COMPLEX NETWORKS

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1. INTRODUCTION

General information

Prerequisites:

- Basic calculus
- Basic statistical physics

Grade:

- Non-compulsary homeworks
- Project work
- Written exam before Christmas

Download and study Gephi (https://gephi.org/)

Networks everywhere

9/11: the attack which changed the world, carried out by a well organized network of terrorists

9/11 terrorist network

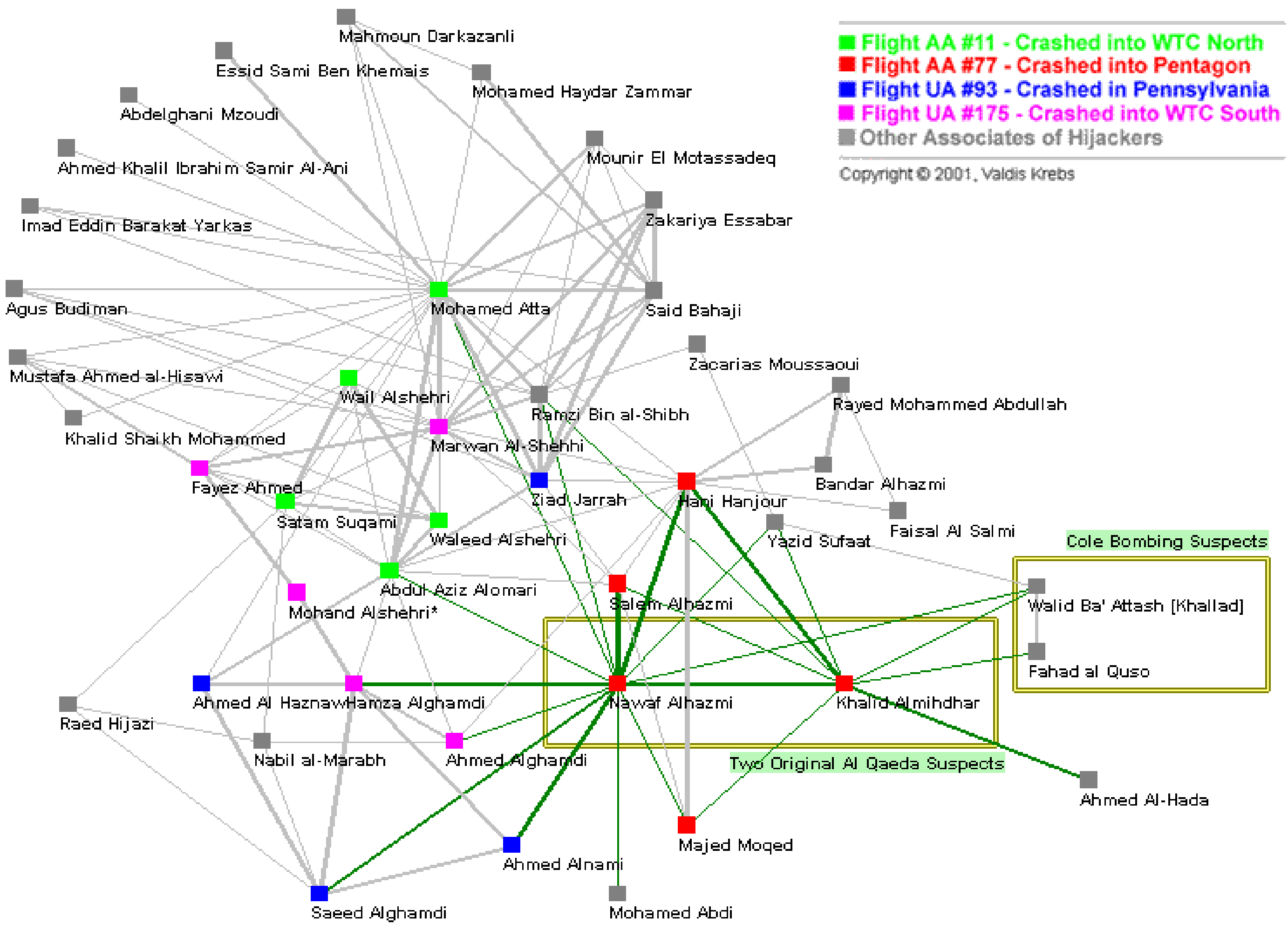


Figure 3 - All Nodes within 2 steps / degrees of original suspects

Connections:
communication
money transfer

http://orgnet.com/tnet.html

Networks everywhere

How to find Saddam?

Map out the hierarchy in governance and army and hope, somebody will know and uncover the secret?

False!

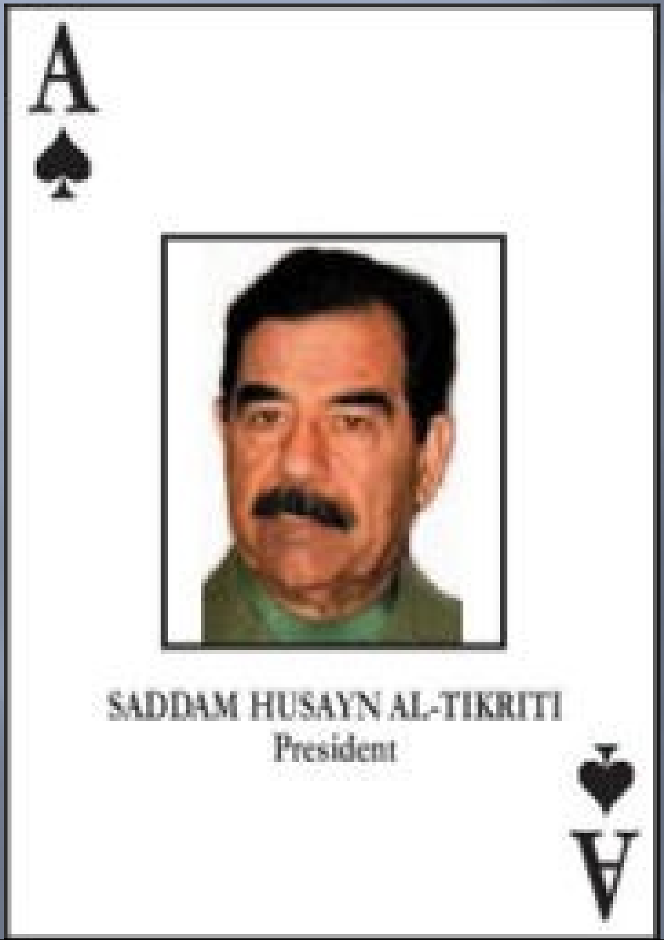
Networks everywhere

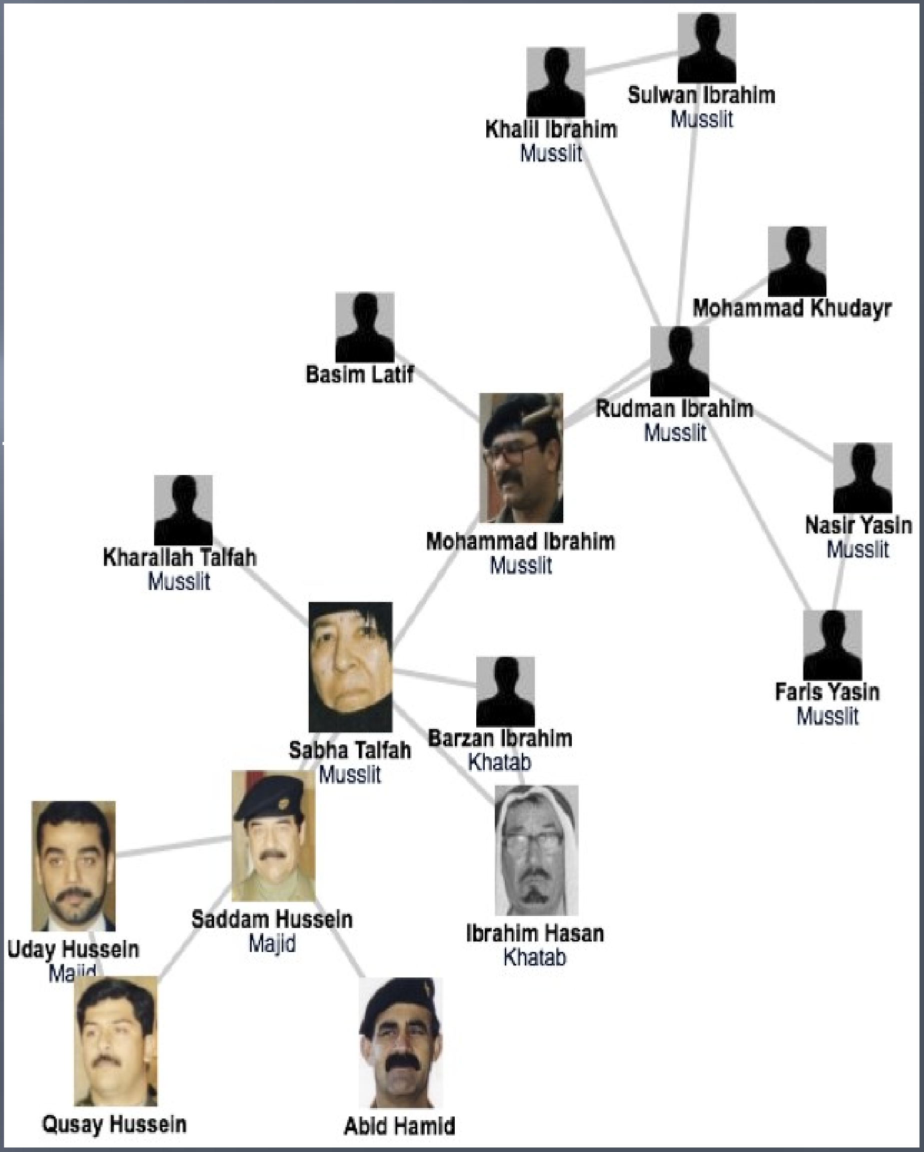
„The brothers began setting forth a story about the apparatus and network of Saddam's security services before he was overthrown from power. They described his network of 25 bodyguards and another group called, "The 40," the members of which were very close to Saddam personally and many of whom were related by blood or very old family ties. The 40 also served as bodyguards and provided personal services – cook, driver, and so forth. Beyond these inner circles, the brothers described something called "route clearers." These consisted of several groups with 800 people each. Saddam, when traveling, would go on any number of routes, choosing which one to travel on a whim. The "route clearers" would proceed ahead on all of the routes he might choose. They weren't openly armed, but would cover all the chokepoints of all the roads he might choose to take."

From Lt. Col. Steve Russell's report

Capturing Saddam with network theory

Networks everywhere





MOVIE
http://link.brightcove.com/services/player/bcpid271557392?bctid=68764580001

Geography of Facebook friendships

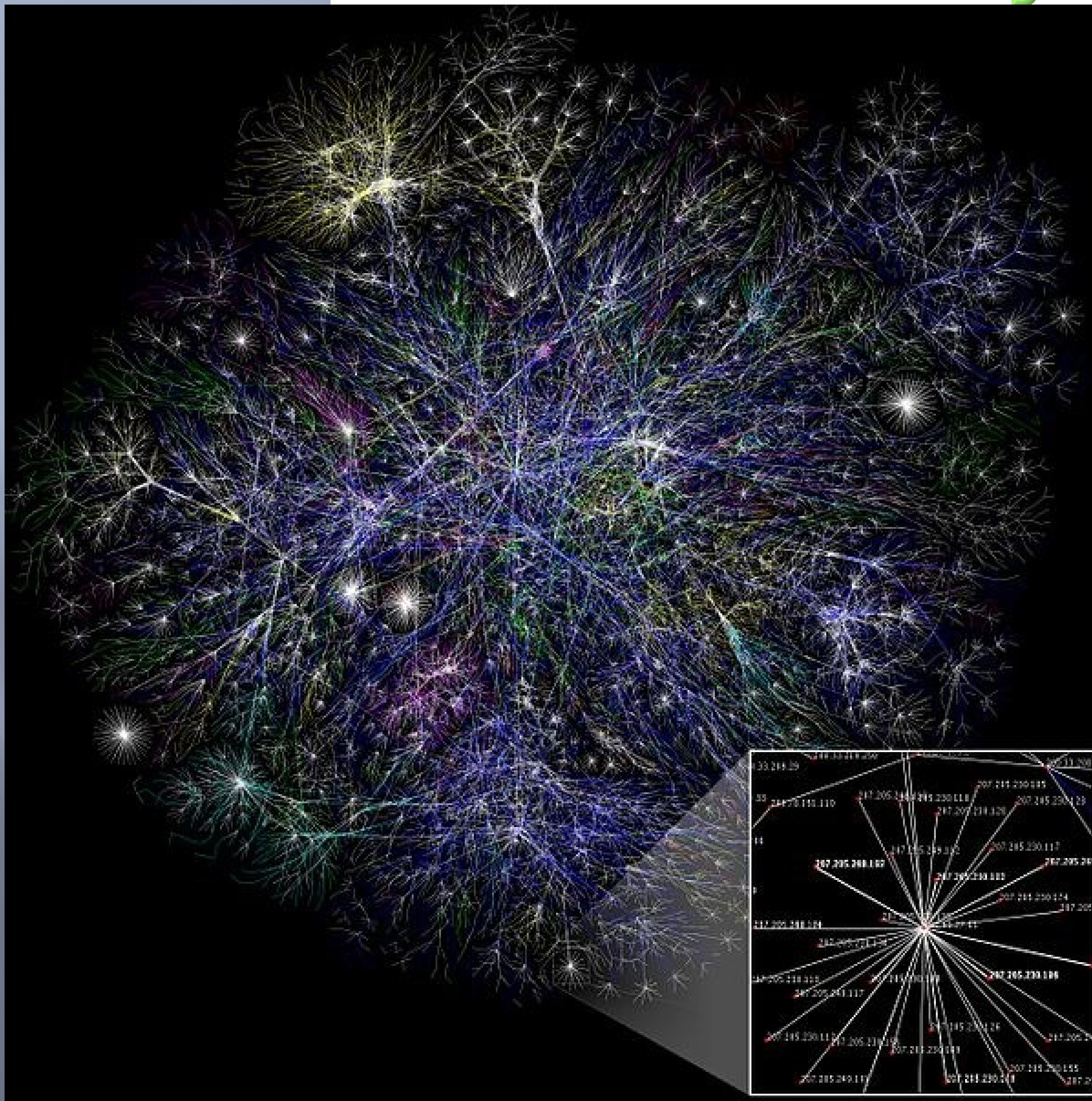
Networks everywhere

Popoulation density + IT development

http://www.facebook.com/notes/facebook-engineering/visualizing-friendships/469716398919

The Internet

Networks everywhere



Self-organized complex structure

http://commons.wikimedia.org/wiki/File%3AInternet_map_1024.jpg

Big NY Blackout

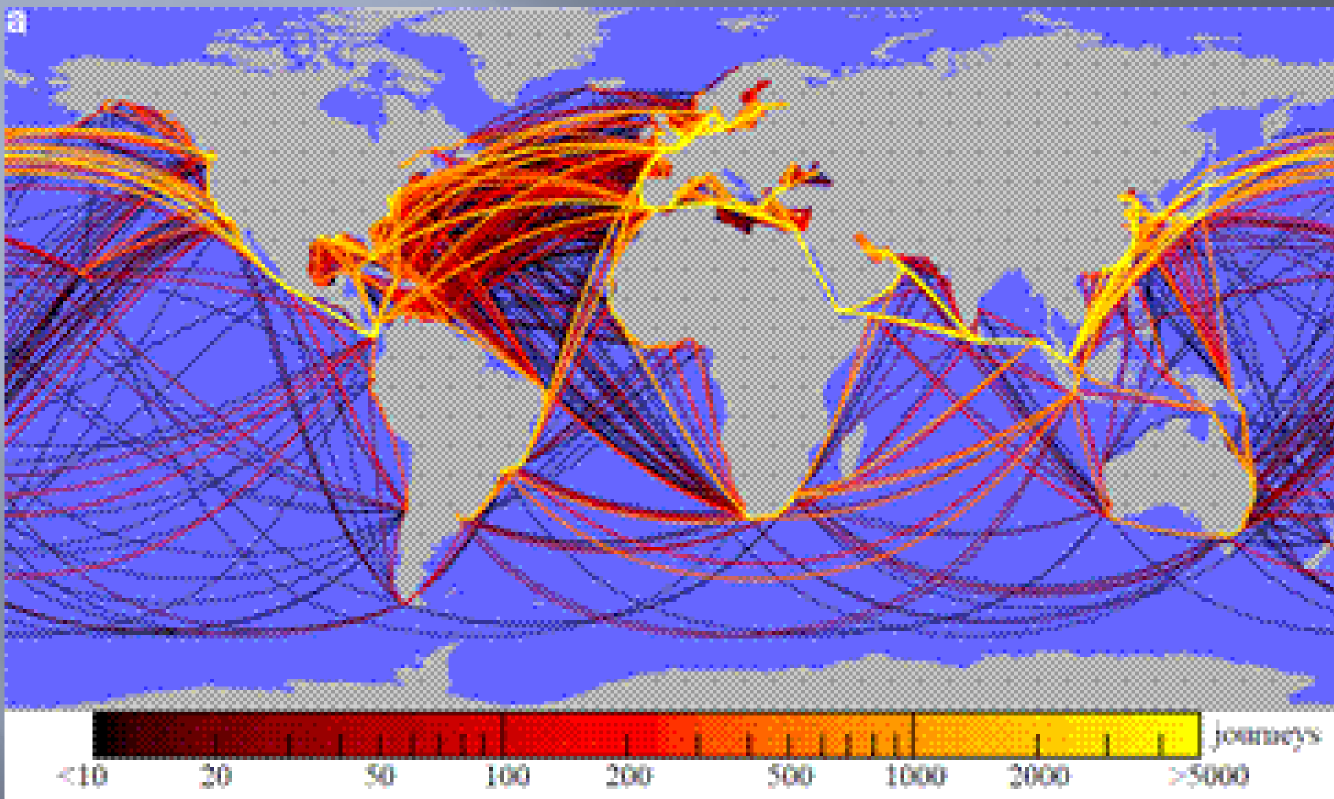
Networks everywhere

August 14, 2003 breakdown of electrical network in the North East of US

FAKED

Global shipping network

Networks everywhere

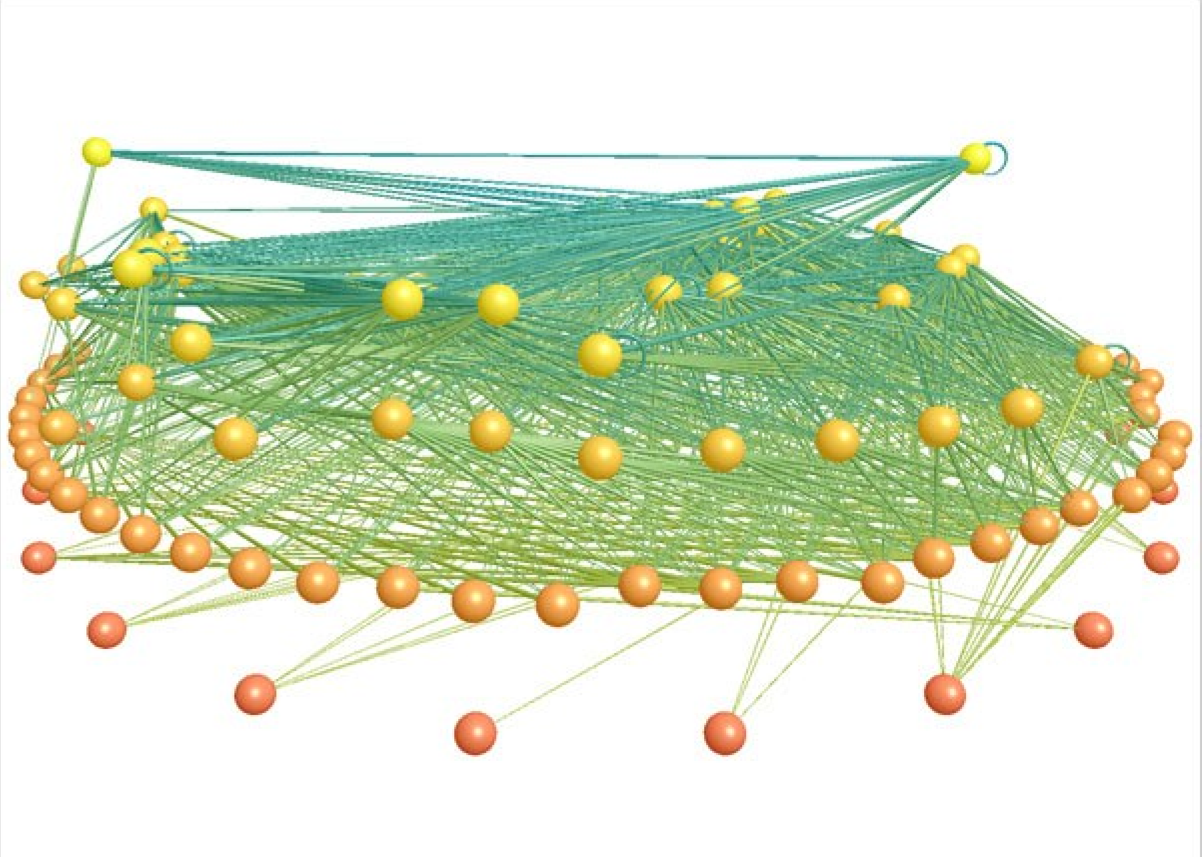


90% of the world's trade is moved around the planet by sea.

http://www.technologyreview.com/view/417128/

Food webs

Networks everywhere



Model of the food web in Little Rock Lake, Wisconsin

www.foodwebs.org

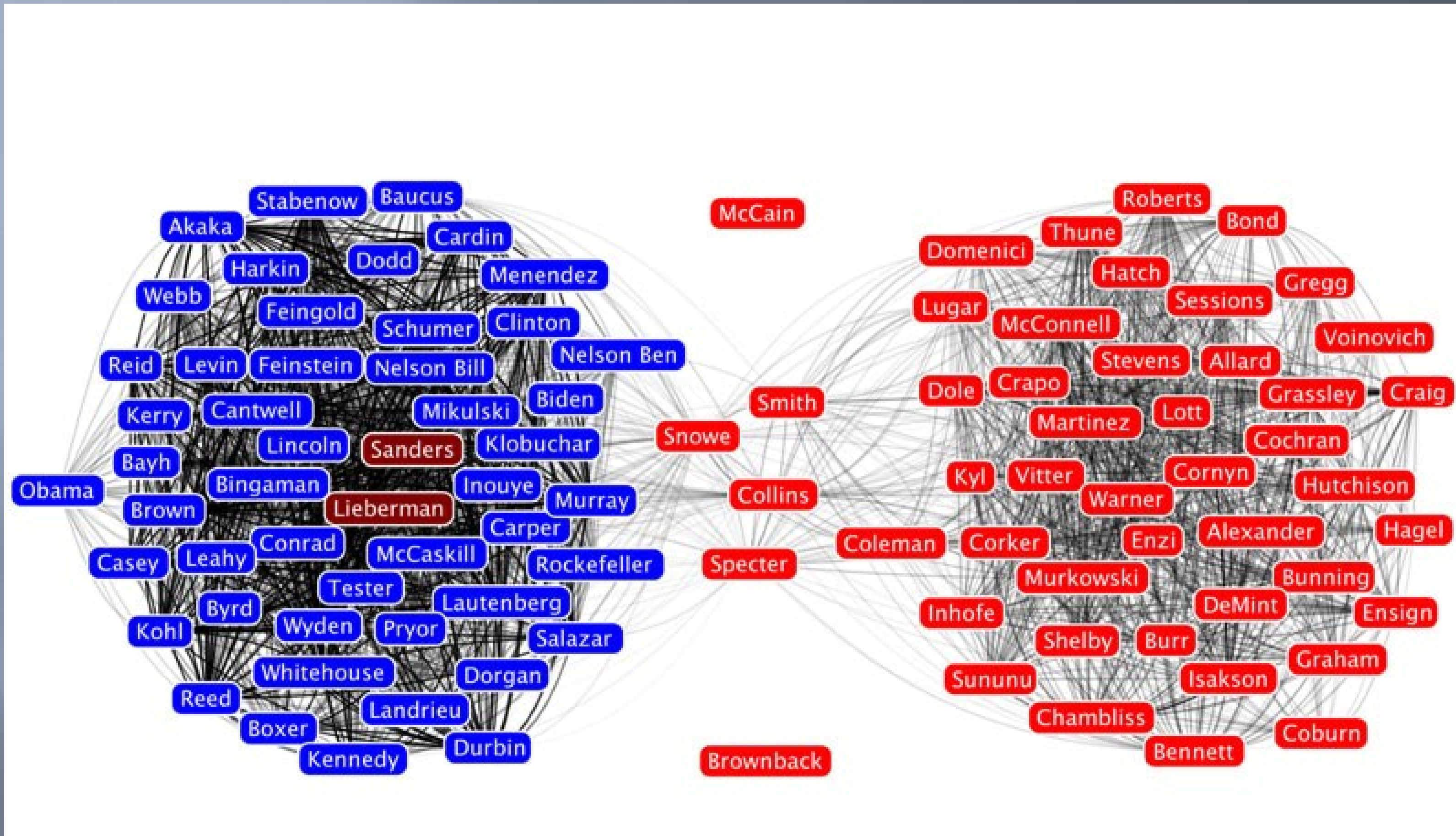
primary predators

intermediate species

plants and detritus

Political networks

Networks everywhere

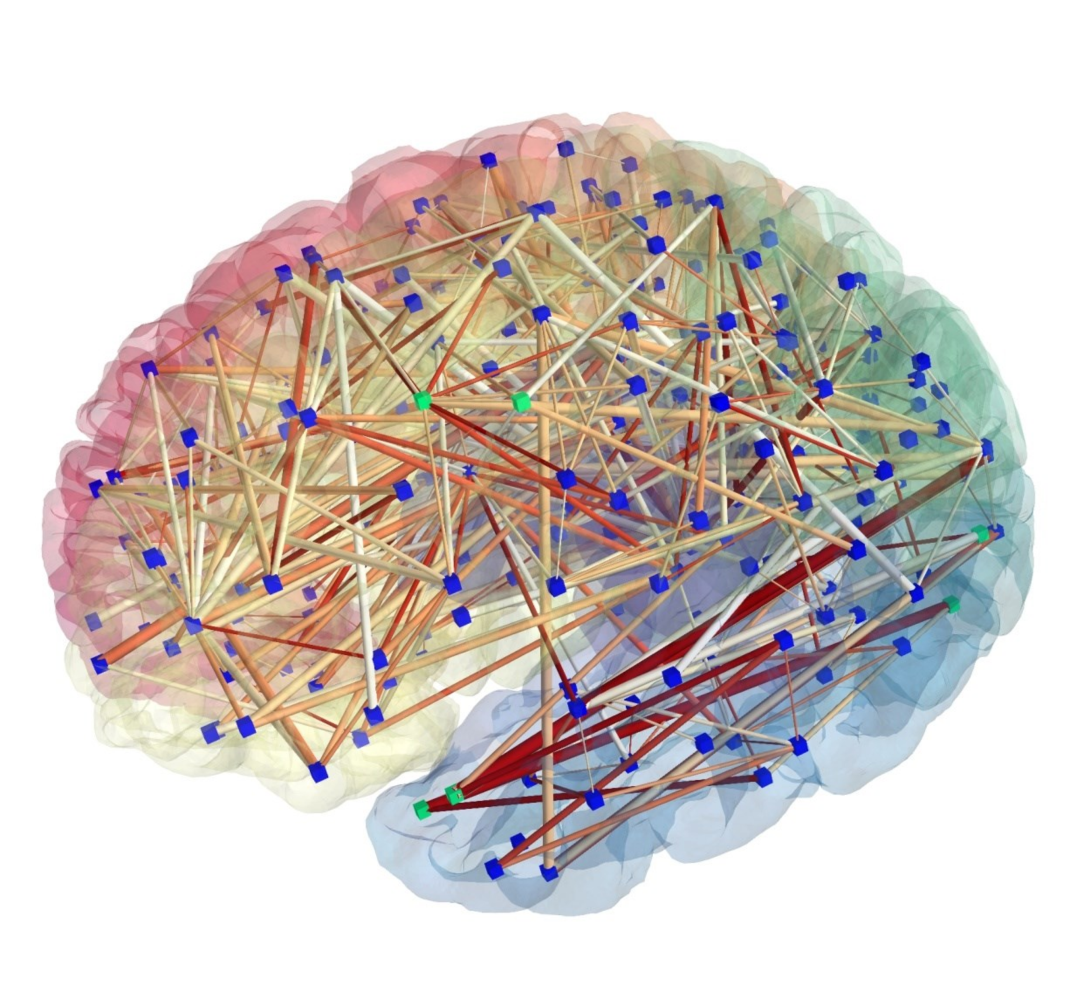


US Senate votes 2007. Network drawn using similarity measure for votes. Note the importance of visualization (independent legislates).

B. Shneiderman, SCIENCE VOL 319 7 MARCH 2008

Brain network

Networks everywhere



Diffusion MRI map of 258 nodes in the cortex and subcortex regions of the brain. Links represent thresholded densities.

http://connectomeviewer.org/viewer

Complexity

Goal: Understanding (and possibly predicting)
- social
- political
- economic
- ecological
- technological
- biological

etc. systems

They are **COMPLEX**

Complexity

- A complex system is a highly structured system, which shows structure with variations (N. Goldenfeld and Kadanoff)
- A complex system is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large, or one in which there are multiple pathways by which the system can evolve (Whitesides and Ismagilov)

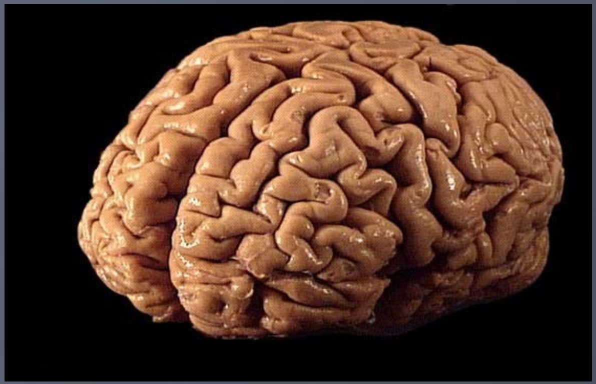
A complex system is one that by design or function or both is difficult to understand and verify (Weng, Bhalla and Iyengar)

A complex system is one in which there are multiple interactions between many different components (D. Rind)

Complex systems are systems in process that constantly evolve and unfold over time (W. Brian Arthur).

From Wikipedia

Complexity



Watch:
complicated

linear chain of logic

Brain:
complex

cells→ … thoughts
emotions

Complexity

Complex systems:
- Many interacting components
- feedback
- nonlinearity
- cooperativity
- emergent phenomena

THE WHOLE IS MORE THAN THE MERE SUM OF THE PARTS

Complexity

Complex systems:

- Many interacting components

- diversity
- feedback
- nonlinearity
- cooperativity
- emergent phenomena

Complexity

Many interacting components

- Biology: brain: 10^2 (Region of Interest) -10^{11}(cells)

Interaction: physical, chemical

- Ecology: 10 -10^4 - 10^7 (species)

Interaction: predator-prey, environmental

- Technology: Internet: 10^9 (need to change IP4 to IP6)

Interaction: physical (function) + human, financial (growth)

- Society: 10-10^2 social relations

10^6 -10^9 societal scale

Interaction: human

Complexity

Complex systems:

- Many interacting components
- **Diversity**
- feedback
- nonlinearity
- cooperativity
- emergent phenomena

Complexity

Diversity

- Biology: Brain: 3 types of neurons according to direction of information transfer, they can have different number of extensions, in addition there are 5 types of glial cells, etc. etc.
- Ecology: Biodiversity
- Technology: Internet: individual, router, autonomous system – hubs
- Society: Gaussian distribution in phenotypical properties (height).

  Broad distribution in socially relevant properties: culture, intellectual capacity, wealth etc.

Complexity

Complex systems:
- Many interacting components
- Diversity
- **Feedback**
- nonlinearity
- cooperativity
- emergent phenomena

Complexity

Feedback

- Biology: Neural regulation results from a balance of activation and blocking
- Ecology: Foxes – rabbits, Lotka-Volterra
- Technology: Route choice depends on traffic
- Society: Social interaction is permanent mutual adjustment

Complexity

Complex systems:
- Many interacting components
- Diversity
- Feedback
- **Nonlinearity**
- cooperativity
- emergent phenomena

Complexity

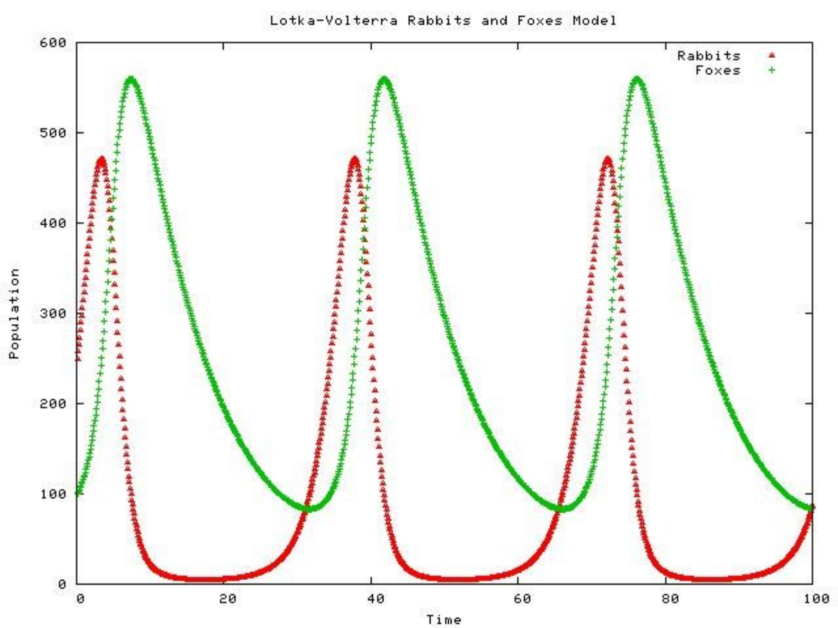
Nonlinearity

(Linerarity: small stimulus – small (proportional) effect)

- Biology: „All or none principle” in neural dynamics
- Ecology: LV coupling

$$\frac{dR}{dt} = a * R$$

$$\frac{dF}{dt} = \quad - d * F$$



- Technology: Congestion
- Society: Elections

Complexity

Complex systems:
- Many interacting components
- Diversity
- Feedback
- Nonlinearity
- **Cooperativity**
- emergent phenomena

Complexity

Cooperativity
(in a general sense)

- Biology: Neuronal avalanches
- Ecology: Symbiotic relationships
- Technology: Cascadic failures
- Society: Movements, turmoils, revolutions

Complexity

Complex systems:
- Many interacting components
- Diversity
- Feedback
- Nonlinearity
- Cooperativity
- **Emergent phenomena**

Complexity

Emergent phenomena

- Biology: Thoughts, emotions
- Ecology: Change of habitats, new co-existence forms
- Technology: Blackout
- Society: New forms of social life, organizations, parties, governance

"More is different"

(1972, P.W. Anderson, Nobel laureate in physics)

Complexity

Complexity, a **scientific theory** which asserts that some systems display behavioral phenomena that are completely inexplicable by any conventional analysis of the systems' constituent parts. These phenomena, commonly referred to as emergent behaviour, seem to occur in many complex systems involving living organisms, such as a stock market or the human brain.

John L. Casti, Encyclopædia Britannica

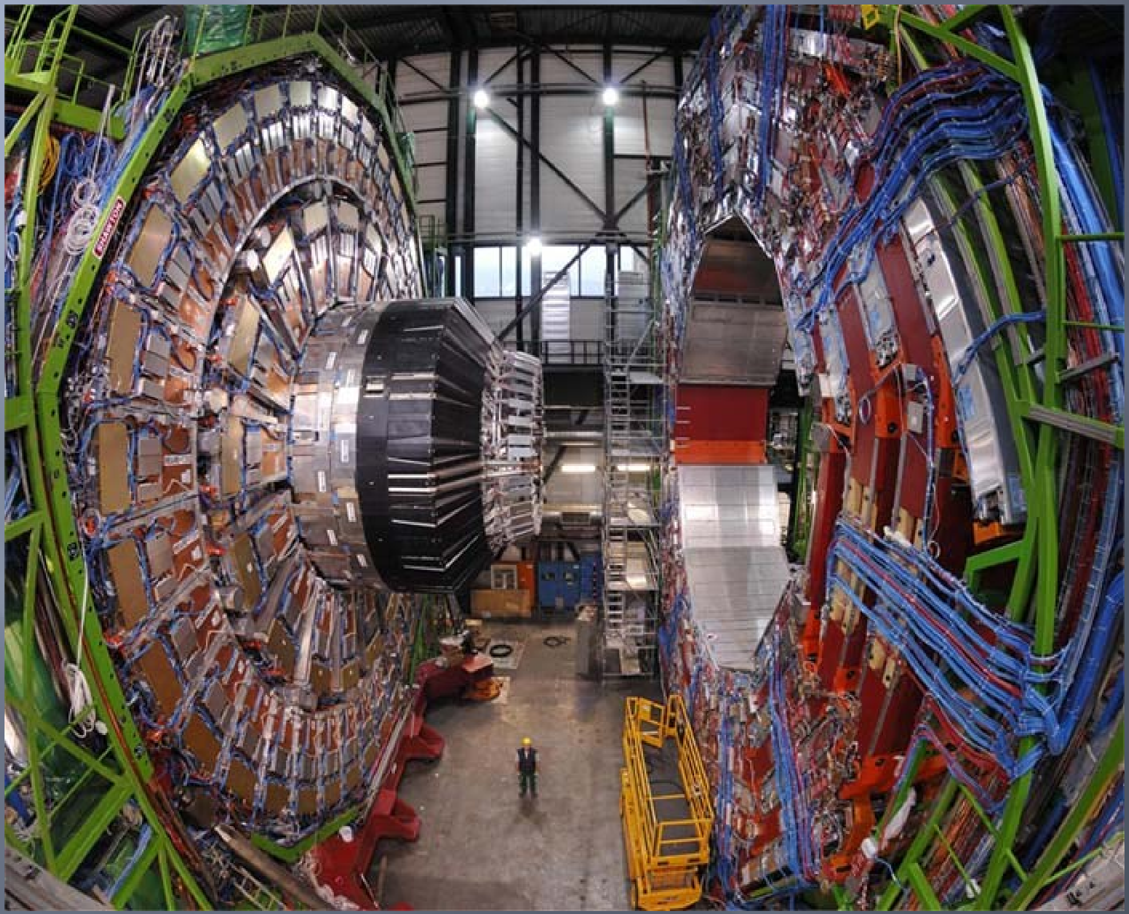
The next century will be the century of complexity

(Stephen Hawking 2000)

Interactions

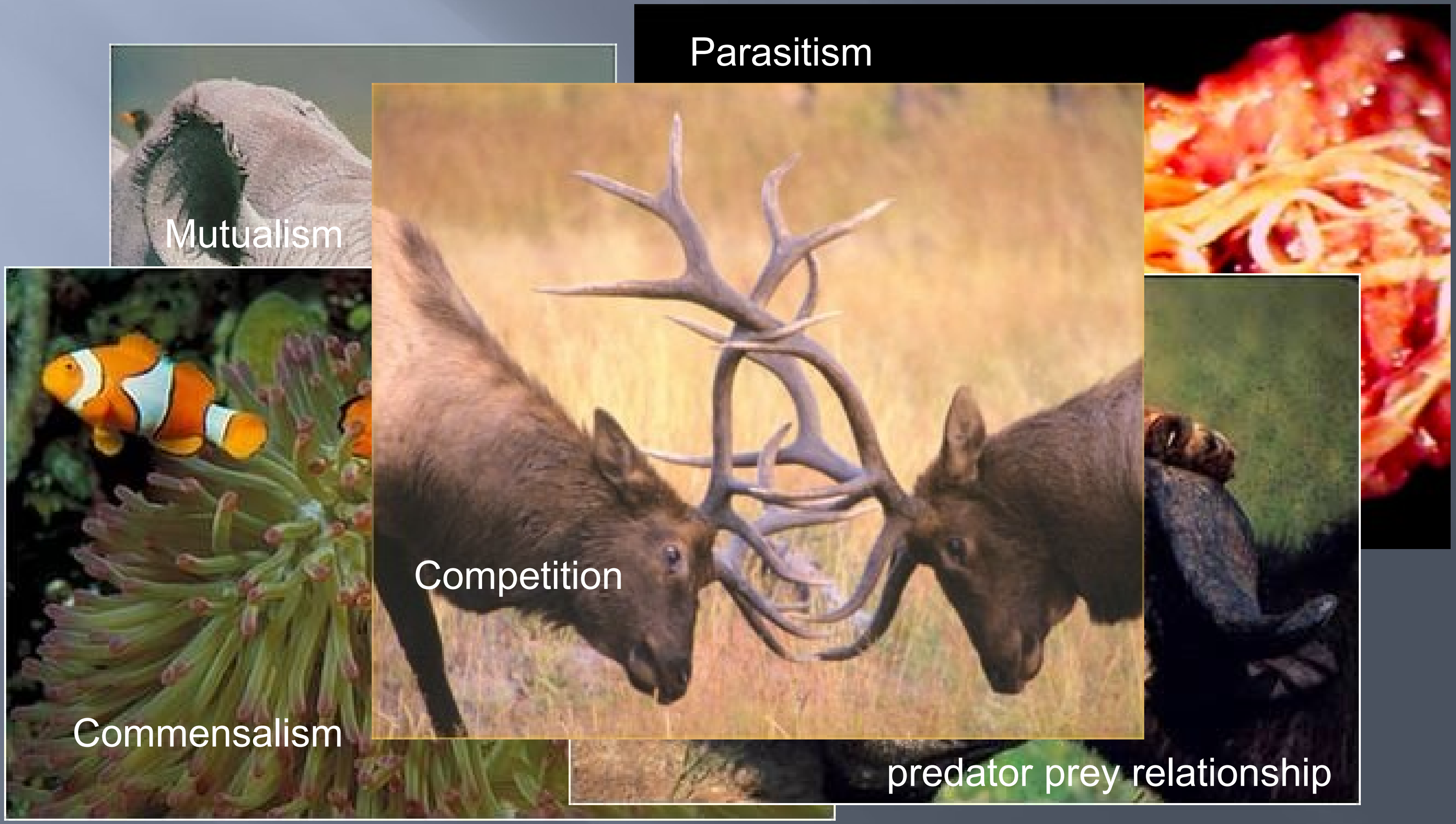
Conventional analysis: understand the interactions

Physics: Well known (Higgs boson!)



Interactions

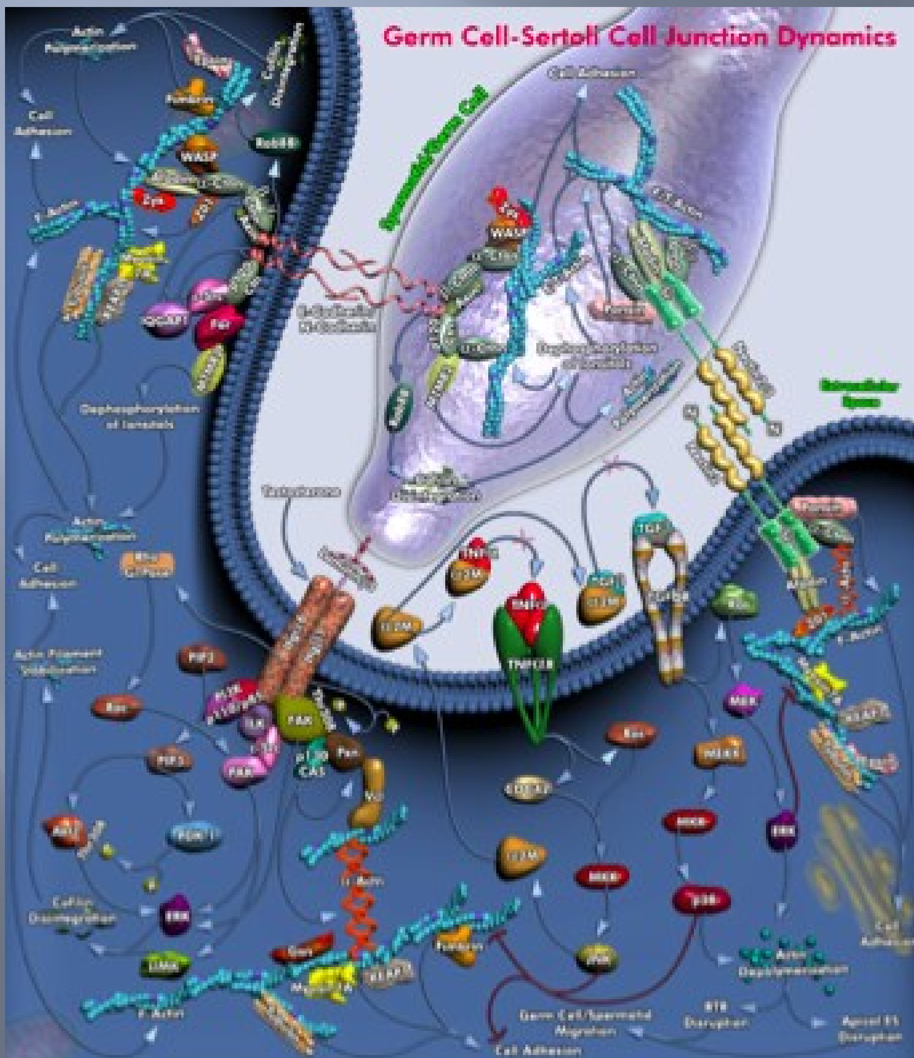
Biology: more…



http://kariecology.blogspot.hu/2011/02/biological-interactions.html

Interactions

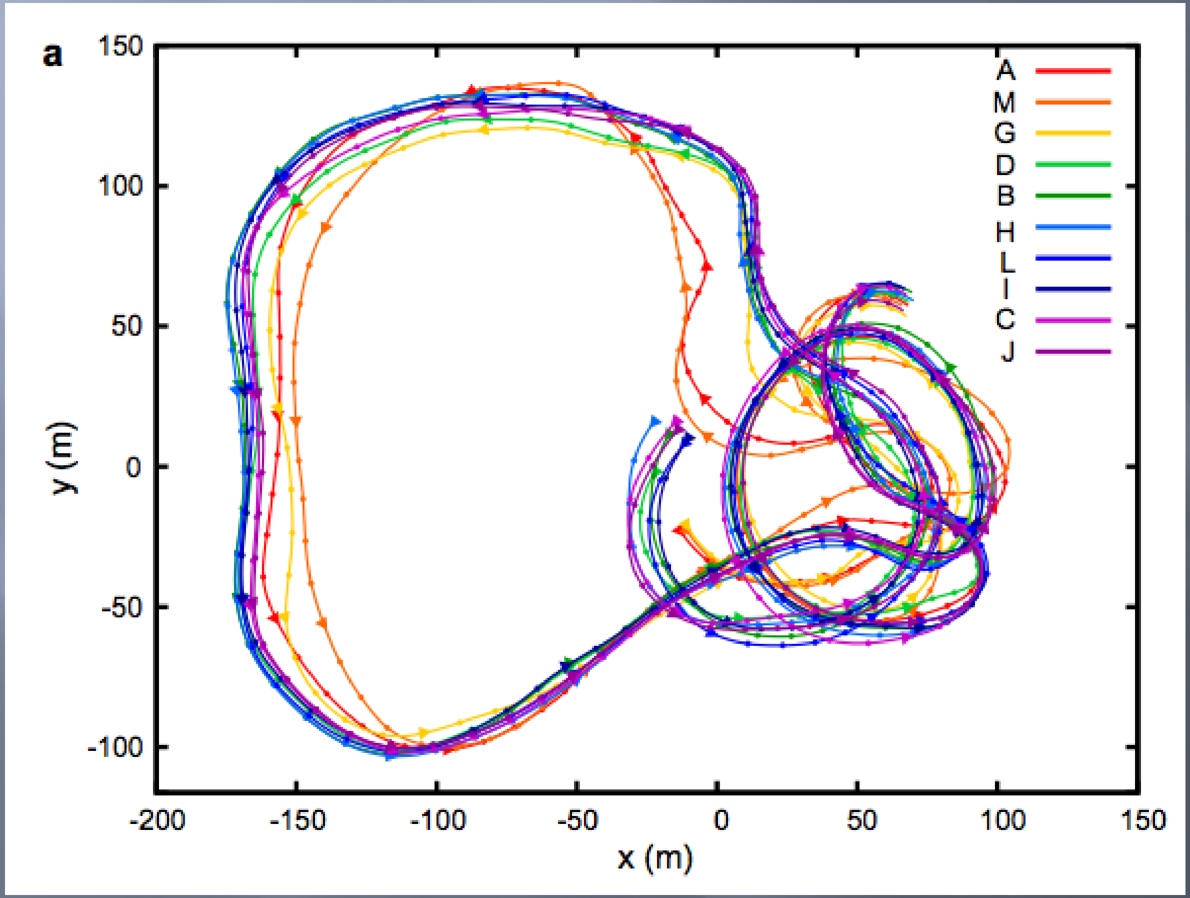
Biology: …or less known



There is much to be learned about interactions at the microscopic, molecular level

Interactions

Social interactions: animals



Flocking flight of 10 pigeons

Permanently changing hierarchy

How do they know?!

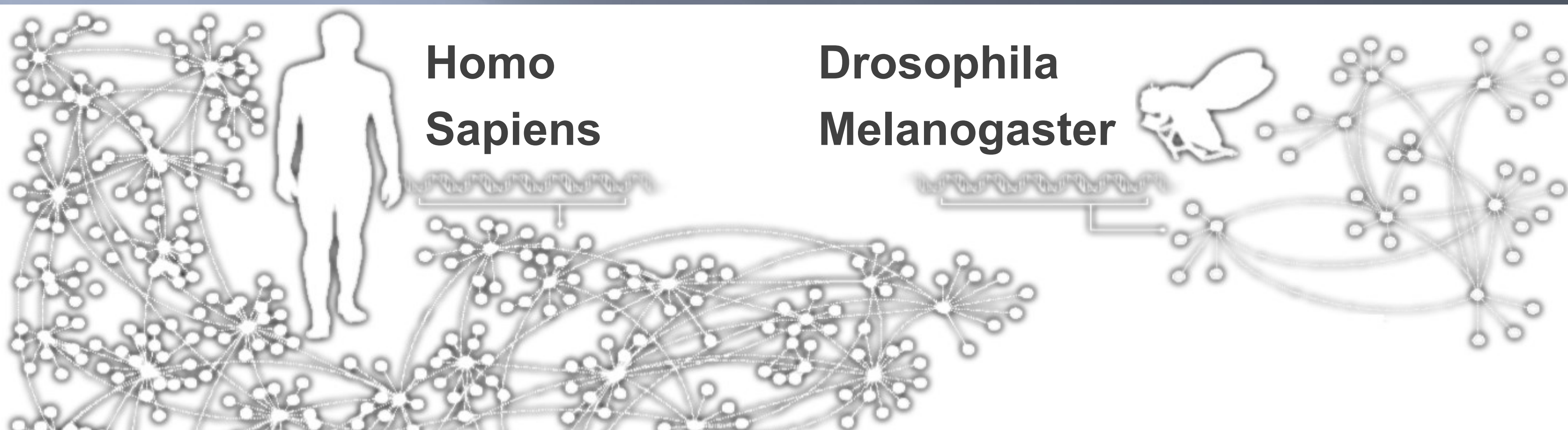
M. Nagy et al. Nature 464, 890-893 (8 April 2010)

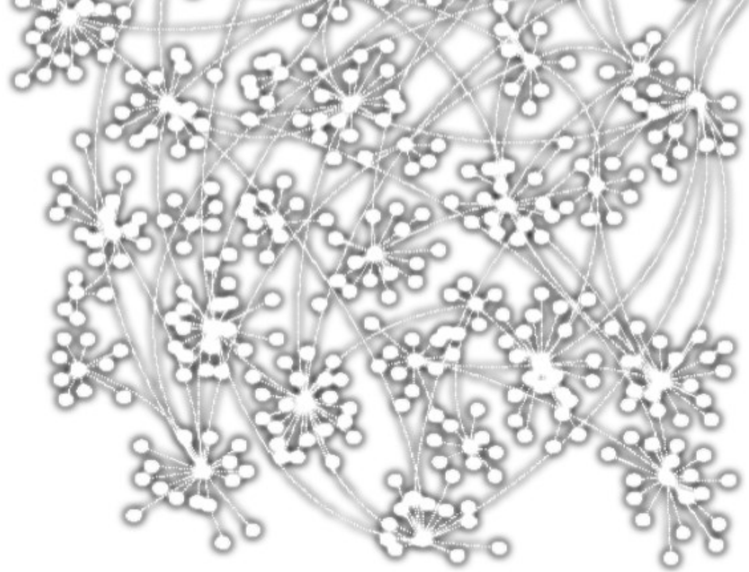
Interactions

Social interactions: humans

Networks

Genetic regulation





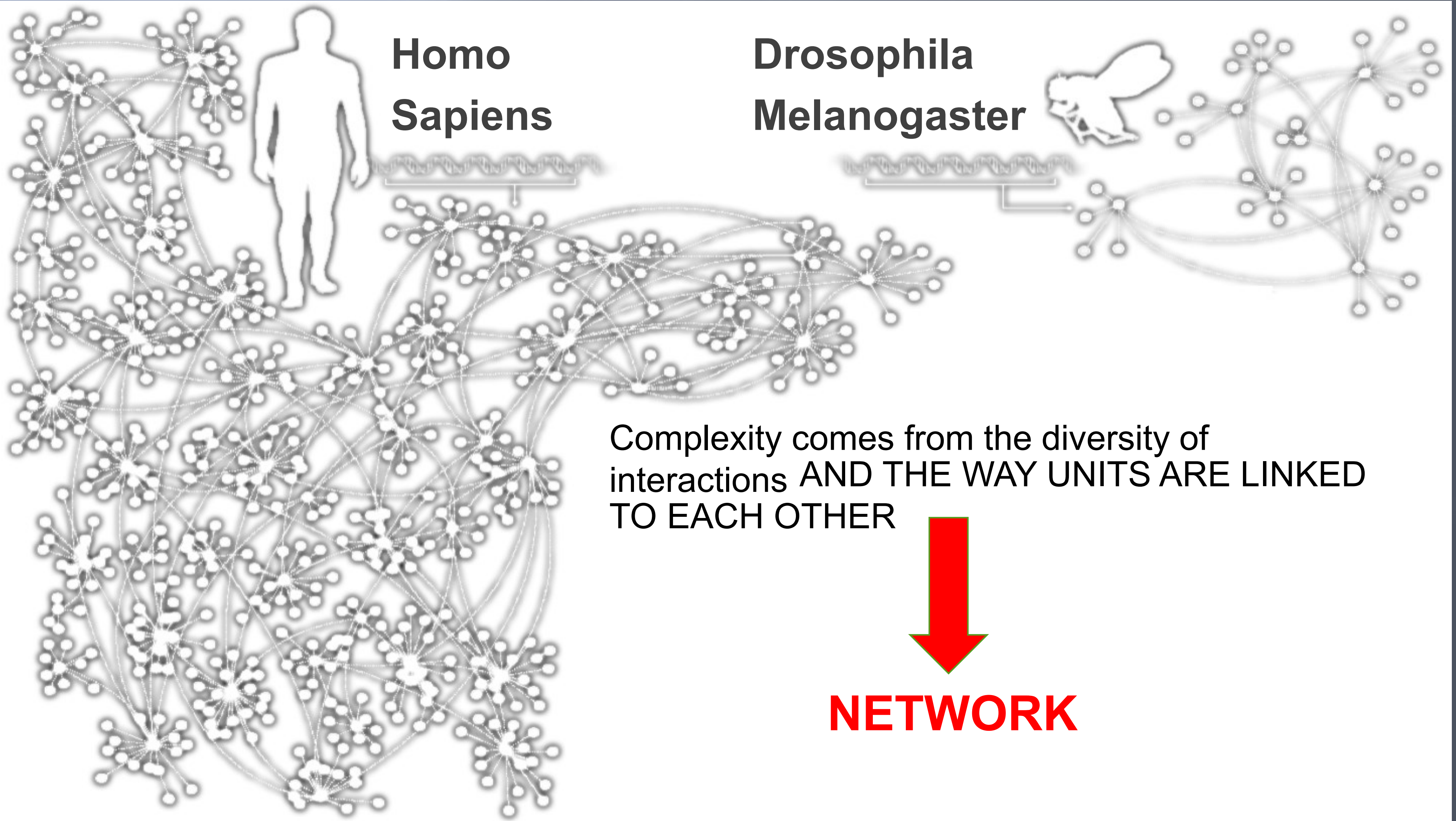
The points represent the elements of each organism's genetic network, and the dotted lines show the interactions between them.

HS: ~30,000 genes, DM: ~15,000 genes

Complexity does not come merely from the number of interacting units!

Networks

Genetic regulation



Complexity comes from the diversity of interactions AND THE WAY UNITS ARE LINKED TO EACH OTHER

NETWORK

Networks

Each complex system has a skeleton: The underlying network. Without apprehending this network we cannot understand the complex system.

Networks

Network Science: Holistic approach

Holism: Looking at systems as a whole is needed for theirs understanding

Reductionism: The precise understanding of the fine details will finally lead to the complete picture

For the last few centuries, the Cartesian project in science has been to break matter down into ever smaller bits, in the pursuit of understanding. And this works, to some extent. We can understand matter by breaking it down to atoms, then protons and electrons and neutrons, then quarks, then gluons, and so on. We can understand organisms by breaking them down into organs, then tissues, then cells, then organelles, then proteins, then DNA, and so on.

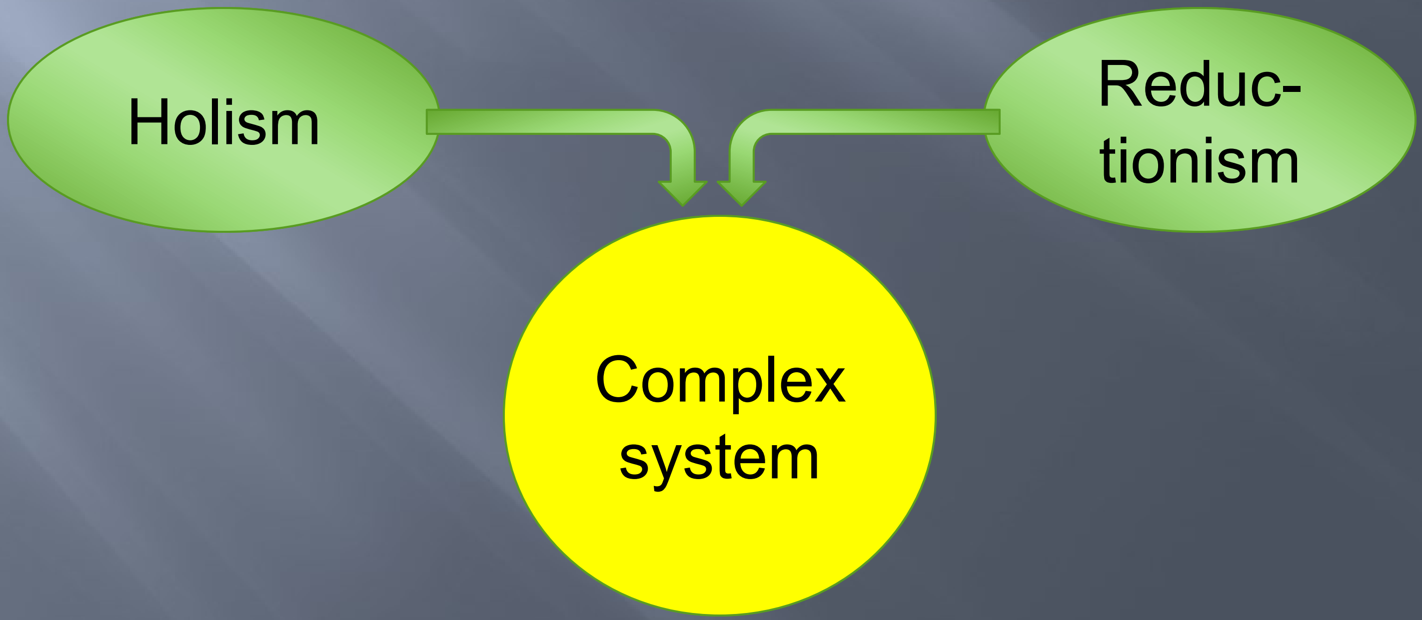
But putting things back together in order to understand them is harder, and typically comes later in the development of a scientist or in the development of science. Think of the difficulties in understanding how all the cells in our bodies work together, as compared with the study of the cells themselves. Whole new fields of neuroscience and systems biology and network science are arising to accomplish just this.

N. Christakis, http://www.edge.org/q2011/q11_6.html

Networks

Network Science: Holistic approach

We do not care about the nature of interactions.
Advantage: Results are applicable to any complex system



Networks

Network Science: Science of the 21st century

Graph theory: 1735, Euler
Social Network Research: 1930s, Moreno
Internet: 1960s
Ecological Networks: May, 1979.
WWW: 1991, CERN, Barners-Lee
Social networking services: 1995- (Facebook 2004, M. Zuckerberg)

WHY NOW NETWORK SCIENCE?

Why now?

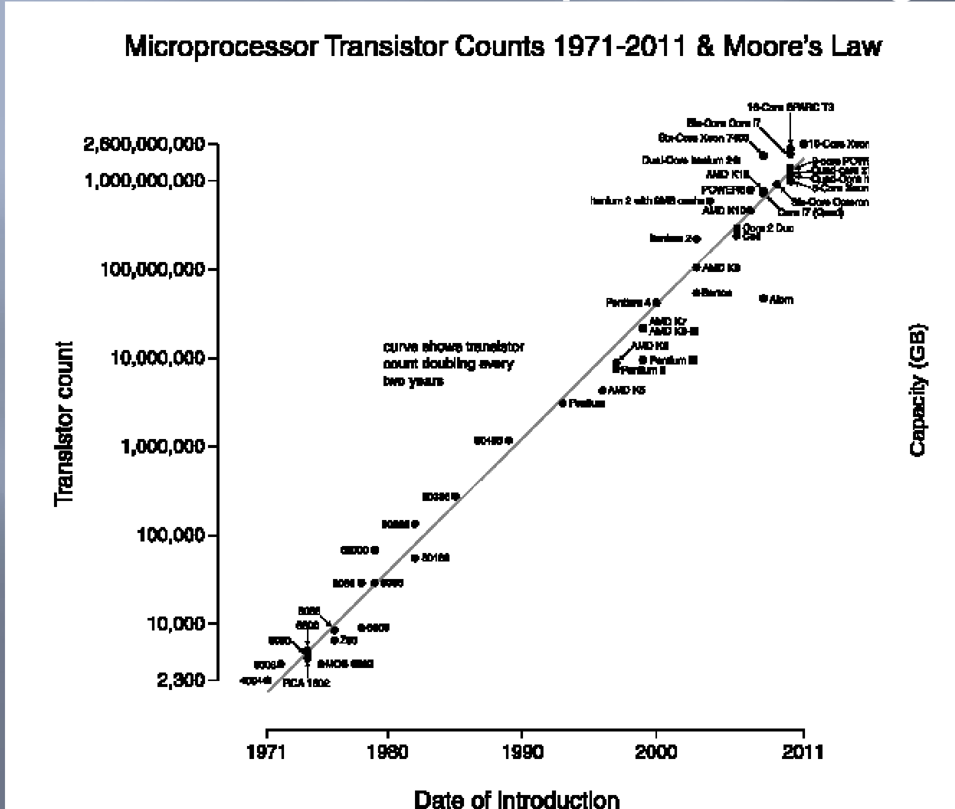
Problems:
- Environmental crisis
- Health maintenance
- Governance in a global world
- Global financial crises
etc.

Great challenges

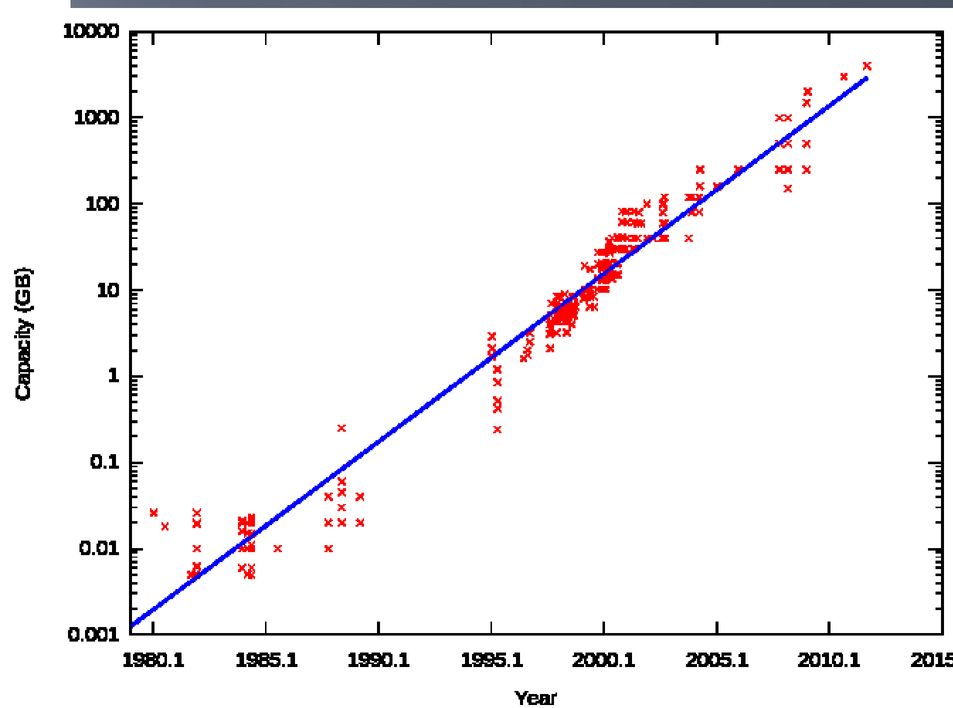
Why now?

Revolution in the information communication technology

Moore's law: exponential growth



Storage capacity



technological tools

Wikipedia

Why now?

-

"Everywhere you look, the quantity of information in the world is soaring. According to one estimate, mankind created 150 exabytes (billion gigabytes) of data in 2005. This year (2010), it will create 1,200 exabytes. Merely keeping up with this flood, and storing the bits that might be useful, is difficult enough. Analyzing it, to spot patterns and extract useful information, is harder still."

The Economist, Feb 2010

Great opportunity due to data deluge

Why now?

Important achievements in different scientific disciplines (physics: cooperative phenomena; biology: genome project; computer science: data mining; social science: quantitative methods, etc.)

At the same time scientists of different disciplines realized the necessity of building on each others results: Inter- and multi-disciplinarity

Great scientific moment

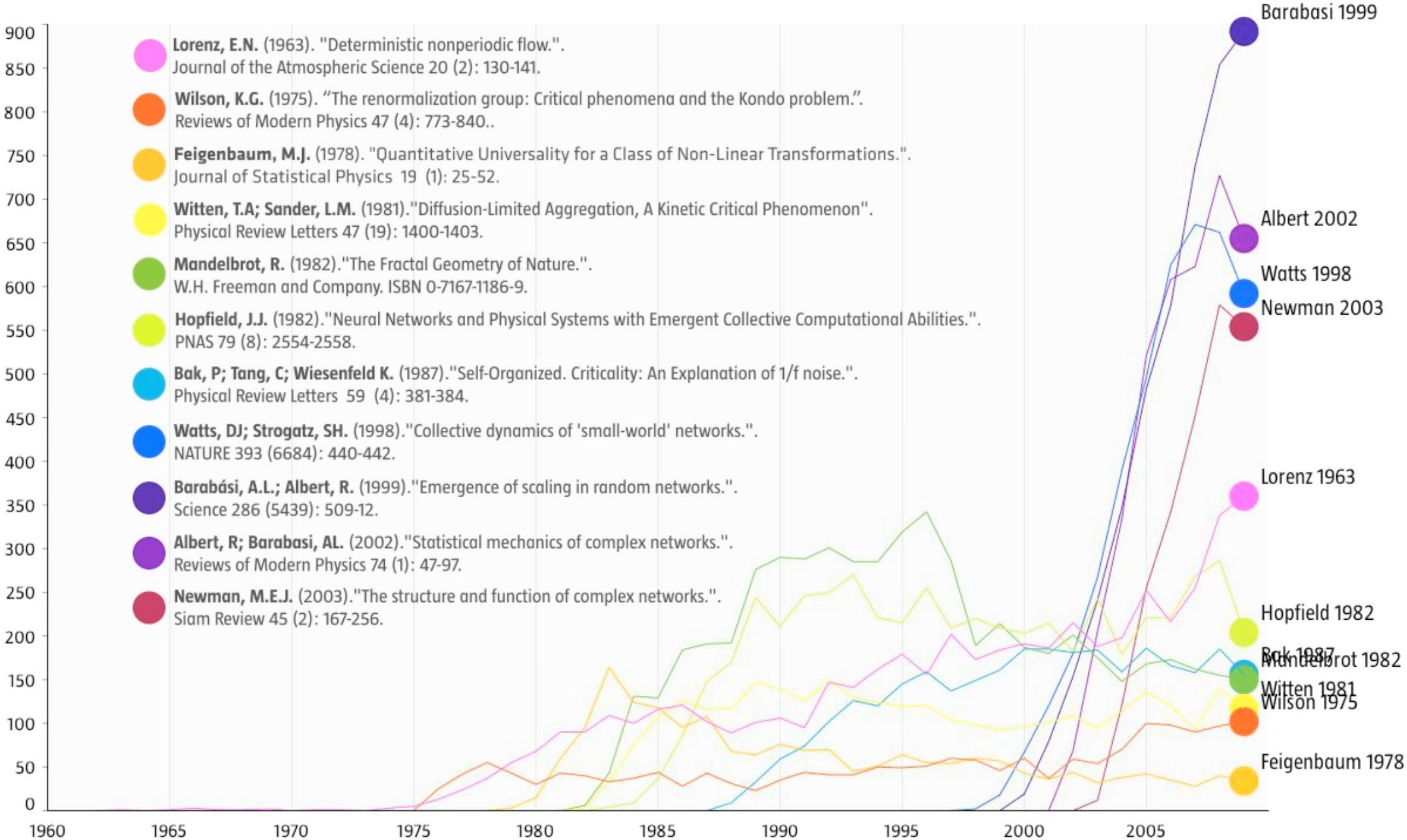
Why now?

Great public interest

Why now?

Great challenges
Great technological tools
Great challenge and opportunity due to data deluge
Great scientific moment
Great public interest

Why now?



Citations per year

Impact of Network Science

Multidisciplinary endeavor:

Graph theory

Social network theory

Statistical physics

Computer science

Biology

Statistics

Mutual benefit

Impact of Network Science

In network science there is a short transition time from basic research to applications

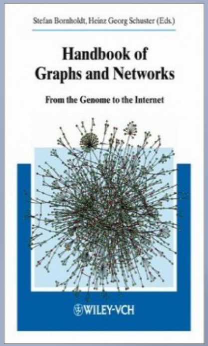
- ICT giants (Google, Cisco, Facebook etc.) use massively results of network theory, have their own research departments. Many small consulting firms using network science resutls, prosper.
- Epidemiology: We are at the advent of a new era, where epidemics can be fought with much higher efficiency due to network science
- Drug design benefits from network science in several ways from mapping out unknown relationships between diseases to revealing networks of molecular mechanisms
- Military and intelligence use network approach successfully in the fight against terrorism and in “cyber war”.

How to construct networks?

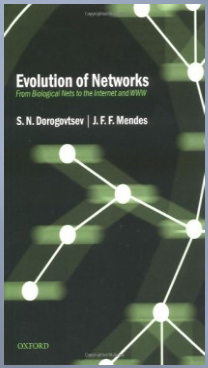
NETWORKS: Graphs, consisting of
nodes (vertices) and
directed or undirected links (edges)

Phenomenon	Nodes	Links
Cell metabolism	Molecules	Chem. reactions
Sci. collaboration	Scientists	Joint papers
WWW	Pages	URL links
Air traffic	Airports	Airline connections
Economy	Firms	Trading
Language	Words	Joint appearance

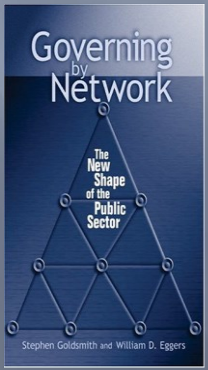
Books



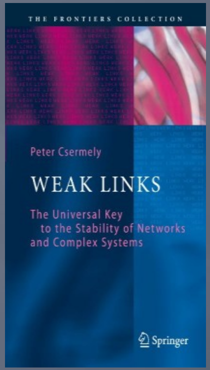
Handbook of Graphs and Networks: From the Genome to the Internet (Wiley-VCH, 2003).



S. N. Dorogovtsev and J. F. F. Mendes, Evolution of Networks: From Biological Nets to the Internet and WWW (Oxford University Press, 2003).



S. Goldsmith, W. D. Eggers, Governing by Network: The New Shape of the Public Sector (Brookings Institution Press, 2004).



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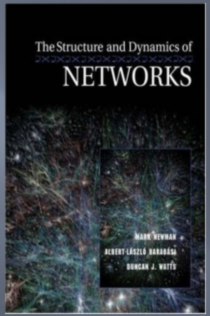
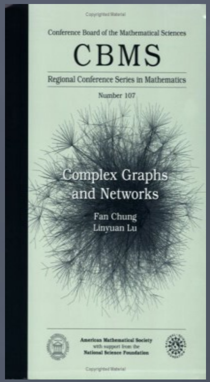
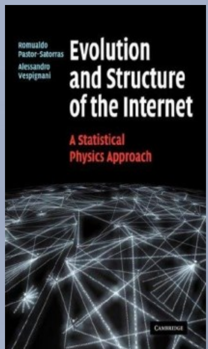


M. Newman, A.-L. Barabasi, D. J. Watts, The Structure and Dynamics of Networks: (Princeton Studies in Complexity) (Princeton University Press, 2006)

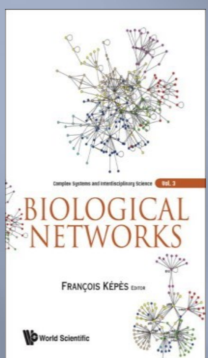


L. L. F. Chung, Complex Graphs and Networks (CBMS Regional Conference Series in Mathematics) (American Mathematical Society, 2006).

Books



R. Pastor-Satorras, A. Vespignani, Evolution and Structure of the Internet: A Statistical Physics Approach (Cambridge University Press, 2007), rst edn.



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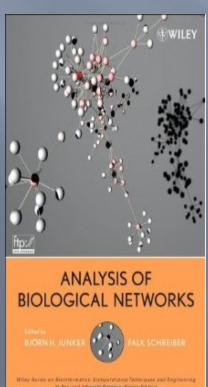

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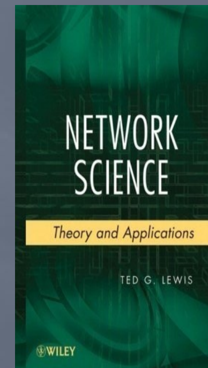

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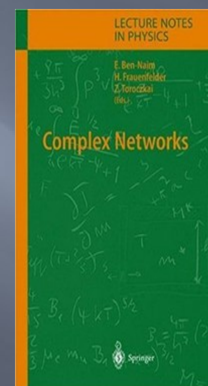
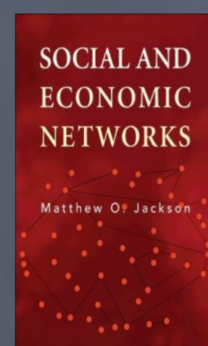


E. Ben Naim, H. Frauenfelder, Z.Torotzai, Complex Networks (Lecture Notes in Physics) (Springer, 2010), rst edn.



M. O. Jackson, Social and Economic Networks (Princeton University Press, 2010).

Original papers

• 1998: Watts-Strogatz paper in the most cited **Nature** publication from 1998; highlighted by ISI as one of the ten most cited papers in physics in the decade after its publication.

•1999: Barabasi and Albert paper is the most cited **Science** paper in 1999;highlighted by ISI as one of the ten most cited papers in physics in the decade after its publication.

•2001: Pastor -Satorras and Vespignani is one of the two most cited papers among the papers published in 2001 by **Physical Review Letters**.

•2002: Girvan-Newman is the most cited paper in 2002 **Proceedings of the National Academy of Sciences**.

Reviews

•The first review of network science by Albert and Barabasi, 2001) is the second most cited paper published in **Reviews of Modern Physics**, the highest impact factor physics journal, published since 1929. The most cited is *Chandaseklar*'s 1944 review on solar processes, but it will be surpassed by the end of 2012 by Albert *et al.*

•The SIAM review of Newman on network science is the most cited paper of any **SIAM journal**.

•BIOLOGY: "Network Biology", by Barabasi and Oltvai (2004) , is the second most cited paper in the history of **Nature Reviews Genetics**, the top review journal in genetics.

This course

We are going to learn about basic concepts and notions of network theory. We are interested in questions like:

- How do diseases spread and how to fight them?
- How to learn about the structure of the society from communication data?
- How robust are complex networks?
- How to construct network models to describe the observations?

Homework: Choose a complex system and identify units, interactions, diversity, feedback, nonlinearity, co-opreativity and emergent phenomena. Try to imagine the related NW.