دانشگاه کردستان
University of Kurdistan
زانکۆی کوردستان

Department of Computer and IT Engineering
University of Kurdistan

Complex Networks

Introduction

By: Dr. Alireza Abdollahpouri

Course Info

Instructor

Dr. Alireza Abdollahpouri

Emails: abdollahpouri@gmail.com

Course Web Page

http://eng.uok.ac.ir/abdollahpouri/CN.html

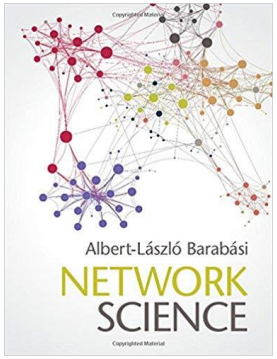
Grading Policy

Homeworks	**20%**
Project	**20%**
Final Exam	**55%**
Class participation	**5%**

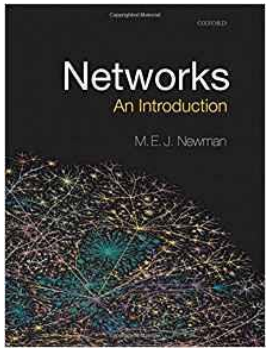
Teaching Materials – Textbooks

- Barabási, Albert-László. *"**Network Science Book,**"* 2015.

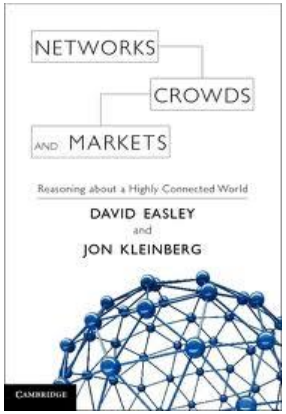
  http://barabasi.com/networksciencebook/



- Mark Newman, ***Networks: an Introduction***



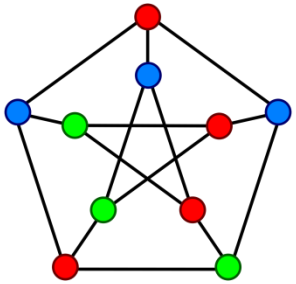
- David Easley and Jon Kleinberg: "***Networks Crowds and Markets. Reasoning about a Highly Connected World***"



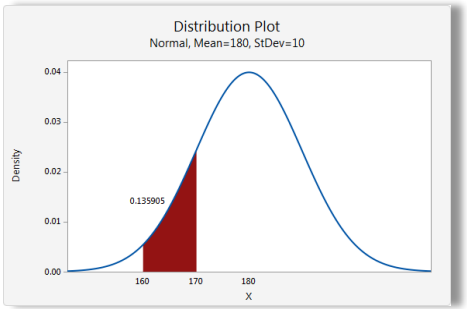
Course Overview

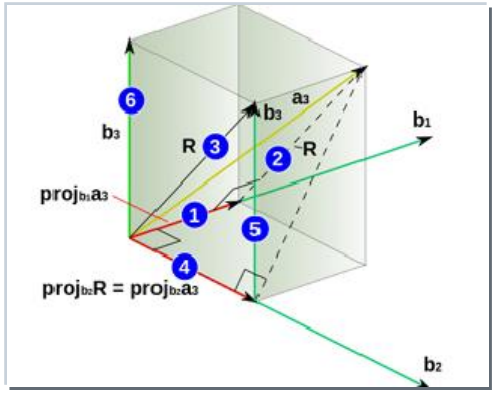
- **Introduction**
- **Graph Theory**
- **Centrality and Ranking**
- **Communities**
- **Network Models**
- **Diffusion models and Influence Maximization**
- **Link Prediction**
- **Network Robustness** (if time allows)

Course Prerequisites



- **Good background in:**
  - Algorithms and graph theory
  - Probability and statistics
  - Linear algebra





- **Programming:**
  - You should be able to write programs (in Python)

Some Ground Rules

- Let’s make this educational and enjoyable.
- It’s a big size class, I enjoy questions and ideas from the class.
- Ask questions and raise points.
- Listen to other people’s questions.
- Be here.
- Be here on time.

What do the following things have in common?

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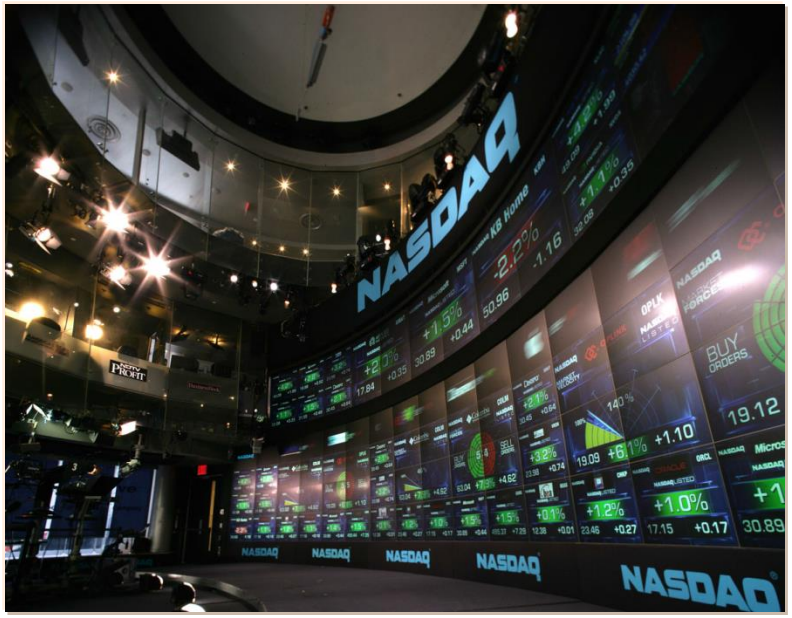
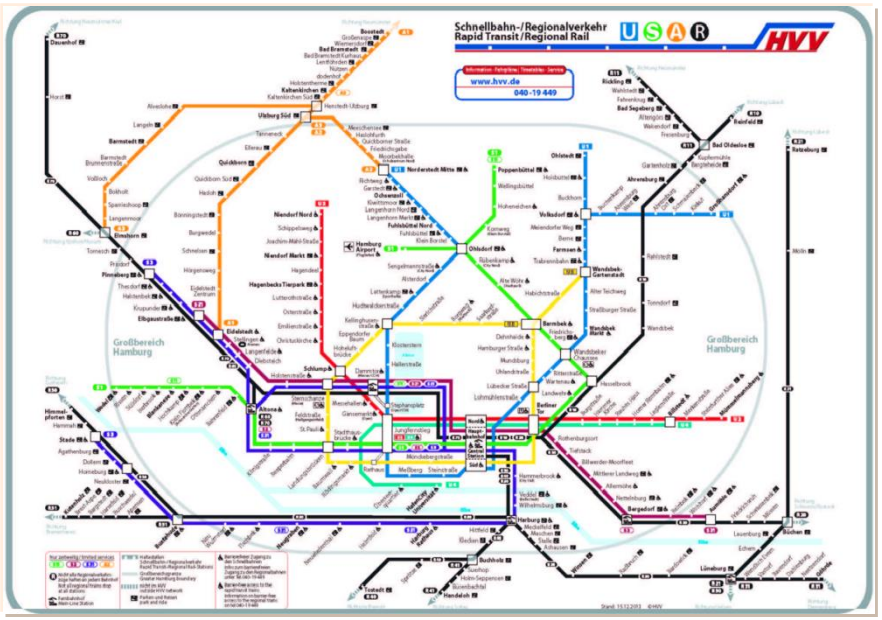


World economy



Metro map

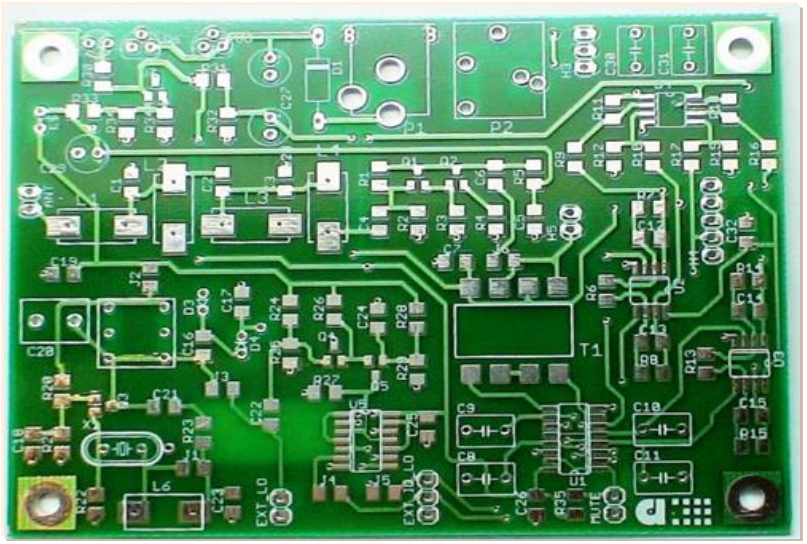
What do the following things have in common?

Human brain

Family and firiends

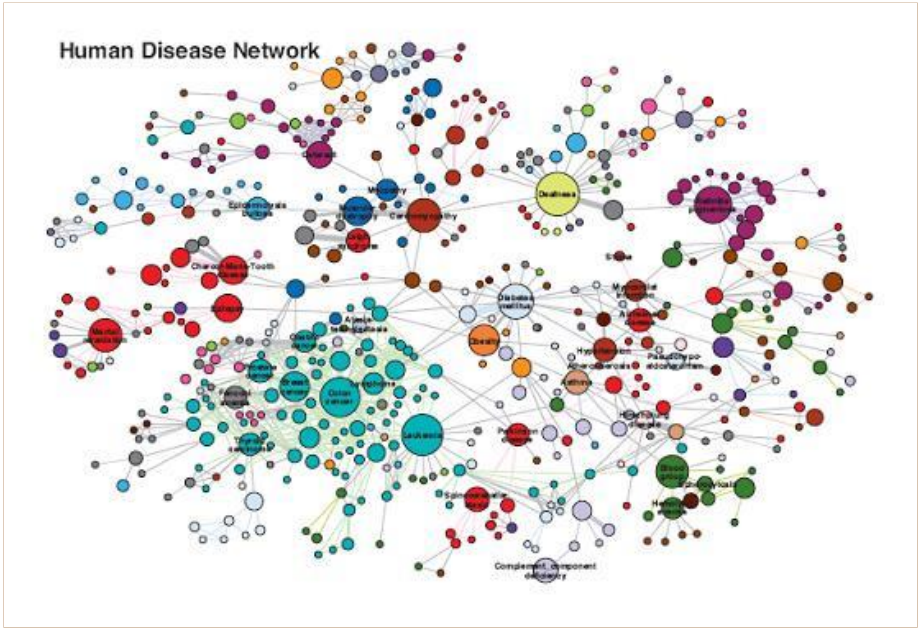
What do the following things have in common?

Power lines



Printed circuit board (PCB)

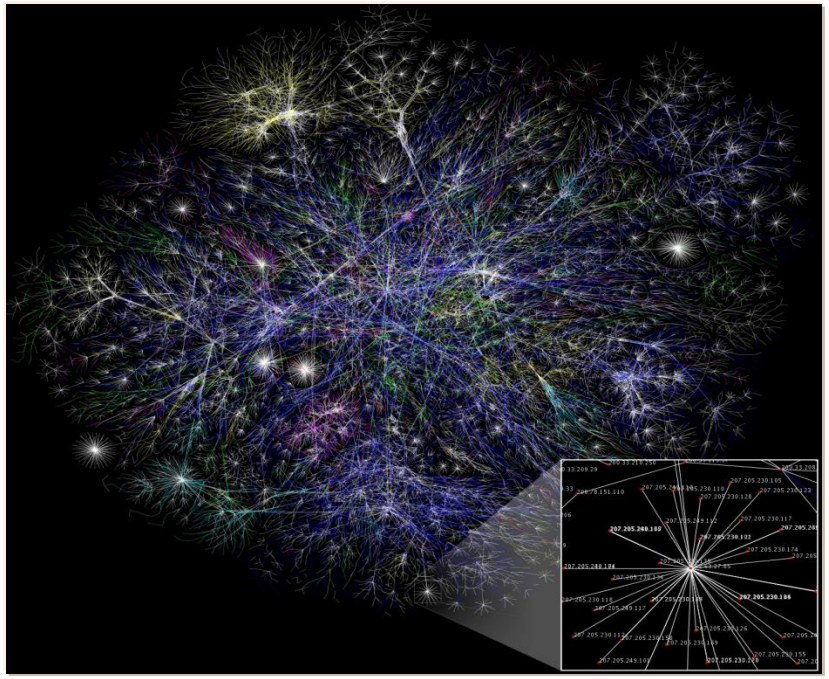
What do the following things have in common?



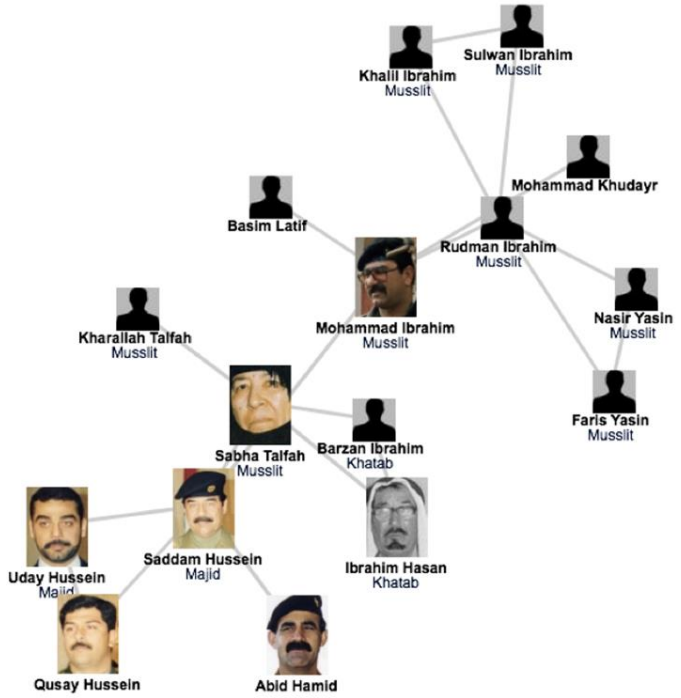
Human diseases map

Transportation highways

What do the following things have in common?



Internet



Terrorism

Behind each complex system there is a NETWORK, that defines the interactions between the component.

We will never understand these systems unless we understand the networks behind them!

Why Networks?

- **Universal language for describing complex data**

  Networks from science, nature, and technology are more similar than one would expect

- **Shared vocabulary between fields**

  Computer Science, Social science, Physics, Economics, Statistics, Biology

What is a Network?

- A collection of nodes (vertices)
- And a collection of edges (links) connecting nodes
- A network model treats all nodes and links the same. But there are heterogeneous networks.
- The spatial location of nodes is arbitrary (in visualization)
- Networks are abstractions of connection and relation

Ubiquity of Networks

Networks appear at all scales

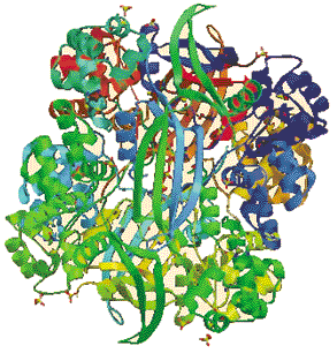
Proteins

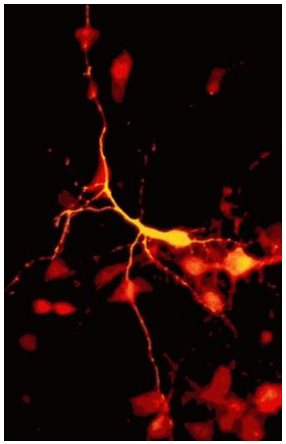
Intra-cellular signalling

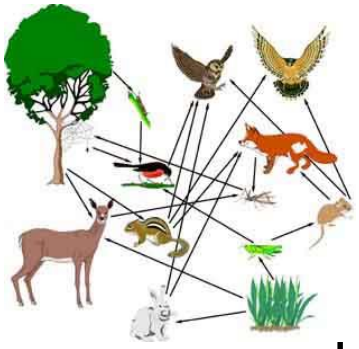
Neuronal communication

Social contact

Food webs







10^{-9} m 10^{-6} m 10^{-3} m 1 m 10^{3} m 10^{6} m

Molecules Cells Organisms Populations Ecologies

Age and size of networks

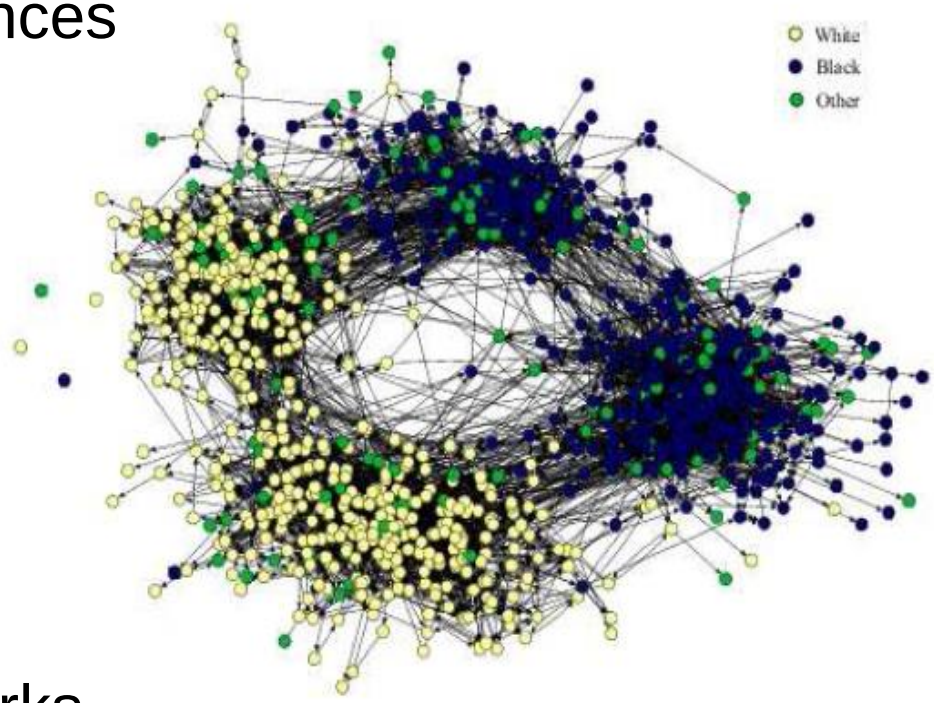
Many examples of networks

- Social Networks
- Technological Networks
- Networks of Information
- Biological Networks
- And …


Social
Networks

Social Networks

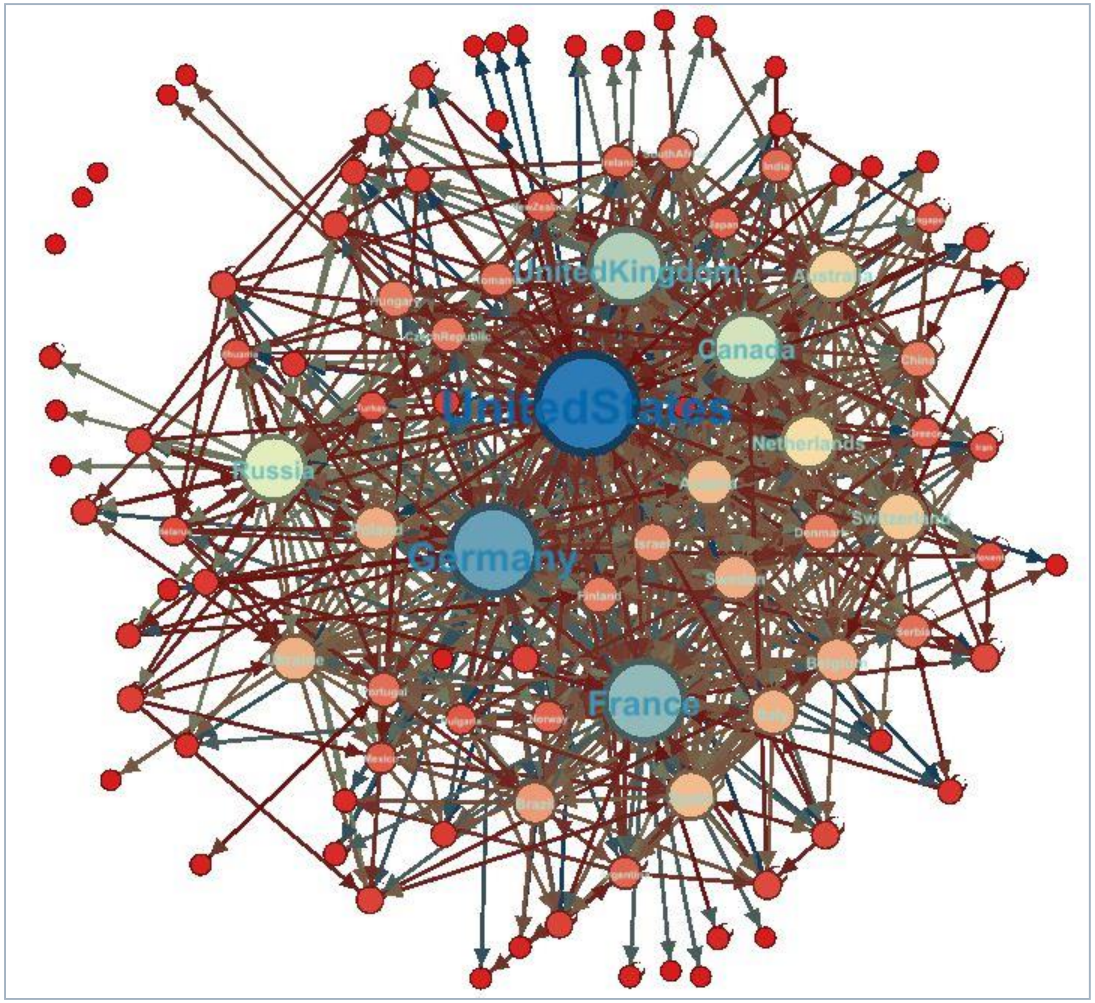
- Links denote a social interaction
  - Networks of acquaintances
  - collaboration networks
    - actor networks
    - co-authorship networks
    - director networks
  - phone-call networks
  - e-mail networks
  - Bluetooth networks
  - home page/blog networks
  - …



Academic Network

104 countries

d = 17.8



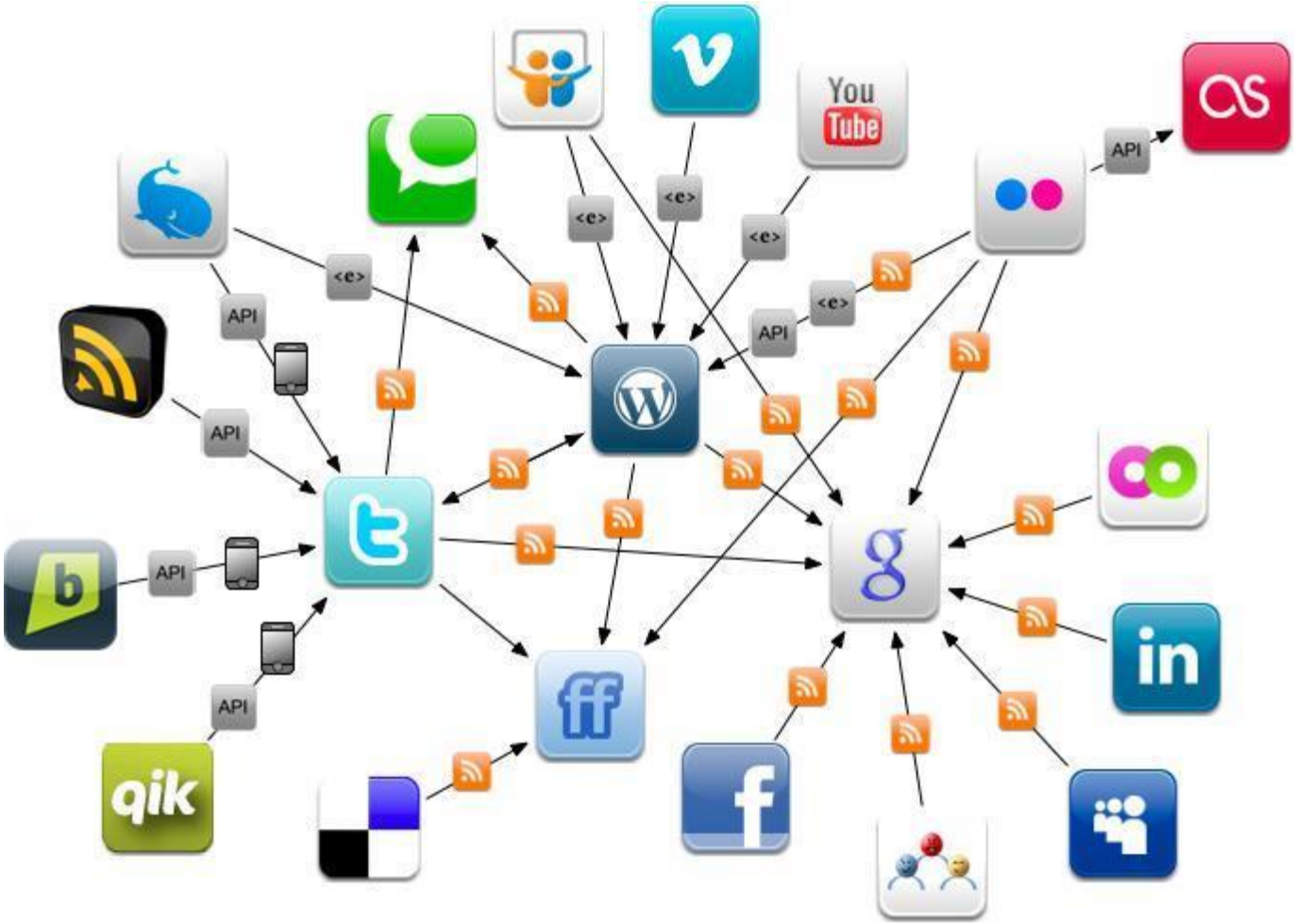
Assortativity = .005
non-assortative

clustering = .37
(random =.06)

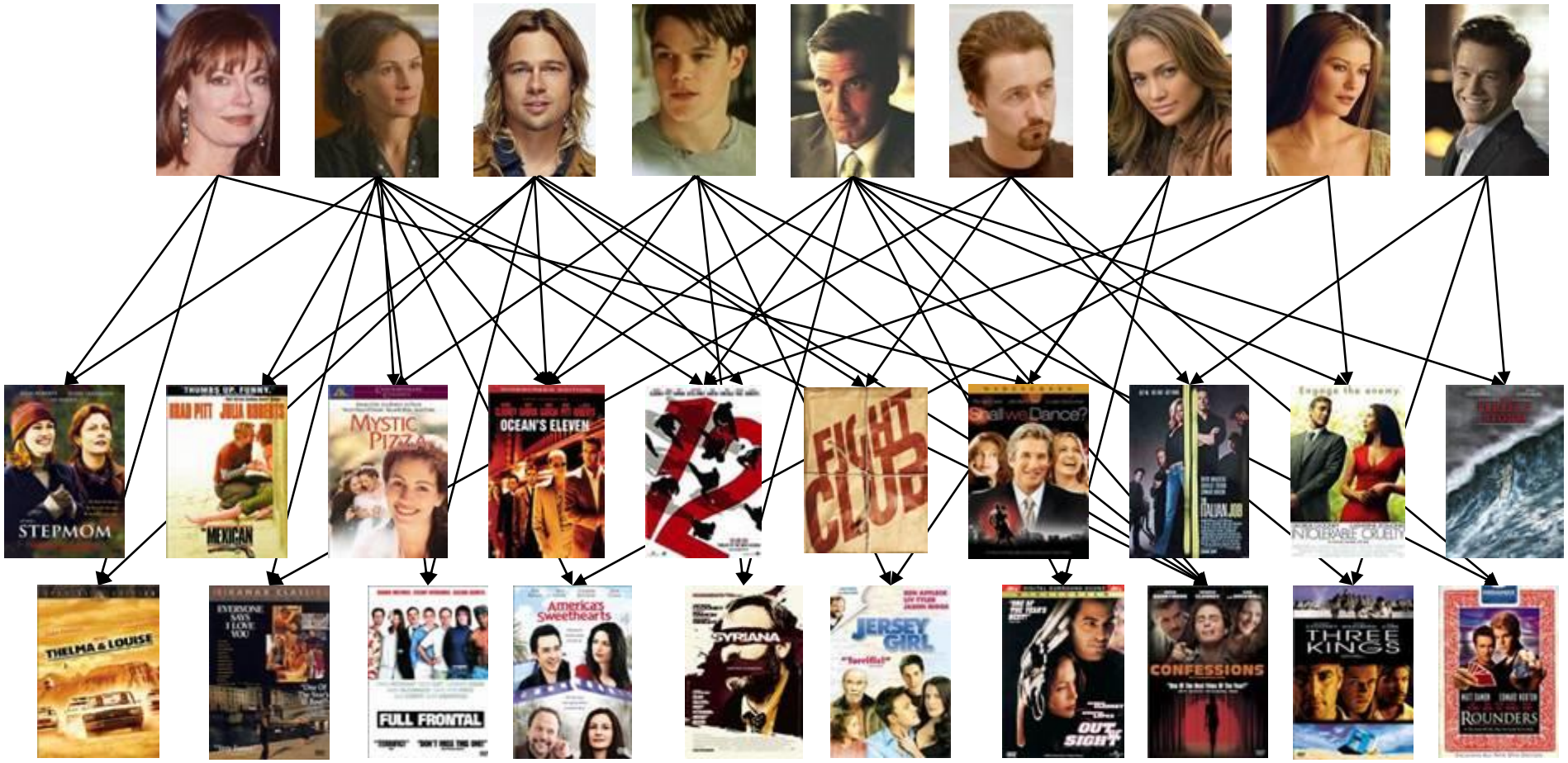
Friendship Network

- Nodes: all persons in some community
- A link exists between two persons if they are friends.

Online Social Networks

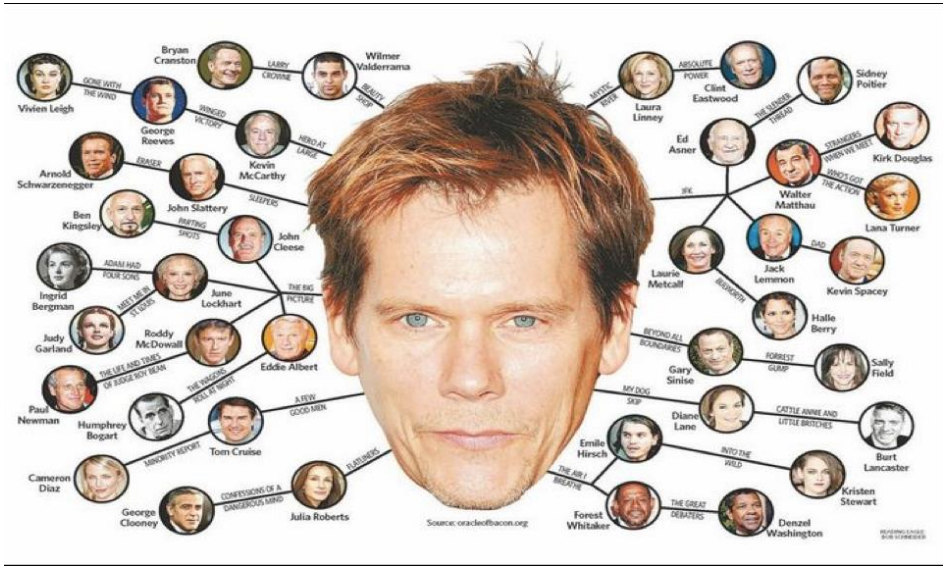


Network of actor co-starring in movies

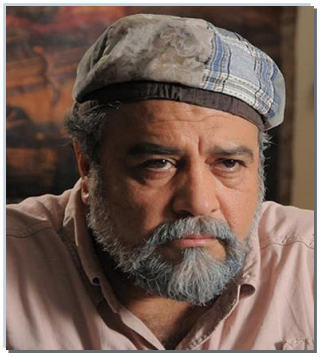


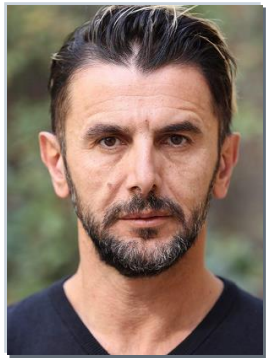
Actor co-starring Network

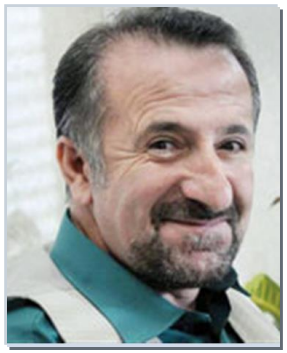
- **The collaboration graph of film actors**
- **Six Degrees of Kevin Bacon**



Who is the co-star hub of Iranian movies?!

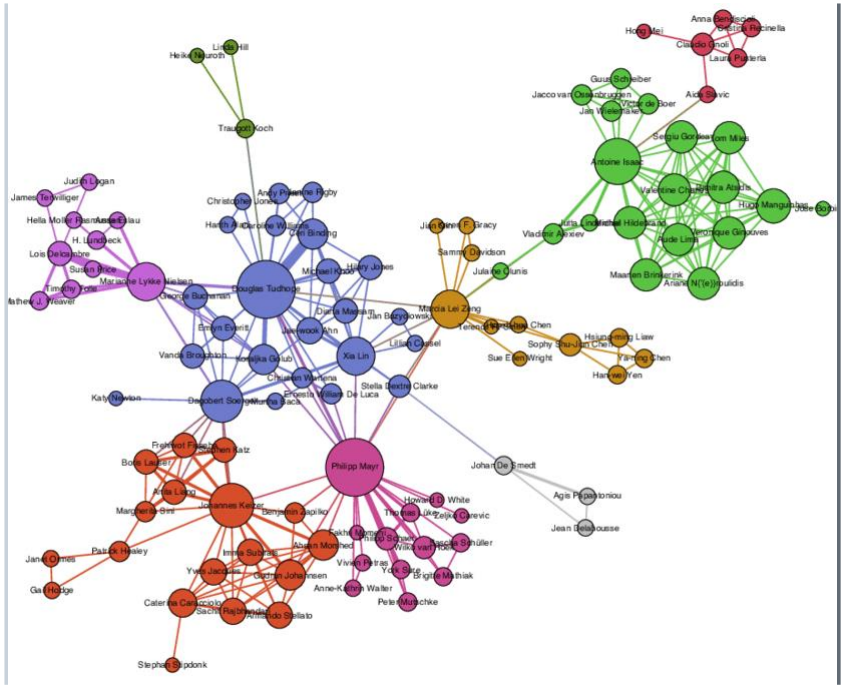


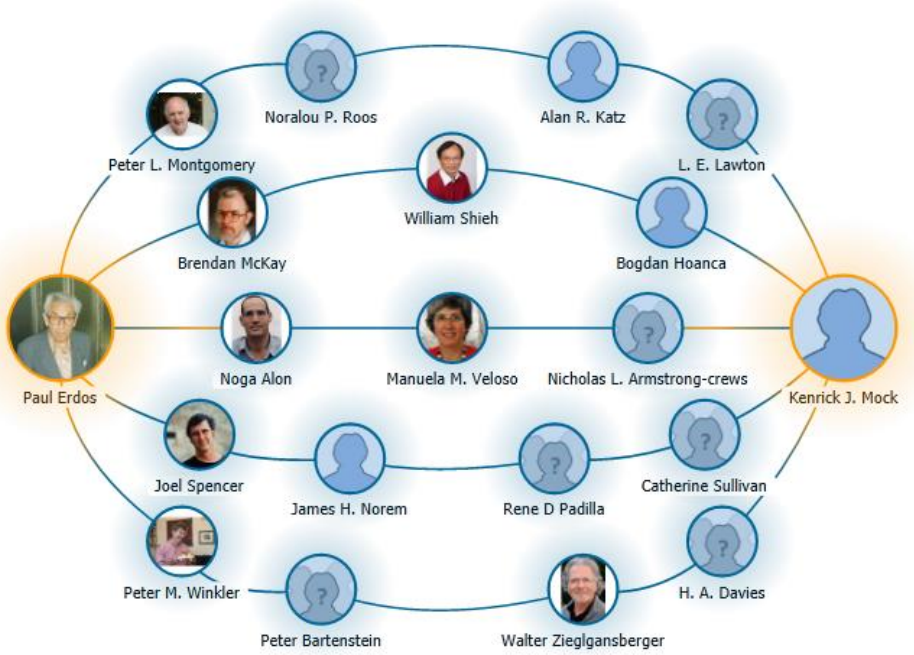




This slide is borrowed from Dr. Aliakbari (SBU)

Co-authorship Network



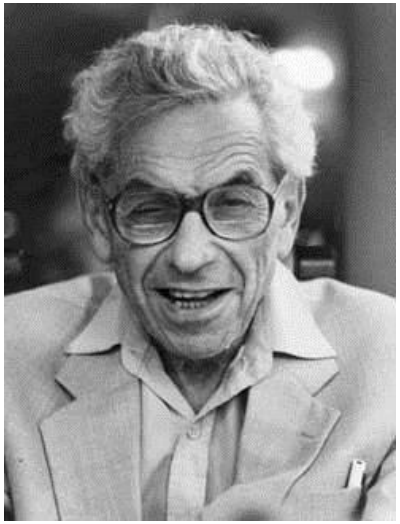


Nodes: all publication authors

A link exists between two authors if they are coauthors in a publication

Co-authorship Network

- **Erdős number:** **is the collaboration distance with mathematician Paul Erdős.**



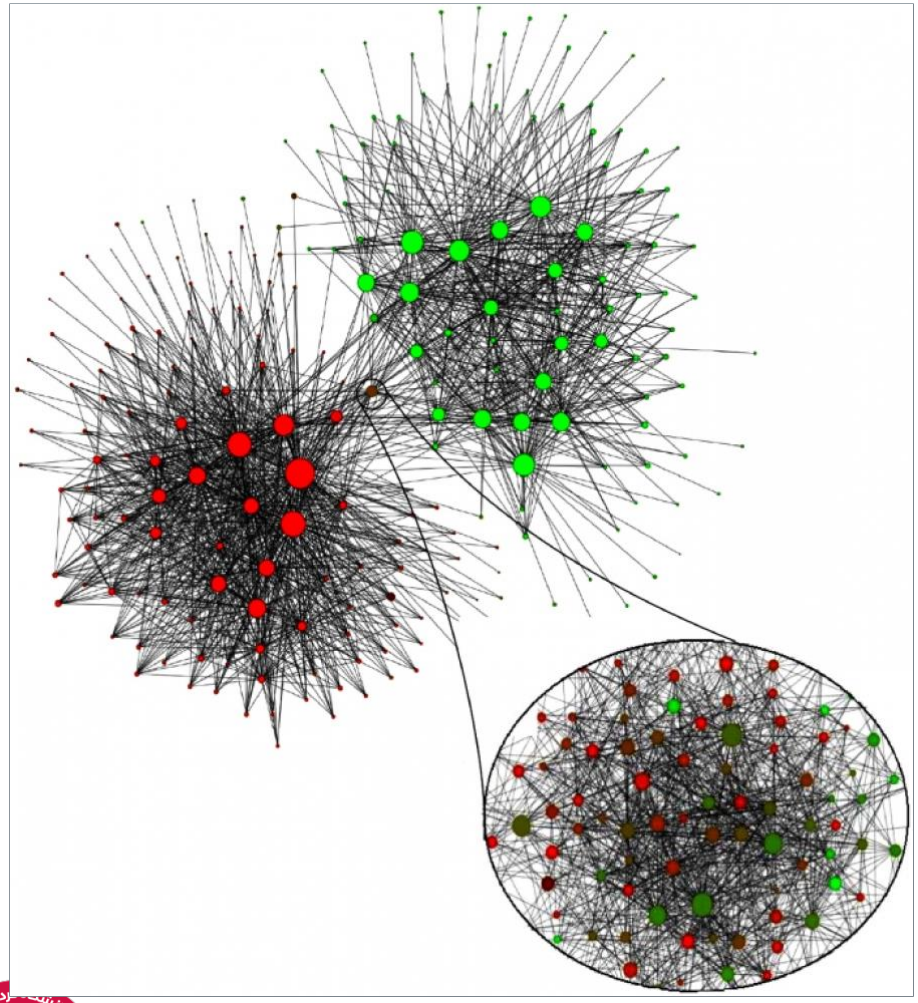
Small world network

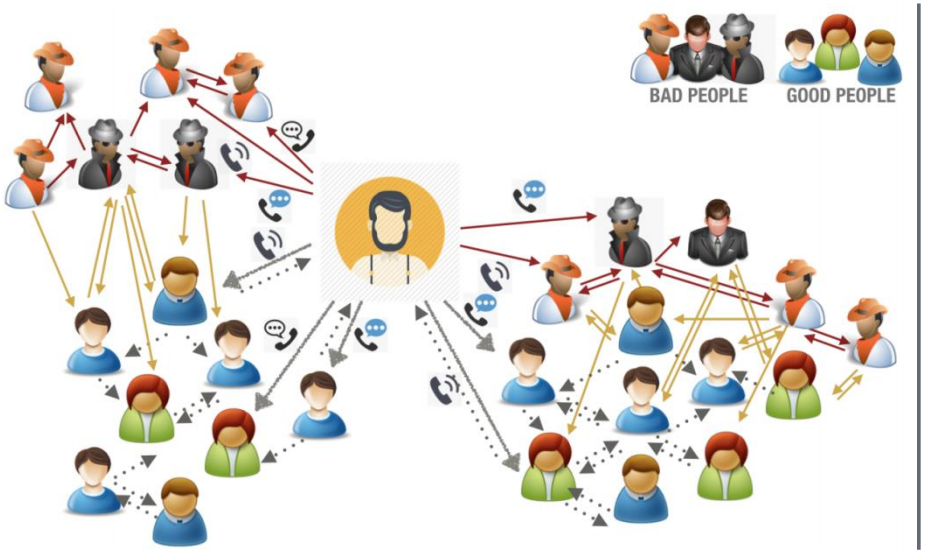
Distribution in Dec.2010

Erdös number 0	---	1 person
Erdös number 1	---	504 people
Erdös number 2	---	6593 people
Erdös number 3	---	33605 people
Erdös number 4	---	83642 people
Erdös number 5	---	87760 people
Erdös number 6	---	40014 people
Erdös number 7	---	11591 people
Erdös number 8	---	3146 people
Erdös number 9	---	819 people
Erdös number 10	---	244 people
Erdös number 11	---	68 people
Erdös number 12	---	23 people
Erdös number 13	---	5 people

* Two persons are linked if they are coauthors of an article.

Phone-call networks

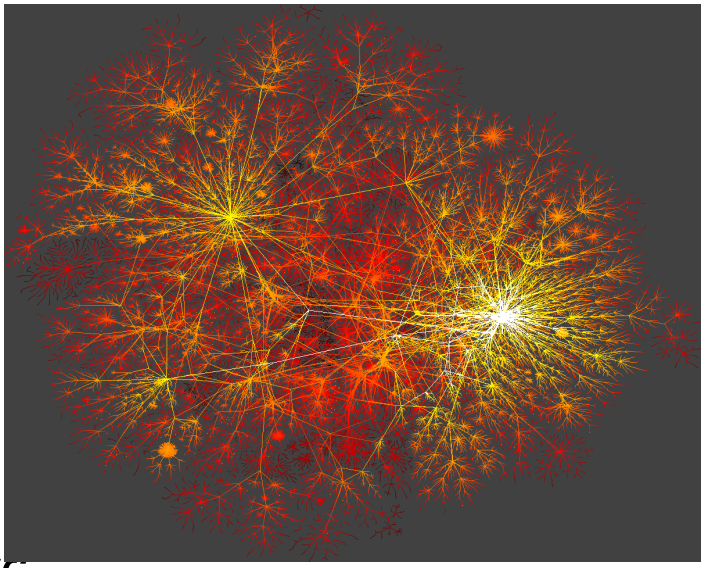




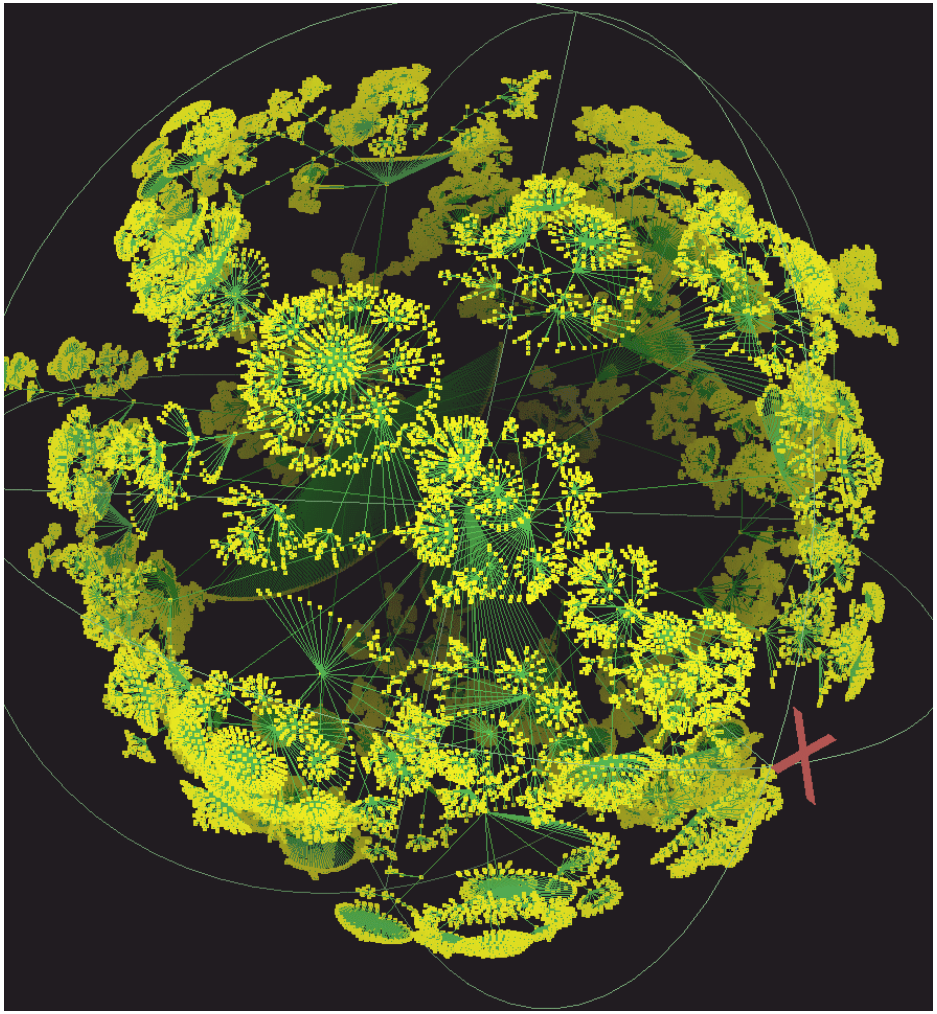

Technological
Networks

Technological networks

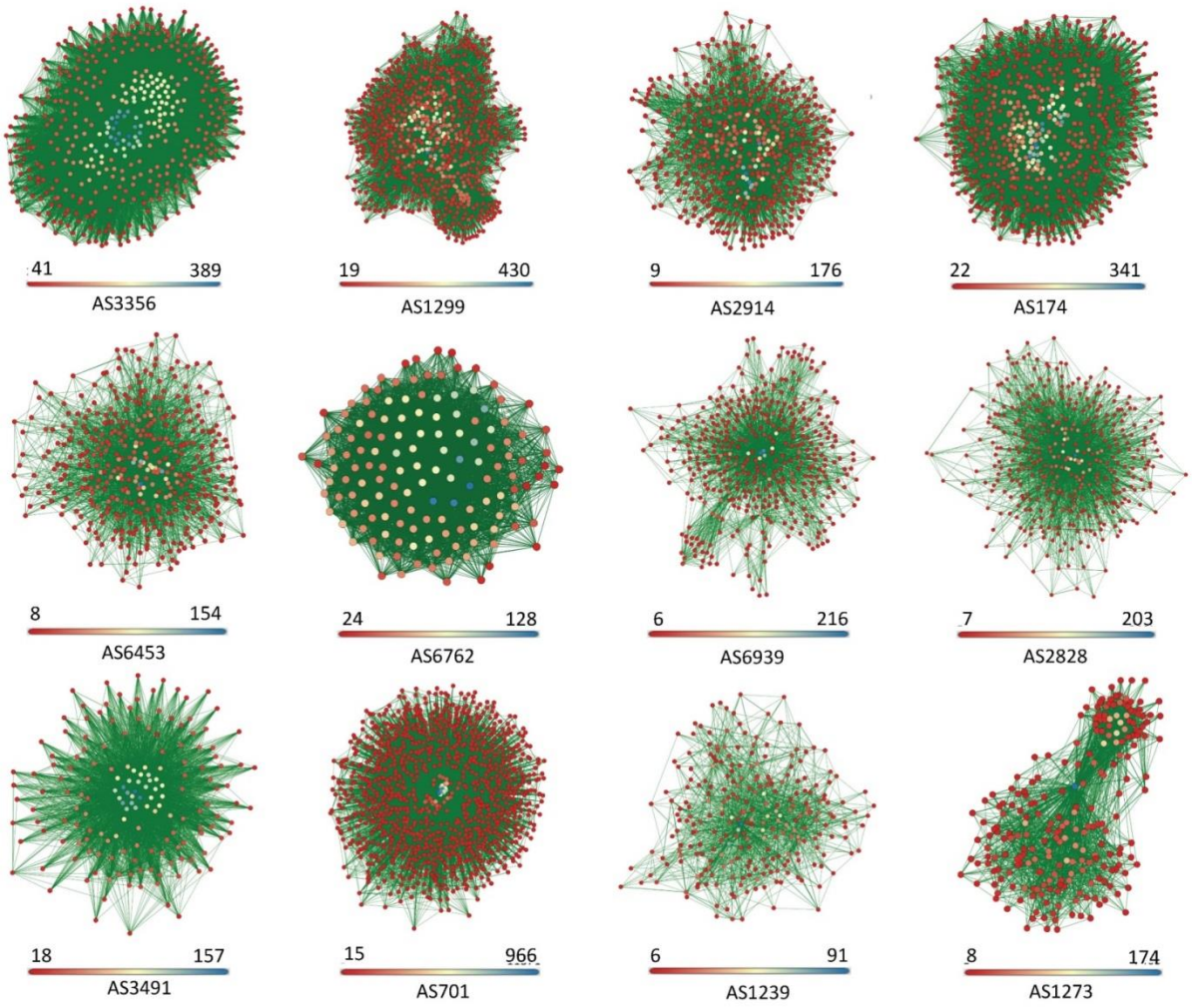
- Networks built for distribution of commodity
  - *The Internet*
    - *router level, AS level*
  - *Power Grids*
  - *Airline networks*
  - *Telephone networks*
  - *Transportation Networks*
    - *roads, railways, pedestrian traffic*



Routers



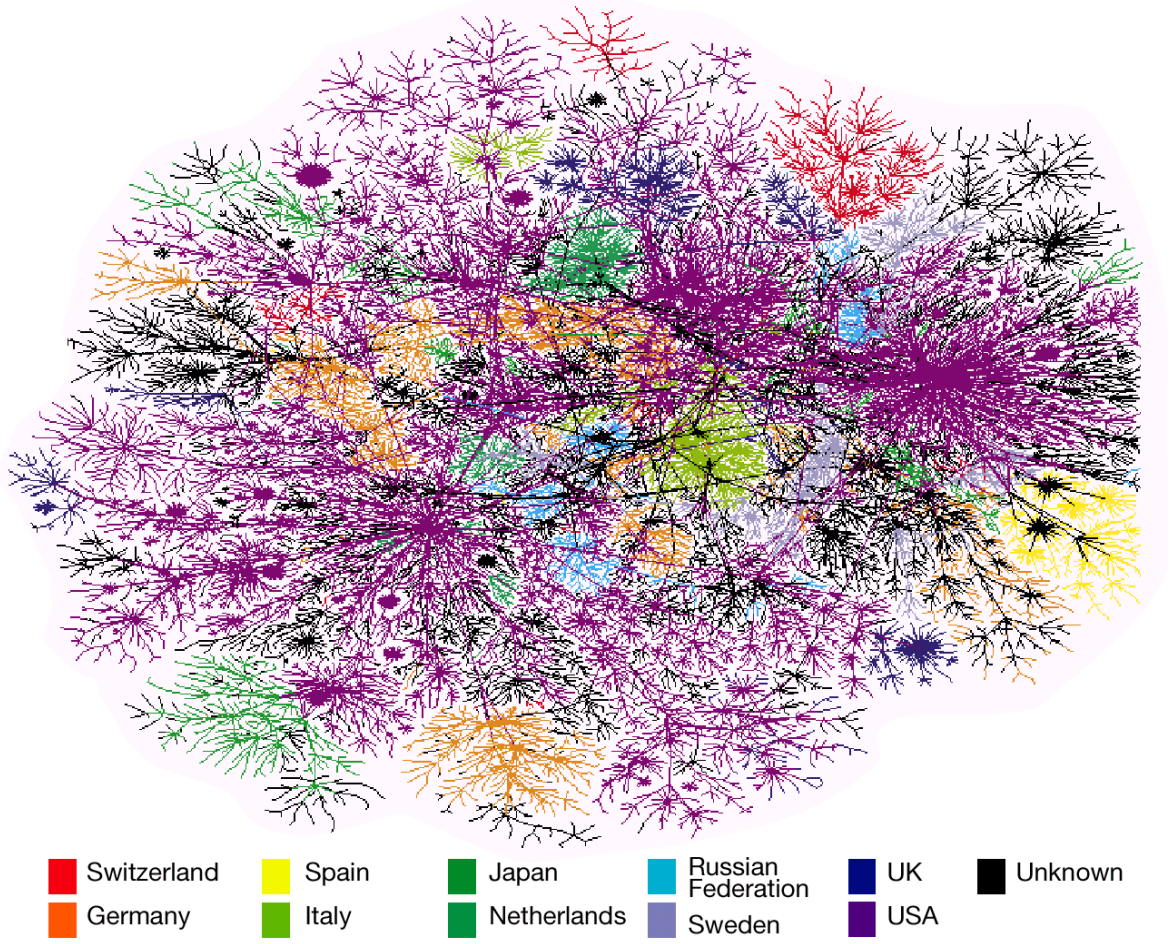
Internet Core Networks (AS level)



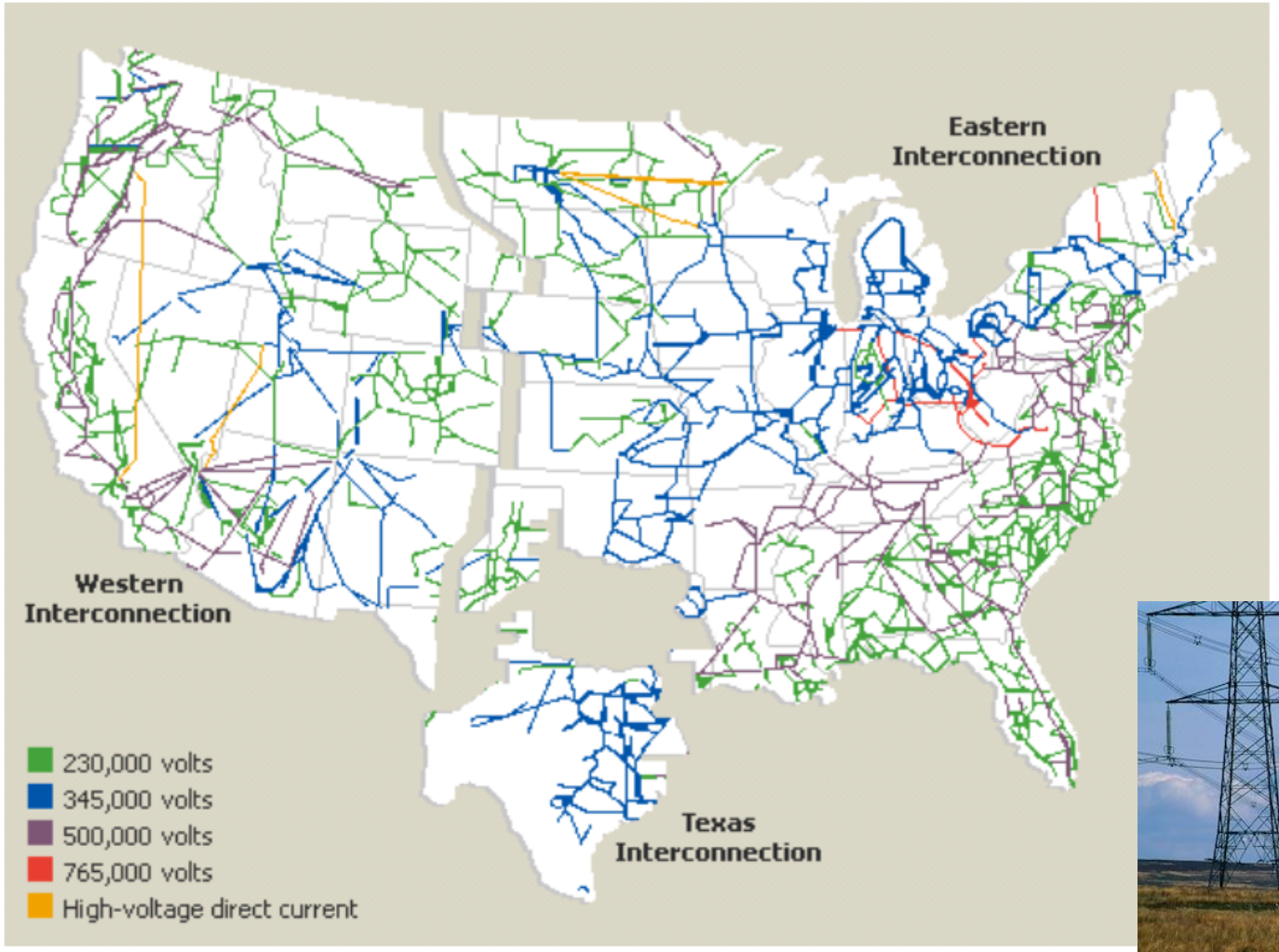
Internet Map

Internet as measured by Hal Burch and Bill Cheswick's Internet Mapping Project.

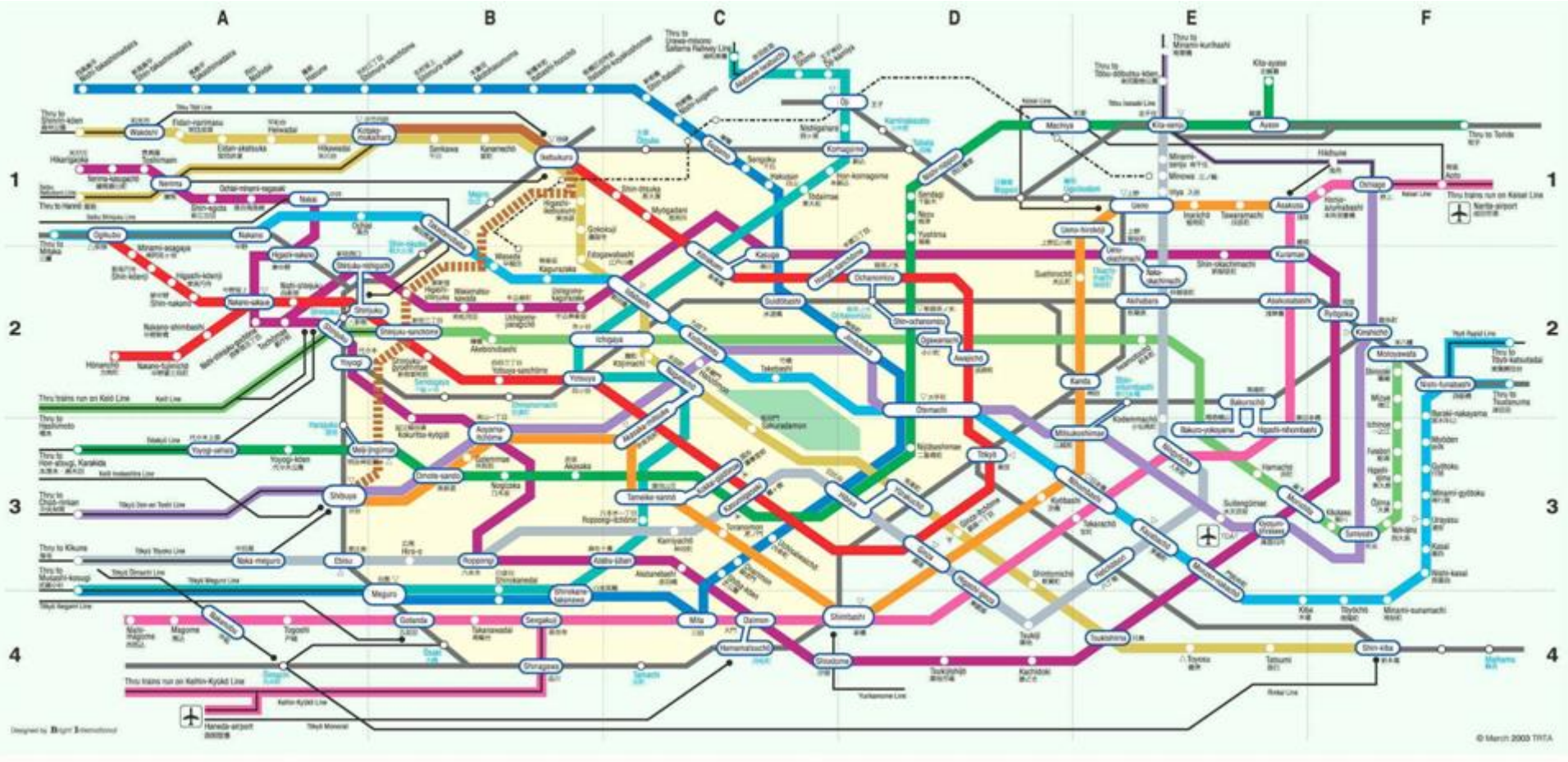
Note: Internet != Web



Power networks

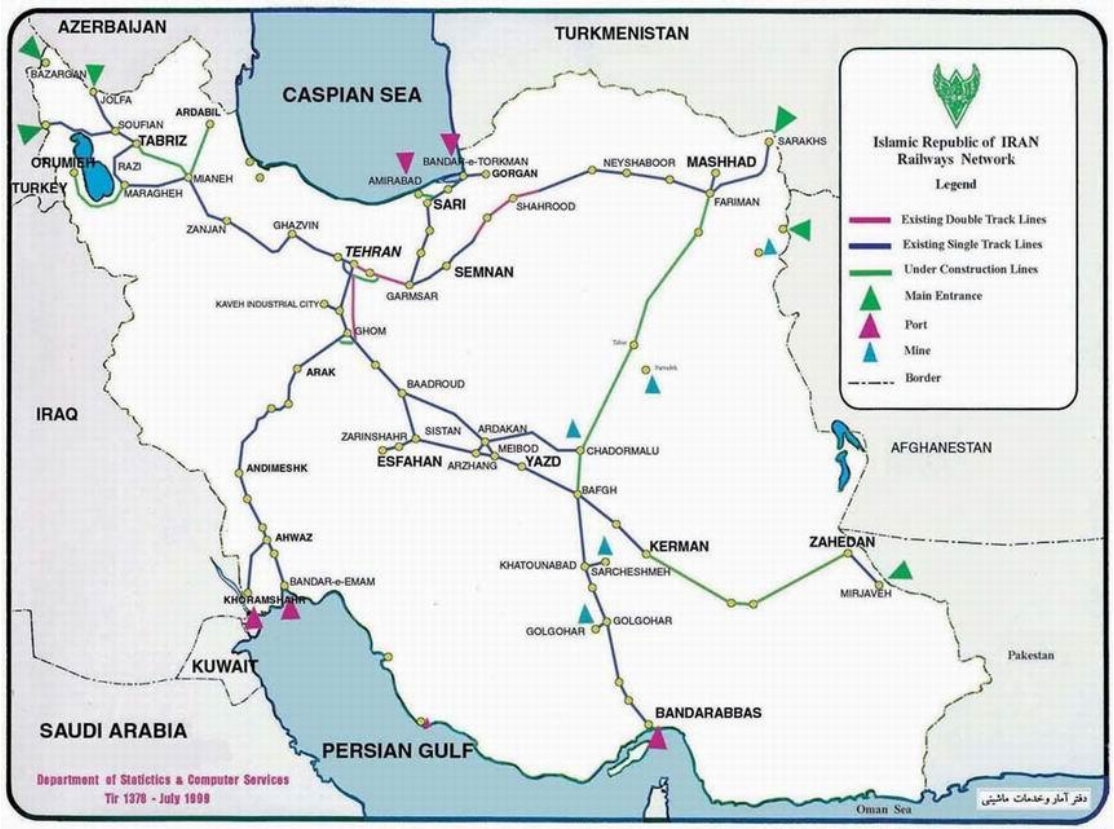


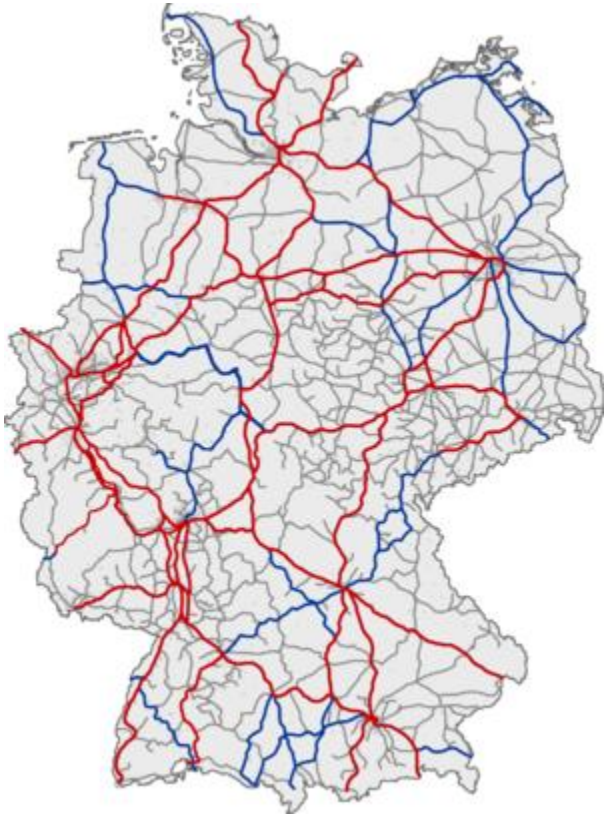
Subway maps



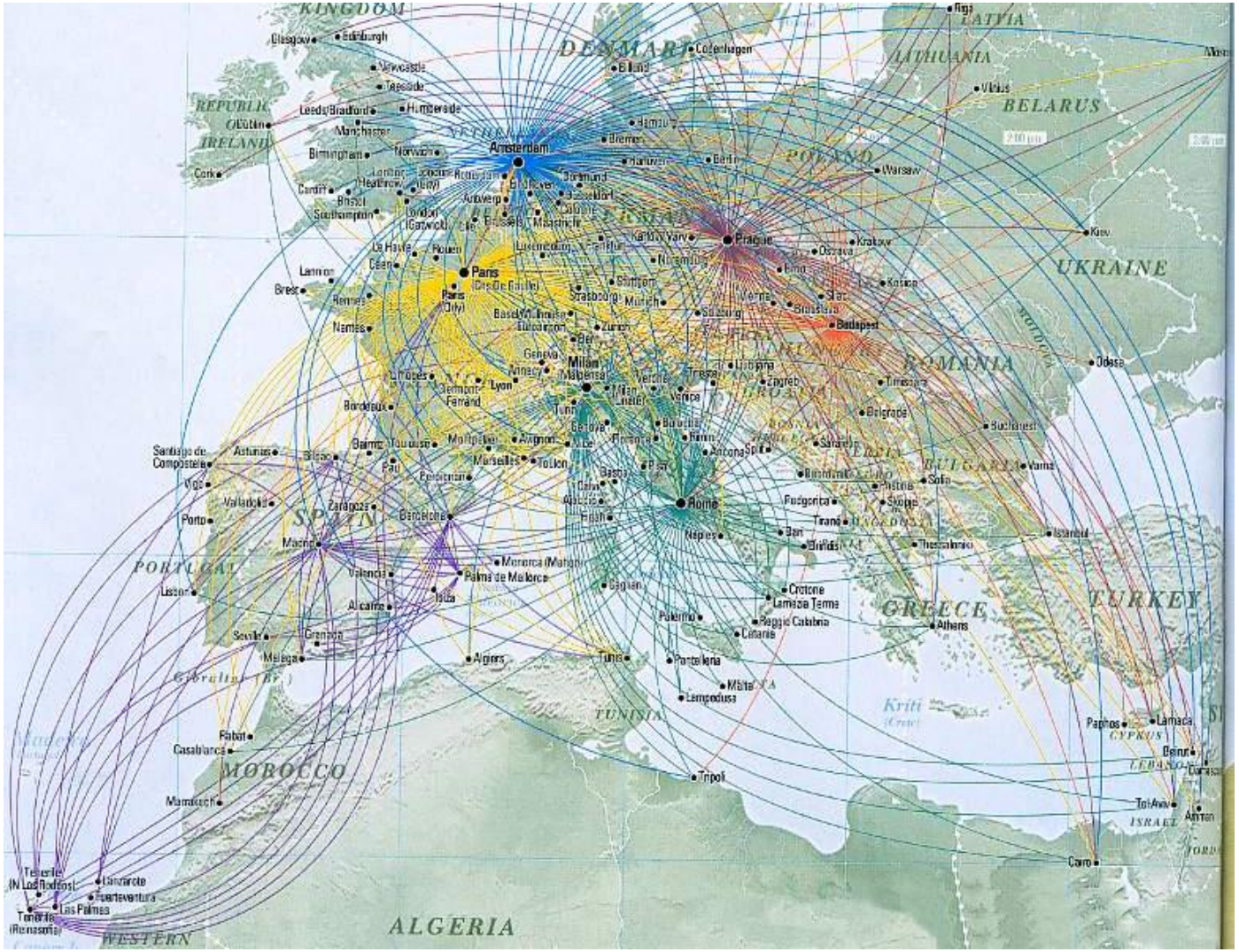
Source: TRTA, March 2003 - Tokyo rail map

Railway Maps

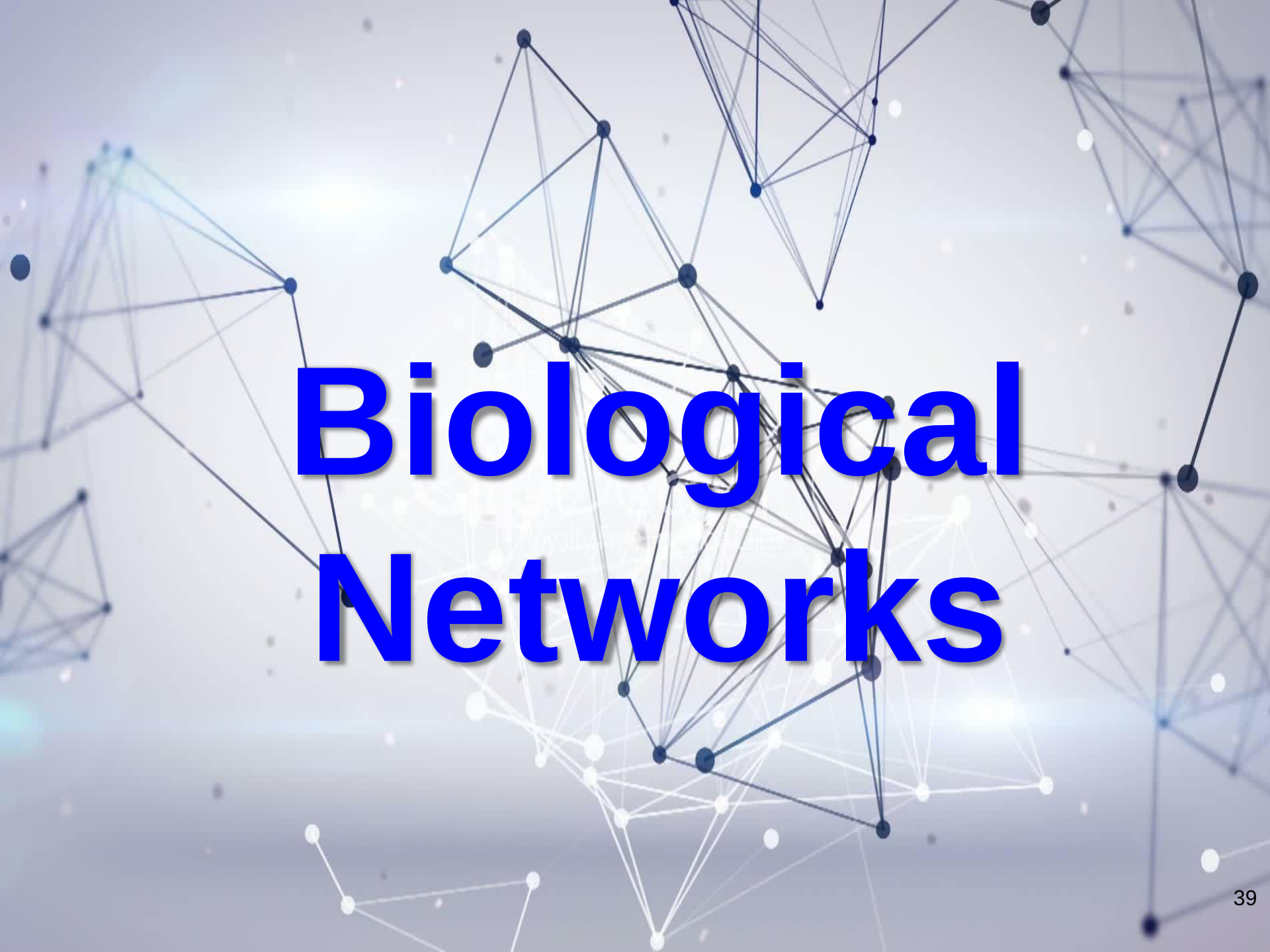




Airline network

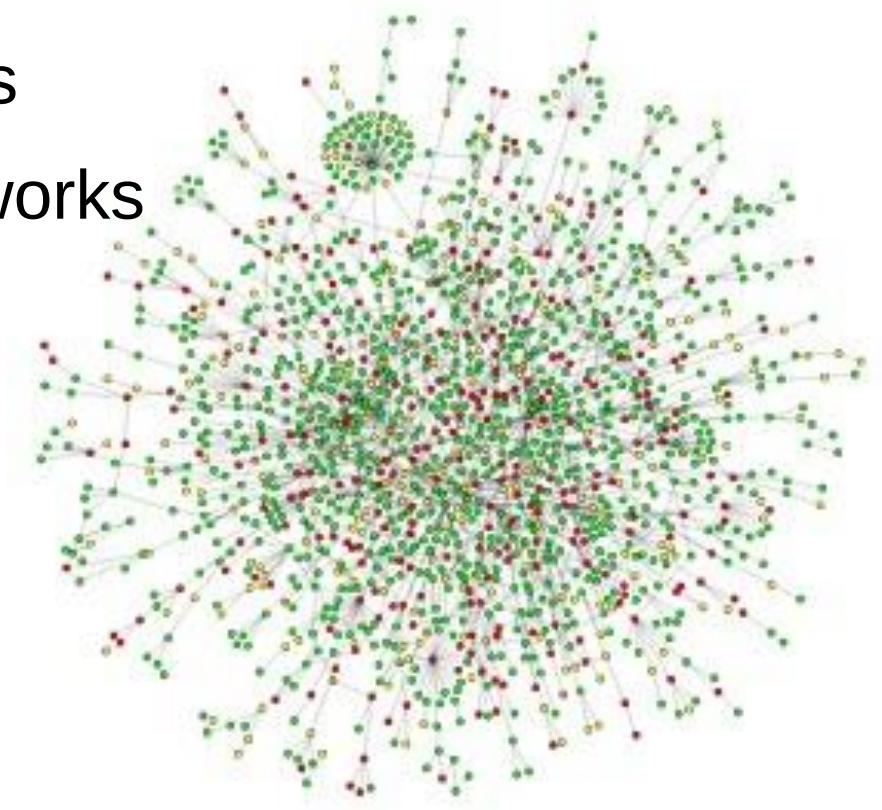


Source: Northwest Airlines WorldTraveler Magazine


Biological
Networks

Biological networks

- Biological systems represented as networks
  - Protein-Protein Interaction Networks
  - Gene regulation networks
  - Gene co-expression networks
  - Metabolic pathways
  - The Food Web
  - Neural Networks



Bio map by L-A Barabasi

GENOME

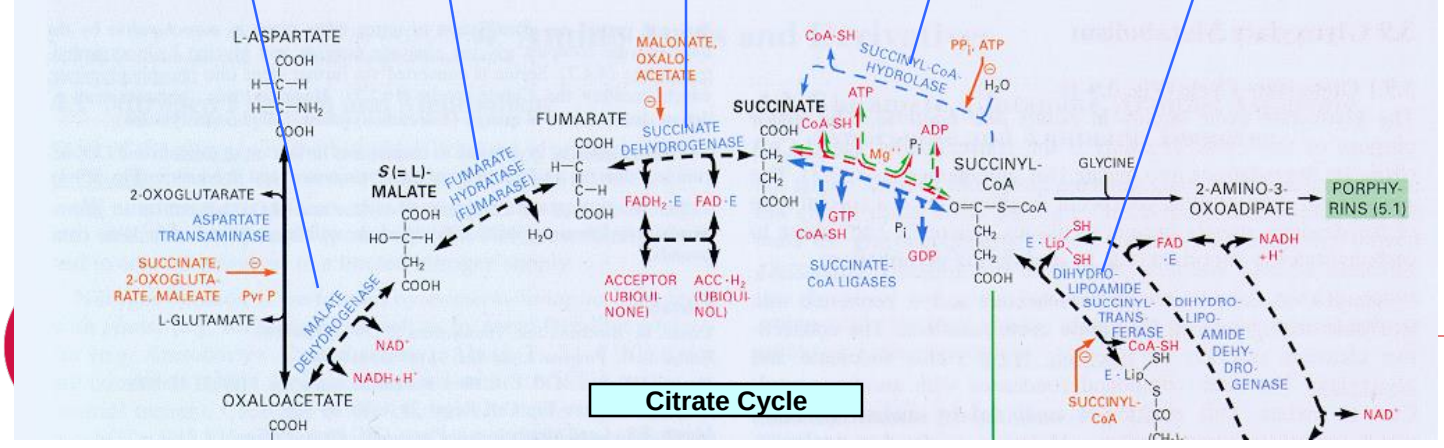
protein-gene interactions

PROTEOME

protein-protein interactions

METABOLISM

Bio-chemical reactions



Protein-Protein Interactions

Classifying the function of proteins in the interactome!

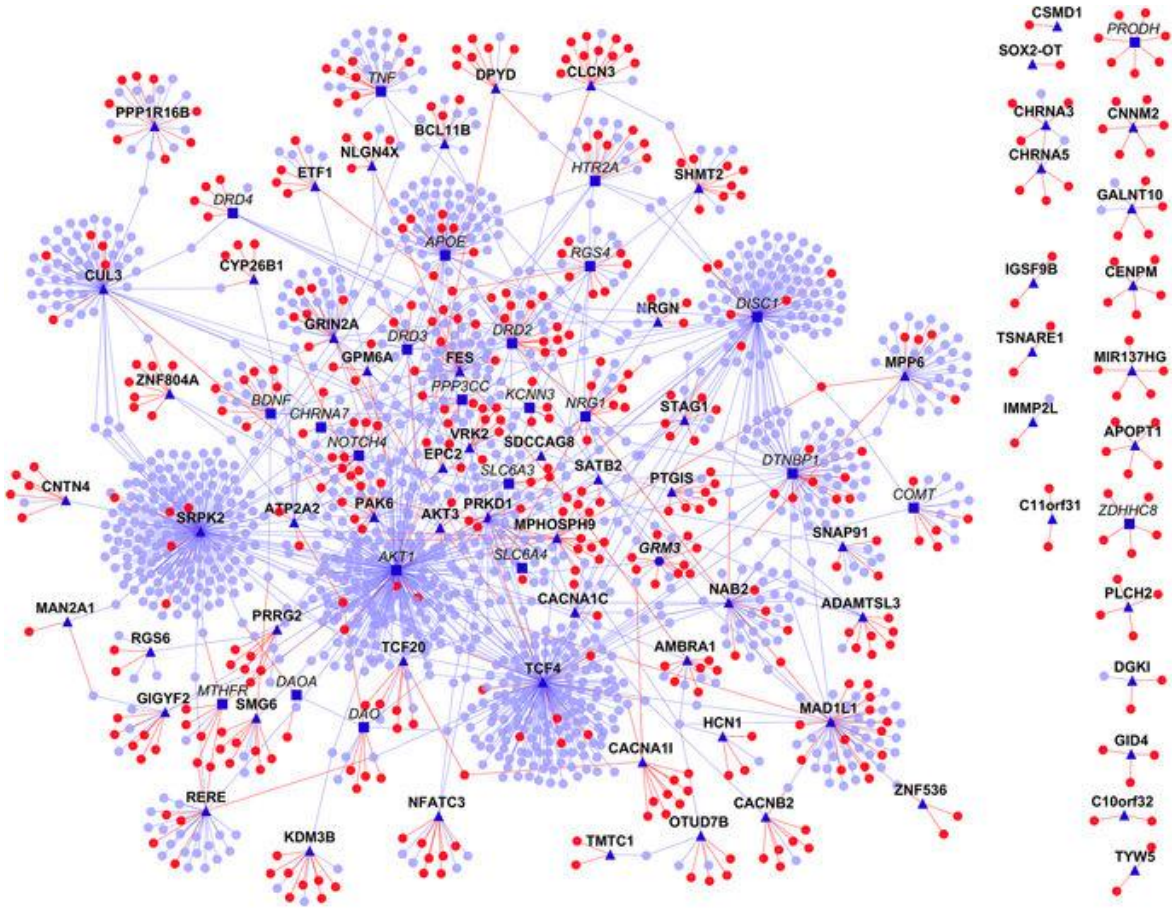
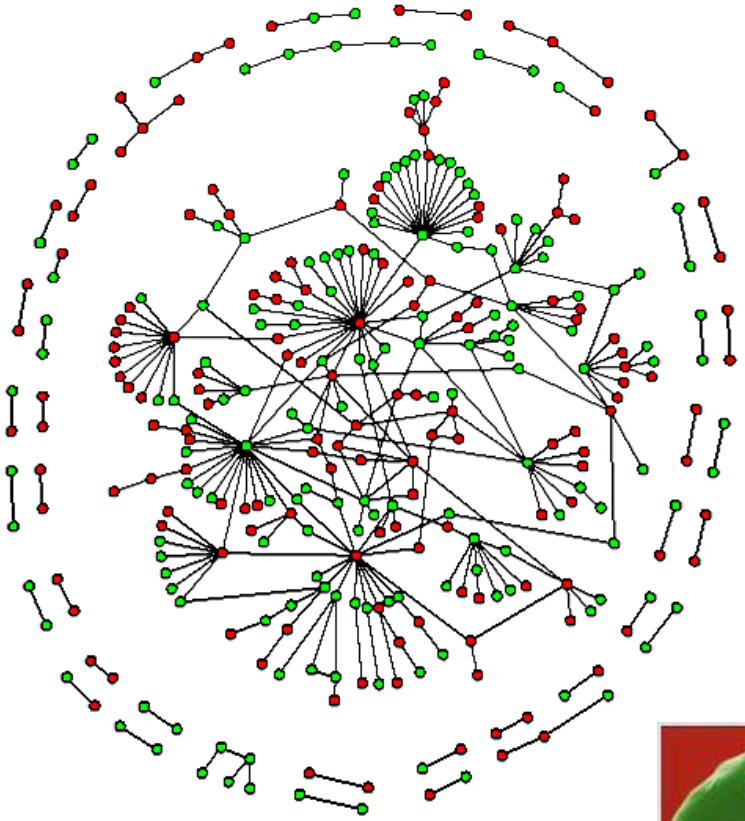
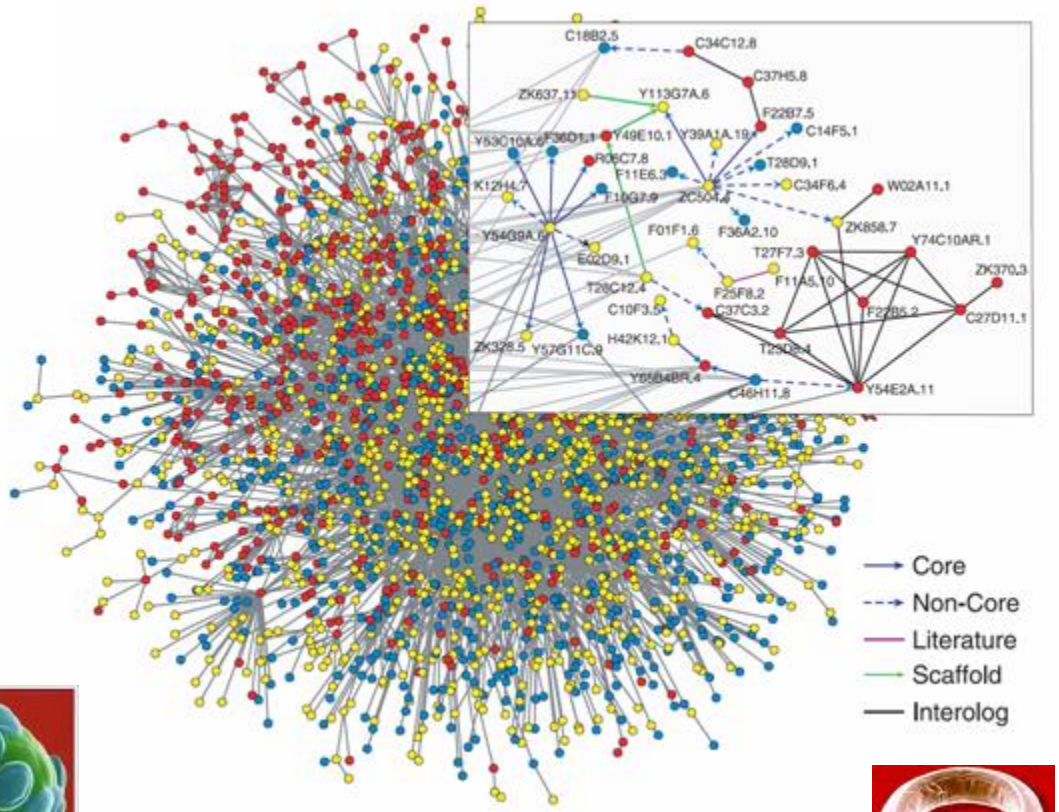


Image from: Ganapathiraju et al. 2016. [Schizophrenia interactome with 504 novel protein–protein interactions](). *Nature*.

Protein binding networks



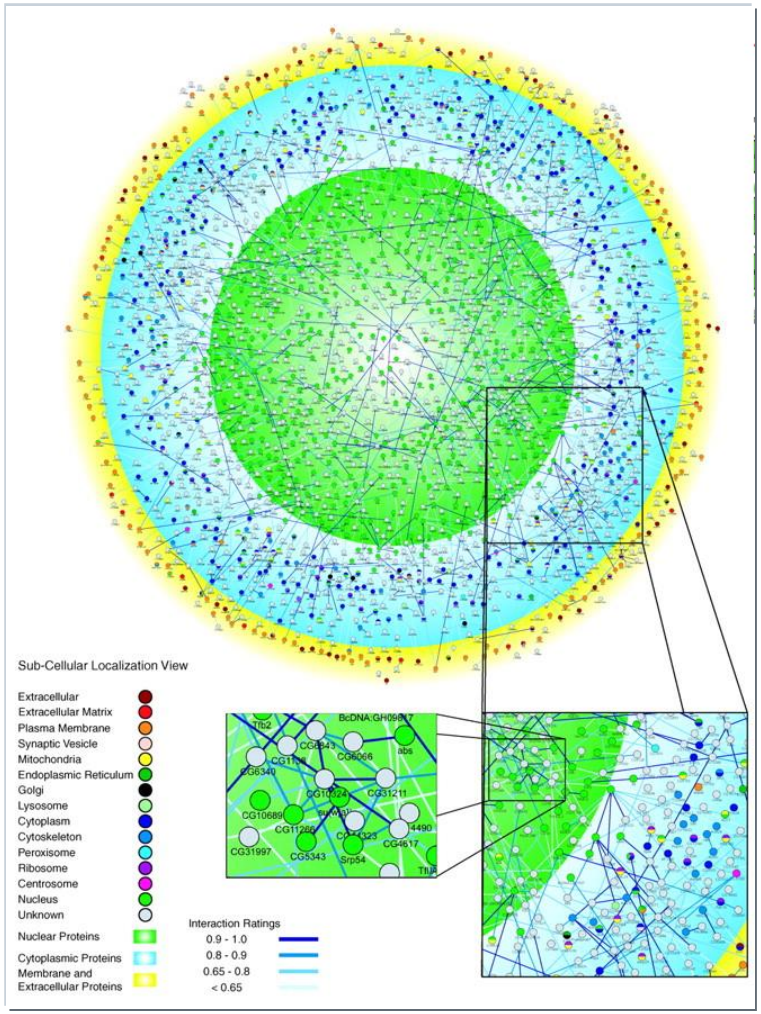


Baker's yeast *S. cerevisiae*
(only nuclear proteins shown)

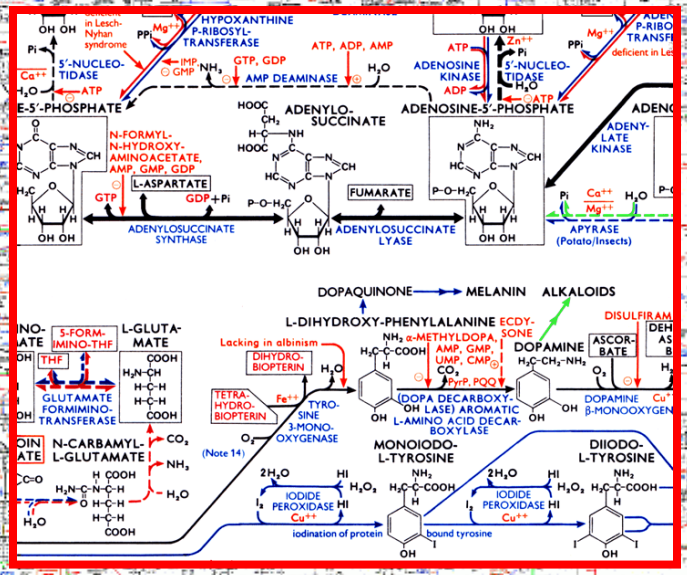
Nematode worm *C.*

The Protein Network of Drosophila

CuraGen Corporation
Science, 2003

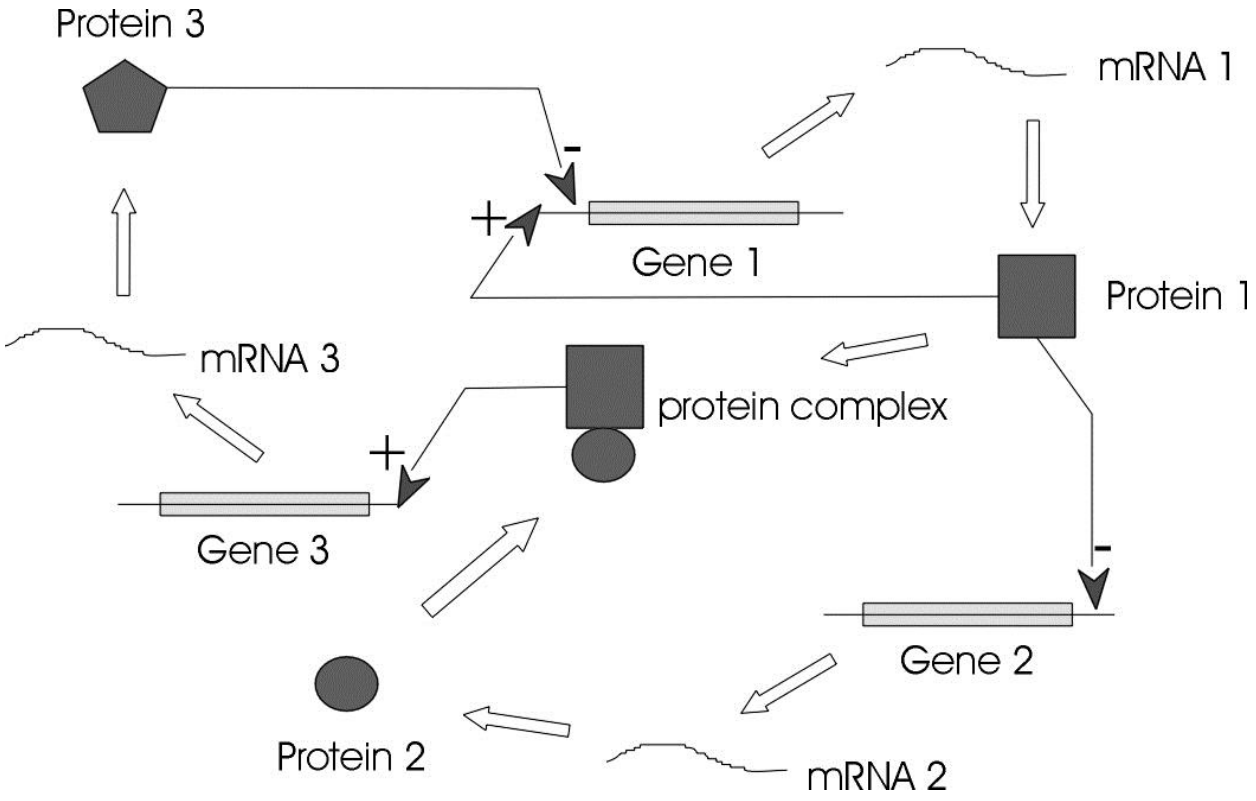


Biochemical pathways (Roche)



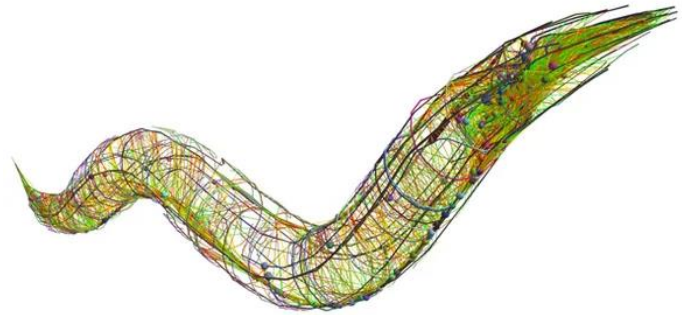
Gene regulatory networks

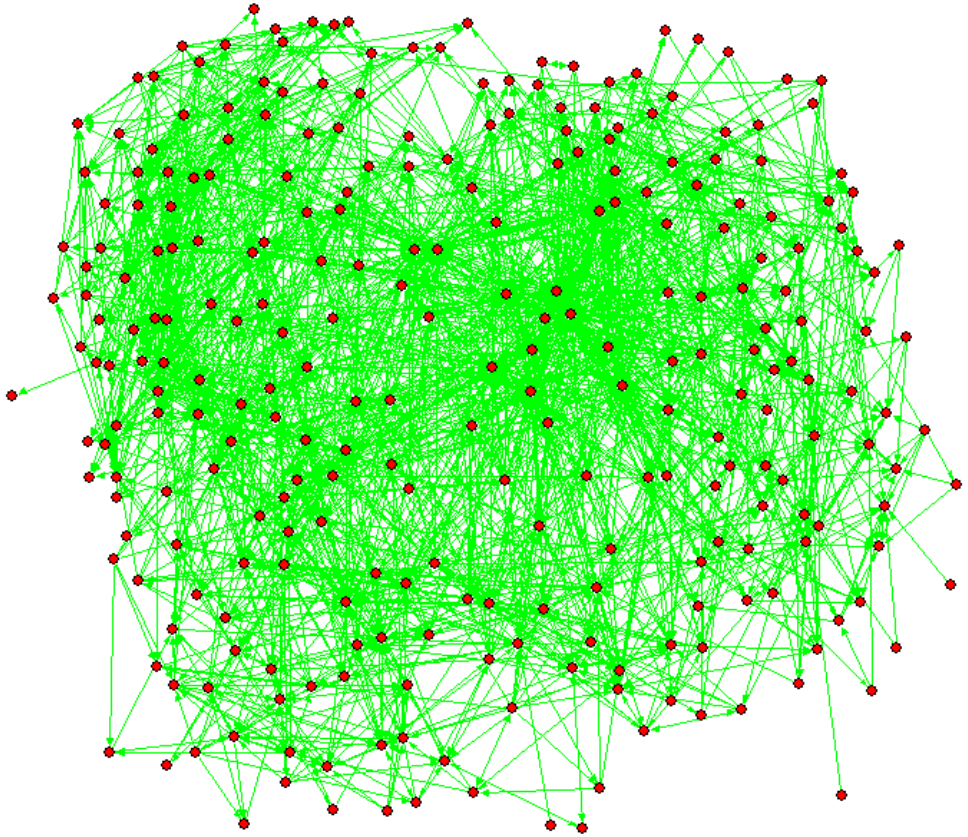
- Humans have 30,000 genes
- The complexity is in the interaction of genes
- Can we predict what result of the inhibition of one gene will be?



Source: http://www.zaik.uni-koeln.de/bioinformatik/regulatorynets.html.en

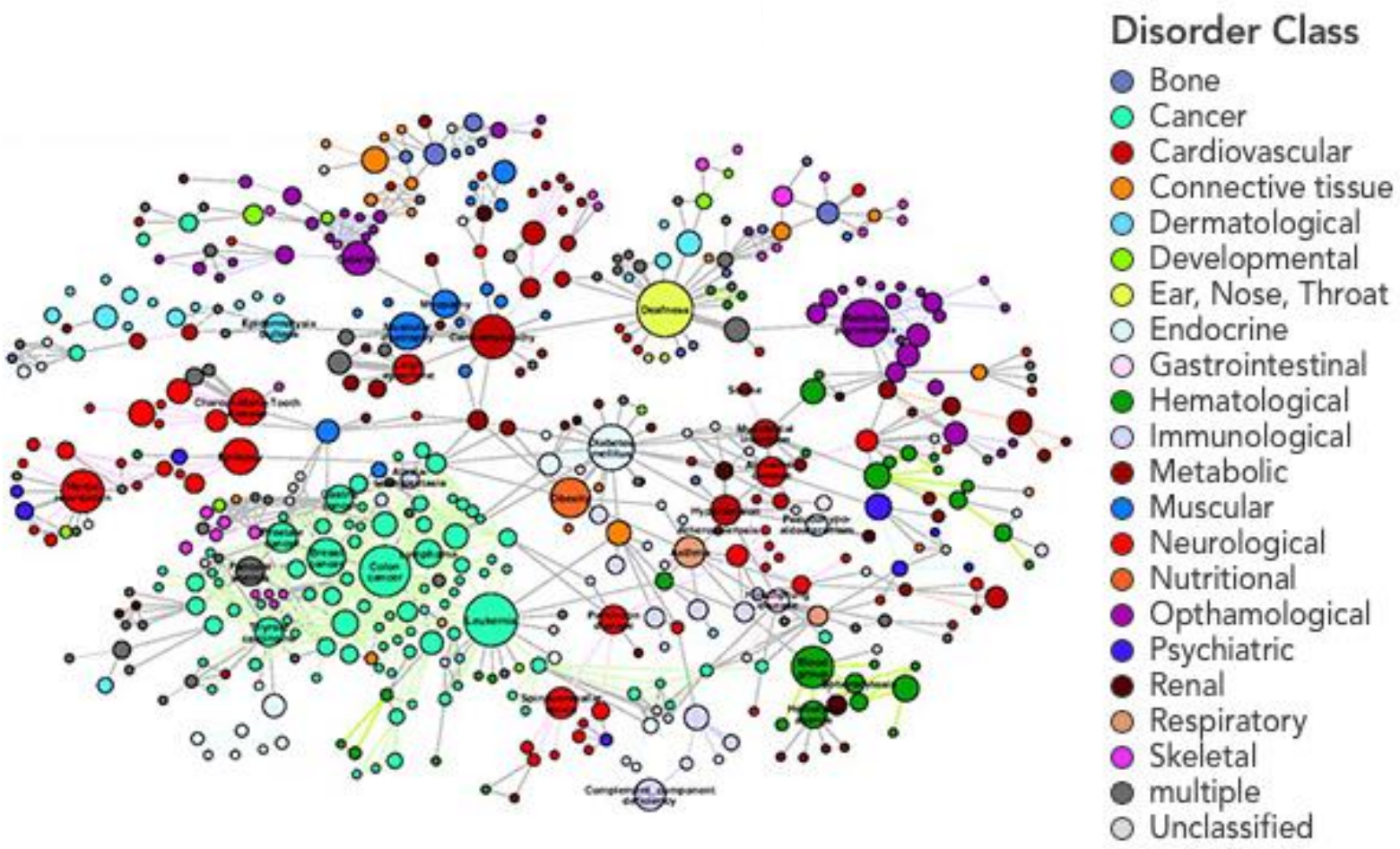
C. Elegans neurons network





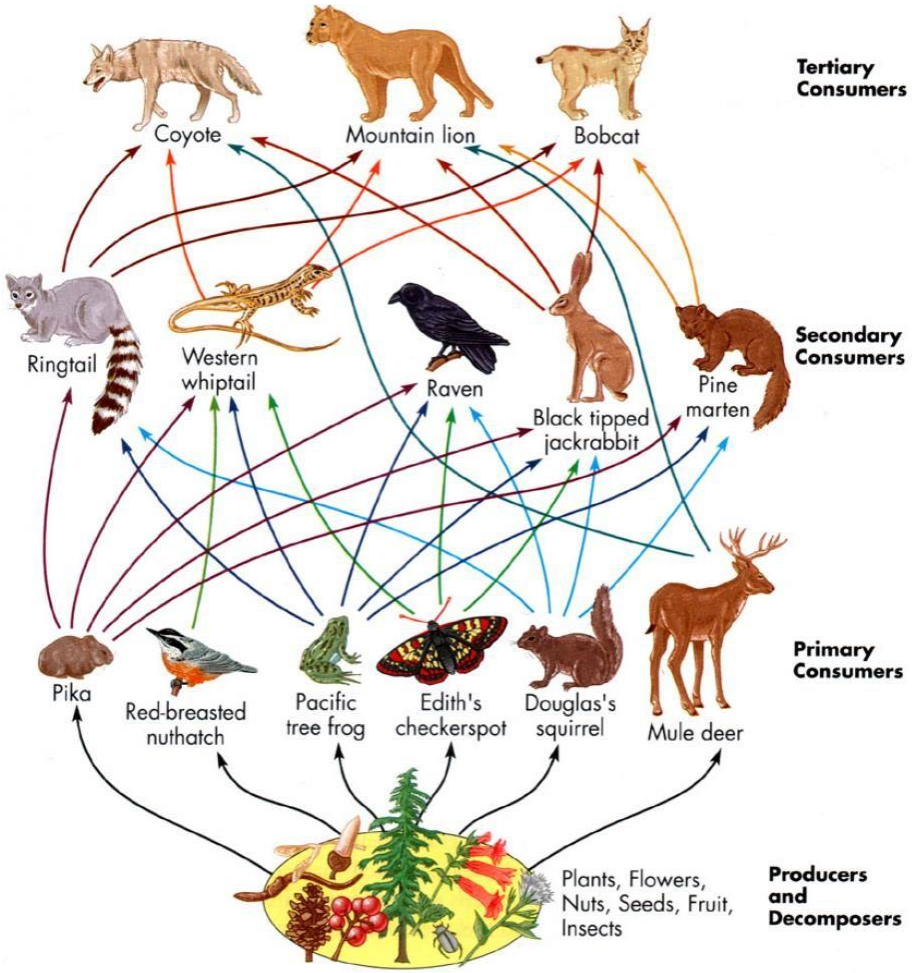
The map of all 302 neurons in the C. elegans nervous system

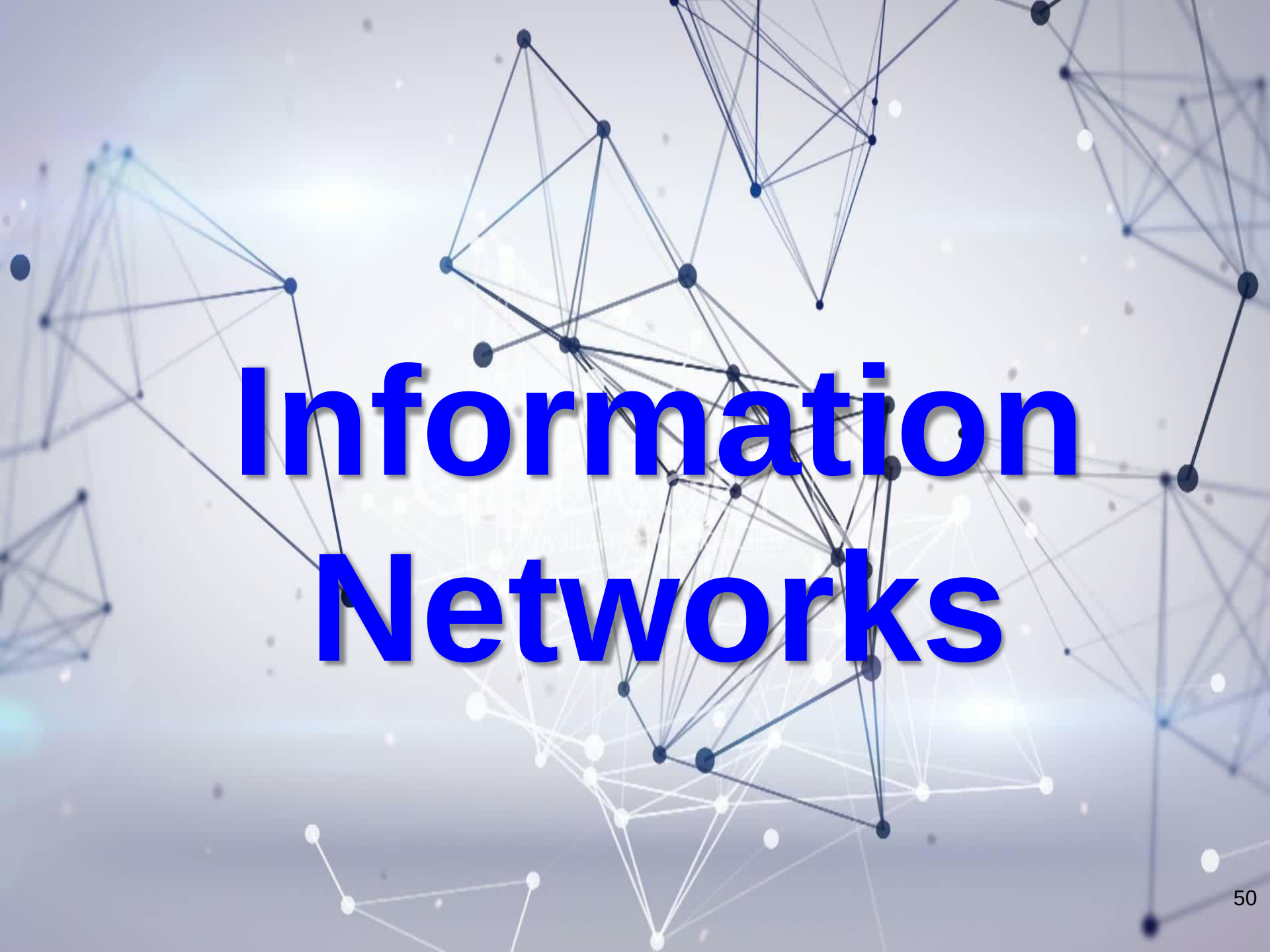
Human disease network



Food Chain Network

Food web is an important conceptual tool for illustrating the feeding relationships among species within a community, revealing species interactions and community structure, and understanding the dynamics of energy transfer in an ecosystem



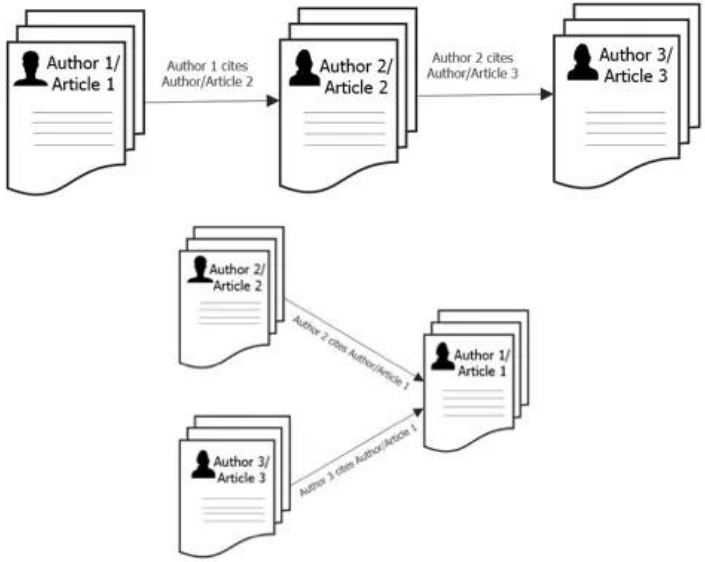

Information
Networks

Knowledge (Information) Networks

Nodes store information, links associate information

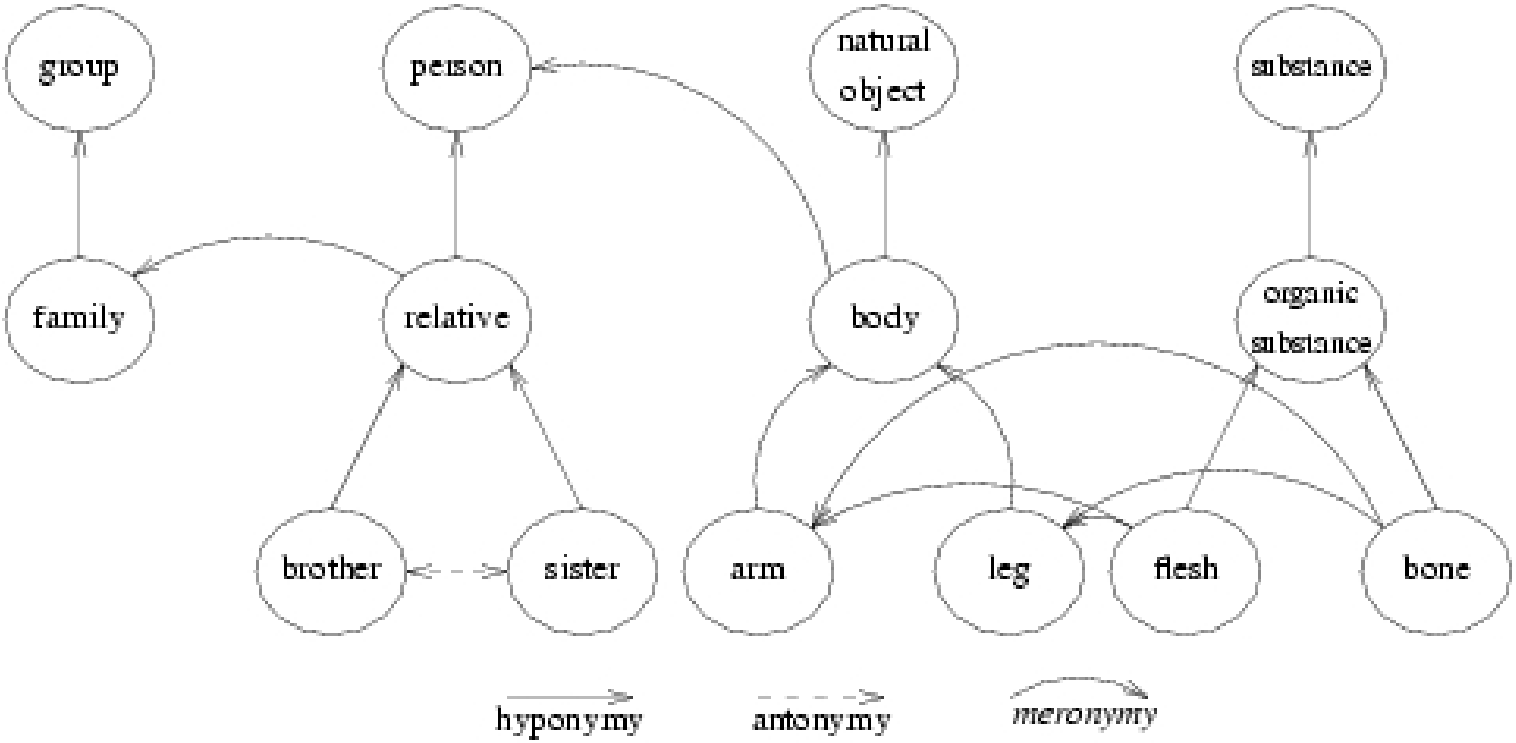
- Citation network (directed acyclic)
- The Web (directed)
- Peer-to-Peer networks
- Word networks
- Networks of Trust
- Software graphs

Citation Network



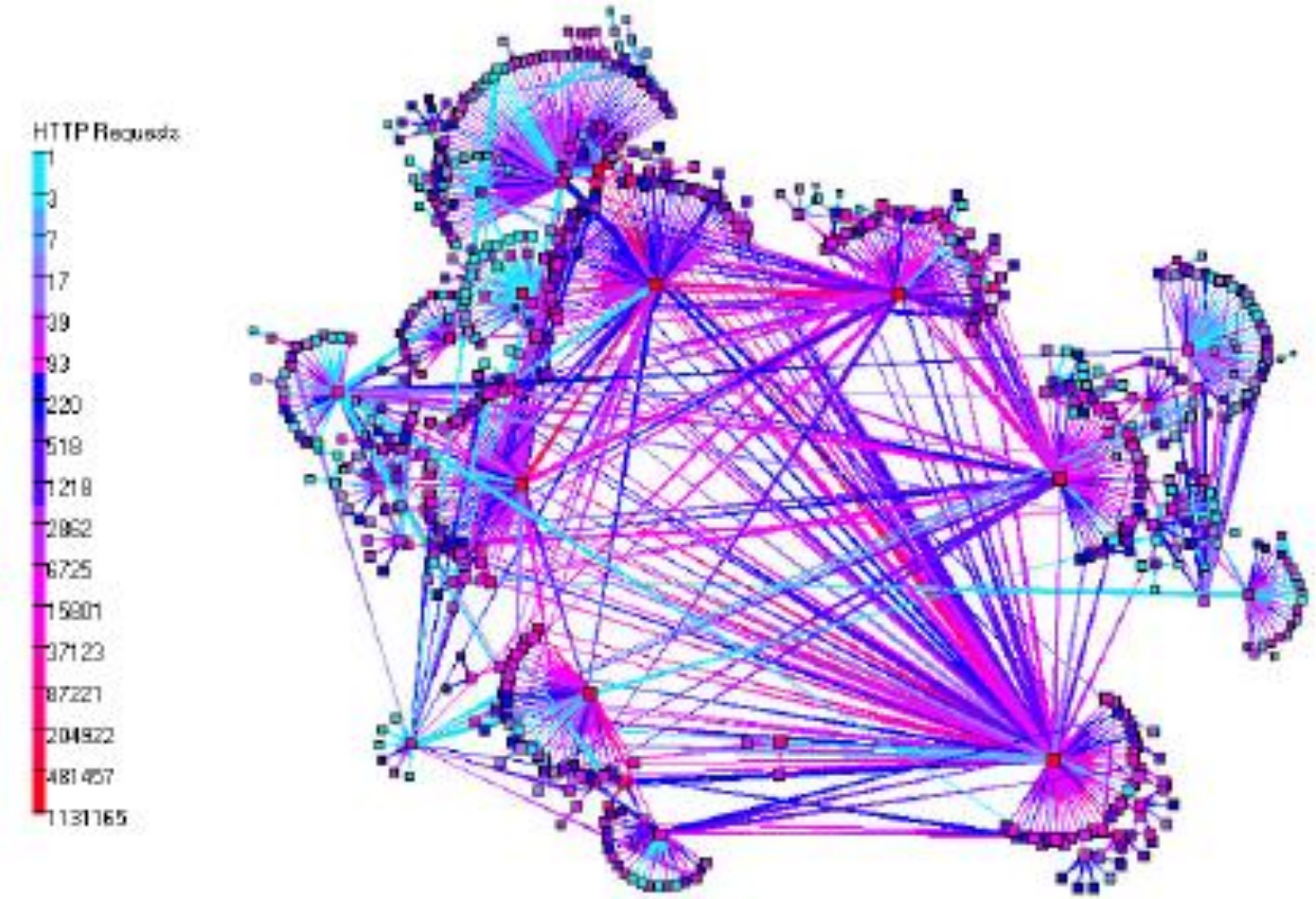
Natural language processing

Wordnet



Source: http://wordnet.princeton.edu

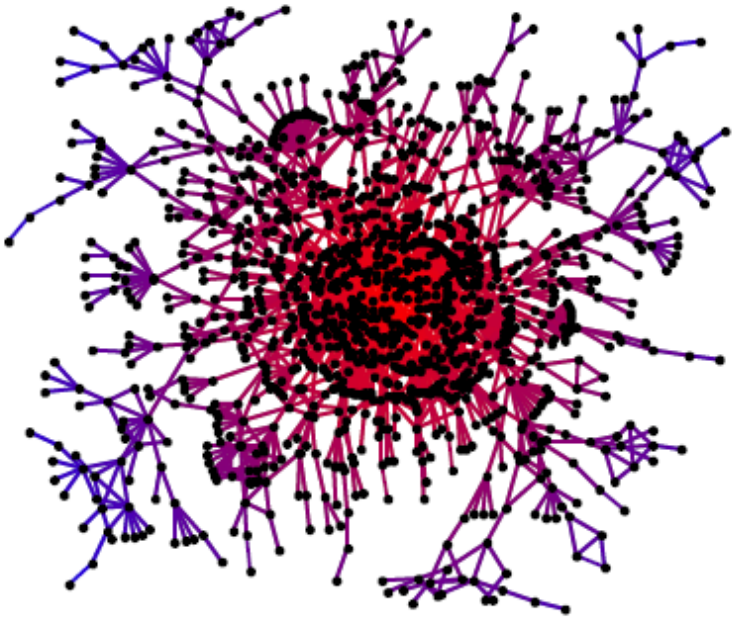
World Wide Web



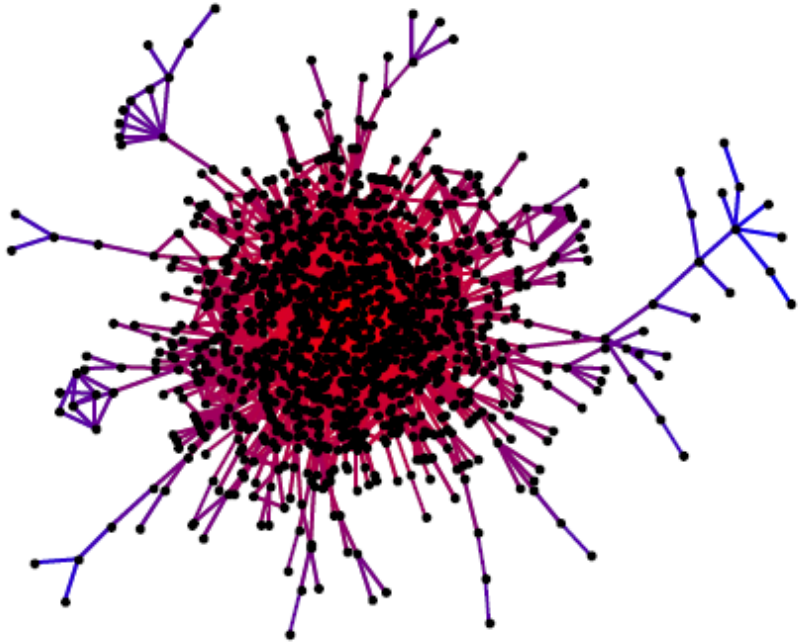
Hierachical topology of the international Web cache

(Bradley Huffaker, http://www.caida.org/tools/visualization/plankton)

Networks of personal homepages



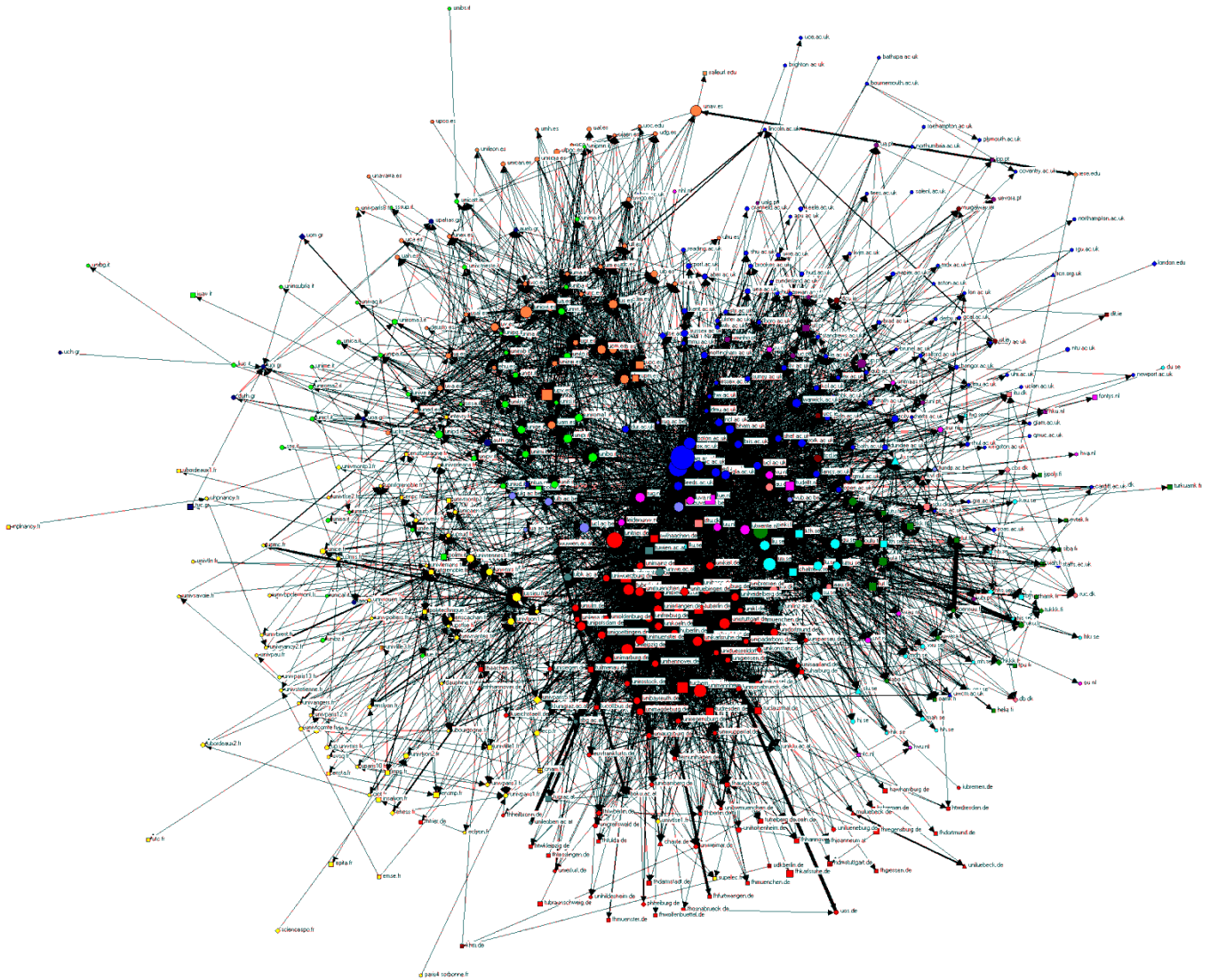
Stanford



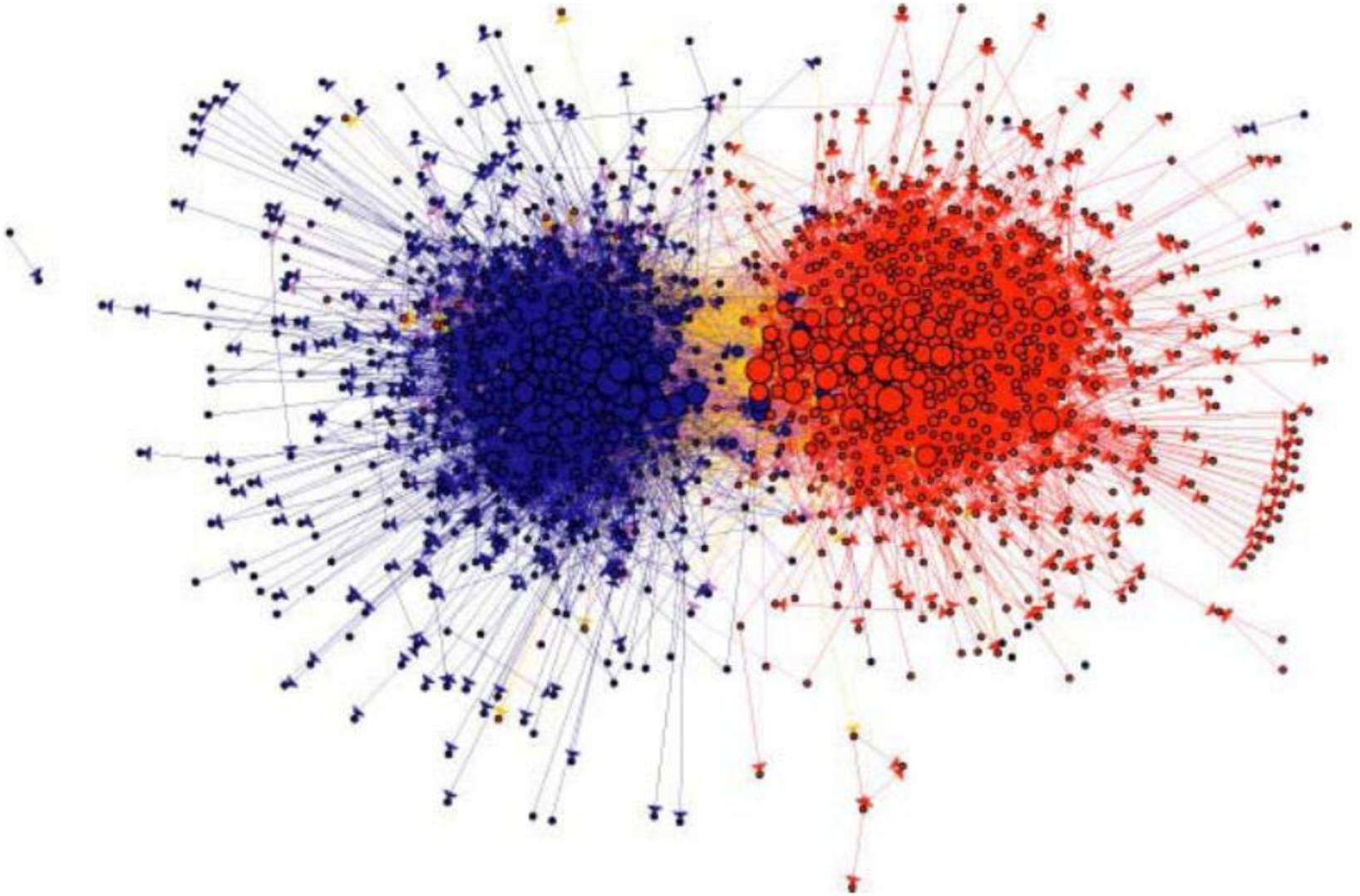
MIT

Source: Lada A. Adamic and Eytan Adar, 'Friends and neighbors on the web', *Social Networks*, 25(3):211-230, July 2003

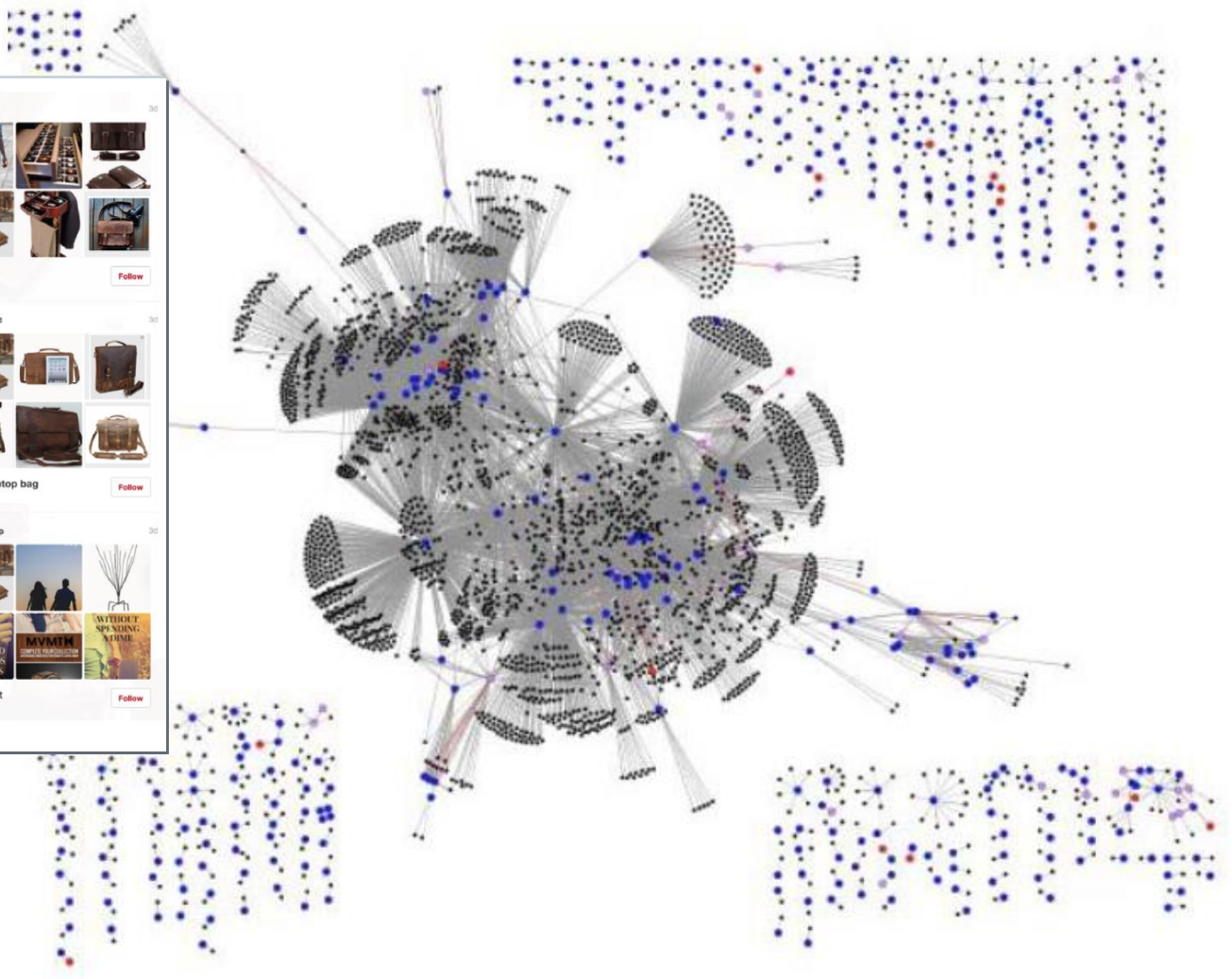
European University Web Pages



Links among blogs (2004 presidential election)

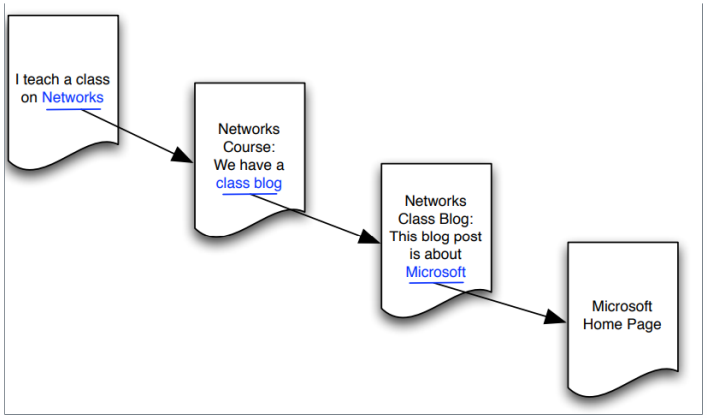


Product recommendations

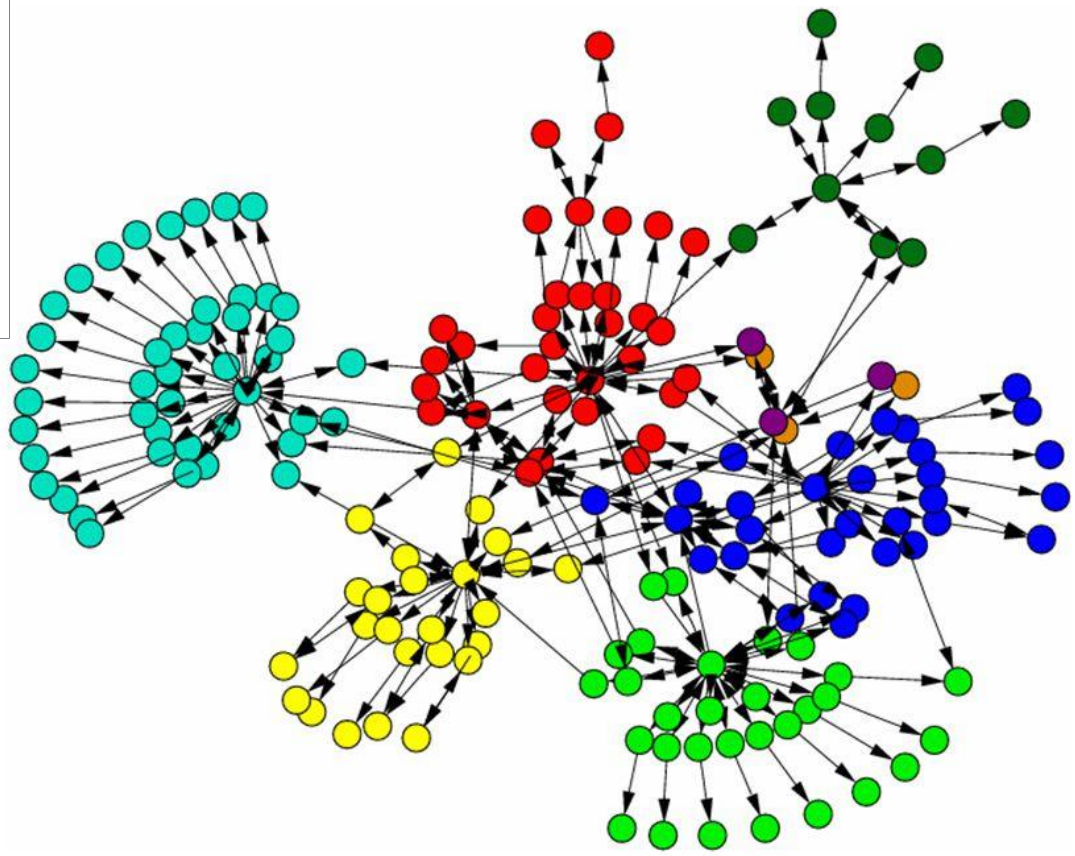


Webpages

Webpages connected by hyperlinks



Webpages connected by hyperlinks on the AT&T website circa 1996 visualized by Mark Newman
Citation networks are similar to the WWW but time-ordered



THE IMPACT OF NETWORK SCIENCE

Economic Impact

licensed under CC Attribution-NonCommercial-ShareAlike 2.0 Germany | Ludwig Gatzke | http://flickr.com/photos/stabilo-boss/

Google
Market Cap(2010 Jan 1):
$189 billion

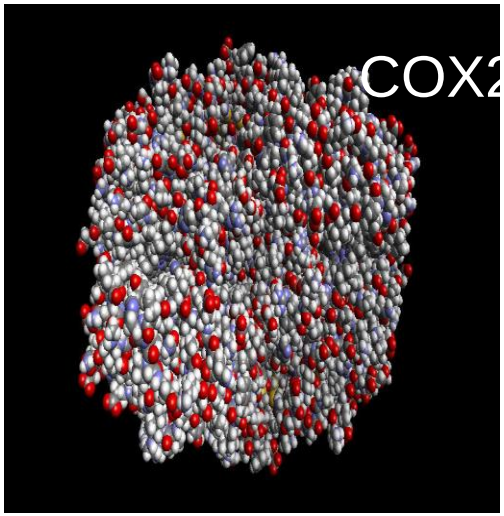
Cisco Systems
networking gear Market cap
(Jan 1, 2019):
$112 billion

Facebook
market cap:
$50 billion

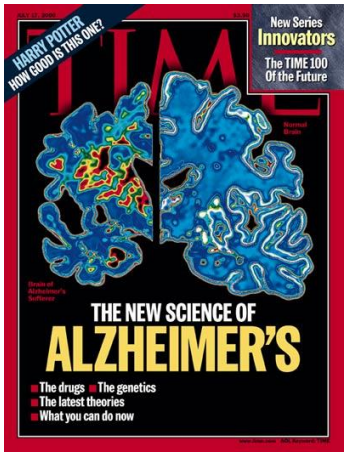
www.bizjournals.com/austin/news/2010/11/15/facebooks... - Cached

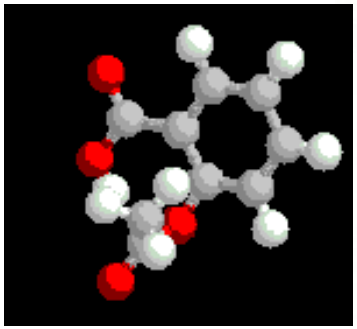
Drug Design, Metabolic Engineering

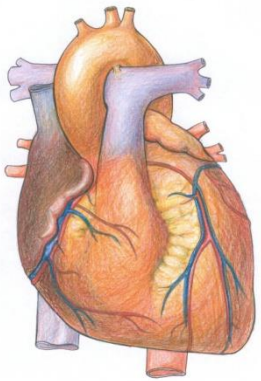
Reduces
Inflammation
Fever
Pain



Prevents
Heart attack
Stroke





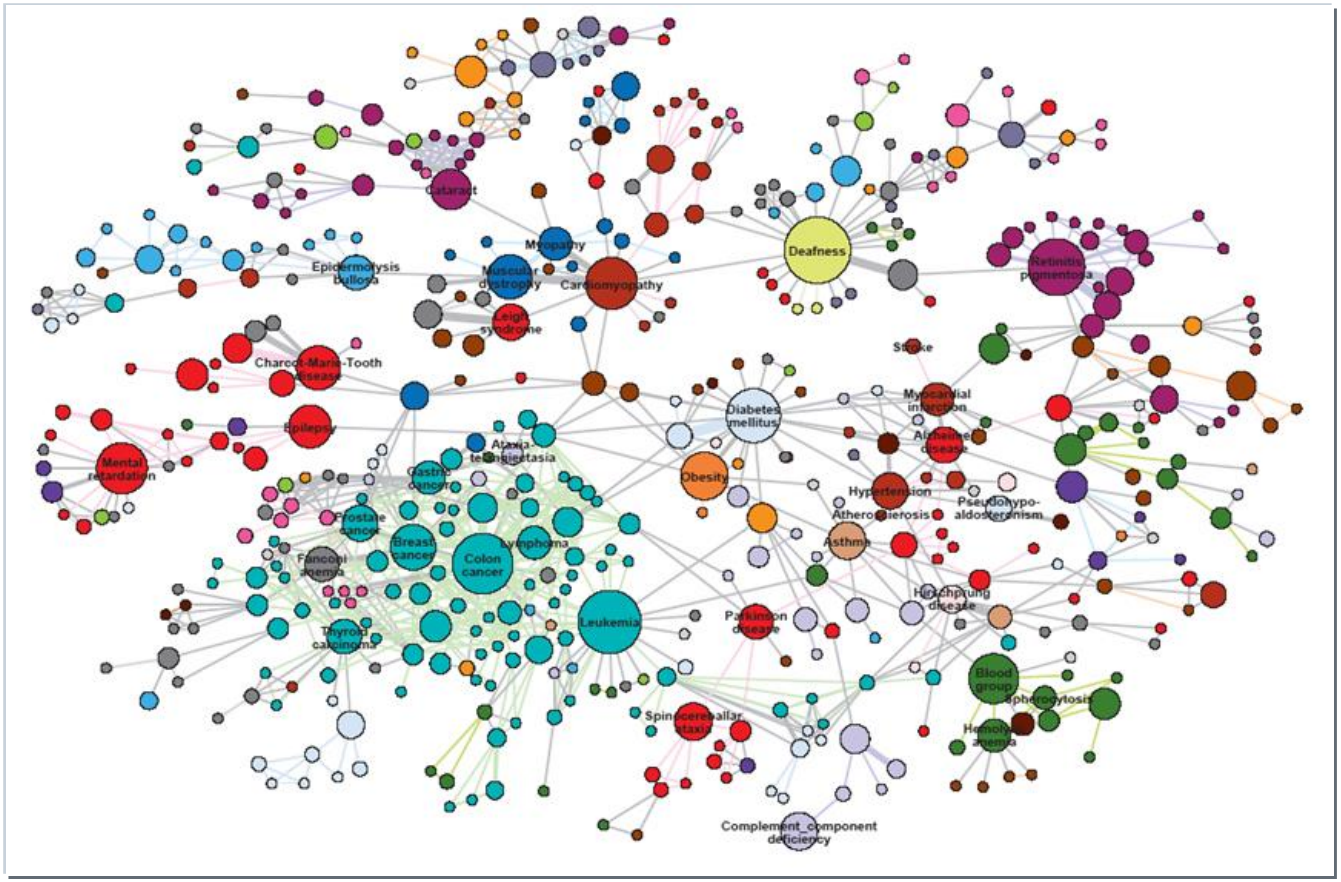


Reduces the risk of
Alzheimer's Disease

Reduces the risk of
breast cancer
ovarian cancers
colorectal cancer

Causes
Bleeding
Ulcer

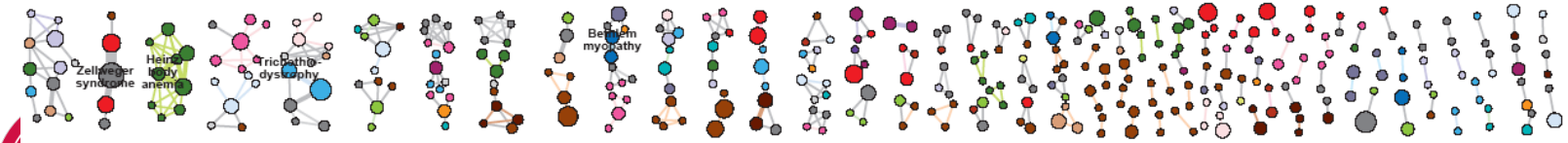
Human Disease Network



Disorder Class

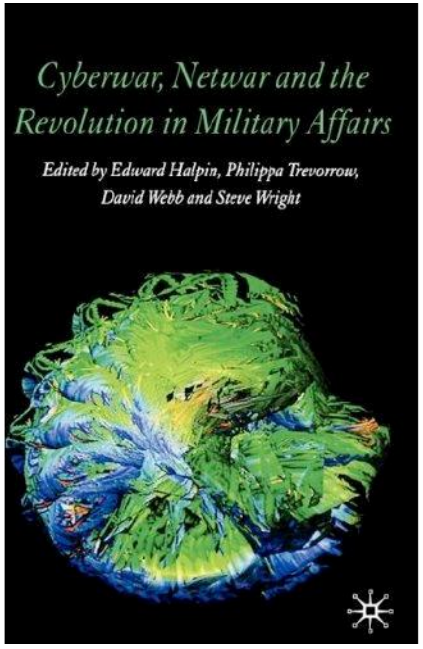
- Bone
- Cancer
- Cardiovascular
- Connective tissue
- Dermatological
- Developmental
- Ear, Nose, Throat
- Endocrine
- Gastrointestinal
- Hematological
- Immunological
- Metabolic
- Muscular
- Neurological
- Nutritional
- Ophthamological
- Psychiatric
- Renal
- Respiratory
- Skeletal
- multiple
- Unclassified

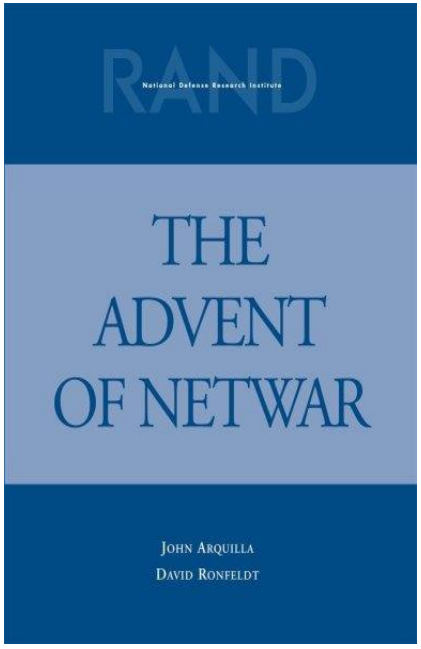
41
34
30
25
21
15
10
5
1



Network Biology/Network Medicine

Fighting Terrorism and Military

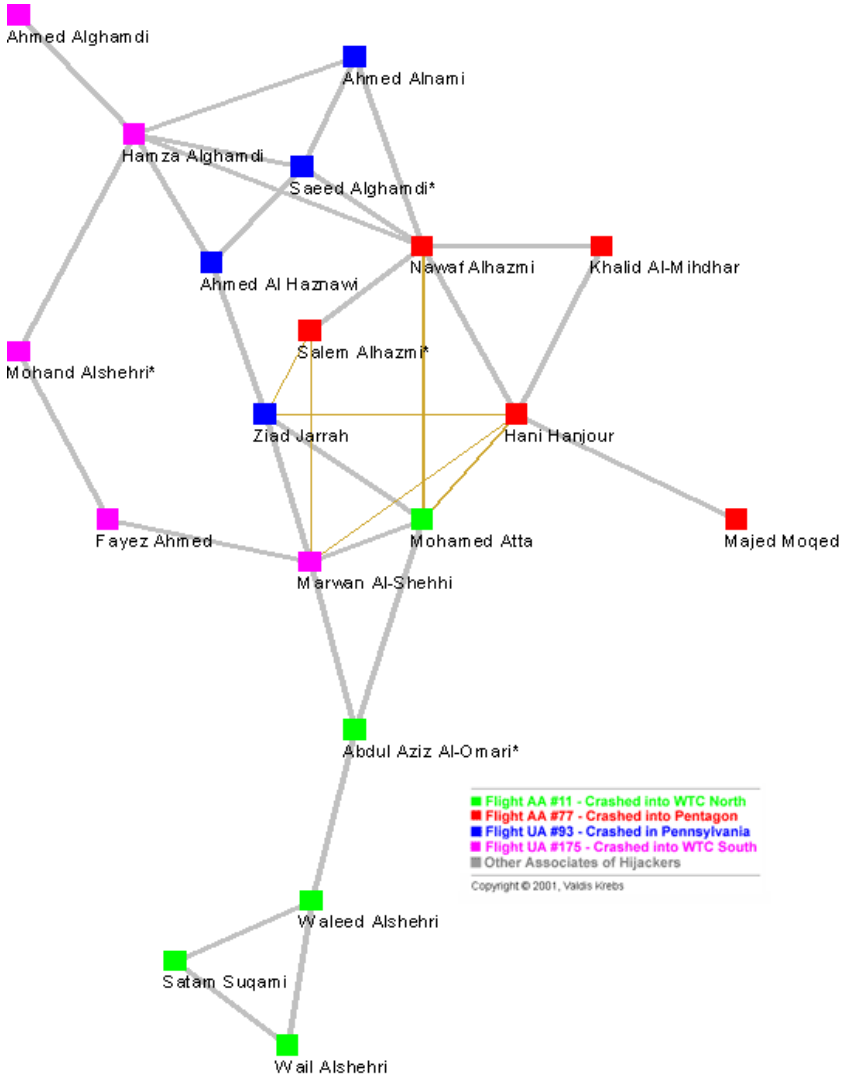


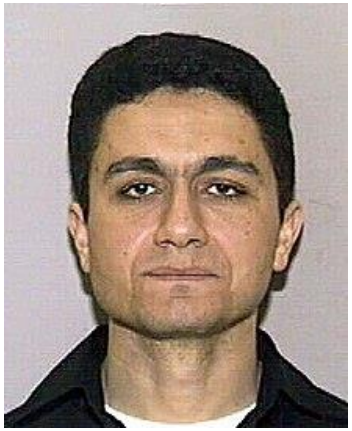


http://www.slate.com/id/2245232

Example: the use of social networks to capture Saddam Hussein

Fighting Terrorism and Military

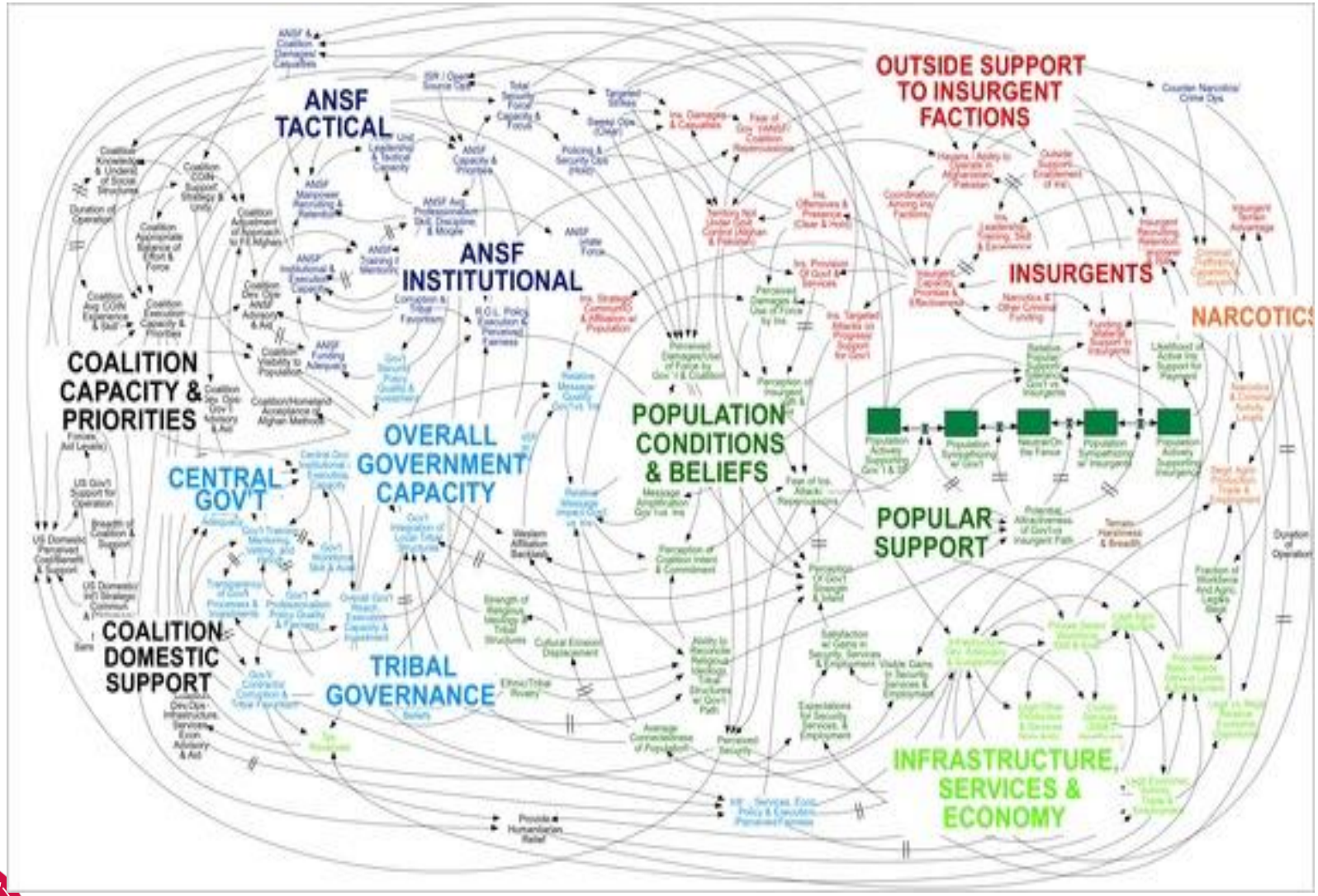




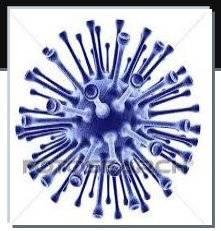
"Six degrees of Mohammed Atta"

Uncloaking Terrorist Networks, by Valdis Krebs

The network behind a military engagement

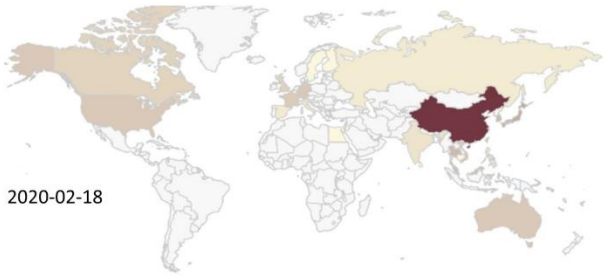


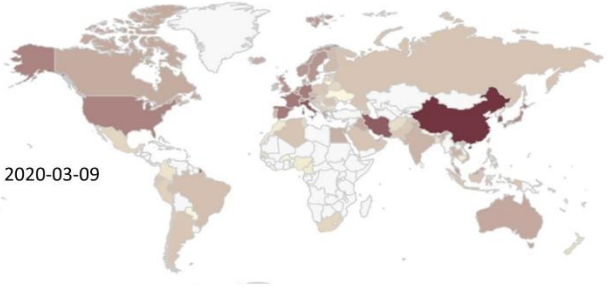
Predicting the H1N1 pandemic

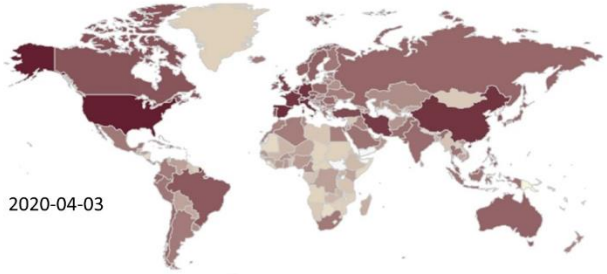


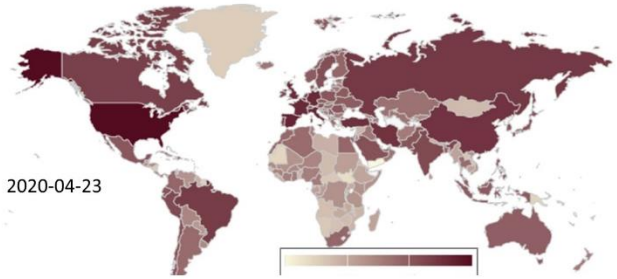
University of Kurdistan

COVID 19 Pandemic







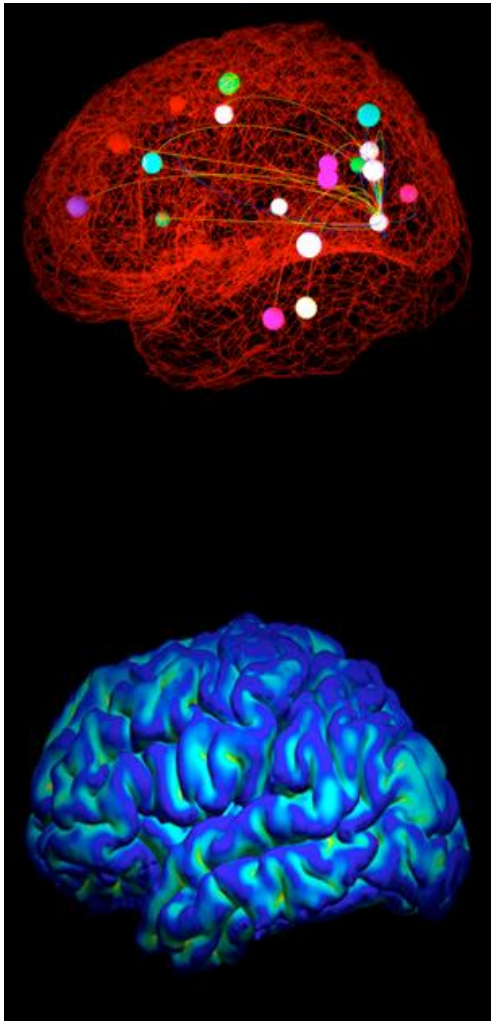


Brain Research

In September 2010 the National Institutes of Health awarded $40 million to researchers at Harvard, Washington University in St. Louis, the University of Minnesota and UCLA, to develop the technologies that could systematically map out brain circuits.

The Human Connectome Project (HCP) with the ambitious goal to construct a map of the complete structural and functional neural connections in vivo within and across individuals.

http://www.humanconnectomeproject.org/overview/



1. **If you were to understand the spread of diseases, can you do it without networks?**

2. **If you were to understand the WWW structure, searchability, etc, hopeless without invoking the Web's topology.**

3. **If you want to understand human diseases, it is hopeless without considering the wiring diagram of the cell.**

Original papers:

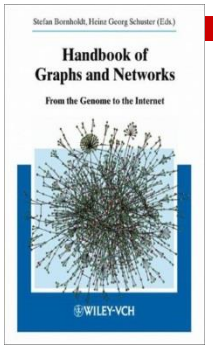
• 1998: Watts-Strogatz paper in the most cited Nature publication from 1998; highlighted by ISI as one of the ten most cited papers in physics in the decade after its publication.

•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.

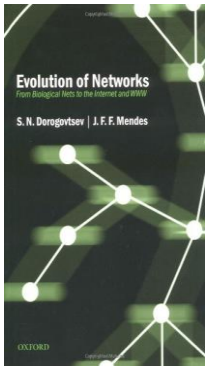
•2001: Pastor -Satorras and Vespignani is one of the two most cited papers among the papers published in 2001 by Physical Review Letters.

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

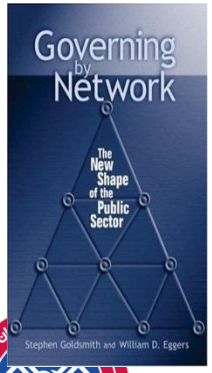
BOOKS



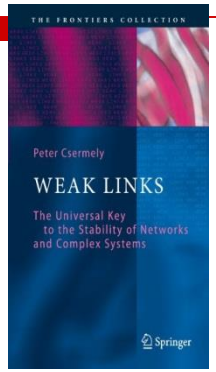
Handbook of Graphs and Networks: From the Genome to the Internet (Wiley-VCH, 2003).



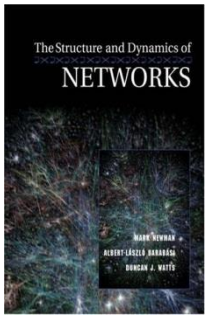
S. N. Dorogovtsev and J. F. F. Mendes, Evolution of Networks: From Biological Nets to the Internet and WWW (Oxford University Press, 2003).



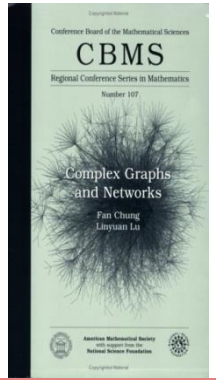
S. Goldsmith, W. D. Eggers, Governing by Network: The New Shape of the Public Sector (Brookings Institution Press, 2004).



P. Csermely, Weak Links: The Universal Key to the Stability of Networks and Complex Systems (The Frontiers Collection) (Springer, 2006), rst edn.

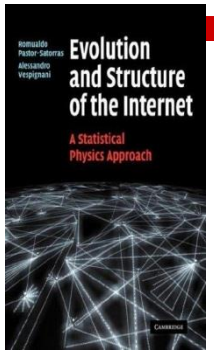


M. Newman, A.-L. Barabasi, D. J. Watts, The Structure and Dynamics of Networks: (Princeton Studies in Complexity) (Princeton University Press, 2006), rst edn.

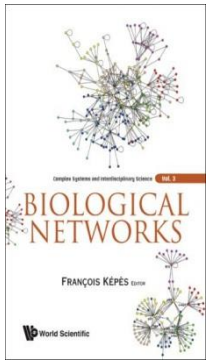


L. L. F. Chung, Complex Graphs and Networks (CBMS Regional Conference Series in Mathematics) (American Mathematical Society, 2006).

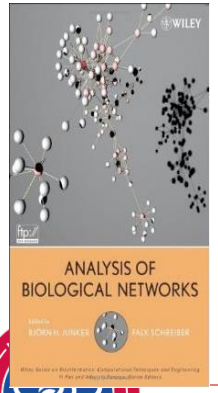
BOOKS



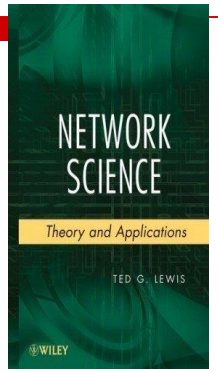
R. Pastor-Satorras, A. Vespignani, Evolution and Structure of the Internet: A Statistical Physics Approach (Cambridge University Press, 2007), rst edn.



F. Kopos, Biological Networks (Complex Systems and Interdisciplinary Science) (World Scientific Publishing Company, 2007), rst edn.



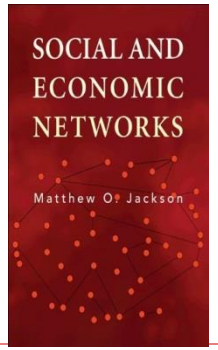
B. H. Junker, F. Schreiber, Analysis of Biological Networks (Wiley Series in Bioinformatics) (Wiley-Interscience, 2008).



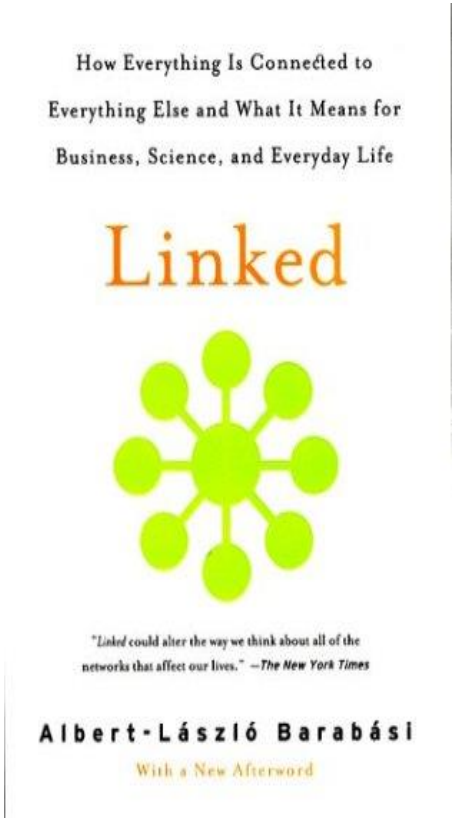
T. G. Lewis, Network Science: Theory and Applications (Wiley, 2009).

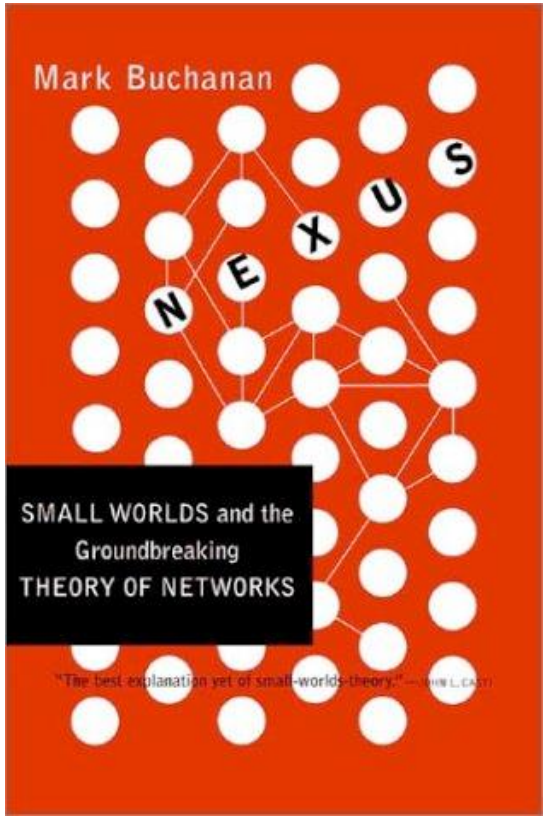
E. Ben Naim, H. Frauenfelder, Z.Torotzai, Complex Networks (Lecture Notes in Physics) (Springer, 2010), rst edn.

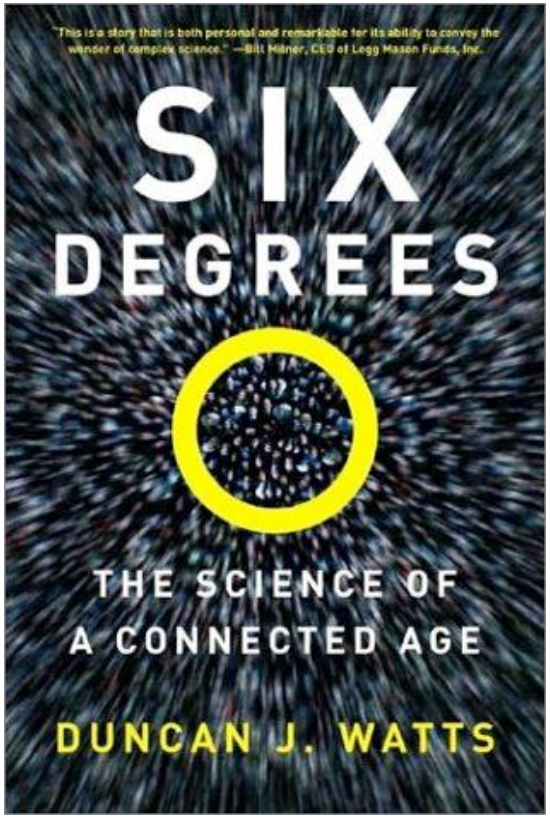
M. O. Jackson, Social and Economic Networks (Princeton University Press, 2010).



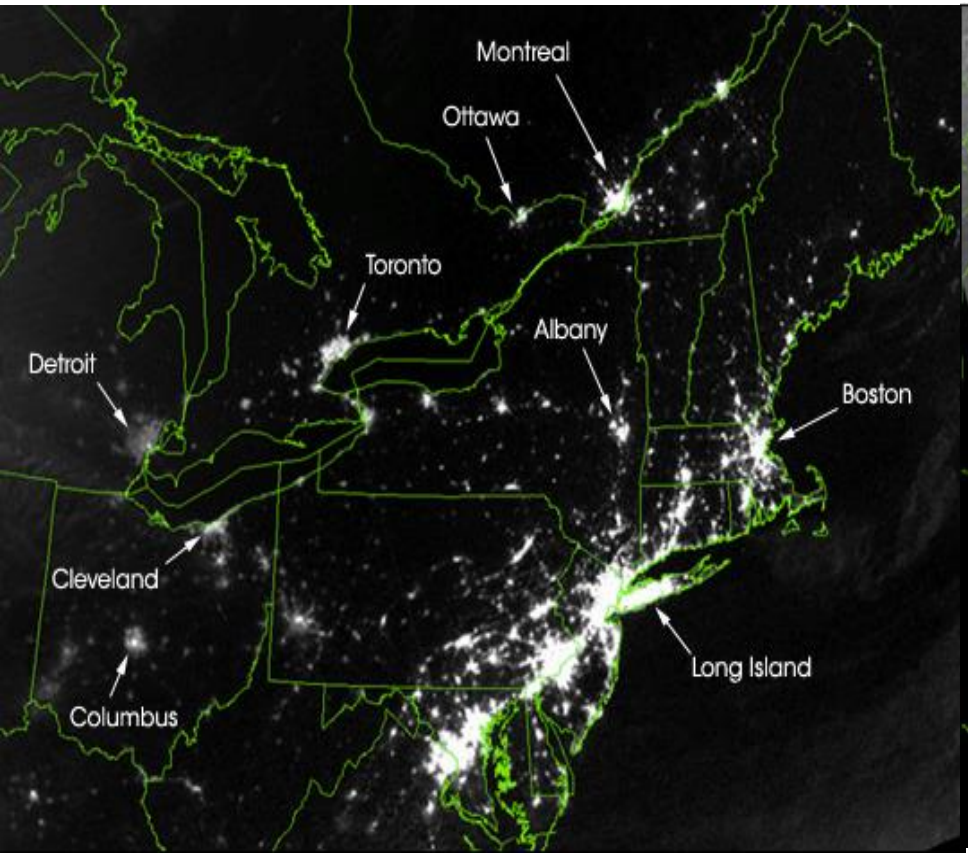
General Audience



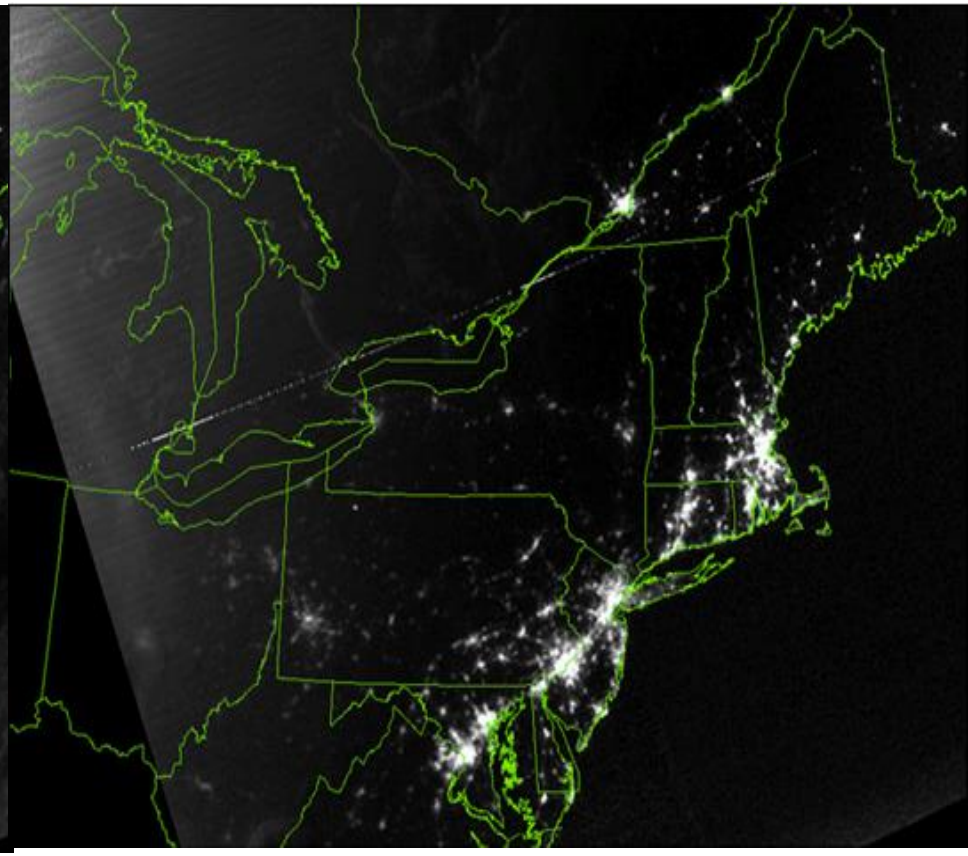




A Simple Story(2): August 15, 2003 blackout



August 14, 2003: 9:29pm EDT
20 hours before



August 15, 2003: 9:14pm EDT
7 hours after

A Simple Story(2): August 15, 2003 blackout

This reveals two important themes of this class:

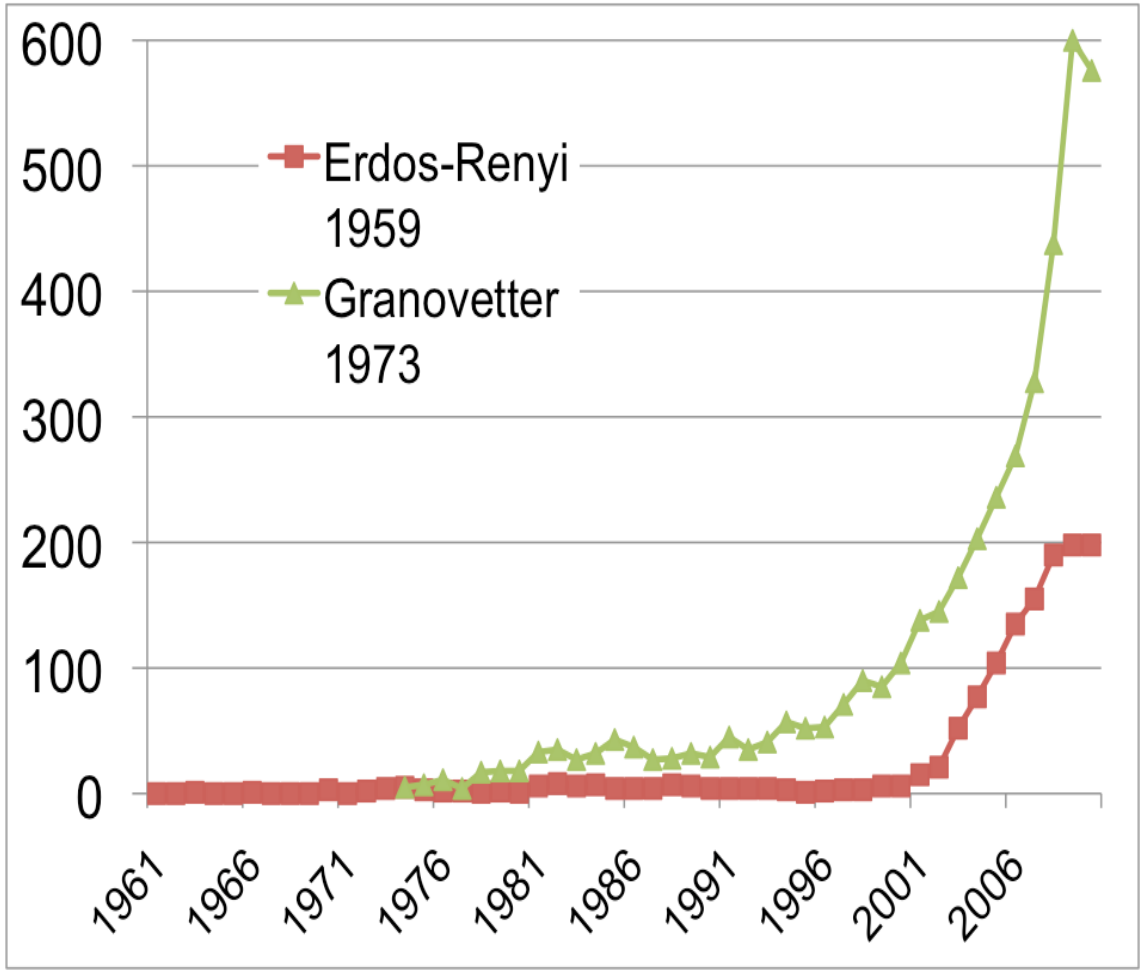
- We must understand how network structure affects the robustness of a system

- Develop quantitative tools to assess the interplay between network structure and the dynamical processes on the networks, and their impact on failures

The History of Network Analysis

- **Graph theory: 1735, Euler**
- **Social Network Research: 1930s, Moreno**
- **Communication networks/internet: 1960s**
- **Ecological Networks: May, 1979.**

The History of Network Analysis



The Emergence of Network Maps

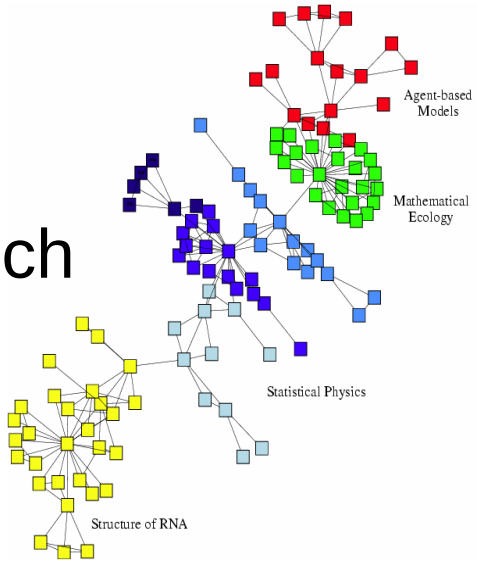
- Movie Actor Network, 1998
- World Wide Web, 1999
- C-elegans neural wiring diagram 1990
- Citation Network, 1998
- Metabolic Network, 2000;
- PPI network, 2001

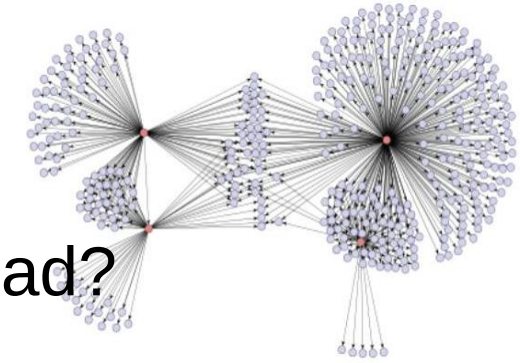
Reasoning about networks

- How do we reason about networks?
  - Empirical: Study network data to find organizational principles
  - Mathematical models: Probabilistic, graph theory
  - Algorithms: analyzing graphs
- What do we hope to achieve from studying networks?
  - Patterns and statistical properties of network data
  - Design principles and models
  - Understand why networks are organized the way they are
    - Predict behavior of networked systems

What do we study in networks?

- Structure and evolution
  - What is the structure of a network?
  - Why and how did it become to have such structure?
- Processes and dynamics
  - Networks provide a “skeleton” for spreading of information, behavior, diseases
  - How do information and diseases spread?





Why to analyze networks?

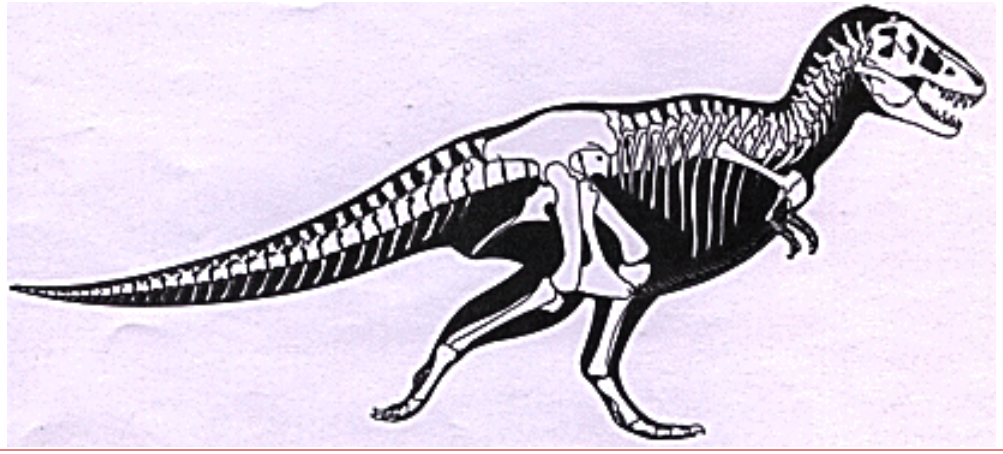
- **Predict the type/color of a given node**
  Node classification
- **Predict whether two nodes are linked**
  Link prediction
- **Identify densely linked clusters of nodes**
  Community detection
- **Measure similarity of two nodes/networks**
  Network similarity

Networks in complex systems

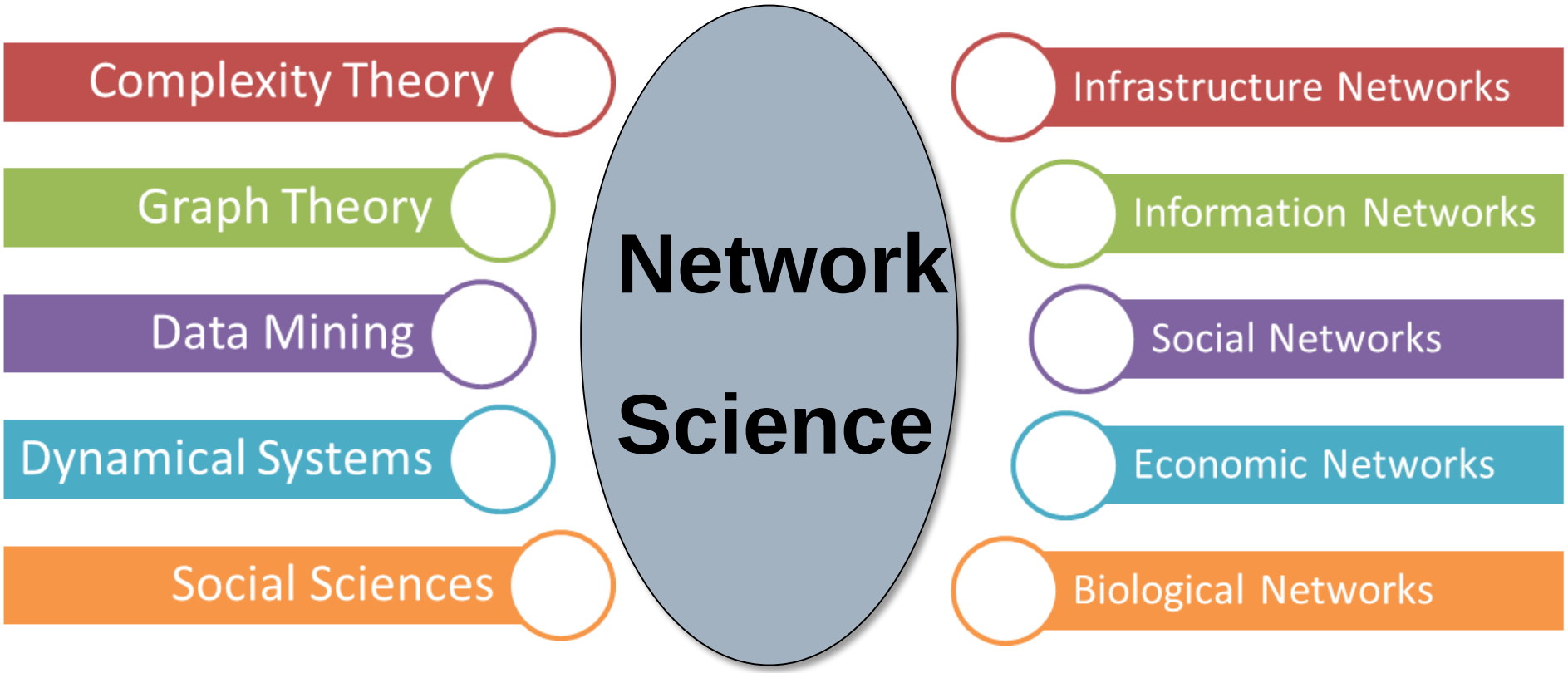
- Complex systems
  - Large number of components interacting with each other
  - All components and/or interactions are different from each other
  - Paradigms:
    - 10^4 types of proteins in an organism,
    - 10^6 routers in the Internet
    - 10^9 web pages in the WWW
    - 10^{11} neurons in a human brain
- The simplest property:
  - who interacts with whom?
    - can be visualized as a network
- Complex networks are just a backbone for complex dynamical systems

Why study the topology of Complex Networks?

- Lots of easily available data
- Large networks may contain information about basic design principles and/or evolutionary history of the complex system
- This is similar to paleontology:
  - learning about an animal from its backbone



A Multidisciplinary Research Field



Network Questions: Structural

1. How many connections does the average node have?
2. Are some nodes more connected than others?
3. Is the entire network connected?
4. On average, how many links are there between nodes?
5. Are there clusters or groupings within which the connections are particularly strong?
6. What is the best way to characterize a complex network?
7. How can we tell if two networks are “different”?
8. Are there useful ways of classifying or categorizing networks?

Network Questions: Communities

1. Are there clusters or groupings within which the connections are particularly strong?

2. What is the best way to discover communities, especially in large networks?

3. How can we tell if these communities are statistically significant?

4. What do these clusters tell us in specific applications?

Network Questions: Dynamics of

1. How can we model the growth of networks?

2. What are the important features of networks that our models should capture?

3. Are there "universal" models of network growth? What details matter and what details don't?

4. To what extent are these models appropriate null models for statistical inference?

5. What's the deal with power laws, anyway?

Network Questions: Dynamics on

1. How do diseases/computer viruses/innovations/ rumors/revolutions propagate on networks?
2. What properties of networks are relevant to the answer of the above question?
3. If you wanted to prevent (or encourage) spread of something on a network, what should you do?
4. What types of networks are robust to random attack or failure?
5. What types of networks are robust to directed attack?
6. How are dynamics of and dynamics on coupled?

Network Questions: Algorithms

1. What types of networks are searchable or navigable?
2. What are good ways to visualize complex networks?
3. How does google page rank work?
4. If the Internet were to double in size, would it still work?

Network Questions: Algorithms

There are also many domain-specific questions:

1. Are networks a sensible way to think about gene regulation or protein interactions or food webs?

2. What can social networks tell us about how people interact and form communities and make friends and enemies?

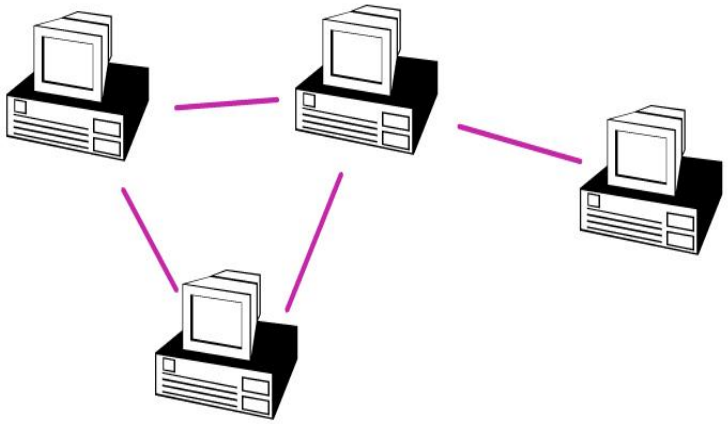
3. Lots and lots of other theoretical and methodological questions...

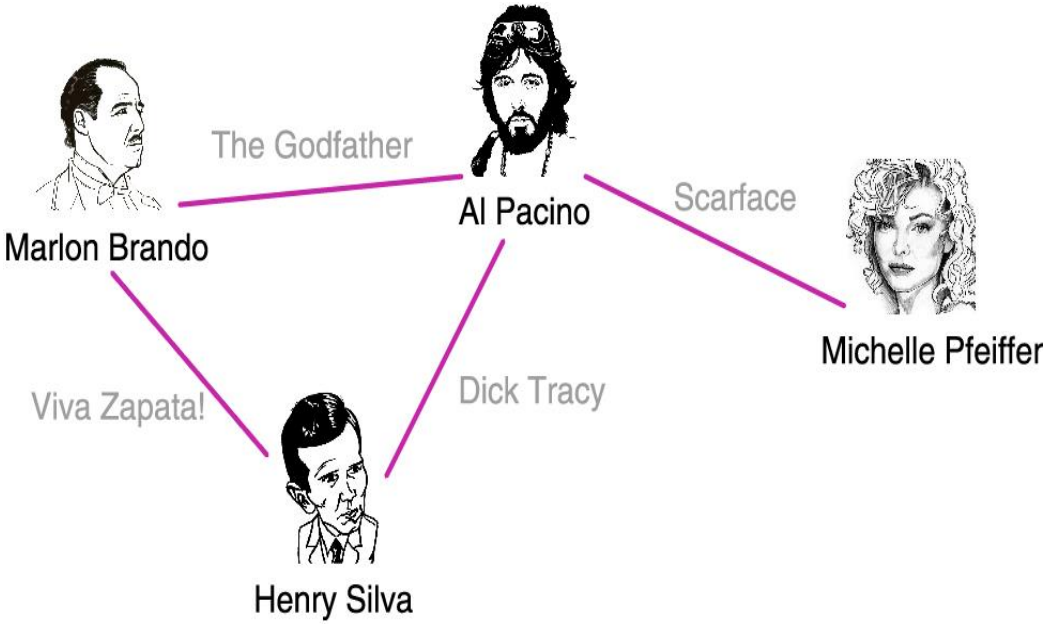
4. What else can be viewed as a network? Many applications await.

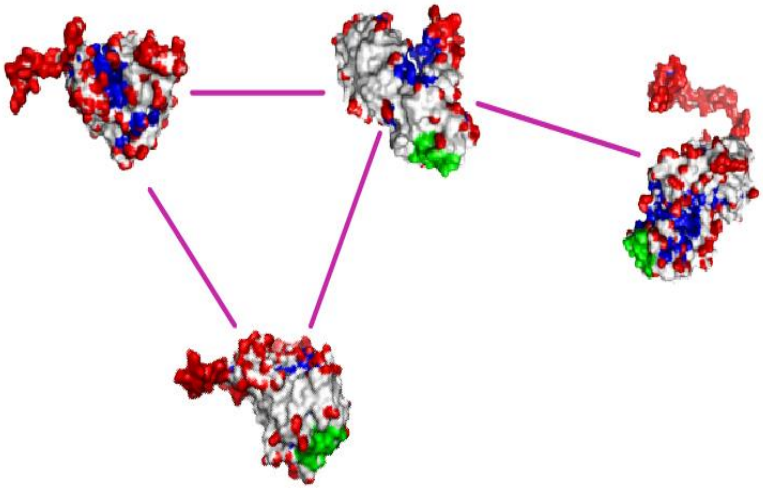
Network Questions: Outlook

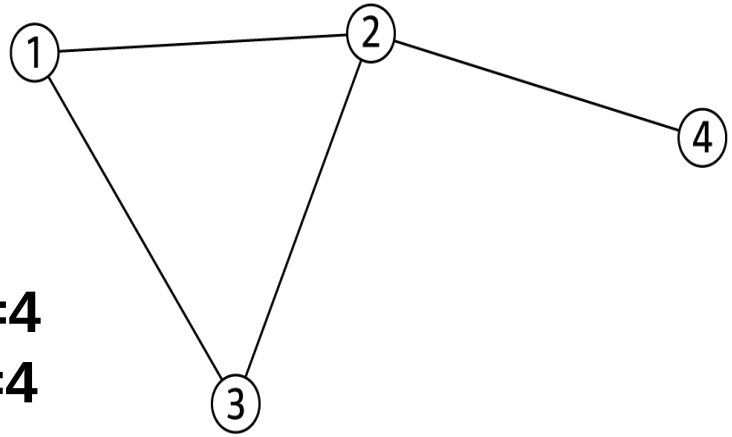
- Advances in available data, computing speed, and algorithms have made it possible to apply network analysis to a vast and growing number of phenomena.
  - This means that there is lots of exciting, novel work being done
  - This work is a mixture of awesome, exploratory, misleading, irrelevant, relevant, fascinating, ground-breaking, important, and just plain wrong
- It is relatively easy to fool oneself into seeing thing that aren't there when analyzing networks.
  - This is the case with almost anything, not just networks
- For networks, how can we be more careful and scientific, and not just descriptive and empirical?

A Common Language









N=4
L=4

A Common Language

Network	Nodes	Edges
biochemical	molecules	chemical reactions
neural	neurons	synaptic connections
epidemiological	healthy, infected individuals	infectious contacts
world wide web	web pages	hyperlinks
trophic	predators, prey	predation interactions
power grid	electrical generators, end users	power lines, substations, transformers
collaborative	scientists, engineers	collaborations
social	people	friendships
internet	computers	routers, ethernet cables

Property of Friendship

- **Six Degrees of Separation**

Milgram (1967)

The experiment:

- **Random people from Nebraska were to send a letter (via intermediaries) to a stock broker in Boston.**
- **Could only send to someone with whom they know.**

Stanley Milgram (1933-1984)

Small world experiment

Milgram's experiment (1960's):

- **Given a target individual and a particular property, pass the message to a person you correspond with who is "closest" to the target. "Six degrees of separation"**

Small World Network

"A **small world network** is a type of mathematical graph in which most nodes are not neighbors of one another, but most nodes can be reached from every other by a **small** number of hops or steps." - Wikipedia

Some Famous Researchers

Mark Newman, 146, 55
- University of Michigan

Albert Laszlo Barabasi, 198, 72
- Harvard University

Jon Kleinberg, 150, 40
- Cornell University

Réka Albert, 78, 31
- Pennsylvania State University

Santo Fortunato, 65, 23
- Institute for Scientific Interchange Foundation

Steven H. Strogatz, 107, 29
- Cornell University

Duncan Watts, 43, 25
- Yahoo Research Labs

Alex Arenas, 92, 27
- University of Zaragoza

Jure Leskovec, 54, 19
- Stanford University

David Kempe, 53, 17
- University of Southern California

Wrap up

- networks are everywhere and can be used to describe many, many systems

- Network science research studies physical, biological, social, artificial, engineered, and other phenomena that arise in systems made of a large number of mutually interacting components whose macroscopic properties are not easy to understand or explain

- by modeling networks we can start to understand their properties and the implications those properties have for processes occurring on the network

Final Word


Questions