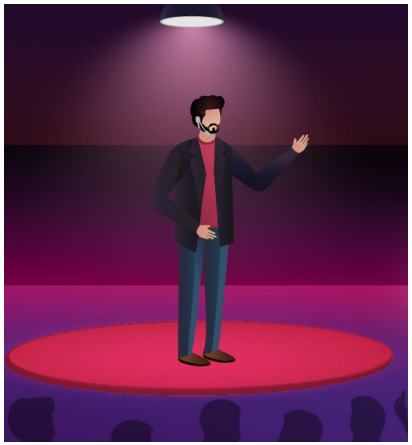
- How to use **network thinking** as a general approach to understand and deal with complex problems;
- Algorithms and **measures** capable of characterizing the structure, resilience and dynamics of complex networks;
- How network topology influences **dynamical processes** like disease spreading, opinion dynamics, or human decision-making;
- How to **build a model**, how to analyze it, characterize its properties and limitations, and **communicate** its results.

Grading

A final written exam



1 project



1 talk

Project (50%)

short paper + presentation on any of topic related with complex networks and complexity in general. We will post some suggestions for your project. This may include (examples):

- An analysis and discussion of a real data set
- Exploration of particular algorithms on graphs
- Creation of a computational or mathematical model

You may resort to one of the suggested software products or network libraries available…

Or develop your own simple network code in your favorite language, implementing some of the network metrics discussed in the course.

NetSci students' open workshop

Our labs

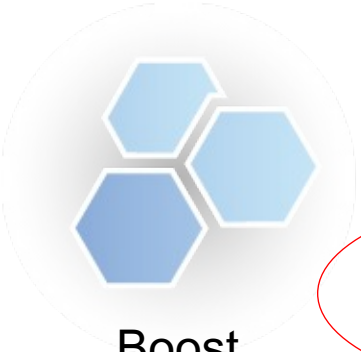
- Laboratories are used to recap what is discussed in the main lectures (or "theory classes") through a list of five problem sets
- In-class development of the Project.

Students are free to choose to work on their own project or solve a particular problem set or exercise benefiting from a one-to-one relationship between student and instructor.

Our labs – 1st class

(next week)

- Try the exercises listed @ Problem set 1.
- You may take a look at the algorithms component (ex. 1) and check if you got the main ideas. 2.
- Try out Gephi (ex. 3 @ Problem Set 1) OR...
- Start exploring a (more serious) network package associated with your favorite language. This may take a bit. Start as soon as possible.
- Choose the topic of your project and let us know if you need any help.



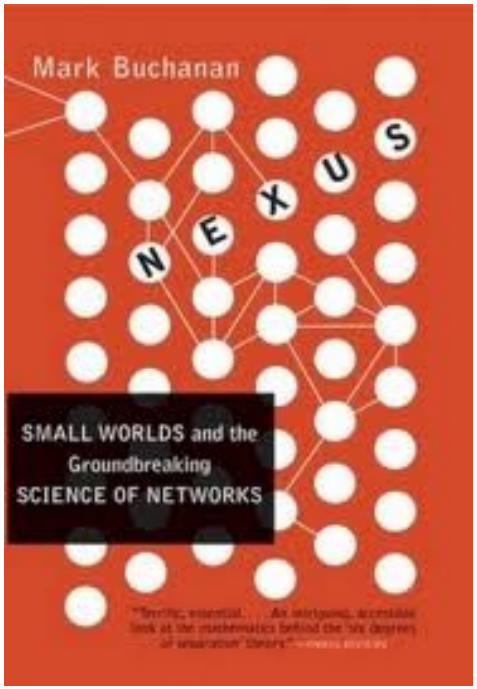
Boost

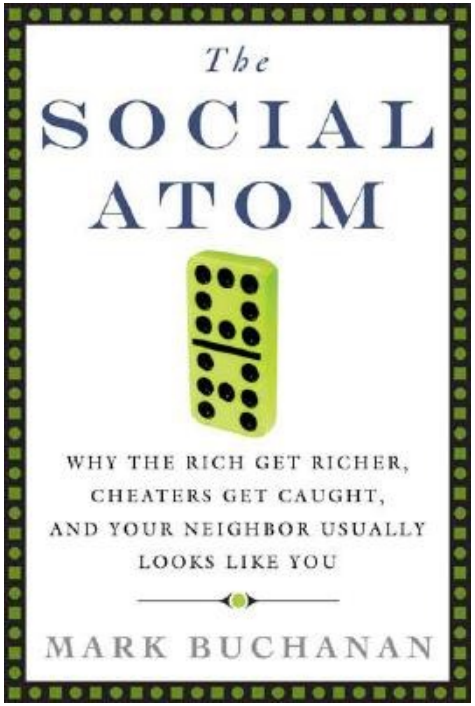
WebGraph

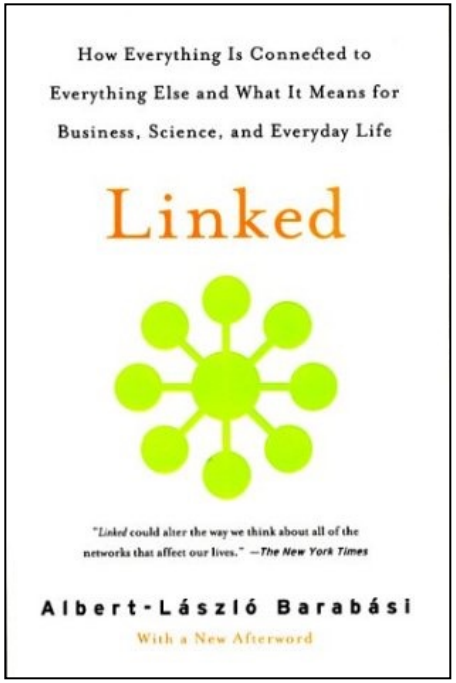
http://webgraph.di.unimi.it/

Mathematica

Easy reading







Thank you!!

https://fenix.tecnico.ulisboa.pt/disciplinas/ARC/2023-2024/1-semestre