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Network Science

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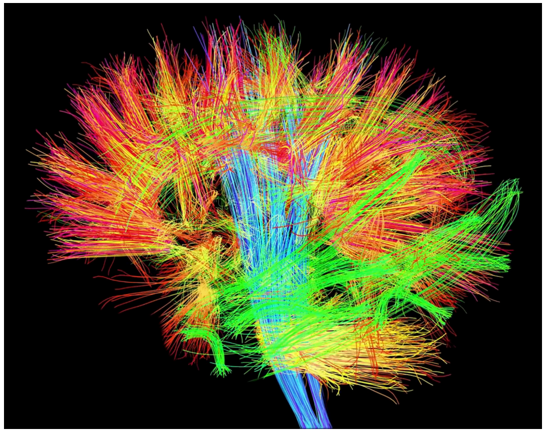
Complexity Theory


…the twenty-first century would be the "century of complexity". ….

Why should we care?

2.5 10^{18} bytes per day = 2500 PB/day ~ 1 Million PB/year

IBM

IBM Offering Information

10 Key Marketing Trends for 2017

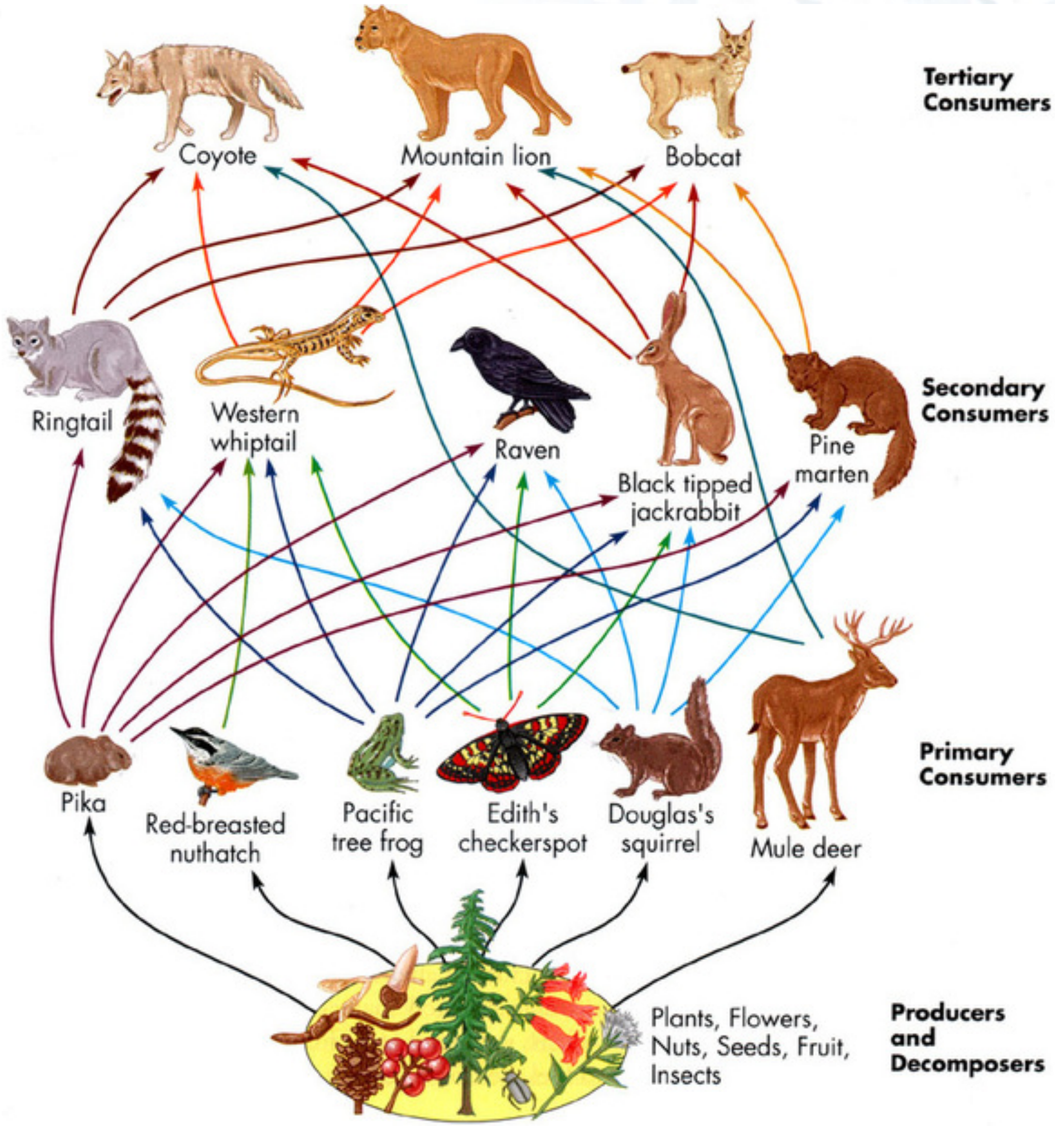
Every day we create 2.5 quintillion bytes of data. Find out which bytes matter most.

Learn more

Launch demo

imt.lu/gc @GuidoCaldarelli Guido.Caldarelli@imtlucca.it

Complex Systems Properties



ce of unexpected behaviours

e relation between stimulus and
!

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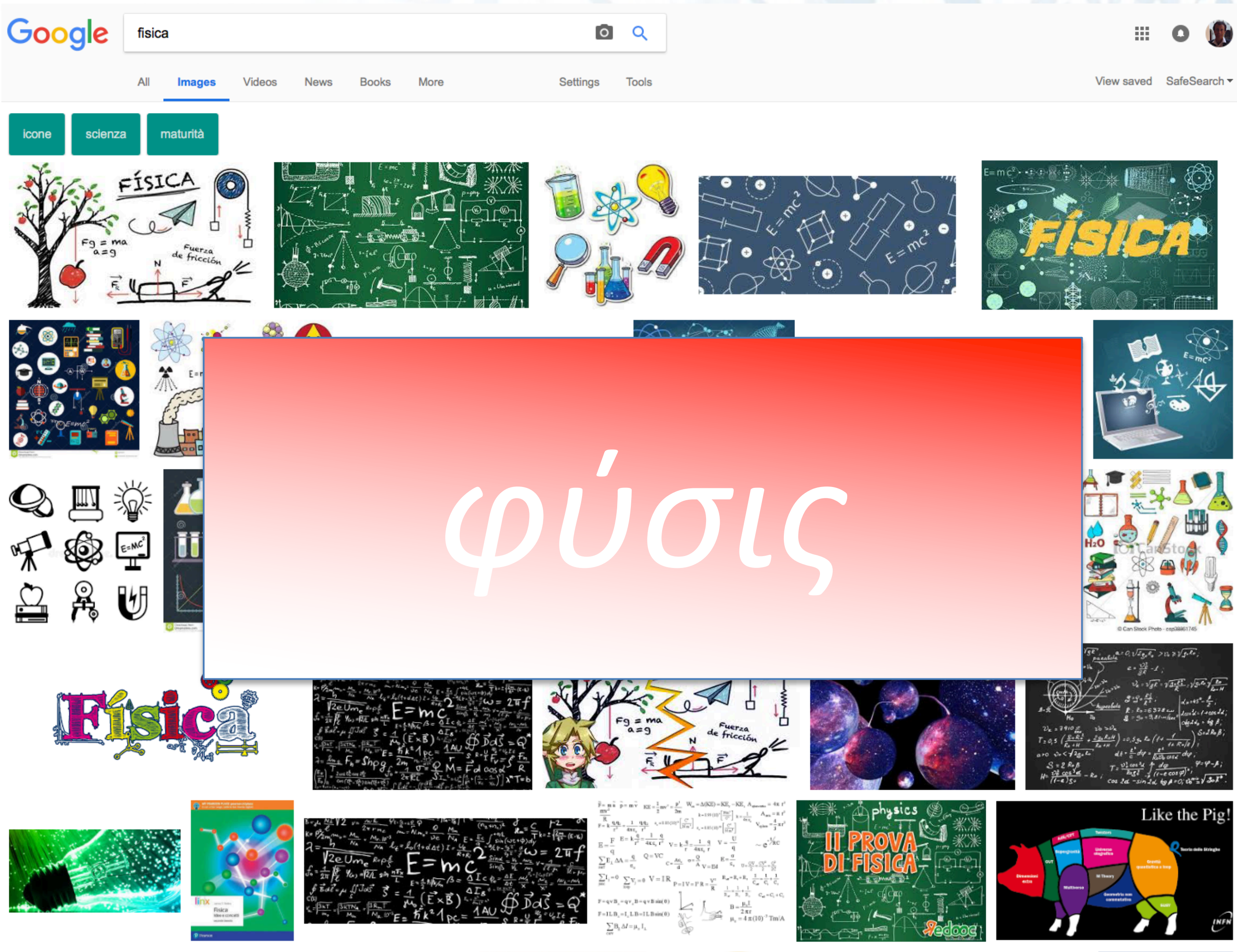
Complexity in Physics



φύσις

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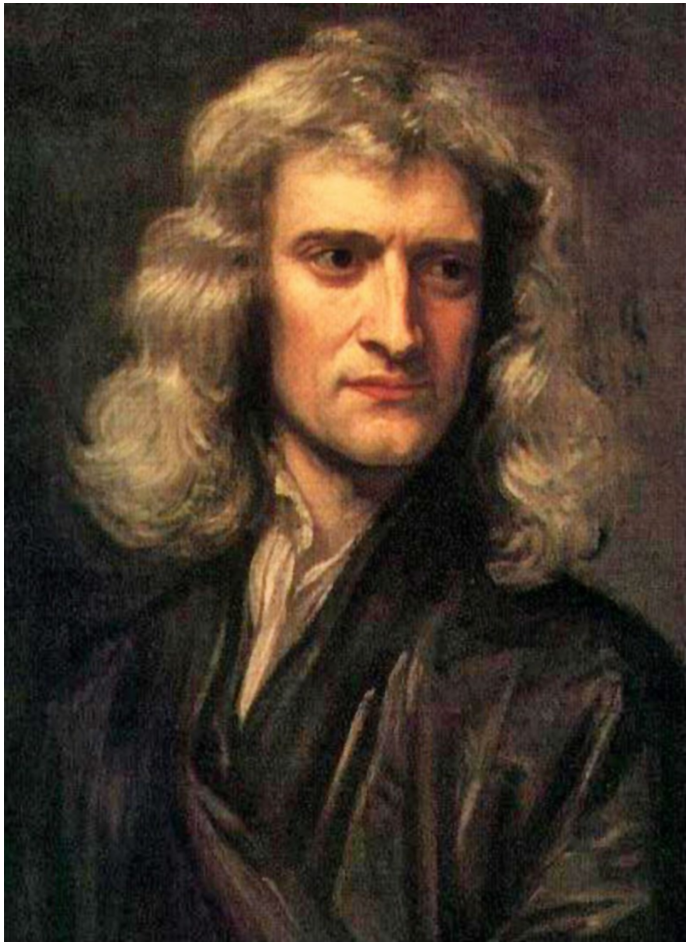
Why Physics?



Physics (at least the aspect) is time invariant!!!!!

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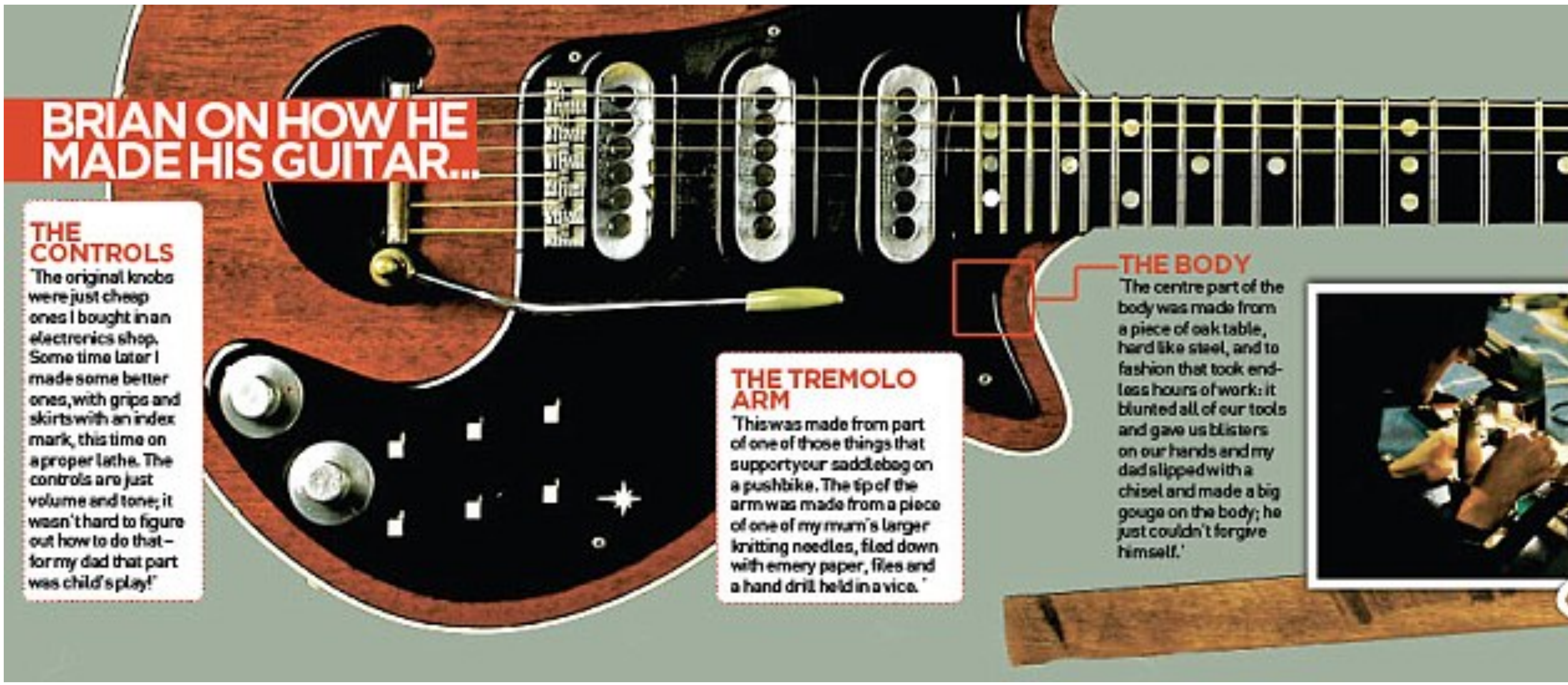
Wembley July 13th 1985

Dr. Brian May (Queen)

Dr. Brian H. May (PhD Imperial College, 2007)
Built himself his guitar (RED SPECIAL)

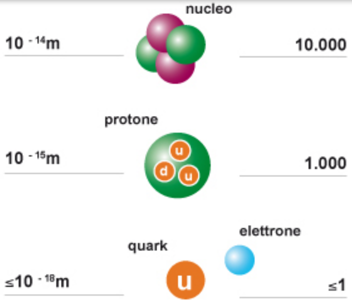


Red Special

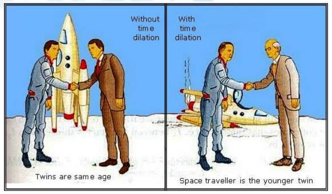
(un)fortunately very frequent approach....

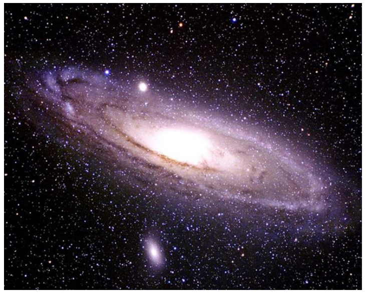
Which Physics?

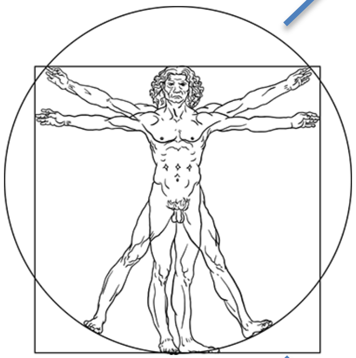
$$-i\hbar\frac{\partial}{\partial t}\Psi(\vec{r},t)=\left(-\frac{\hbar^2}{2m}\nabla^2+V(\vec{r},t)\right)\Psi(\vec{r},t)$$



velocity

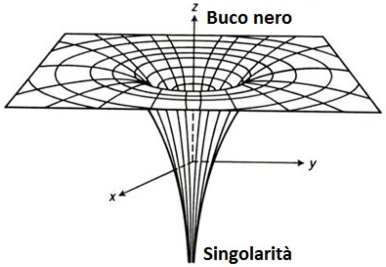


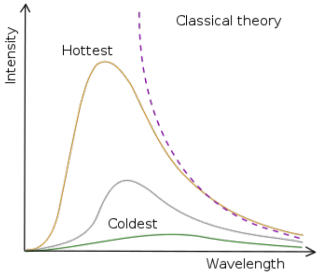


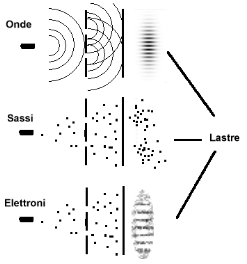


(size, m)

10^{-20} 10^{-10} 10^{21}







$$\Delta x\Delta p\geq\frac{\hbar}{2}$$

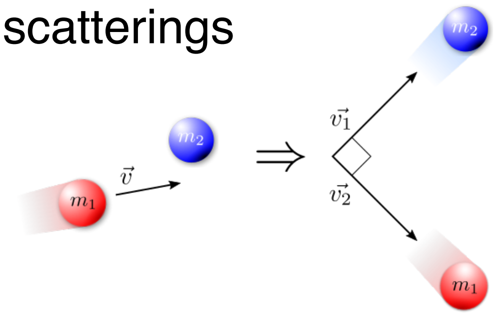
10^{23}

Number of parts

Scatterings

That's how we see ourselves…

Physicists study scatterings



To know what happens in a glass of water, I simply study the molecules' scatterings

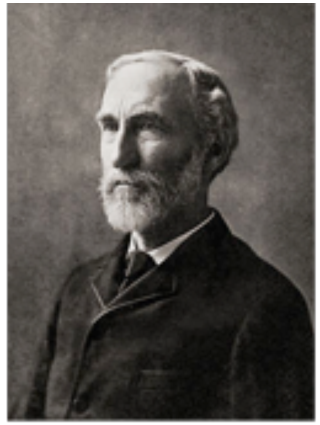
Problem: We have 10^{23}-10^{24} of them

If every molecule were a rice grain, to match the number of molecules in a glass of water we should collect the harverst of 27 milions of years

(at the present rate of 739 milions of tons/year)

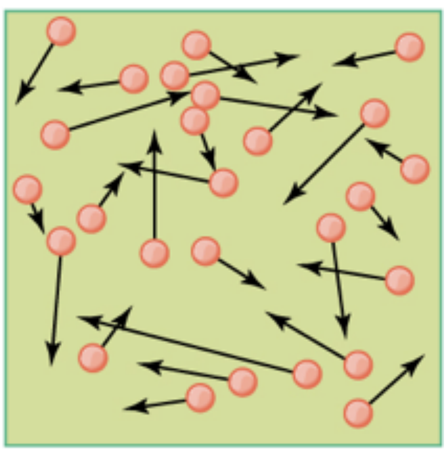
Statistical Physics

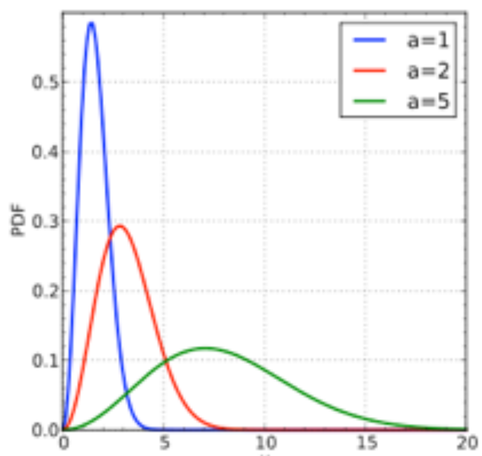
Ludwig Boltzmann



Joshua Willard Gibbs

James Clerk Maxwell





$$PV = \frac{1}{3} N m \overline{v^2}$$

$$E = \frac{3}{2} k_B T$$

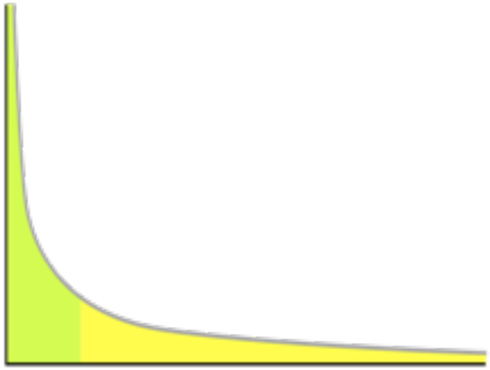
$$S = k_B \ln W$$

Statistical Physics and Complexity

What can we learn?

People are not described by 2 variables only, and react differently.

All we know, is the geometry of interaction



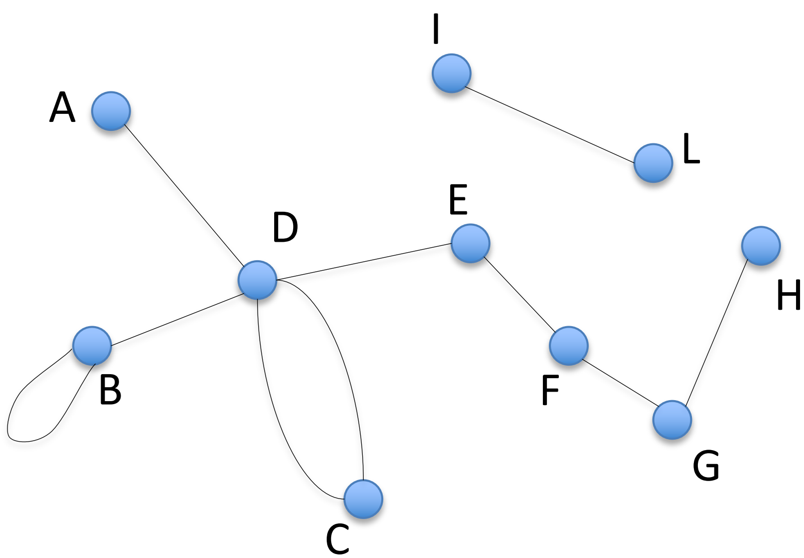
?????

Internet shape

Graph Theory

undirected

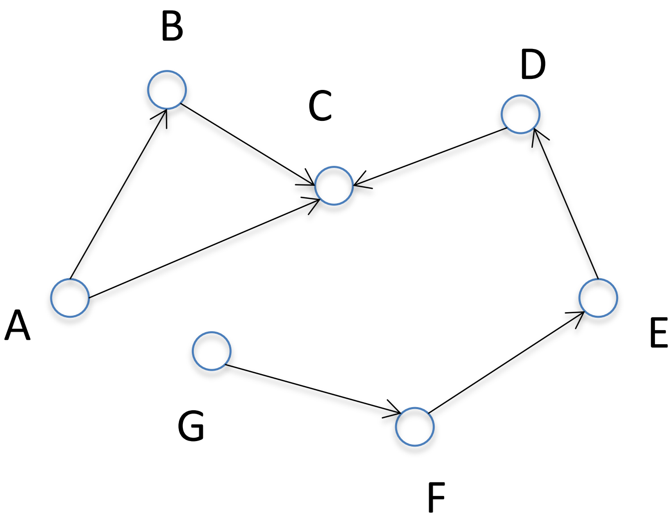
Undirected links



Example
Collaborations (movies, papers)
Protein Interactions
Internet

directed

Directed links



Example
WWW
Phone calls
Metabolic reactions

Properties of complex networs

Networks are game changer once we understand their properties

1 **scale invariance** that is highly heterogeneous

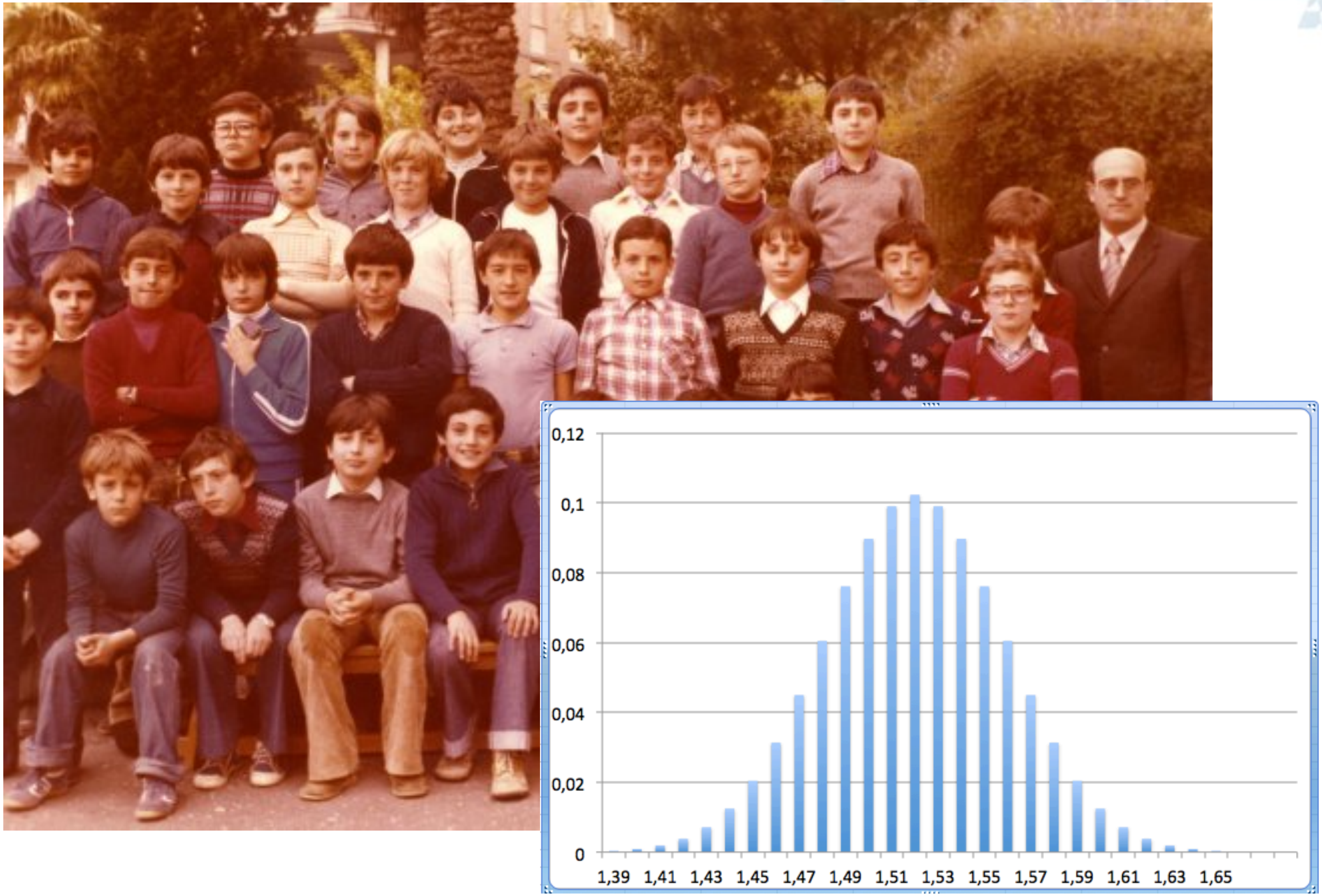
2 **small world** that is easy to travel

3 **highly clustered** that is community are present

4 **centrality made** that is some are more important than others

And much more

1) 12-years old students



1) NYSE


NYSE
NYSE
NYSE
NYSE
NYSE
NYSE
10
100,0
10,0
1,0
0,1
1
3
5
7
9
11
13
15
17
19
21

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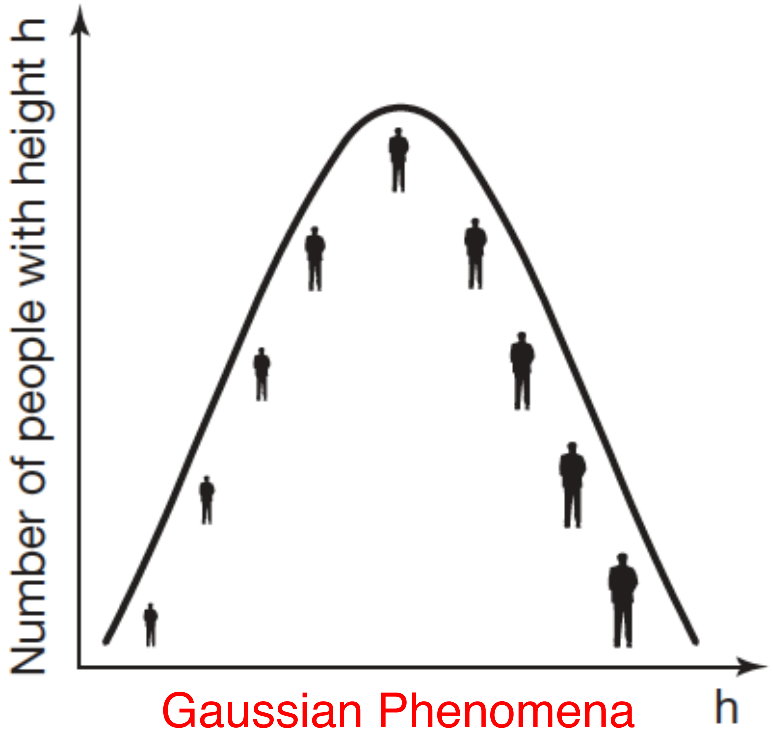
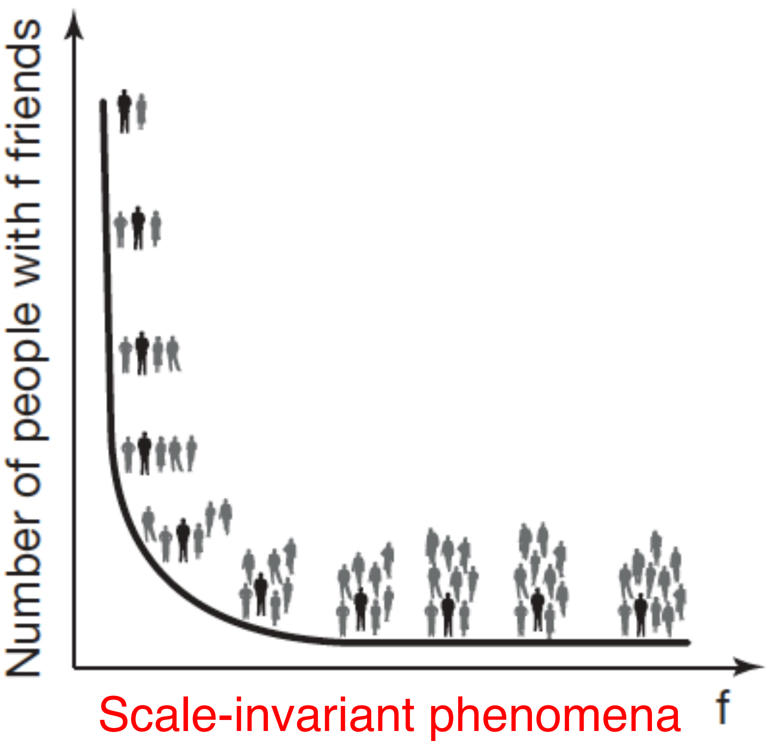
1) Scale invariance





Nobody is 3mm or 20Km tall

But somebody has 10000 more friends on Facebook than us!

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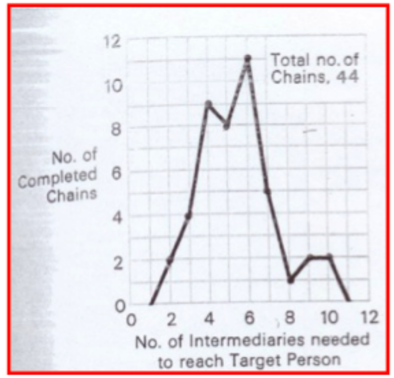
2) Small world



As a crude beginning, we thought it best to draw our starting persons from a distant city, so we chose Wichita, Kansas for our first study and Omaha, Nebraska for our second. (From Cambridge, these cities seem vaguely 'out there,' on the Great Plains or somewhere.) To obtain our sample, letters of solicitation were sent to residents in

1st REMOVE
Self-employed friend in Council Bluffs, Iowa

these cities asking them to participate in a study of social contact in American society. The target person in our first study lived in Cambridge and was the wife of a divinity school student. In the

This tells the person who receives the folder exactly who sent it to him. The roster also has another practical effect; it prevents endless looping of the folder through participants who have already served as links in the chain, because each participant can see exactly what sequence of persons has led up to his own participation.

In addition to the document, the folder contains a stack of 15 business reply, or "tracer" cards. Each person receiving the folder takes out a card, fills it in, returns it to us, and sends the remaining cards along with the document to the next link.

Several other features of the procedure need to be emphasized. First, each

2nd REMOVE

setts? Part of the excitement of experimental social psychology is that it is all so new we often have no way of knowing whether our techniques will work or simply turn out to be wispy pipe dreams.

The answer came fairly quickly. It will be recalled that our first target person

3rd REMOVE
Tanner in Sharon, Mass.

was the wife of a student living in Cambridge. Four days after the folders were sent to a group of starting persons in Kansas, an instructor at the Episcopal Theological Seminary approached our target person on the street. "Alice," he said, thrusting a brown folder toward her, "this is for you." At first she thought he was simply returning a folder

the median at five [*see illustration above*]. A median of five intermediate persons is, in certain ways, impressive, considering the distances traversed. Recently, when I asked an intelligent friend of mine how many steps he thought it

5th REMOVE
Dentist in Sharon, Mass.

would take, he estimated that it would require 100 intermediate persons or more to move from Nebraska to Sharon. Many people make somewhat similar estimates, and are surprised to learn that only five intermediaries will—on the average—suffice. Somehow it does not accord with intuition. Later, I shall try to explain the basis of the discrepancy

giving us the illusion that the chains are shorter than they really are. There is a certain decay in the number of active chains over each remove, even when they do not drop out because they reach the target person. Of 160 chains that started in Nebraska, 44 were completed and 126 dropped out. These chains die before completion because on each remove a certain proportion of participants simply do not cooperate and fail to send on the folder. Thus, the results we obtained on the distribution of chain lengths occurred within the general

6th REMOVE
Printer in Sharon, Mass.

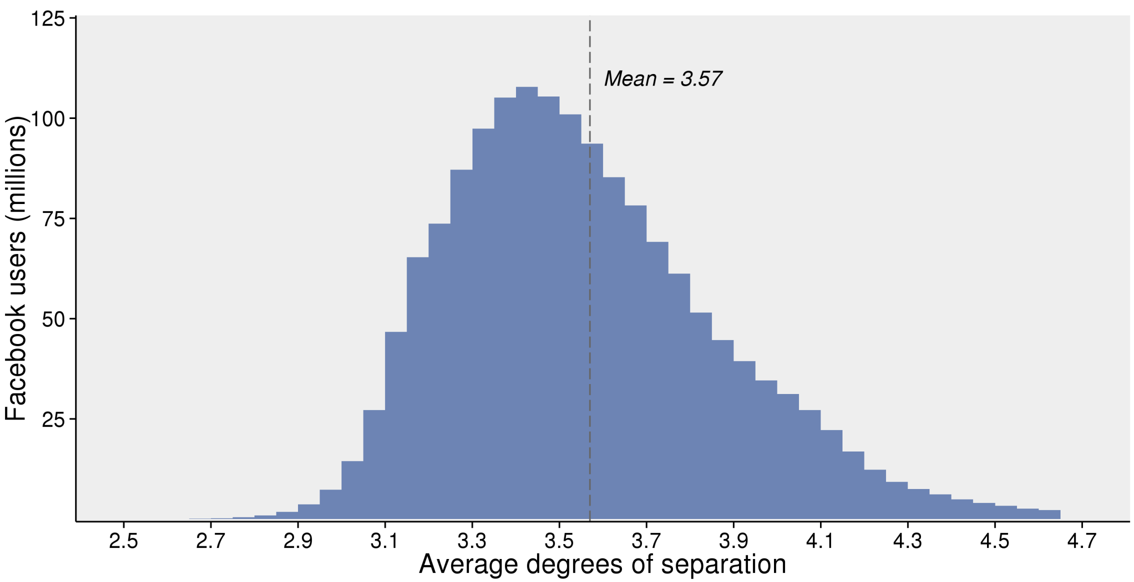
7th REMOVE
Clothing merchant in Sharon, Mass.

Participants indicated on the reply cards whether they were sending the folder on to a friend, a relative, or an acquaintance. In the Kansas Study, 123 sent the folder to friends and acquaintances, while only 22 sent it to relatives. Cross-cultural comparison would seem useful here. It is quite likely that in societies which possess extended kinship systems, relatives will be more heavily represented in the communication network than is true in the United States. In American society, where extended kinship links are not maintained, ac-

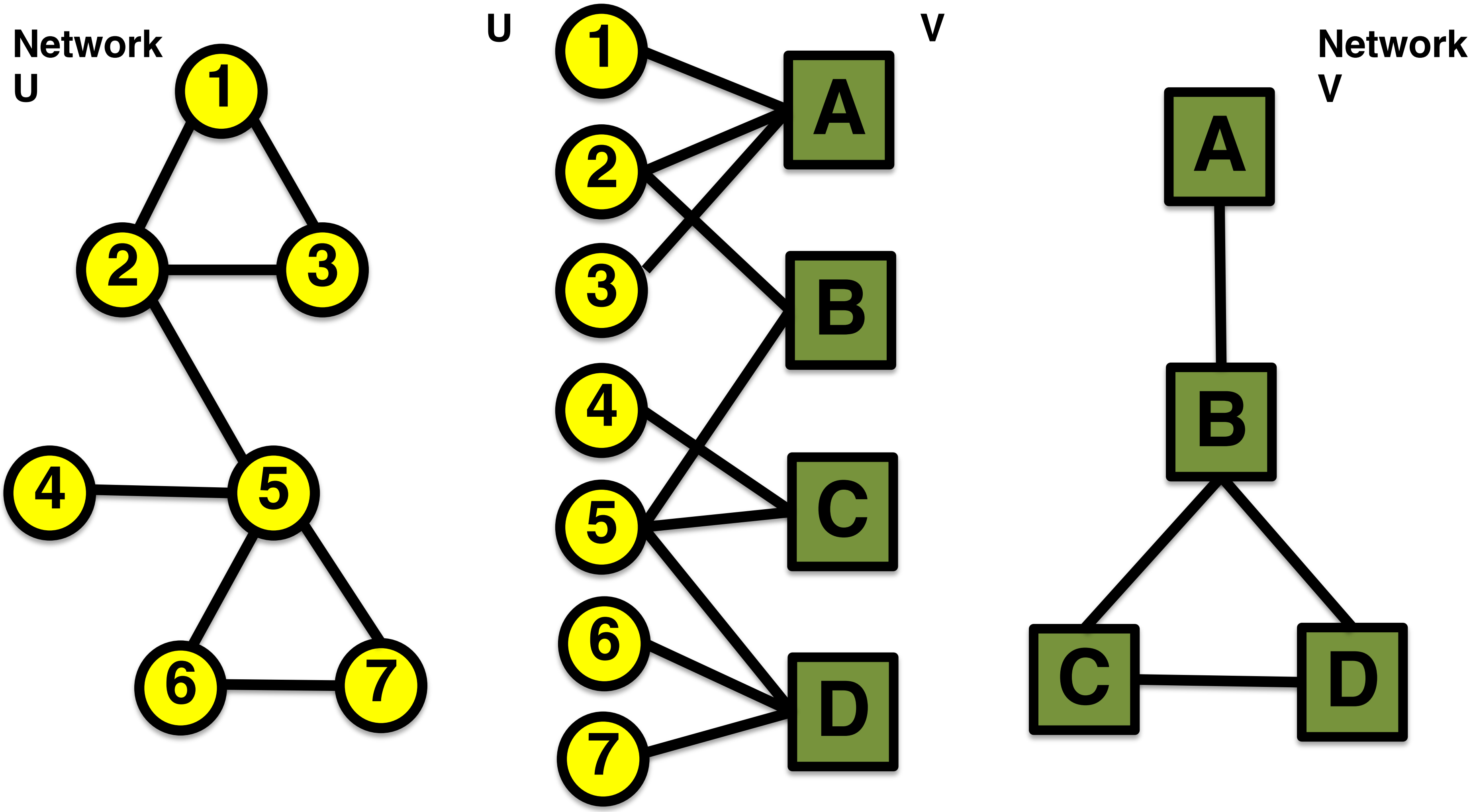
2) Small world

On average we are at six
Degrees of separation

Much less actually



3) Bipartite networks, clusters



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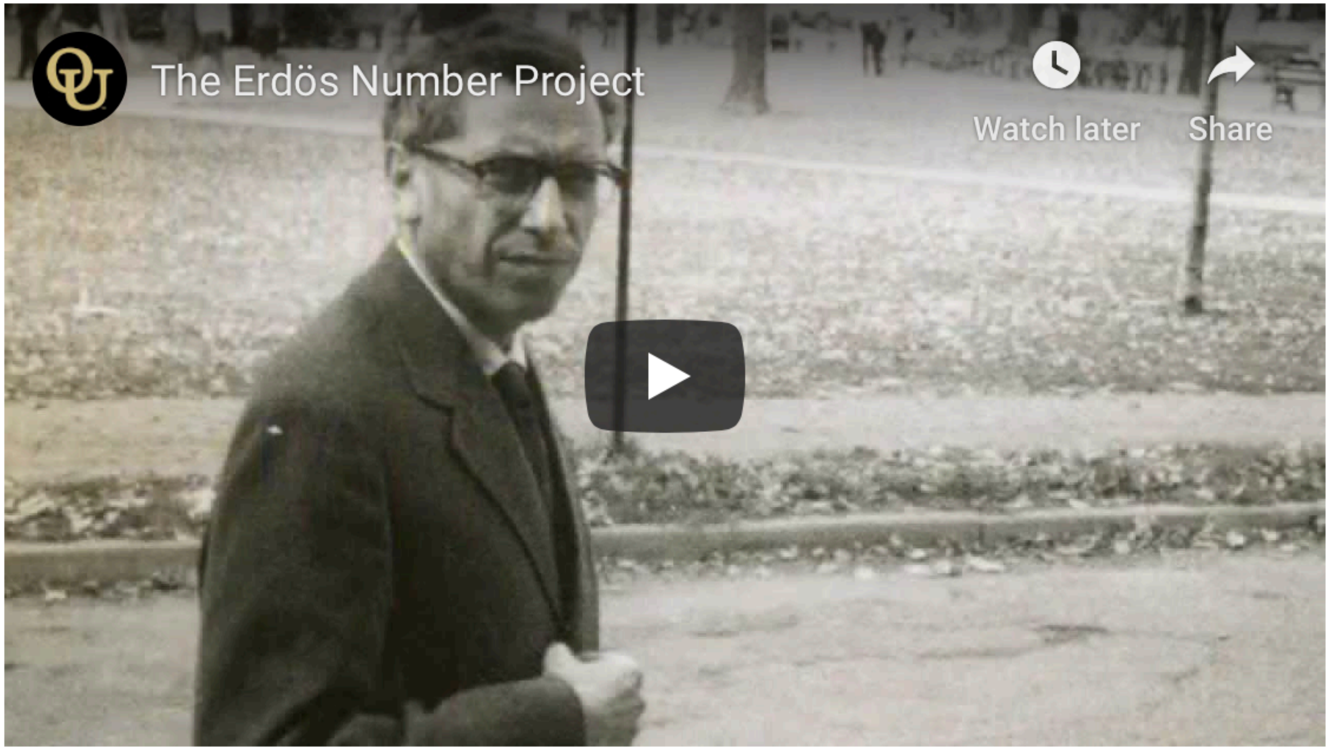
3) Bipartite networks, Erdos number



*Read Aug. 1, 2014 **News at OU article** on the popularity of this website.*

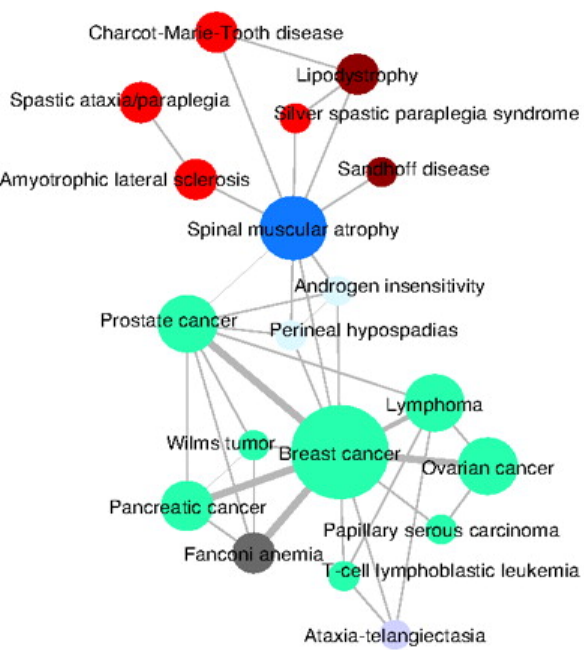
The Erdös Number Project

This is the website for the Erdös Number Project, which studies research collaboration among mathematicians.

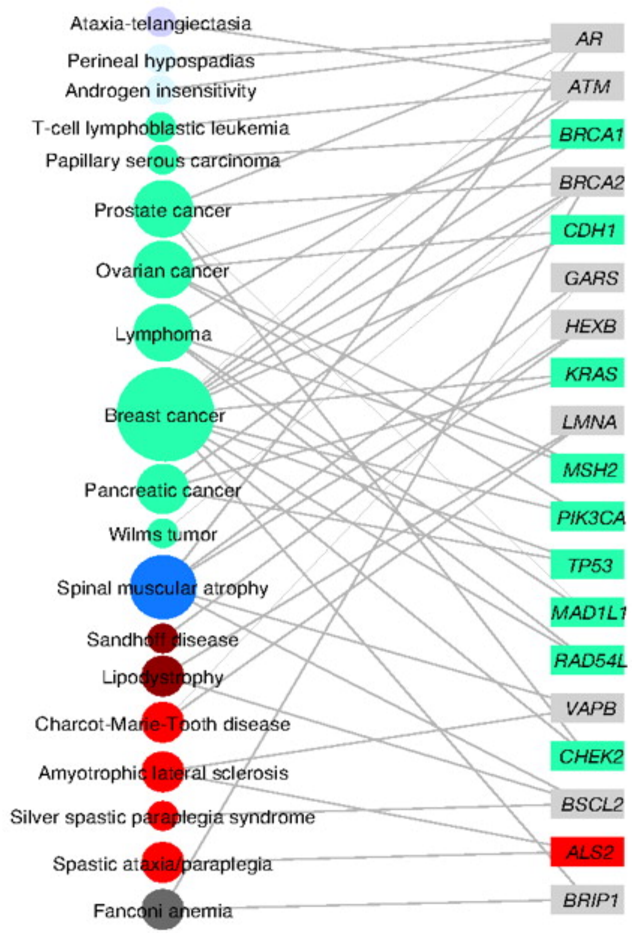
3) Bipartite networks, Bacon number

3) Bipartite networks, clusters

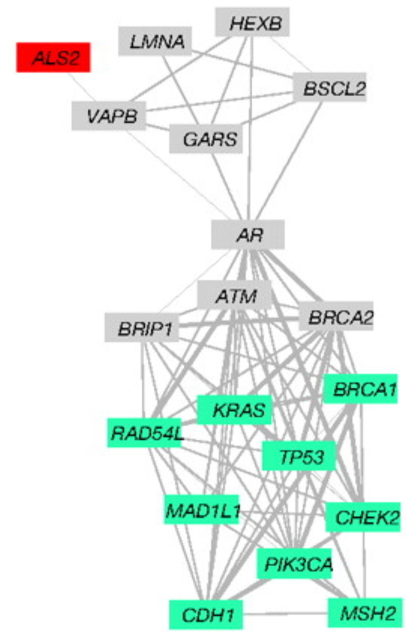
Human Disease Network (HDN)



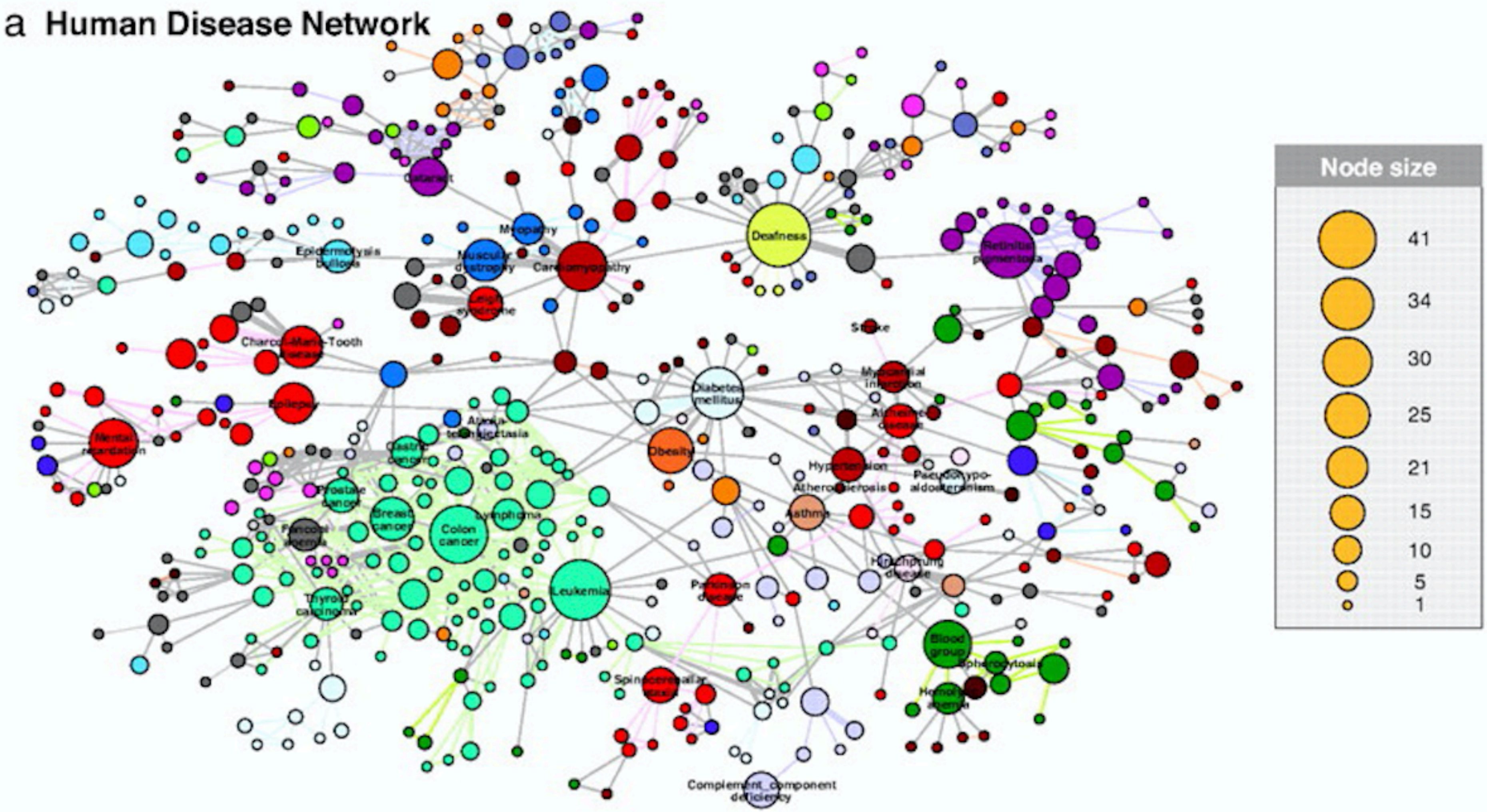
DISEASOME



Disease Gene Network (DGN)



3) Bipartite networks, clusters



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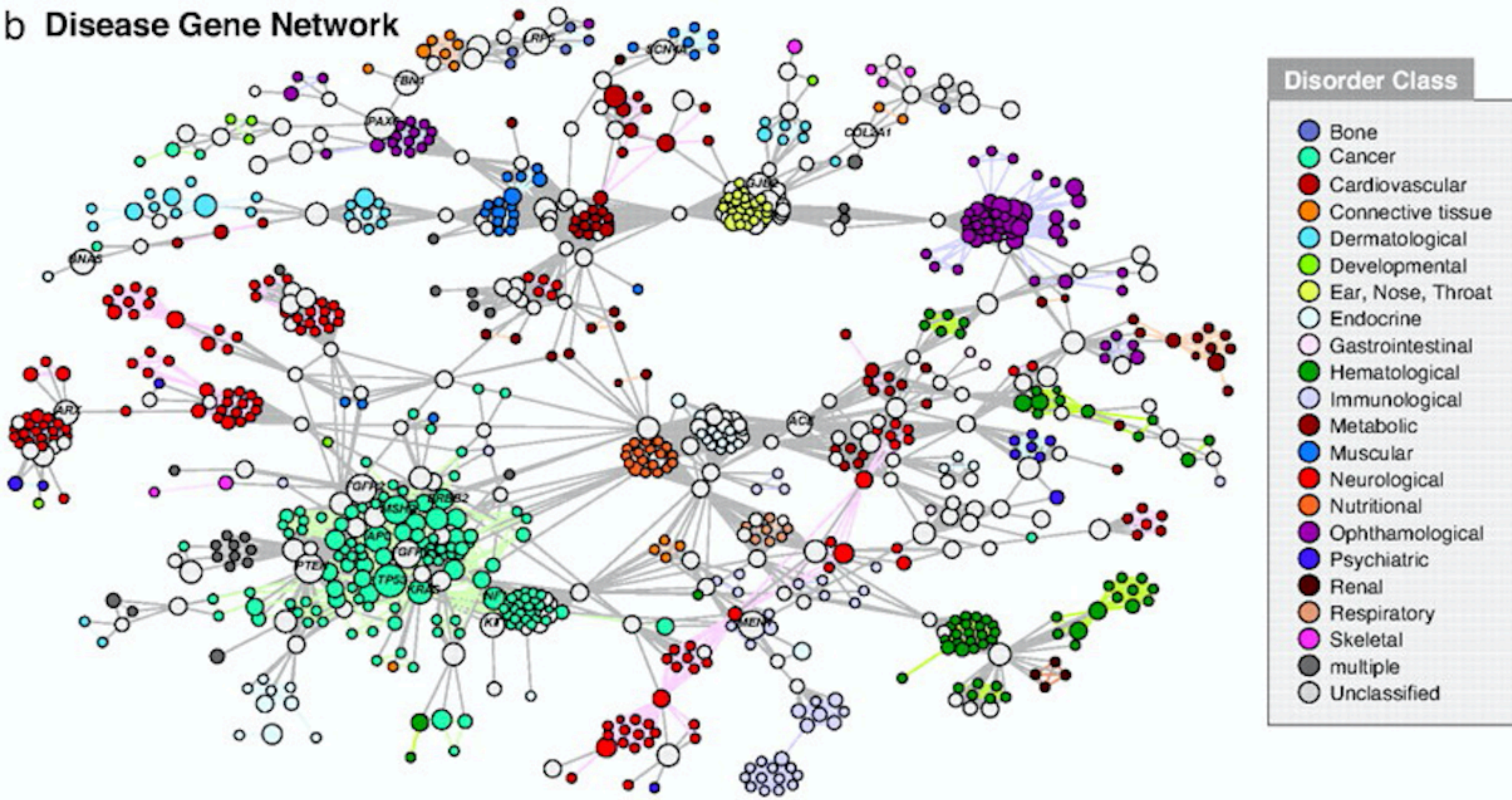
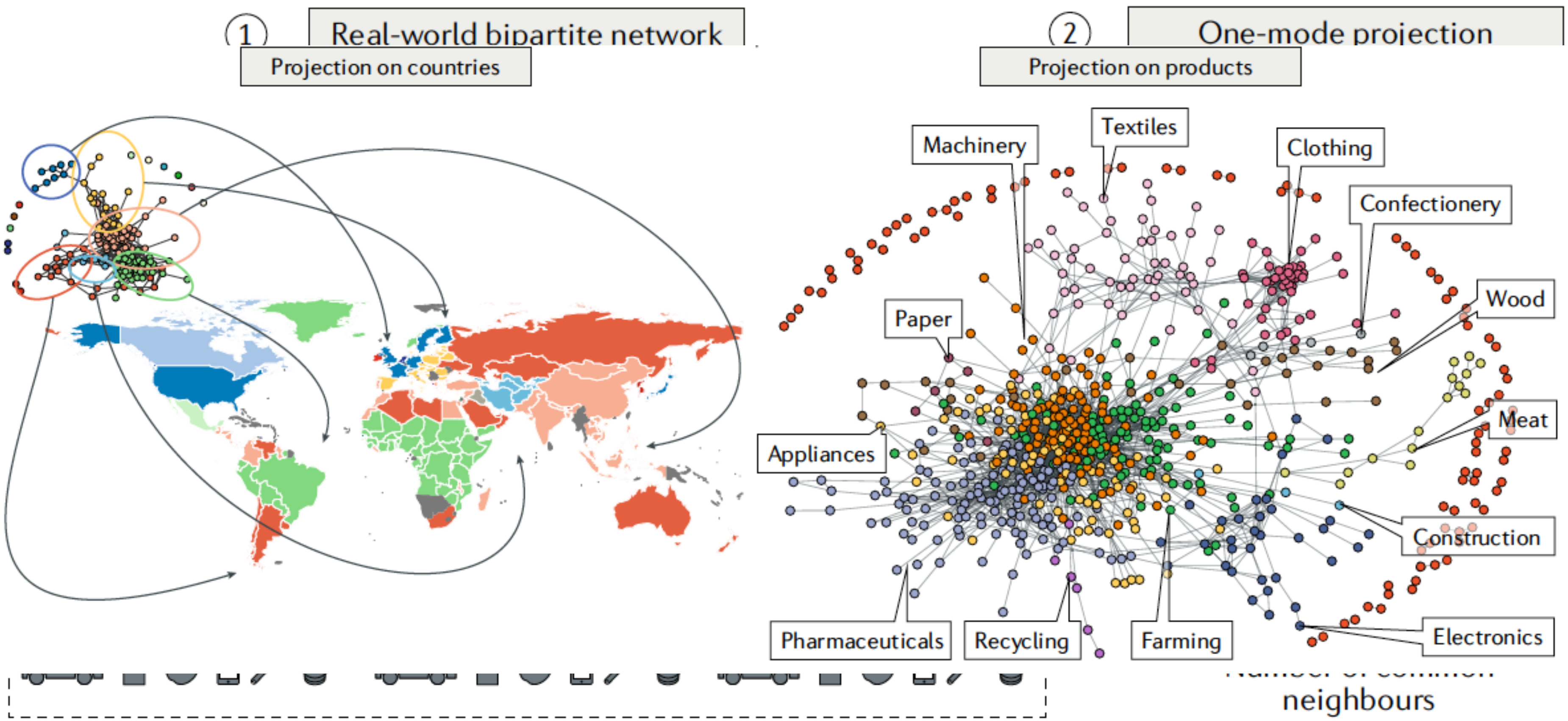
3) Bipartite networks, clusters



World Trade Web



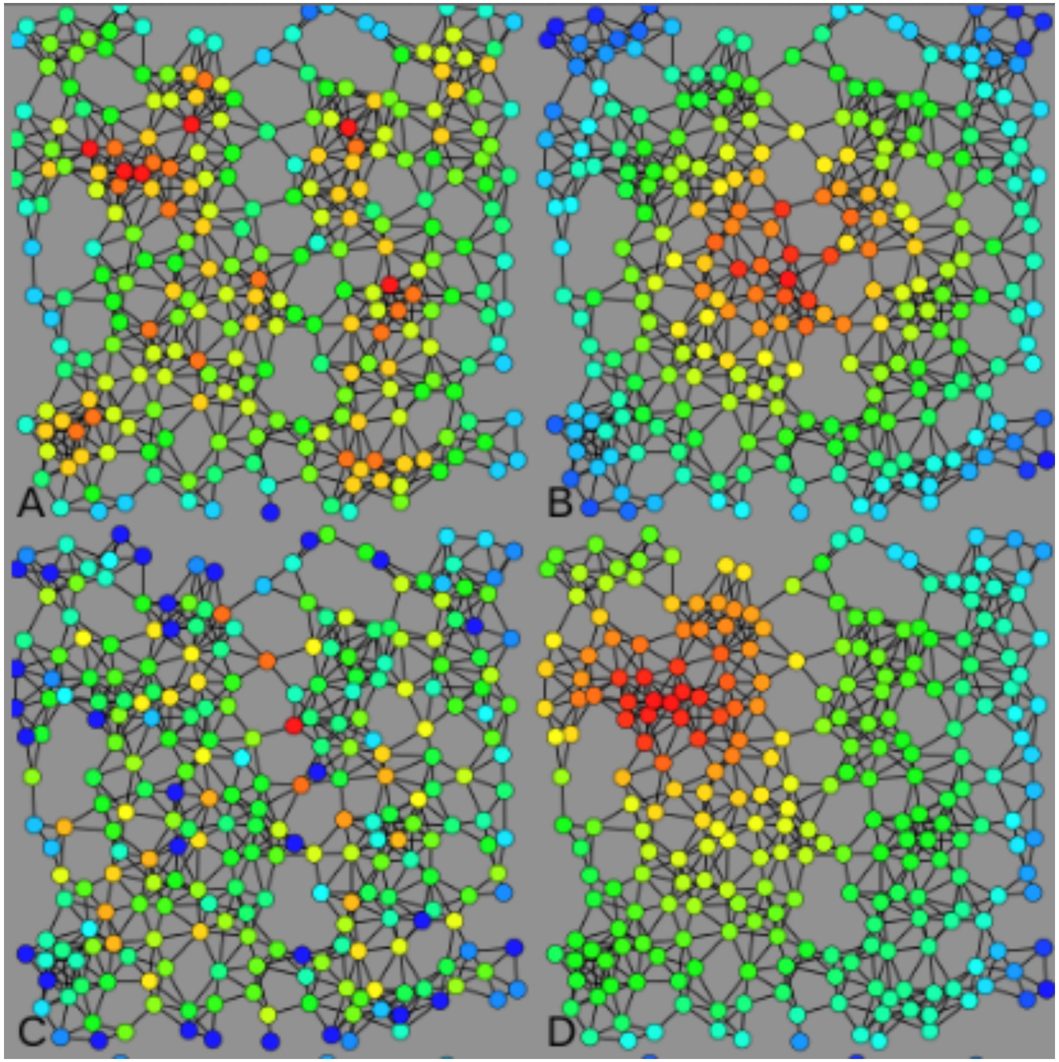
4) Centrality

A Degree Centrality

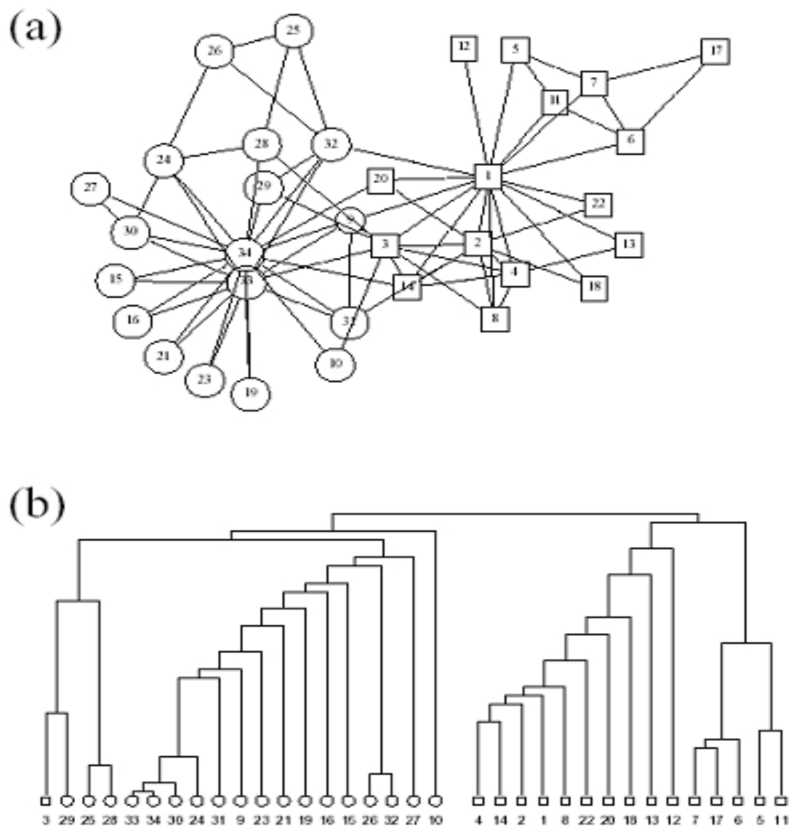
B Distance Centrality

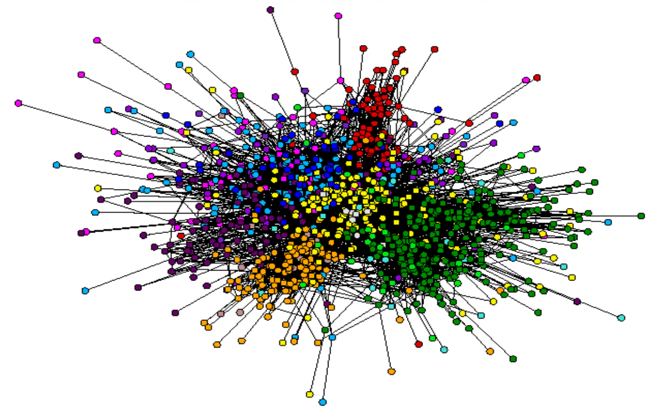
C Betweenness Centrality

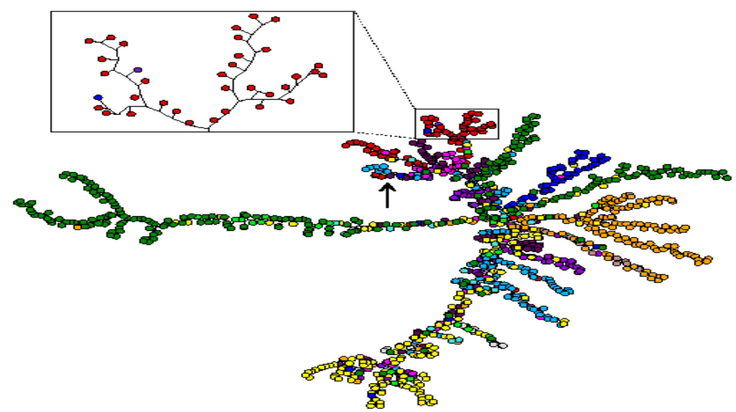
D Eigenvector Centrality



4) Clustering







(a)

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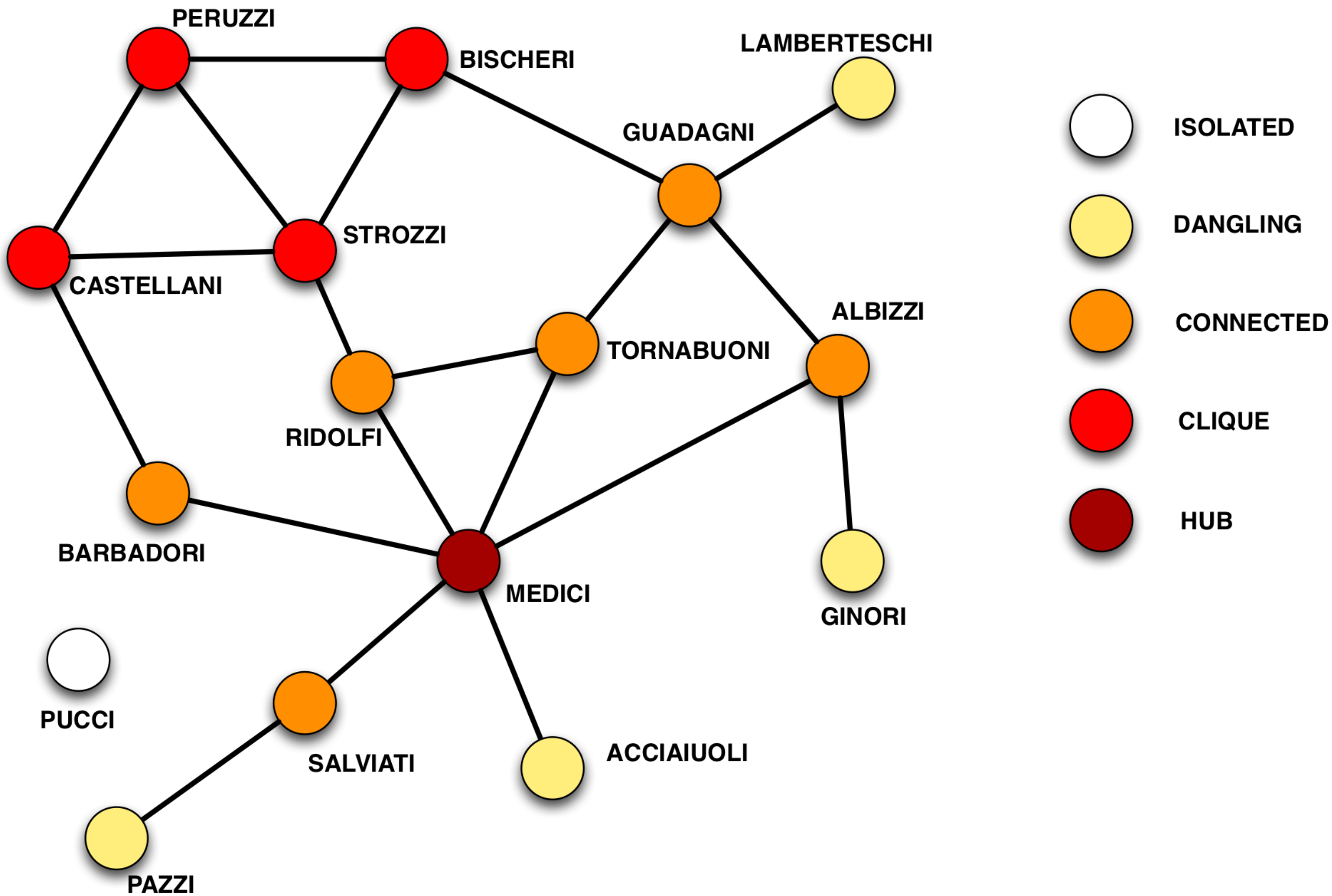
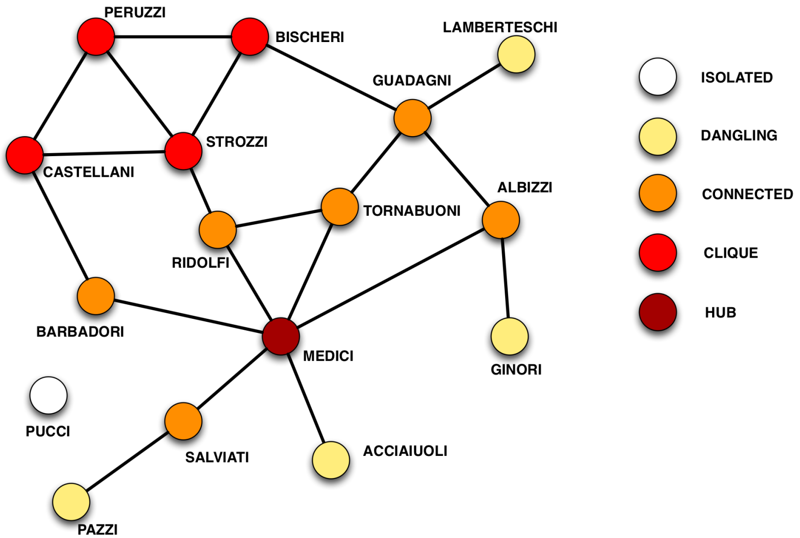
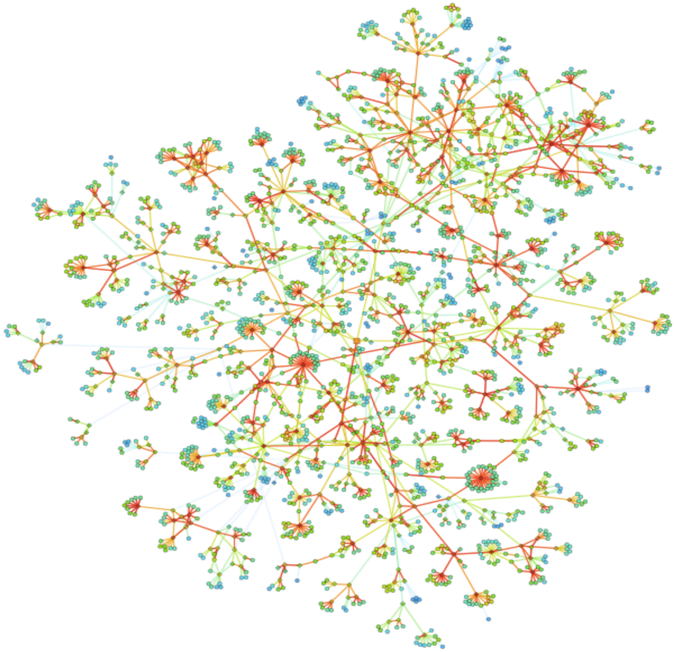
4) Centrality in politics



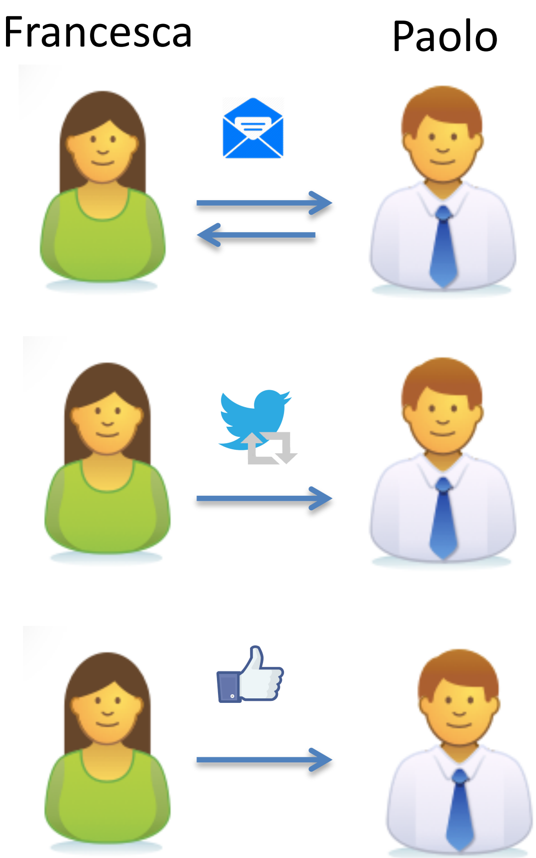
Our interactions are a network





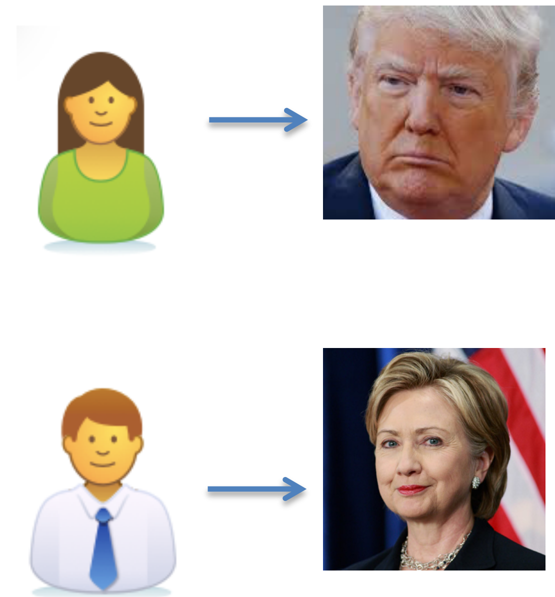
Networks and user profiling

Friendship



Goods

Political Opinions



Profiling is quite effective

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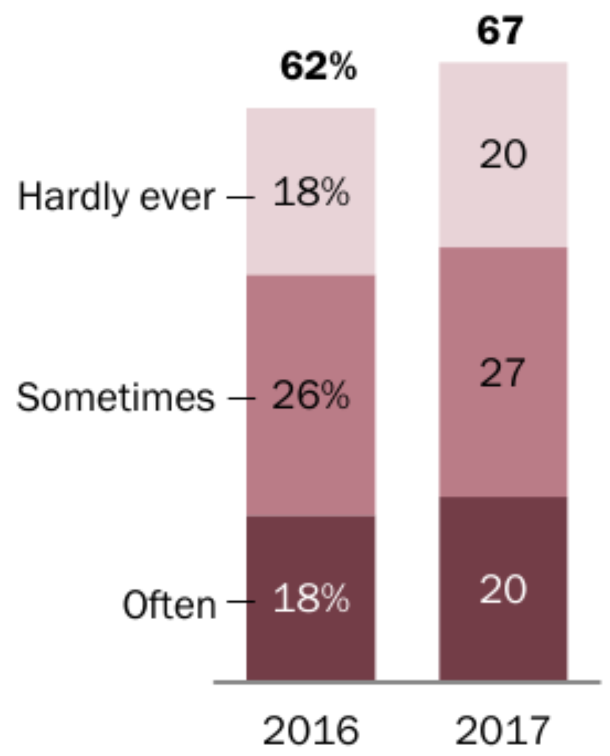
With great powers comes great responsibility (Spiderman)

2 Relevance

In 2016, roughly 50% of Americans aged 18-29 used online platforms as their primary source of news while 27% watched the news on television and 5% read print newspapers[Niklewicz 2017];

As of August 2017, two-thirds (67%) of US adults report that they get at least some of their news on social media[Shearer and Gottfried 2017];

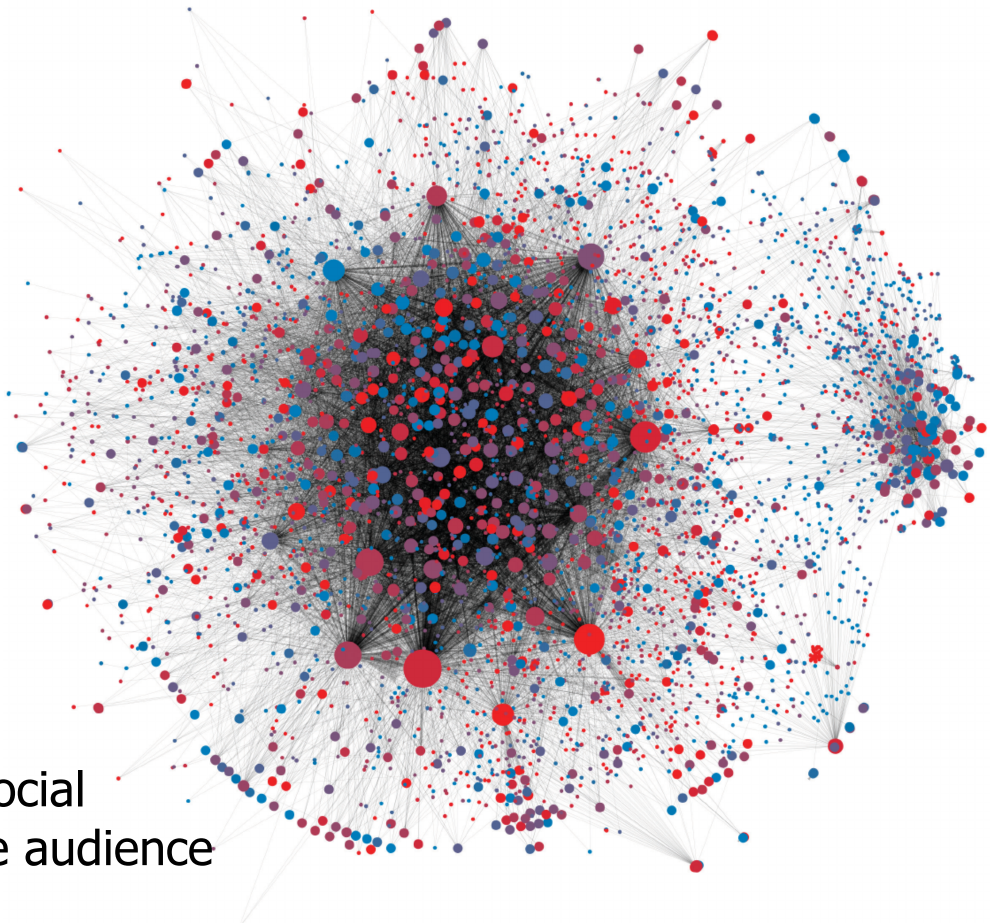
% of U.S. adults who get news from social media sites ...



Twitter networks

Retweet network for the #SB277 hashtag, about a California law on vaccination;

- The node size represents influence;
- The color represents bot scores:
  - red nodes: bot accounts;
  - blue nodes: humans.



Social bots can alter the perception of social media influence, artificially enlarging the audience of some topics[Ferrara et al. 2017]

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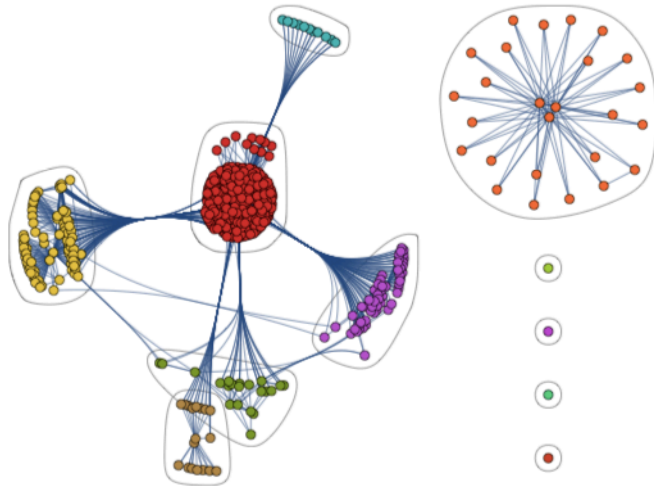
Latest results

Data mining has revealed previously unknown Russian Twitter troll campaigns

Trolls left forensic fingerprints that cybersecurity experts used to find other disinformation campaigns both in the US and elsewhere.

by Emerging Technology from the arXiv   October 11, 2018



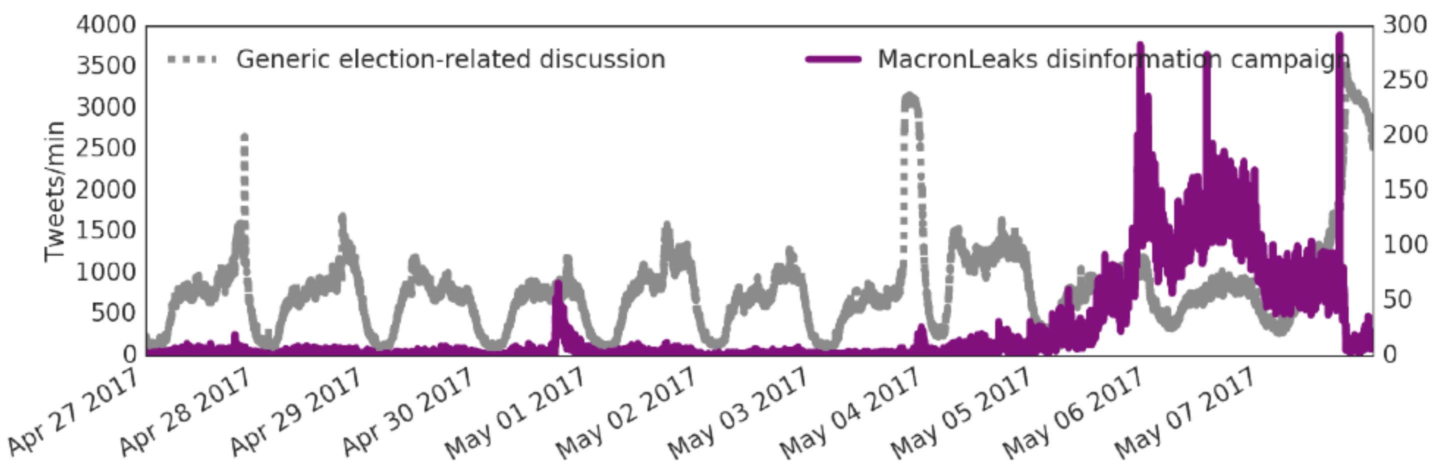
arxiv.org/abs/1810.01466 : Unsupervised Machine Learning of Open Source Russian Twitter Data Reveals Global Scope and Operational Characteristics

Emotions

Manipulation of public opinion:

- **Societal debate interference**: misinformation may strongly influence individuals' beliefs on several topics, (e.g effectiveness of vaccination[Schmidt et al. 2018]);
- **Disinformation** in political campaign: massive diffusion of fake news on social media during the 2017 French presidential elections [Ferrara 2017] and the 2016 US presidential elections [Shao et al. 2018].

Timeline of the tweets volume generated every minute during April 27, 2017 through May 7, 2017 (French presidential election date).

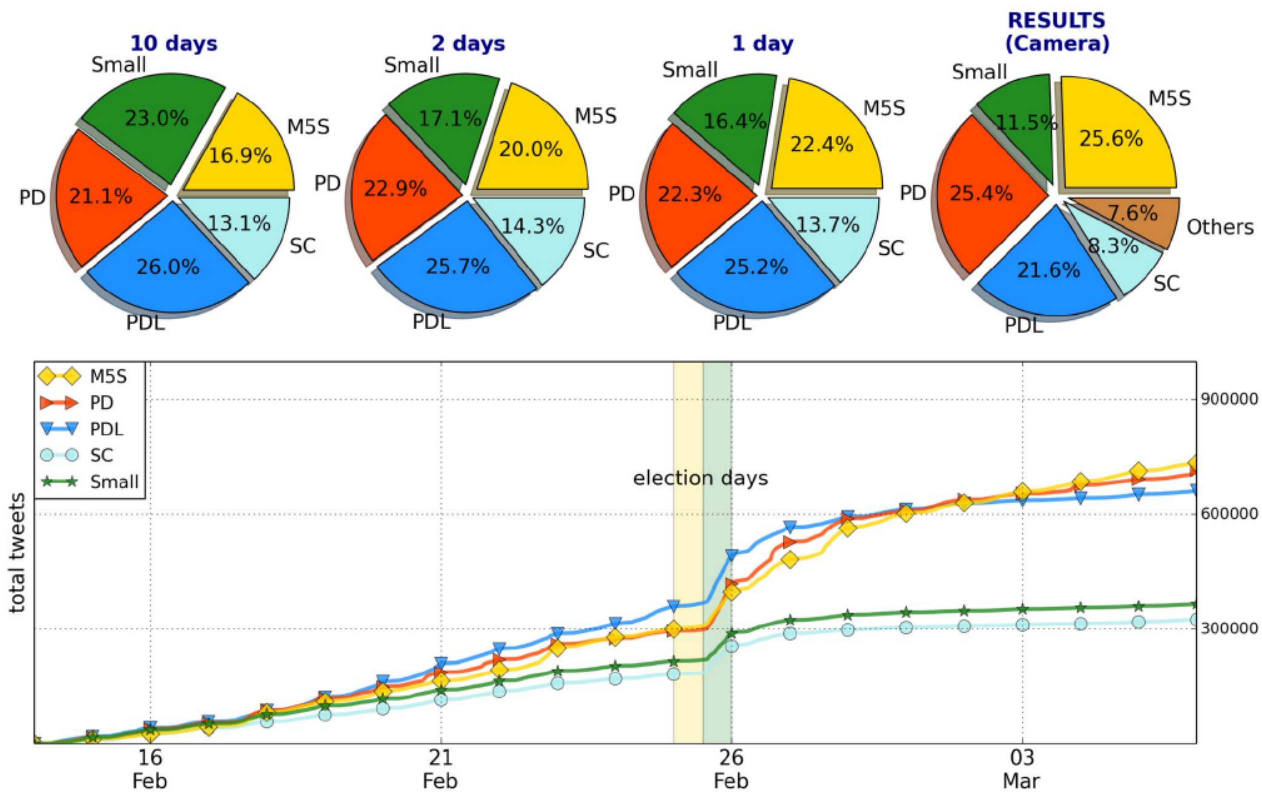


Purple line: tweets on MacronLeaks;
Gray line: tweets on generic election-related discussion

Study of Twitter votes

A Multi-Level Geographical Study of Italian Political Elections from Twitter Data

Guido Caldarelli[1,2,3,4], Alessandro Chessa[1,4], Fabio Pammolli[1,5], Gabriele Pompa[1], Michelangelo Puliga[1,4]*, Massimo Riccaboni[1,6], Gianni Riotta[1,7]



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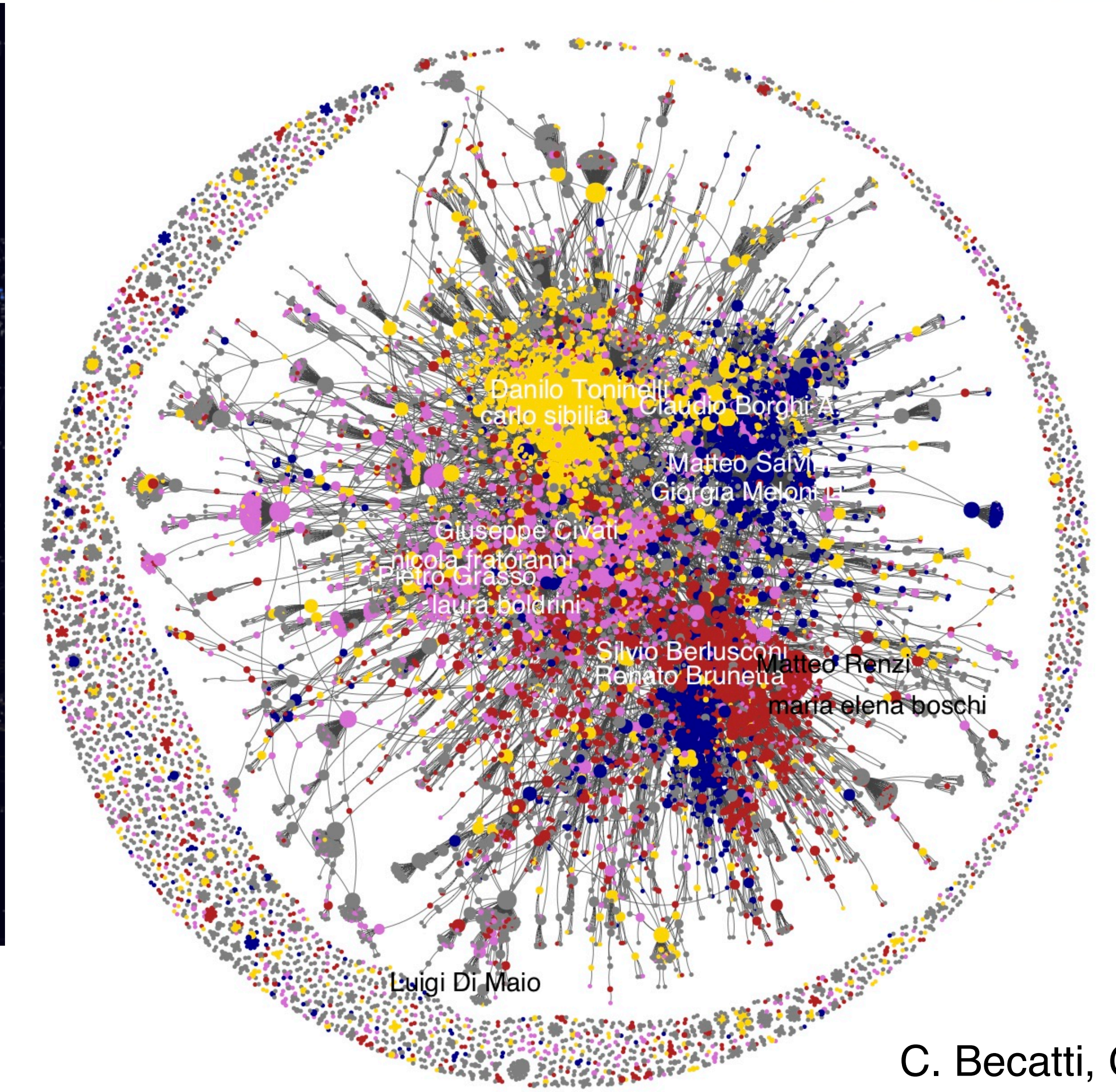
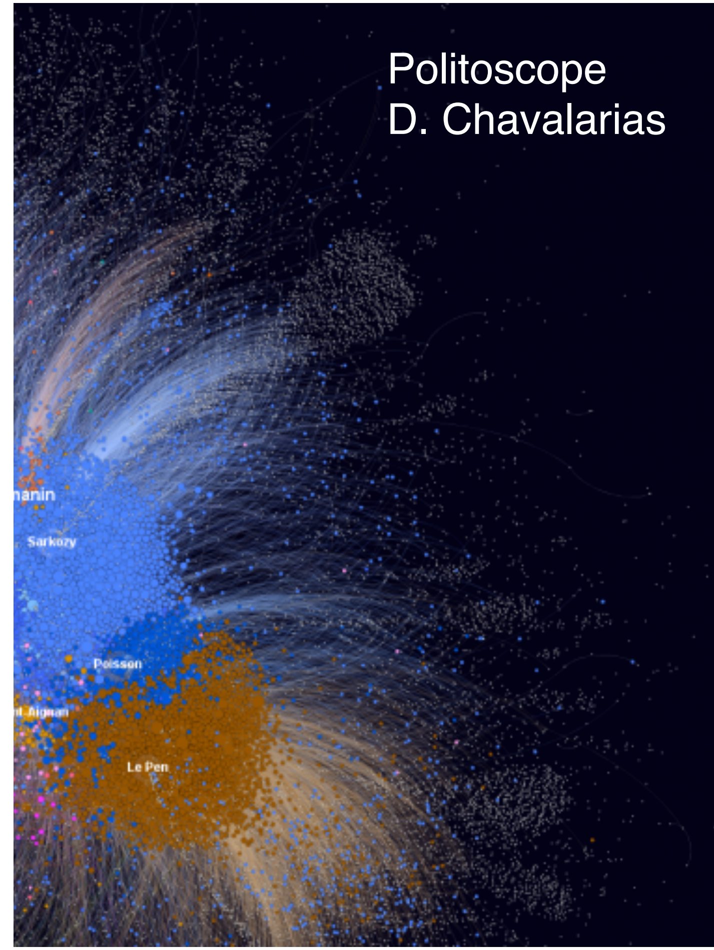
Centrality in political debate (France-Italy)





C. Becatti, G.C. R. Lambiotte, F. Saracco

Applications

Other than Economics and Medicine:

Intelligence: we can track down the network of terrorists

Finance: for systemic risk in the interbank market

Brain: for diagnosis and analysis of diseases

Intelligence and Networks

1. Incompleteness – the inevitability of missing nodes and links that the investigators will not uncover.
2. Fuzzy boundaries – the difficulty in deciding who to include and who not to include.
3. Dynamic – these networks are not static, they are always changing. Instead of looking at the presence or absence of a tie between two individuals, Sparrow suggests looking at the waxing and waning strength of a tie depending upon the time and the task at hand.

Twin Towers atack 11 September 2001

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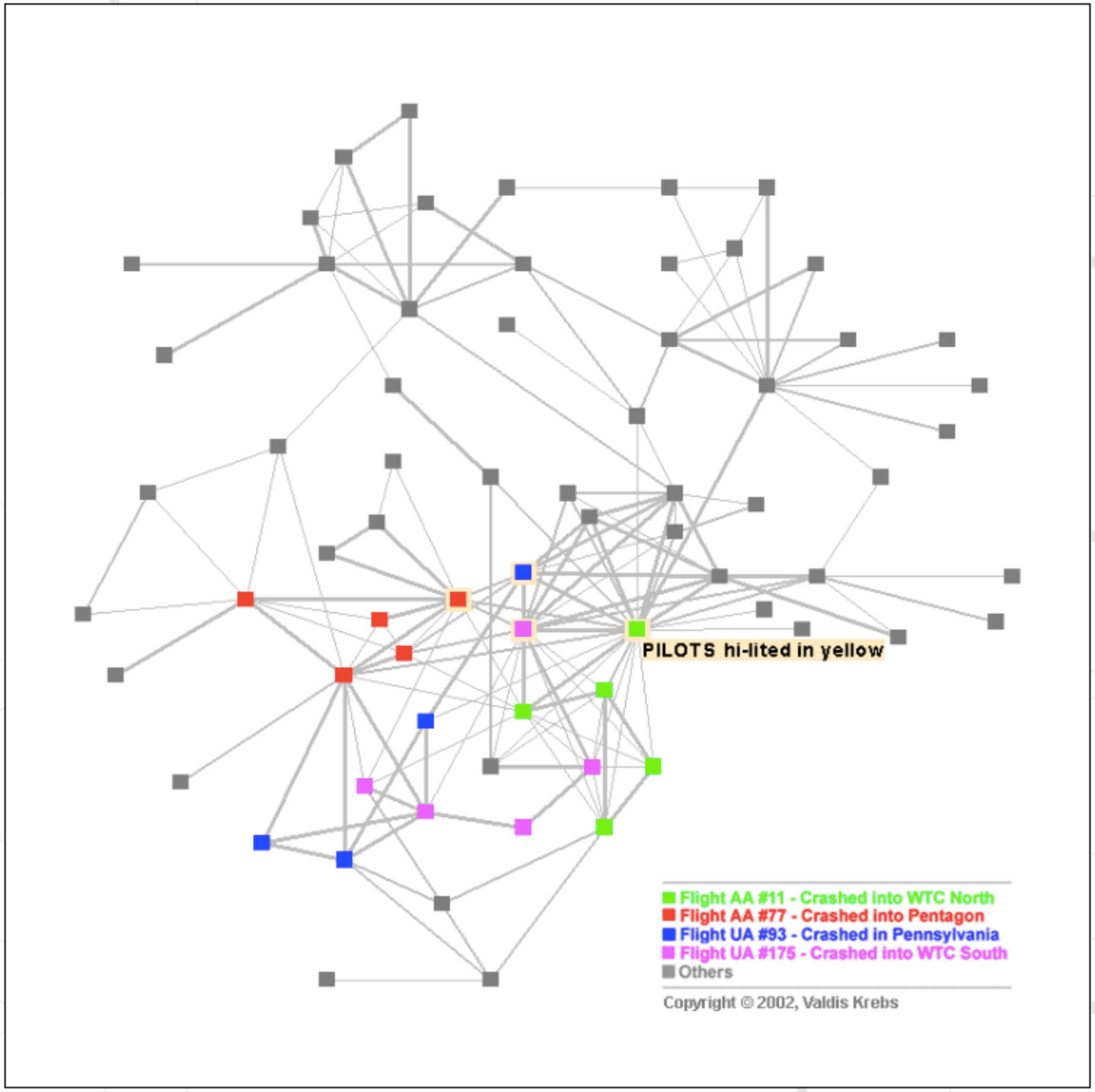
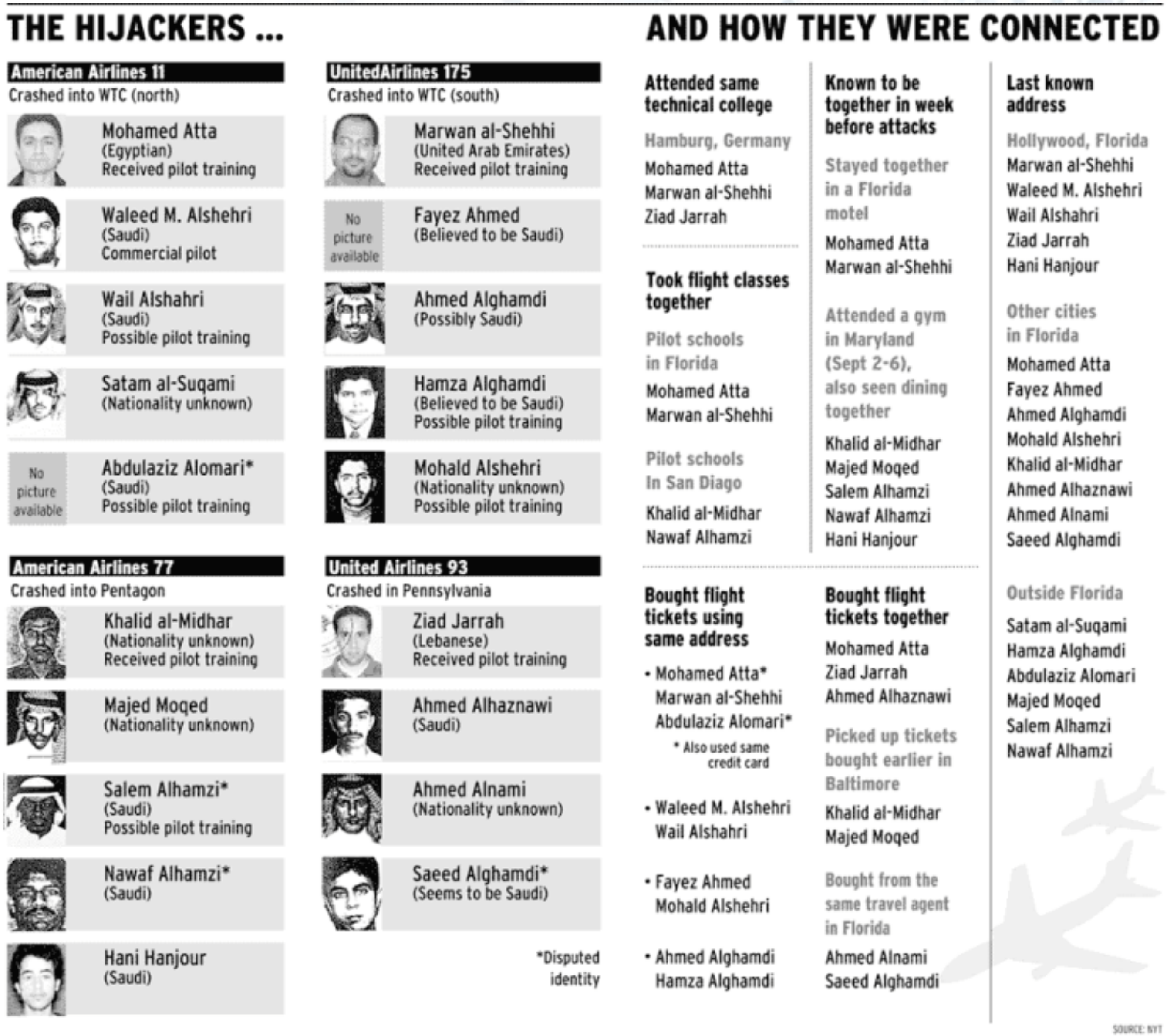
Network of attackers



Attackers



THE HIJACKERS ... AND HOW THEY WERE CONNECTED

American Airlines 11
Crashed into WTC (north)

- Mohamed Atta (Egyptian) Received pilot training
- Waleed M. Alshehri (Saudi) Commercial pilot
- Wail Alshahri (Saudi) Possible pilot training
- Satam al-Suqami (Nationality unknown)
- Abdulaziz Alomari* (Saudi) Possible pilot training — No picture available

UnitedAirlines 175
Crashed into WTC (south)

- Marwan al-Shehhi (United Arab Emirates) Received pilot training
- Fayez Ahmed (Believed to be Saudi) — No picture available
- Ahmed Alghamdi (Possibly Saudi)
- Hamza Alghamdi (Believed to be Saudi) Possible pilot training
- Mohald Alshehri (Nationality unknown) Possible pilot training

American Airlines 77
Crashed into Pentagon

- Khalid al-Midhar (Nationality unknown) Received pilot training
- Majed Moqed (Nationality unknown)
- Salem Alhamzi* (Saudi) Possible pilot training
- Nawaf Alhamzi* (Saudi)
- Hani Hanjour (Saudi)

United Airlines 93
Crashed in Pennsylvania

- Ziad Jarrah (Lebanese) Received pilot training
- Ahmed Alhaznawi (Saudi)
- Ahmed Alnami (Nationality unknown)
- Saeed Alghamdi* (Seems to be Saudi)

*Disputed identity

Attended same technical college
Hamburg, Germany
Mohamed Atta
Marwan al-Shehhi
Ziad Jarrah

Took flight classes together
Pilot schools in Florida
Mohamed Atta
Marwan al-Shehhi

Pilot schools In San Diago
Khalid al-Midhar
Nawaf Alhamzi

Known to be together in week before attacks
Stayed together in a Florida motel
Mohamed Atta
Marwan al-Shehhi

Attended a gym in Maryland (Sept 2-6), also seen dining together
Khalid al-Midhar
Majed Moqed
Salem Alhamzi
Nawaf Alhamzi
Hani Hanjour

Last known address
Hollywood, Florida
Marwan al-Shehhi
Waleed M. Alshehri
Wail Alshahri
Ziad Jarrah
Hani Hanjour

Other cities in Florida
Mohamed Atta
Fayez Ahmed
Ahmed Alghamdi
Mohald Alshehri
Khalid al-Midhar
Ahmed Alhaznawi
Ahmed Alnami
Saeed Alghamdi

Outside Florida
Satam al-Suqami
Hamza Alghamdi
Abdulaziz Alomari
Majed Moqed
Salem Alhamzi
Nawaf Alhamzi

Bought flight tickets using same address
- Mohamed Atta*
  Marwan al-Shehhi
  Abdulaziz Alomari*
  * Also used same credit card
- Waleed M. Alshehri
  Wail Alshahri
- Fayez Ahmed
  Mohald Alshehri
- Ahmed Alghamdi
  Hamza Alghamdi

Bought flight tickets together
Mohamed Atta
Ziad Jarrah
Ahmed Alhaznawi

Picked up tickets bought earlier in Baltimore
Khalid al-Midhar
Majed Moqed

Bought from the same travel agent in Florida
Ahmed Alnami
Saeed Alghamdi

SOURCE: NYT

Attackers

Degrees		Betweenness		Closeness	
0.417	Mohamed Atta	0.334	Nawaf Alhazmi	0.571	Mohamed Atta
0.389	Marwan Al-Shehhi	0.318	Mohamed Atta	0.537	Nawaf Alhazmi
0.278	Hani Hanjour	0.227	Hani Hanjour	0.507	Hani Hanjour
0.278	Nawaf Alhazmi	0.158	Marwan Al-Shehhi	0.500	Marwan Al-Shehhi
0.278	Ziad Jarrah	0.116	Saeed Alghamdi*	0.480	Ziad Jarrah
0.222	Ramzi Bin al-Shibh	0.081	Hamza Alghamdi	0.429	Mustafa al-Hisawi
0.194	Said Bahaji	0.080	Waleed Alshehri	0.429	Salem Alhazmi*
0.167	Hamza Alghamdi	0.076	Ziad Jarrah	0.424	Lotfi Raissi
0.167	Saeed Alghamdi*	0.064	Mustafa al-Hisawi	0.424	Saeed Alghamdi*
0.139	Lotfi Raissi	0.049	Abdul Aziz Al-Omari*	0.419	Abdul Aziz Al-Omari*
0.139	Zakariya Essabar	0.033	Satam Suqami	0.414	Hamza Alghamdi
0.111	Agus Budiman	0.031	Fayez Ahmed	0.414	Ramzi Bin al-Shibh
0.111	Khalid Al-Mihdhar	0.030	Ahmed Al Haznawi	0.409	Said Bahaji
0.111	Mounir El Motassadeq	0.026	Nabil al-Marabh	0.404	Ahmed Al Haznawi
0.111	Mustafa al-Hisawi	0.016	Raed Hijazi	0.400	Zakariya Essabar
0.111	Nabil al-Marabh	0.015	Lotfi Raissi	0.396	Agus Budiman
0.111	Rayed Abdullah	0.012	Mohand Alshehri*	0.396	Khalid Al-Mihdhar
0.111	Satam Suqami	0.011	Khalid Al-Mihdhar	0.391	Ahmed Alnami
0.111	Waleed Alshehri	0.010	Ramzi Bin al-Shibh	0.391	Mounir El Motassadeq
0.083	Abdul Aziz Al-Omari*	0.007	Salem Alhazmi*	0.387	Fayez Ahmed
0.083	Abdussattar Shaikh	0.004	Ahmed Alghamdi	0.387	Mamoun Darkazanli
0.083	Ahmed Al Haznawi	0.004	Said Bahaji	0.371	Zacarias Moussaoui
0.083	Ahmed Alnami	0.002	Rayed Abdullah	0.367	Ahmed Khalil Al-Ani
0.083	Fayez Ahmed	0.000	Abdussattar Shaikh	0.360	Abdussattar Shaikh

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Financial Networks

nature physics

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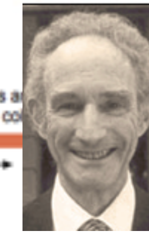

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ARTICLE

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DOI: 10.1038/ncomms14416

OPEN

Pathways towards instability in financial networks

Marco Bardoscia[1,2], Stefano Battiston[1], Fabio Caccioli[3,4] & Guido Caldarelli[2,5,6]

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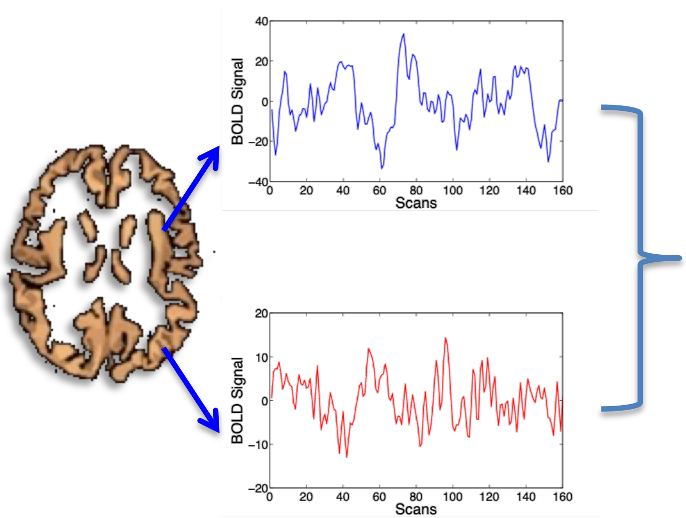
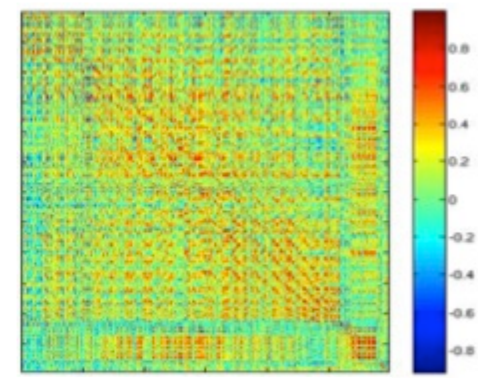
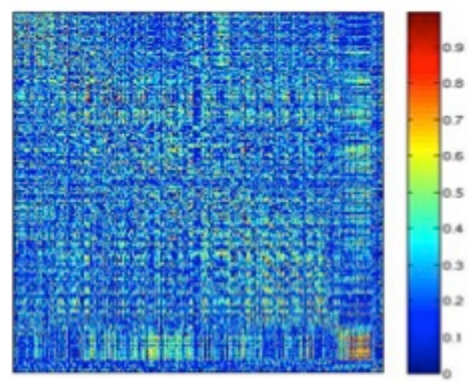
Research question: Brain Networks

We can extract information on Functional Magnetic Resonance Imaging



$$r = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{N}(y_i - \bar{y})^2}}$$

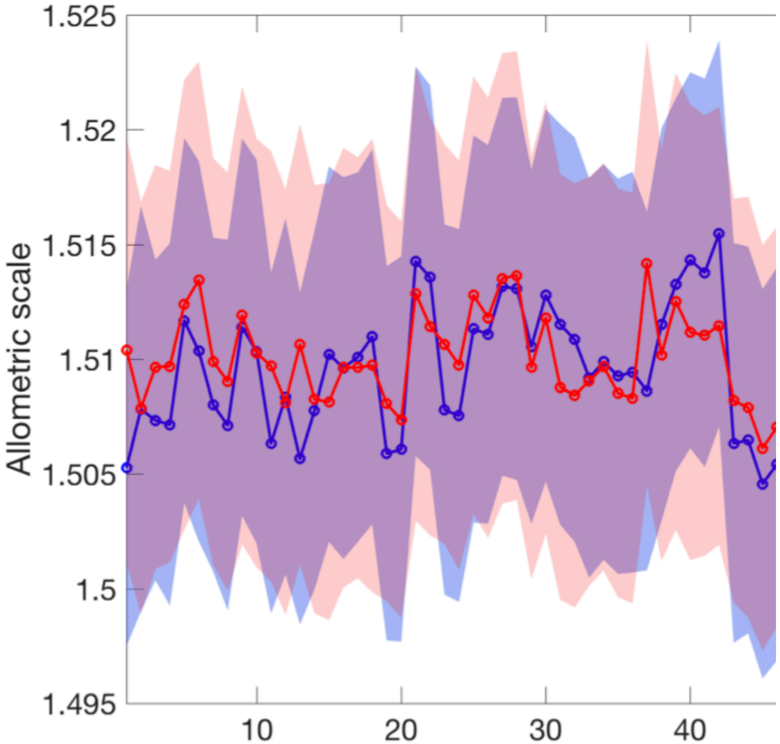




$$r \rightarrow r^2$$

R. Mastrandrea, F. Piras, A. Gabrielli, G. Caldarelli, G. Spalletta, T. Gili
arXiv:1901.08521

Research question: Brain Networks



Allometric scale: first rank MST

Healthy subjects   Schizophrenic patients

Can we use Networks for Disease Diagnosis ?

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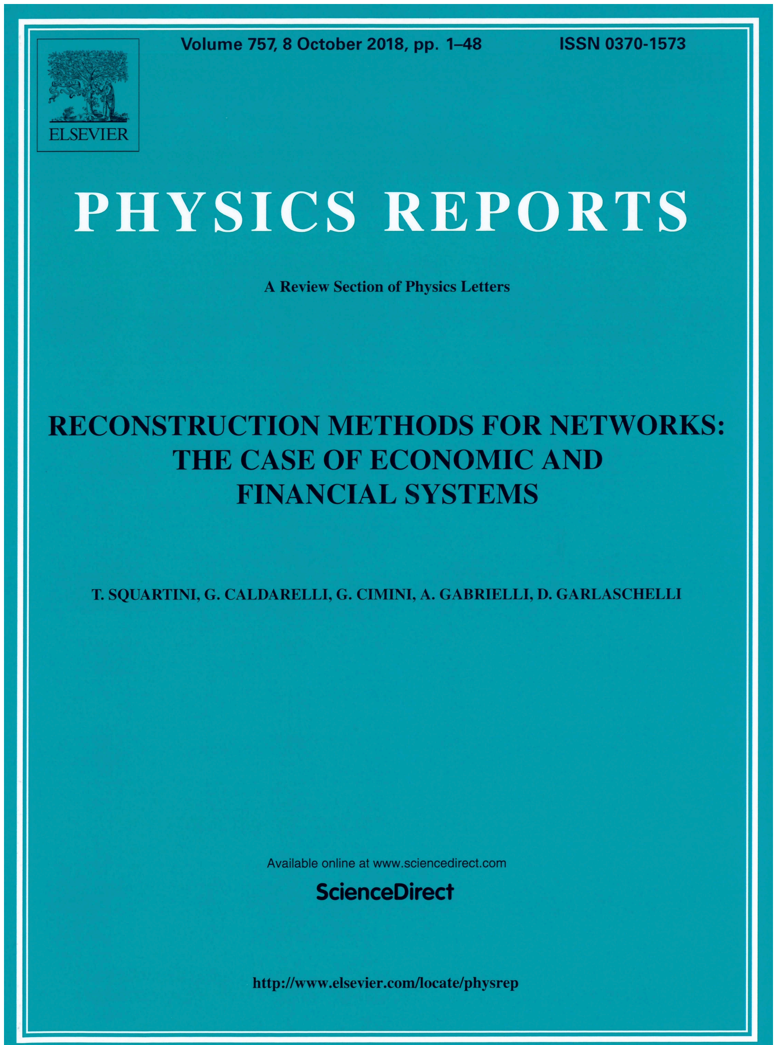
Statistical Physics of Networks


Volume 757, 8 October 2018, pp. 1–48 ISSN 0370-1573

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PHYSICS REPORTS

A Review Section of Physics Letters

RECONSTRUCTION METHODS FOR NETWORKS: THE CASE OF ECONOMIC AND FINANCIAL SYSTEMS

T. SQUARTINI, G. CALDARELLI, G. CIMINI, A. GABRIELLI, D. GARLASCHELLI

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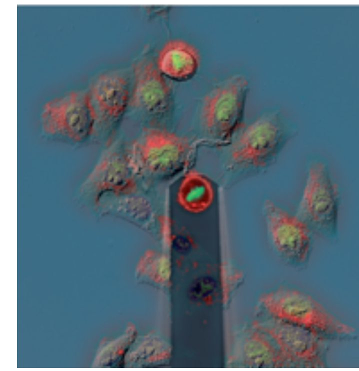


TECHNICAL REVIEWS

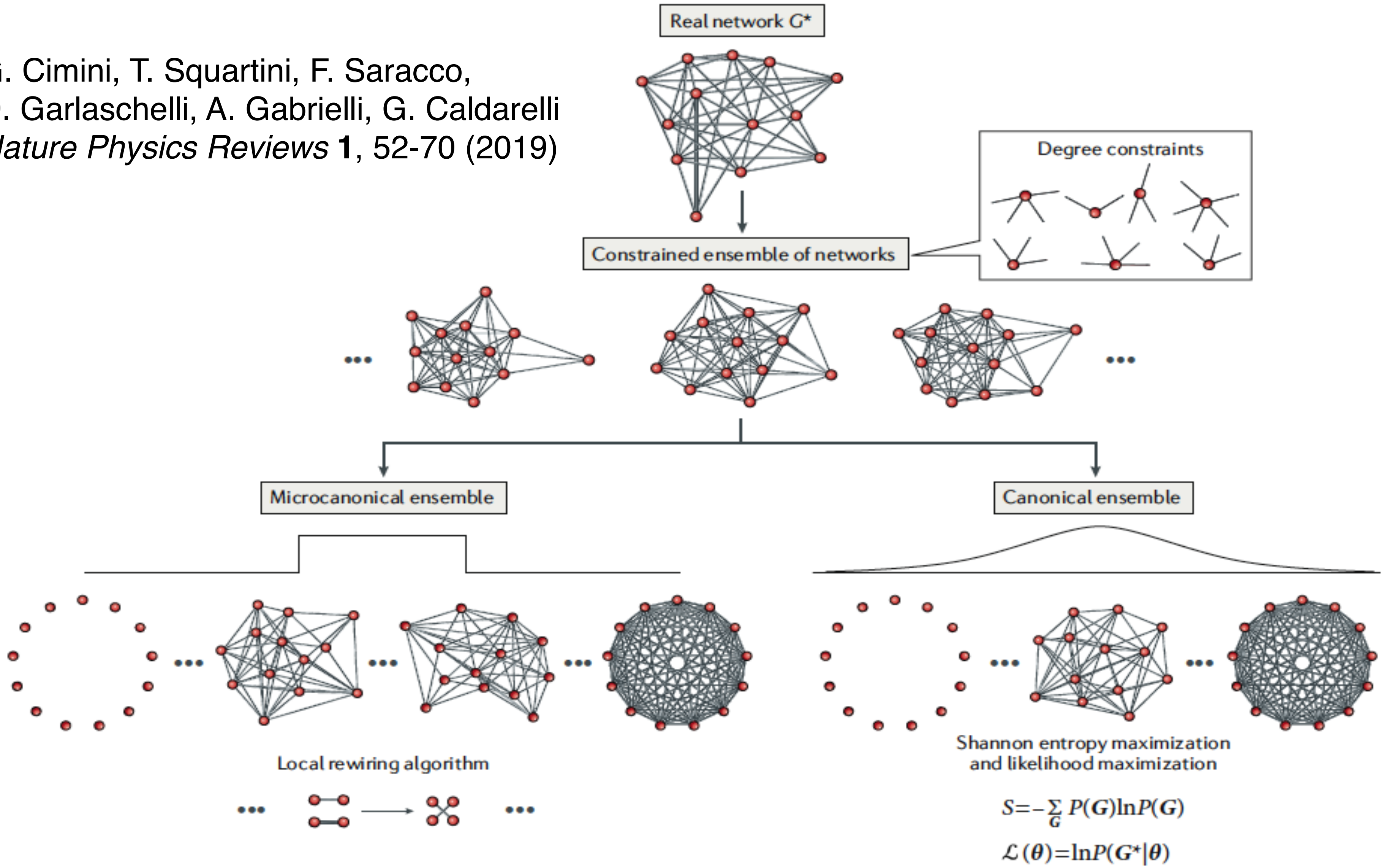
The statistical physics of real-world networks

*Giulio Cimini[1,2], Tiziano Squartini[1], Fabio Saracco[1], Diego Garlaschelli[1,3], Andrea Gabrielli[1,2] and Guido Caldarelli[1,2,4,5]**

Abstract | In the past 15 years, statistical physics has been successful as a framework for modelling complex networks. On the theoretical side, this approach has unveiled a variety of physical phenomena, such as the emergence of mixed distributions and ensemble non-equivalence, that are observed in heterogeneous networks but not in homogeneous systems. At the same time, thanks to the deep connection between the principle of maximum entropy and information theory, statistical physics has led to the definition of null models for networks that reproduce features of real-world systems but that are otherwise as random as possible. We review here the statistical physics approach and the null models for complex networks, focusing in particular on analytical frameworks that reproduce local network features. We show how these models have been used to detect statistically significant structural patterns in real-world networks and to reconstruct the network structure in cases of incomplete information. We further survey the statistical physics models that reproduce more complex, semilocal network features using Markov chain Monte Carlo sampling, as well as models of generalized network structures, such as multiplex networks, interacting networks and simplicial complexes.

Reconstructing from partial information

G. Cimini, T. Squartini, F. Saracco,
D. Garlaschelli, A. Gabrielli, G. Caldarelli
Nature Physics Reviews **1**, 52-70 (2019)



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Concluding

COMPLEX NETWORKS

ALLOW TO MEASURE (QUANTITATIVELY) SEVERAL RELATIONS

DESCRIBES DYNAMICAL PROCESSES AND TIME SERIES

MODELS THE EMERGENCE OF COMPLEXITY

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A Societal challenge

nature physics

correspondence

G. Caldarelli, S. Wolf, Y. Moreno *Nature Physics* **14** 870 (2018).

Physics of humans, physics for society

To the Editor — Today, the massive use of information and communication technologies (ICT) has made it possible to attach a traceable set of data to almost any person. We argue that these data provide the opportunity to build a 'physics of society': describing a society — composed of many interacting heterogeneous entities (people, businesses, institutions) — as a physical system. While important ethical implications have to be taken into account, the benefits in developing such physics of society would be tremendous. Indeed, it could help understanding, anticipating and forecasting future societal trends and human behavioural responses, and their associated uncertainty[1]; or address societal challenges in which globally networked risks play a role[2,3]. A case in point is modern epidemiology and its success in predicting the large-scale spreading of infectious diseases[4].

like to find quantities similar to pressure — the integral of the particles' impulse — but, since individuals do not follow a well-behaved Maxwell–Boltzmann distribution function, this could simply be unachievable.

Yet, despite all of the above, we argue that physics can still play a pivotal role in the quest to find regularities in societal dynamics based on patterns of human interactions. Sociotechnical systems where human interactions are partly mediated by ICT exhibit emerging dynamics and are more often than not out of equilibrium. They also involve many temporal and spatial scales, are governed by nonlinear effects and can adapt to external and internal perturbations. We have roughly all the ingredients of a truly out-of-equilibrium complex system, for the study of which physics provides methods and tools.

How should we proceed? The first step, in

would say necessary to address social problems. An example is data-driven stochastic microsimulation of the Zika virus epidemic[10], which helps our understanding of a global and socially relevant dynamics, and at the same time contributes to the more traditional problem of characterizing diffusion in disordered media.

However, the pursuit of a physics for society would bear fruit only if physicists were ready to leave their traditional comfort zone and establish unconventional collaborations with researchers in other disciplines — such as computer and social scientists, and economists, in addition to mathematicians. We believe that such vision and agenda can only be realized with the support of international organizations like the European Commission, which triggered the development of the field with its Future and Emerging Technology

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Thank you!!!!

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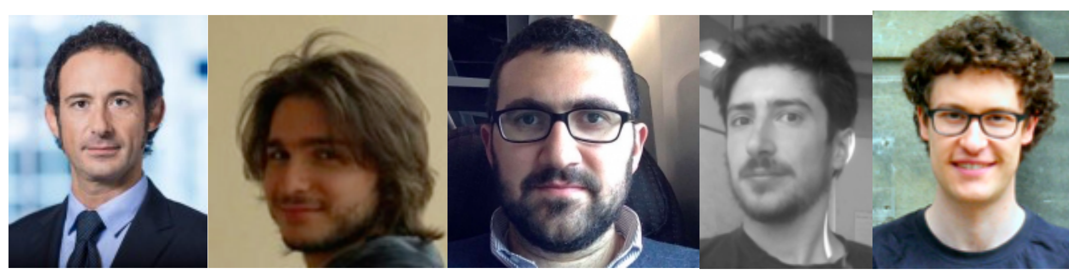

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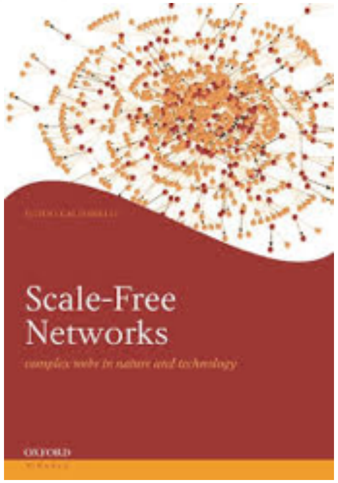

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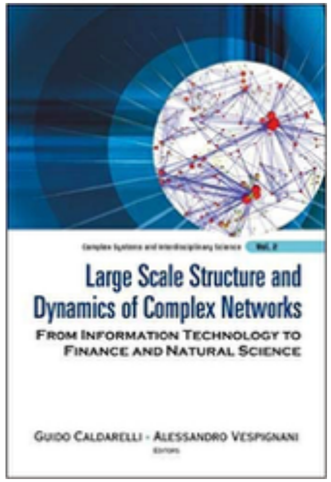

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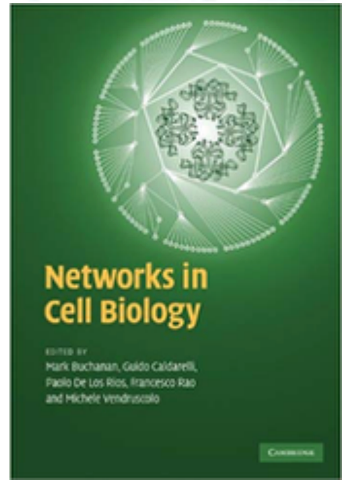

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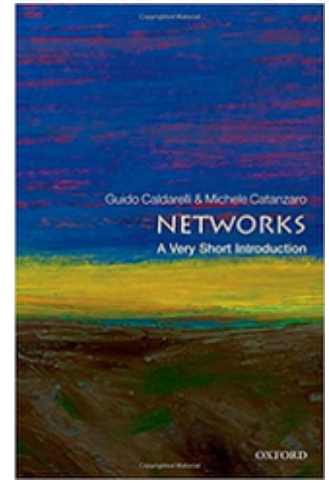

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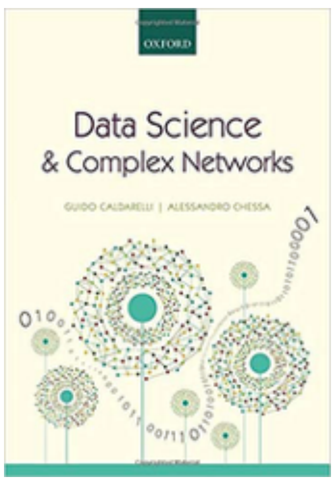

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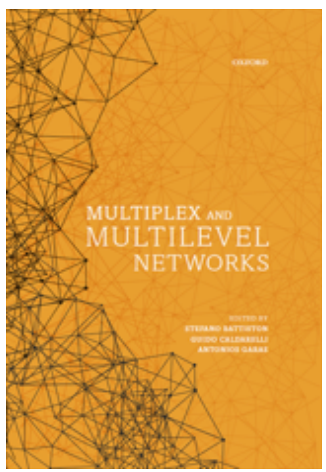

OUP 2019

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