Overview of Complex Networks

Principles of Complex Systems | @pocsvox
CSYS/MATH 300, Fall, 2017

Prof. Peter Dodds | @peterdodds

Dept. of Mathematics & Statistics | Vermont Complex Systems Center
Vermont Advanced Computing Core | University of Vermont

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Principles of Complex Systems
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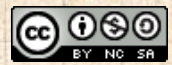
What's the Story?



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What's the Story?

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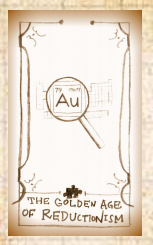
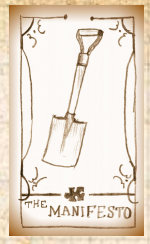
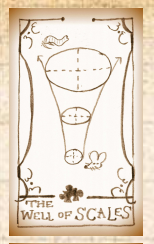
Outline


THE SUN


THE GOLDEN AGE OF REDUCTIONISM

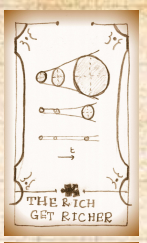

THE MANIFESTO

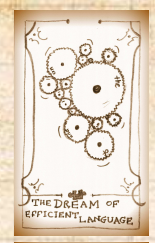

THE WELL OF SCALES


THE LAWS OF DECAYING POWER


MINISTRY OF RANDOM WALKS


THE UNEXPECTED TRANSFIGURATION


THE RICH GET RICHER


THE DREAM OF EFFICIENT LANGUAGE


THE LAW OF DIGITS FIRST


THE SURPRISE OF BEING ROBUST YET FRAGILE


THE MISREADING OF THE BOOK OF SAND


THE SUPPLY MOST FAIR


THE SUPPLY TO THE MOST


THE MANY TALES OF MANY TAILS

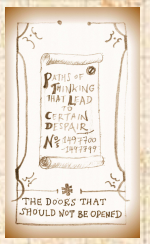

THE MEASURING


THE DATA POOR


THE POURING DATA


THE CHARMS OF THE MANY WRONG PATHS


THE KNOWLEDGE OF DEAD MONKS


THE DOORS THAT SHOULD NOT BE OPENED


THE EMERGENCE OF STRUCTURE


THE EMERGENCE OF DESTRUCTION


THE EMERGENCE OF THINKING


It was the best of times,
THE EMERGENCE OF STORIES


THE MECHANICS STATISTICAL


THE THRESHOLDS OF PERCOLATION


THE ELEMENTS OF WEBS


THE ARK OF THE RANDOM NETWORK


THE BIRDS OF A FEATHER


THE BIRDS OF NOT A FEATHER


THE STRANGENESS OF FRIENDS

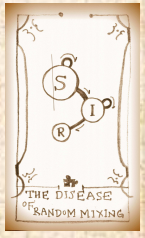

THE SMALLNESS OF WORLDS

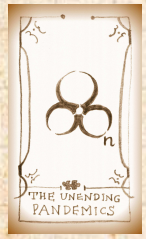

THE THEORY OF SIX DEGREES


THE NETWORKS FREE OF SCALE


CLASSIFIED
PHOENIX
BIO HAZARD
THE CONTAGION


THE CONFUSION OF CONTAGIONS


THE DISEASE OF RANDOM MIXING


THE UNENDING PANDEMICS


THE RATIO OF GAIN

THE THRESHOLDS OF THE MIND

THE SOCIAL WILD

THE SOCIAL CONTAGION

THE MECHANICS OF FAME

THE STORIES CONTAGIOUS

THE PATHS OF UNIVERSALITY

THE DEPENDENT PATHS

THE TROUSERS OF BIFURCATING REALITIES

THE UNKNOWN MECHANISM

THE JOHN DORY

THE STORYTELLERS

THE ADJACENT NARRATIVES

THE END

THE NETWORKS COMPLEX

Outline

net•work |ˈnetˌwərk|

noun

1 an arrangement of intersecting horizontal and vertical lines.

- a complex system of roads, railroads, or other transportation routes *: a network of railroads.*

2 a group or system of interconnected people or things *: a trade network.*

- a group of people who exchange information, contacts, and experience for professional or social purposes *: a support network.*
- a group of broadcasting stations that connect for the simultaneous broadcast of a program *: the introduction of a second TV network* | [as adj.] *network television.*
- a number of interconnected computers, machines, or operations *: specialized computers that manage multiple outside connections to a network* | *a local cellular phone network.*
- a system of connected electrical conductors.

verb [trans.]

connect as or operate with a network *: the stock exchanges have proven to be resourceful in networking these deals.*

- link (machines, esp. computers) to operate interactively : [as adj.] (**networked**) *networked workstations.*
- [intrans.] [often as n.] (**networking**) interact with other people to exchange information and develop contacts, esp. to further one's career *: the skills of networking, bargaining, and negotiation.*

Thesaurus deliciousness:

network

noun

1 *a network of arteries* WEB, lattice, net, matrix, mesh, crisscross, grid, reticulum, reticulation; Anatomy plexus.

2 *a network of lanes* MAZE, labyrinth, warren, tangle.

3 *a network of friends* SYSTEM, complex, nexus, web, webwork.

Ancestry:

From Keith Briggs's excellent etymological investigation:

- Opus reticulatum:
- A Latin origin?

[http://serialconsign.com/2007/11/we-put-net-network]

Ancestry:

First known use: Geneva Bible, 1560

‘And thou shalt make unto it a grate like networke of brass (Exodus xxvii 4).’

From the OED via Briggs:

- 1658–: reticulate structures in animals
- 1839–: rivers and canals
- 1869–: railways
- 1883–: distribution network of electrical cables
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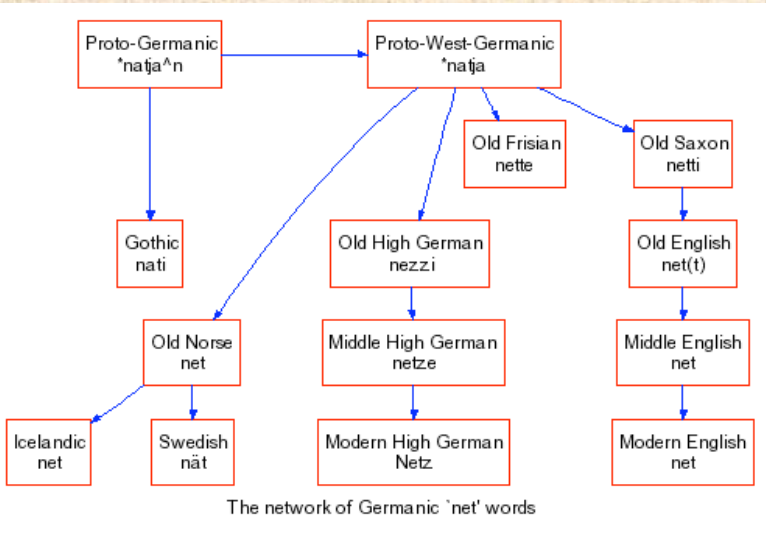
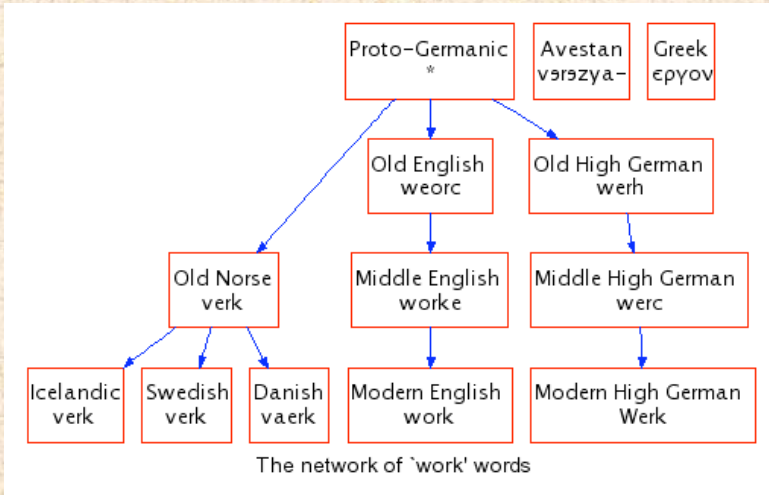
Net and Work are venerable old words:

- ‘Net’ first used to mean spider web (King Ælfréd, 888).
- ‘Work’ appear to have long meant purposeful action.



The network of Germanic `net' words



The network of `work' words

- ‘Network’ = something built based on the idea of natural, flexible lattice or web.
- c.f., ironwork, stonework, fretwork.

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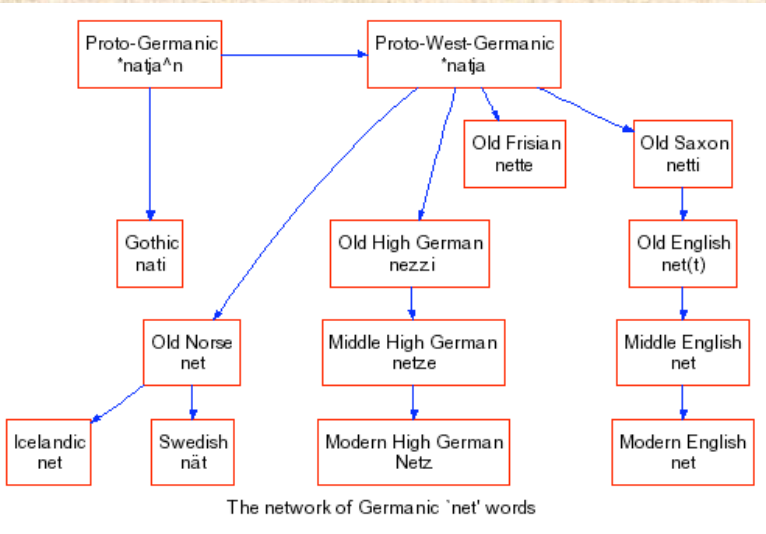

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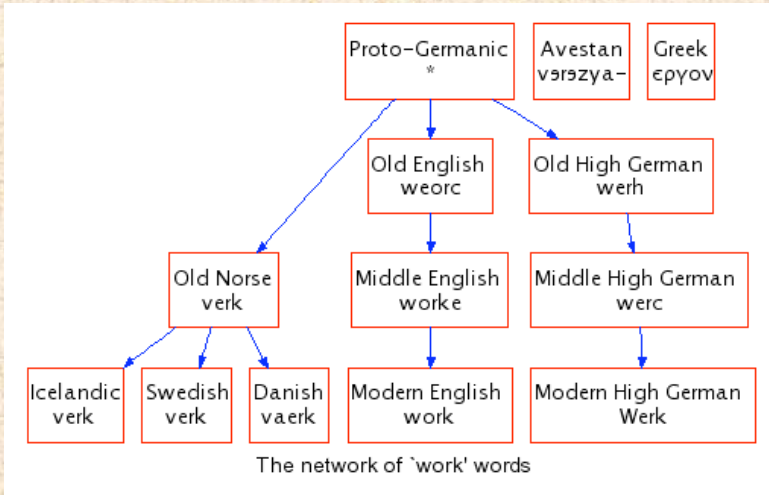

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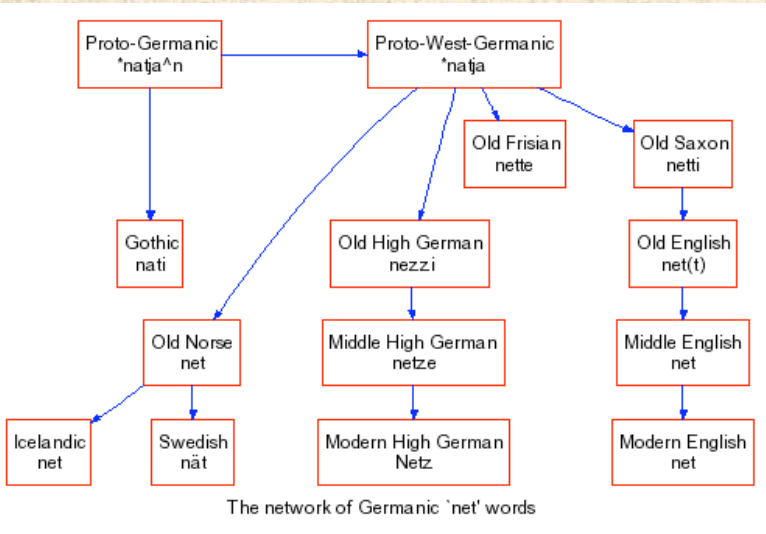

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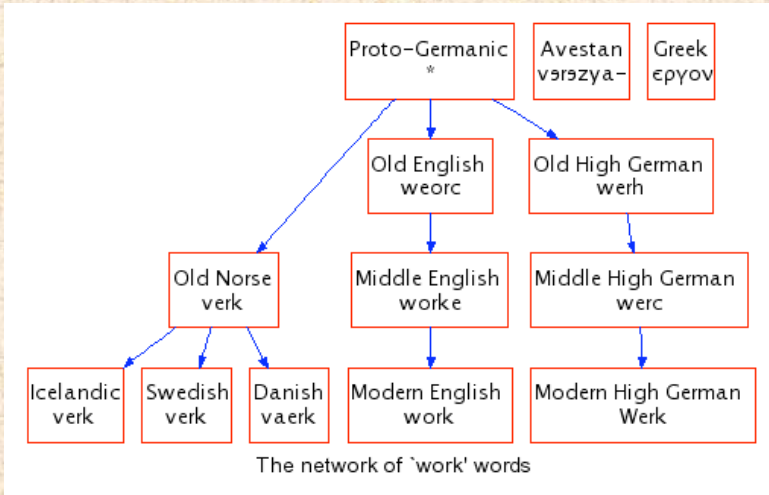

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- Many complex systems can be viewed as complex networks of physical or abstract interactions.
- Opens door to mathematical and numerical analysis.
- Dominant approach of last decade of a theoretical-physics/stat-mechish flavor.
- Mindboggling amount of work published on complex networks since 1998 ...
- ...largely due to your typical theoretical physicist:

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  - *Piranha physicus*
  - Hunt in packs.
  - Feast on new and interesting ideas (see chaos, cellular automata, ...)
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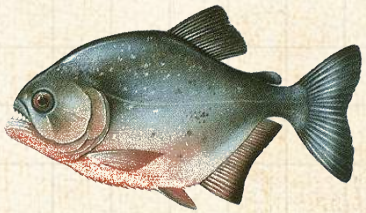

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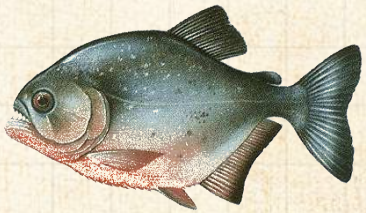

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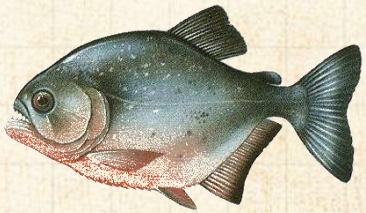

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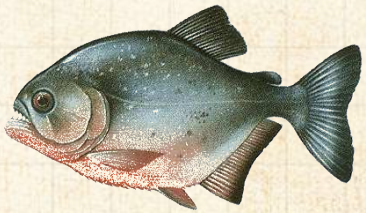

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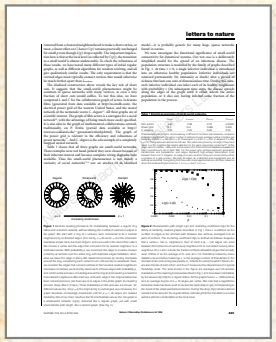

"Collective dynamics of 'small-world' networks"
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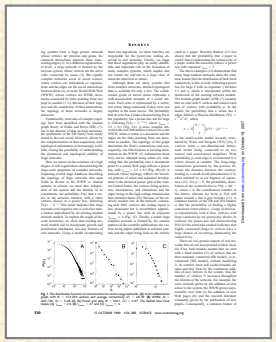

"Emergence of scaling in random networks"
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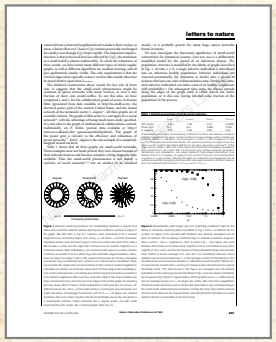

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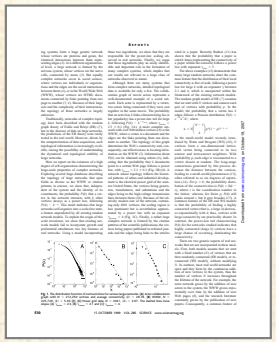

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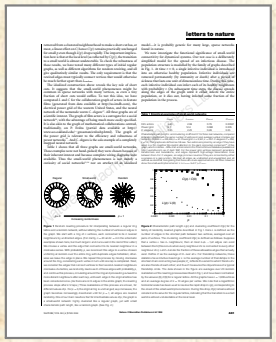

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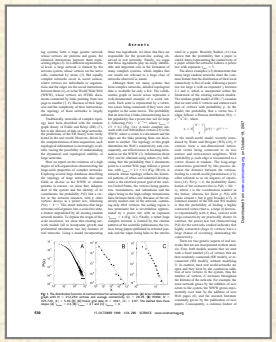

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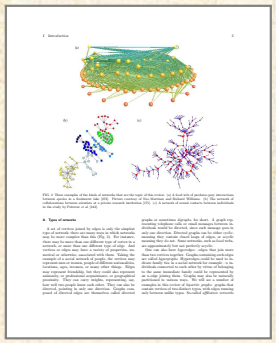
Review articles:

"Complex Networks: Structure and Dynamics"
Boccaletti et al.,
Physics Reports, **424**, 175–308, 2006. [3]

Times cited: ∼ 7,689 (as of October 24, 2017)



"The structure and function of complex networks"
M. E. J. Newman,
SIAM Rev., **45**, 167–256, 2003. [10]

Times cited: ∼ 16,436 (as of October 24, 2017)

"Statistical mechanics of complex networks"
Albert and Barabási,
Rev. Mod. Phys., **74**, 47–97, 2002. [1]

Times cited: ∼ 19,104 (as of October 24, 2017)

Popularity according to textbooks:

Textbooks:

- Mark Newman (Physics, Michigan)
  "Networks: An Introduction"
- David Easley and Jon Kleinberg (Economics and Computer Science, Cornell)
  "Networks, Crowds, and Markets: Reasoning About a Highly Connected World"

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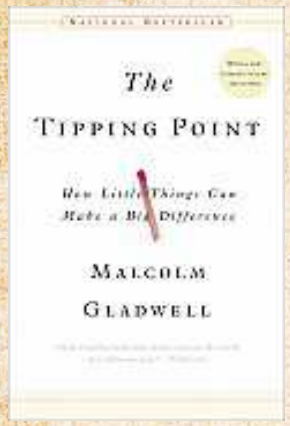
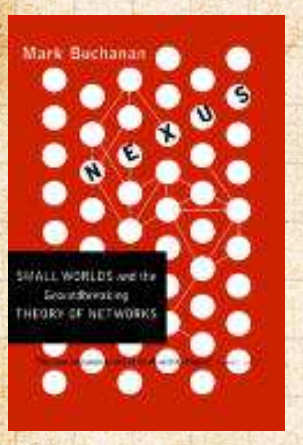


The Tipping Point: How Little Things can make a Big Difference—Malcolm Gladwell [7]



Nexus: Small Worlds and the Groundbreaking Science of Networks—Mark Buchanan

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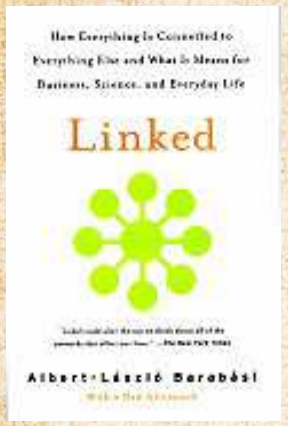
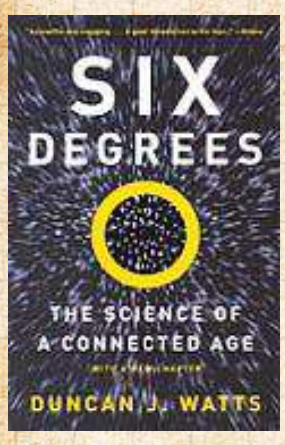


Linked: How Everything Is Connected to Everything Else and What It Means—Albert-Laszlo Barabási



Six Degrees: The Science of a Connected Age—Duncan Watts [13]

Numerous others ...

- Complex Social Networks—F. Vega-Redondo [12]
- Fractal River Basins: Chance and Self-Organization—I. Rodríguez-Iturbe and A. Rinaldo [11]
- Random Graph Dynamics—R. Durette
- Scale-Free Networks—Guido Caldarelli
- Evolution and Structure of the Internet: A Statistical Physics Approach—Romu Pastor-Satorras and Alessandro Vespignani
- Complex Graphs and Networks—Fan Chung
- Social Network Analysis—Stanley Wasserman and Kathleen Faust
- Handbook of Graphs and Networks—Eds: Stefan Bornholdt and H. G. Schuster [5]
- Evolution of Networks—S. N. Dorogovtsev and J. F. F. Mendes [6]

Outline

More observations

- But surely networks aren't new ...
- Graph theory is well established ...
- Study of social networks started in the 1930's ...
- So why all this 'new' research on networks?
- Answer: Oodles of Easily Accessible Data.
- We can now inform (alas) our theories with a much more measurable reality.*
- A worthy goal: establish mechanistic explanations.

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**If this is upsetting, maybe string theory is for you ...*

More observations

- Web-scale data sets can be overly exciting.

Witness:

- The End of Theory: The Data Deluge Makes the Scientific Theory Obsolete (Anderson, Wired)
- "The Unreasonable Effectiveness of Data," Halevy et al. [8].
- cf. Wigner's "The Unreasonable Effectiveness of Mathematics in the Natural Sciences" [15]

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Outline

Super Basic definitions

Nodes = A collection of entities which have properties that are somehow related to each other

- e.g., people, forks in rivers, proteins, webpages, organisms, ...

Links = Connections between nodes

- Links may be directed or undirected.
- Links may be binary or weighted.

Other spiffing words: vertices and edges.

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Node degree = Number of links per node

- Notation: Node i's degree = k_i.
- k_i = 0,1,2,....
- Notation: the average degree of a network = $\langle k \rangle$
- Connection between number of edges m and average degree:

$$\langle k \rangle = \frac{2m}{N}.$$

- Defn: $\mathcal{N}_i$ = the set of i's k_i neighbors

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Adjacency matrix:

- We represent a directed network by a matrix A with link weight a_{ij} for nodes i and j in entry (i, j).
- e.g.,

$$A = \begin{bmatrix} 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

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So what passes for a complex network?

- Complex networks are large (in node number)
- Complex networks are sparse (low edge to node ratio)
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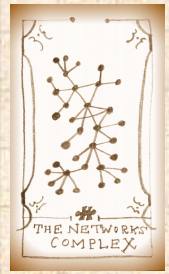
Physical networks

- River networks
- Neural networks
- Trees and leaves
- Blood networks
- The Internet
- Road networks
- Power grids

- Distribution (branching) versus redistribution (cyclical)



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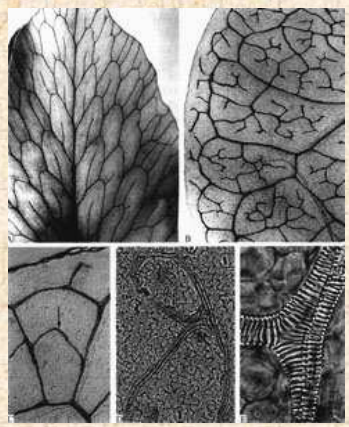

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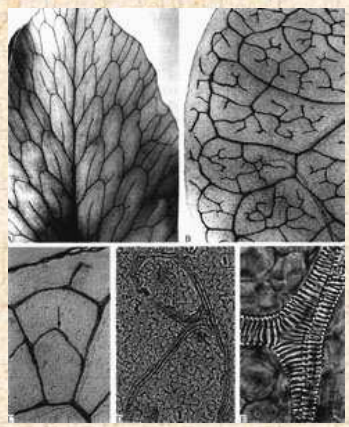

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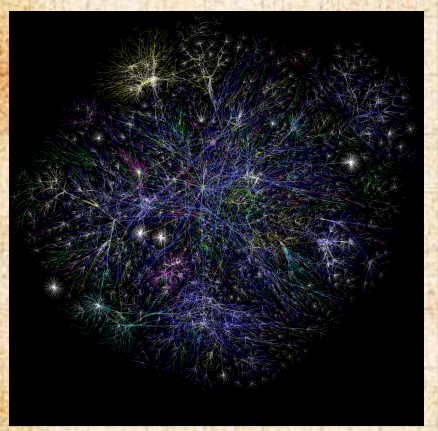

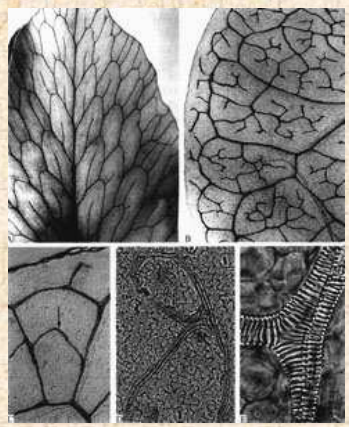

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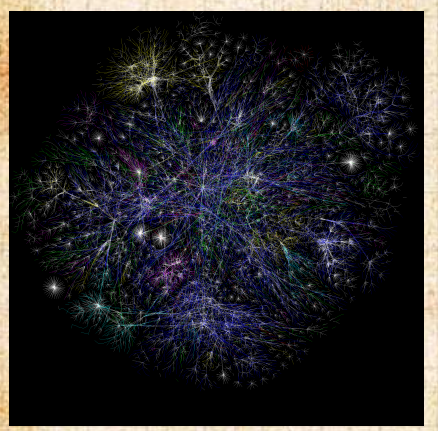

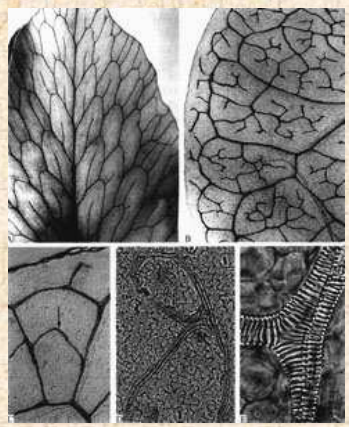

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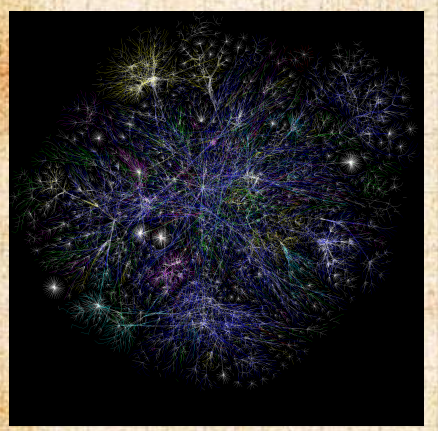

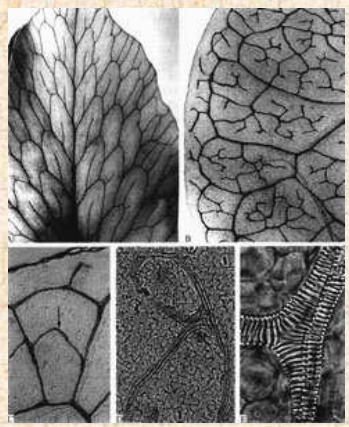

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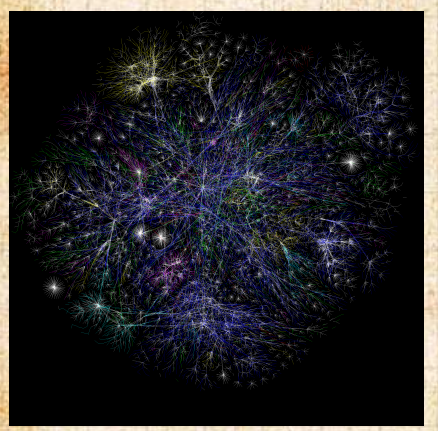

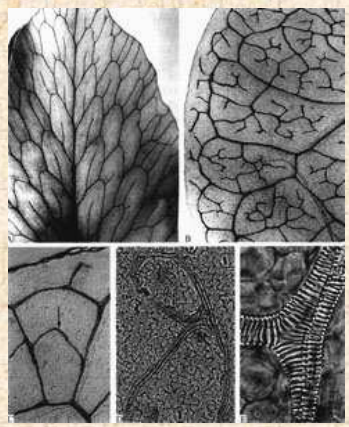

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Interaction networks

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- Biochemical networks
- Gene-protein networks
- Food webs: who eats whom
- The World Wide Web (?)
- Airline networks
- Call networks (AT&T)
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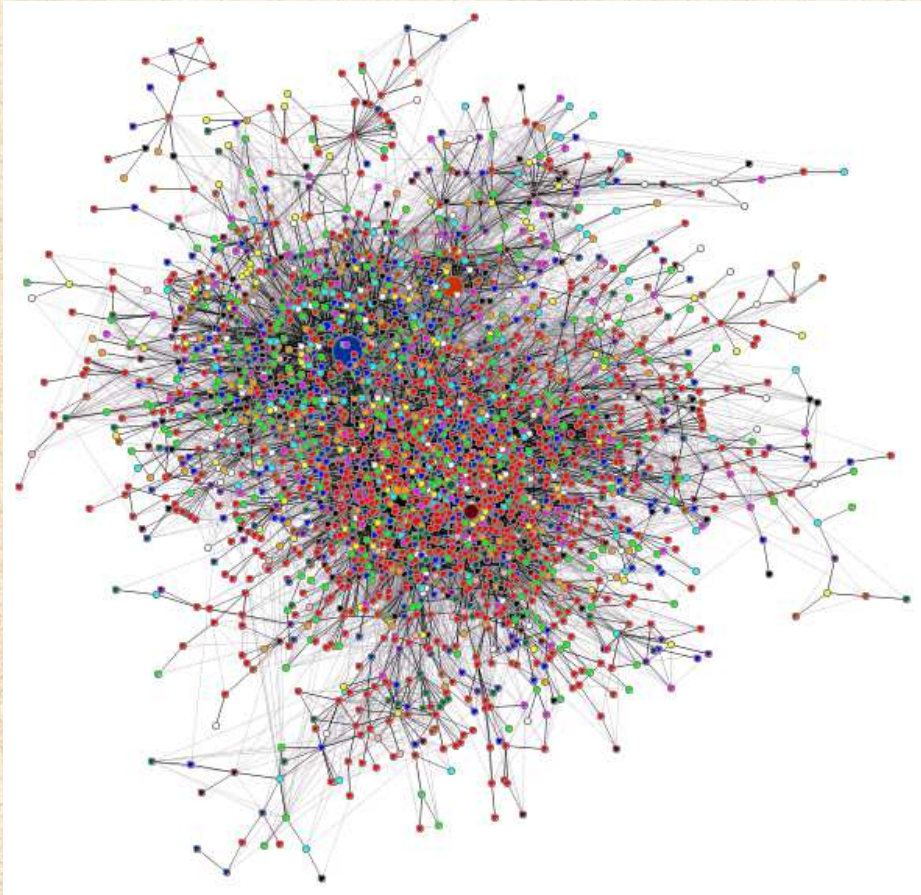

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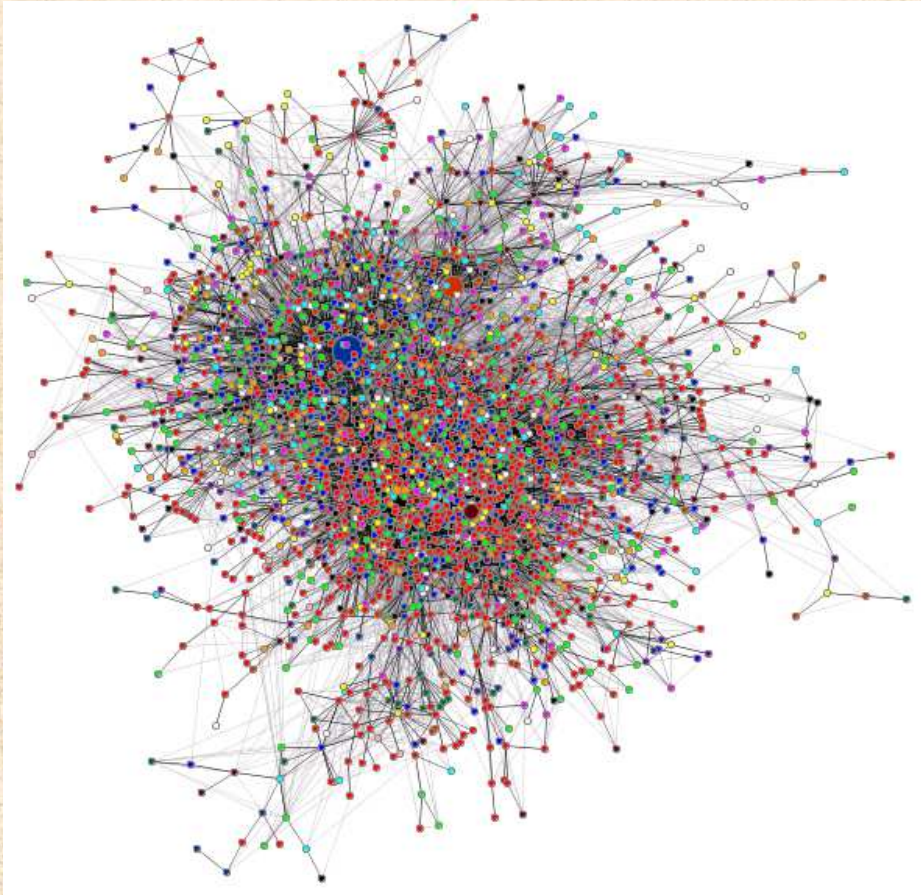

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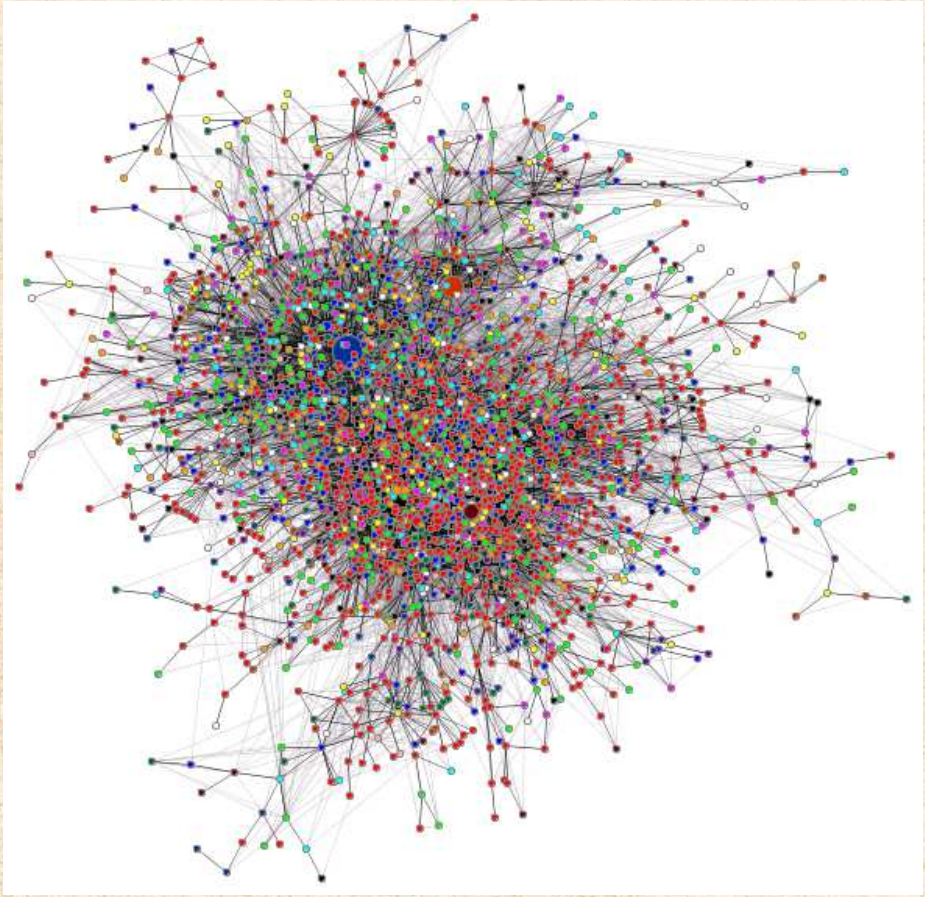

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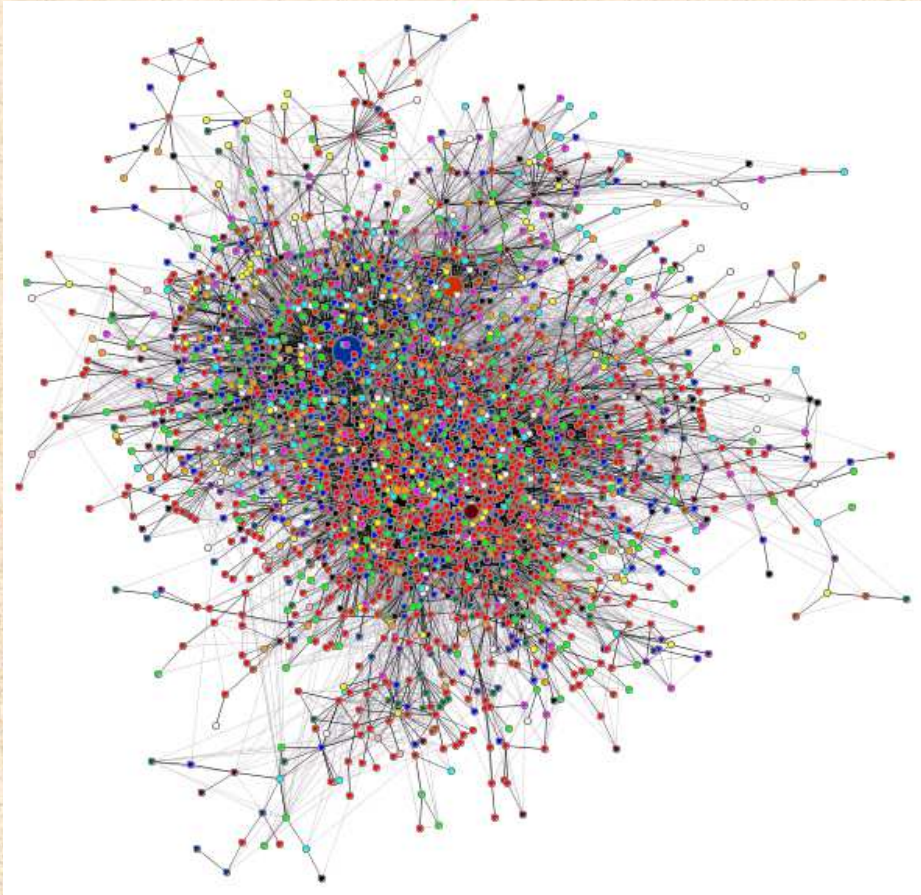

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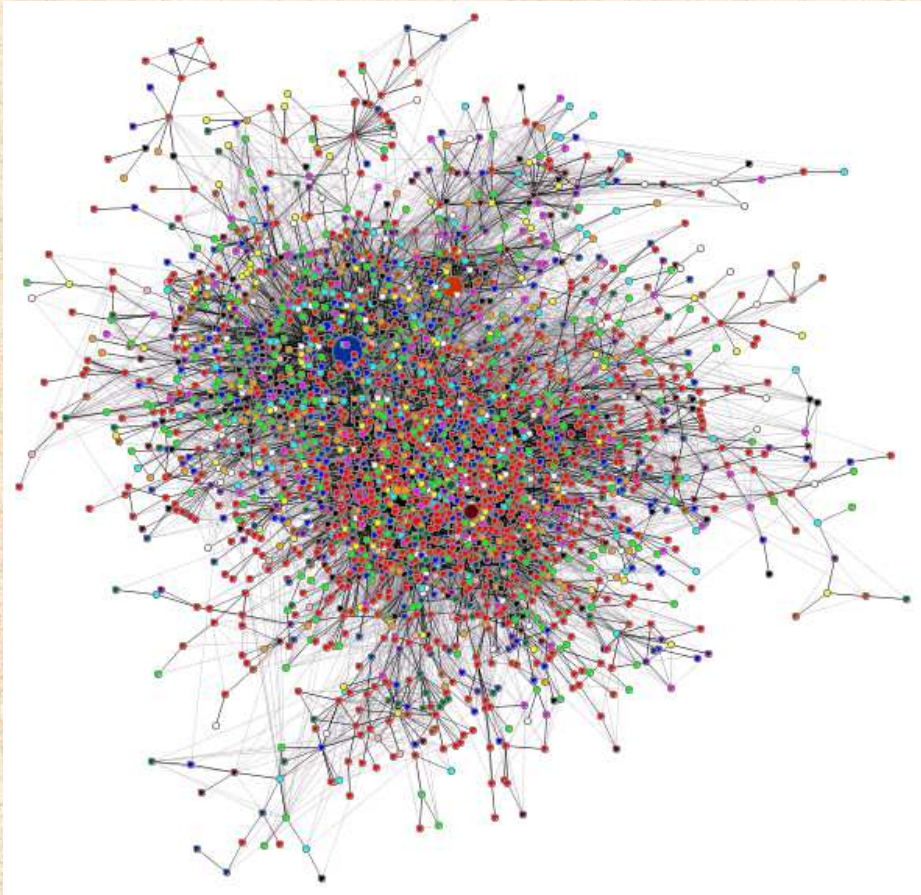

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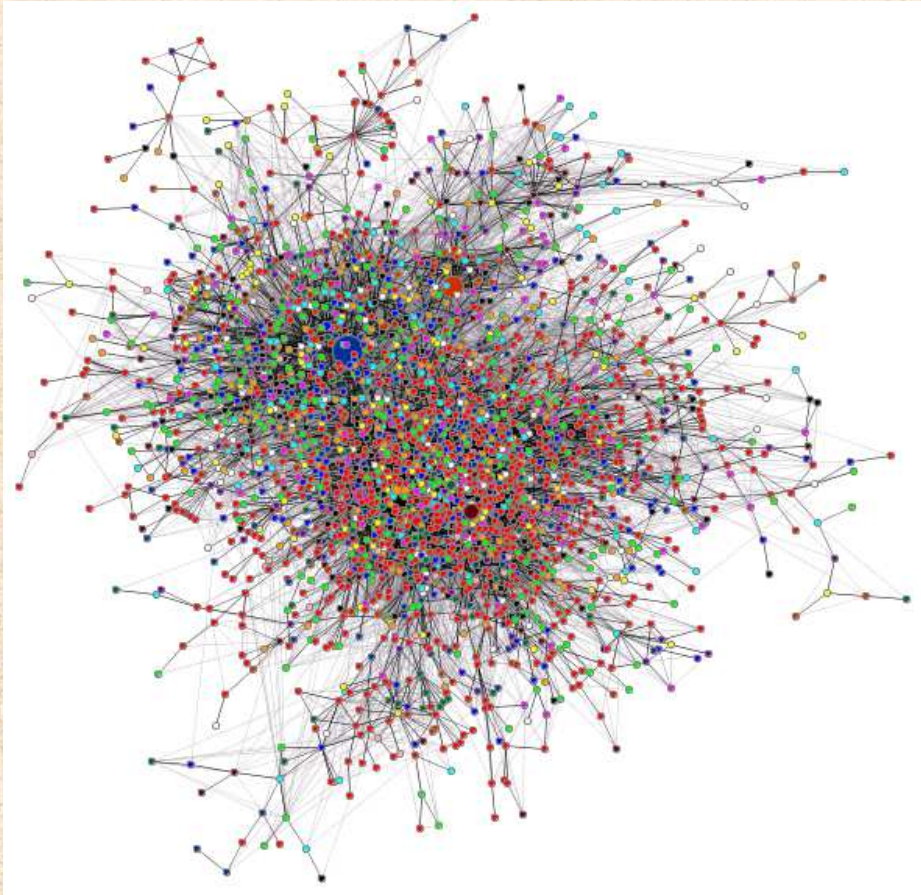

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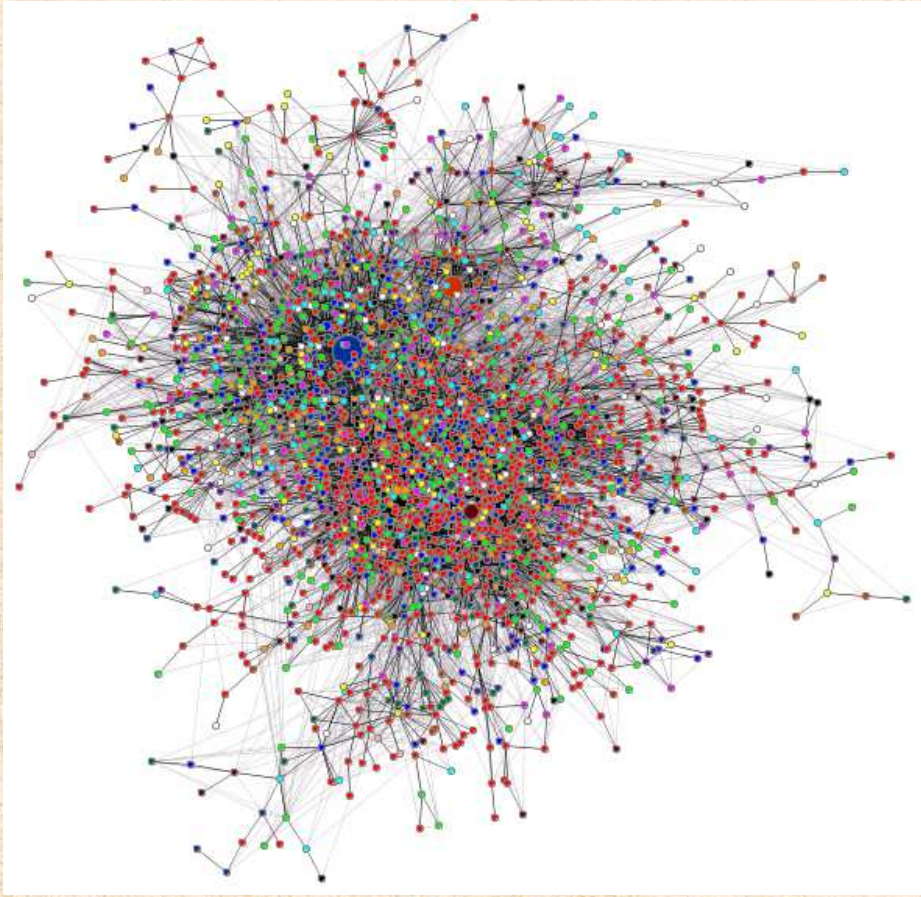

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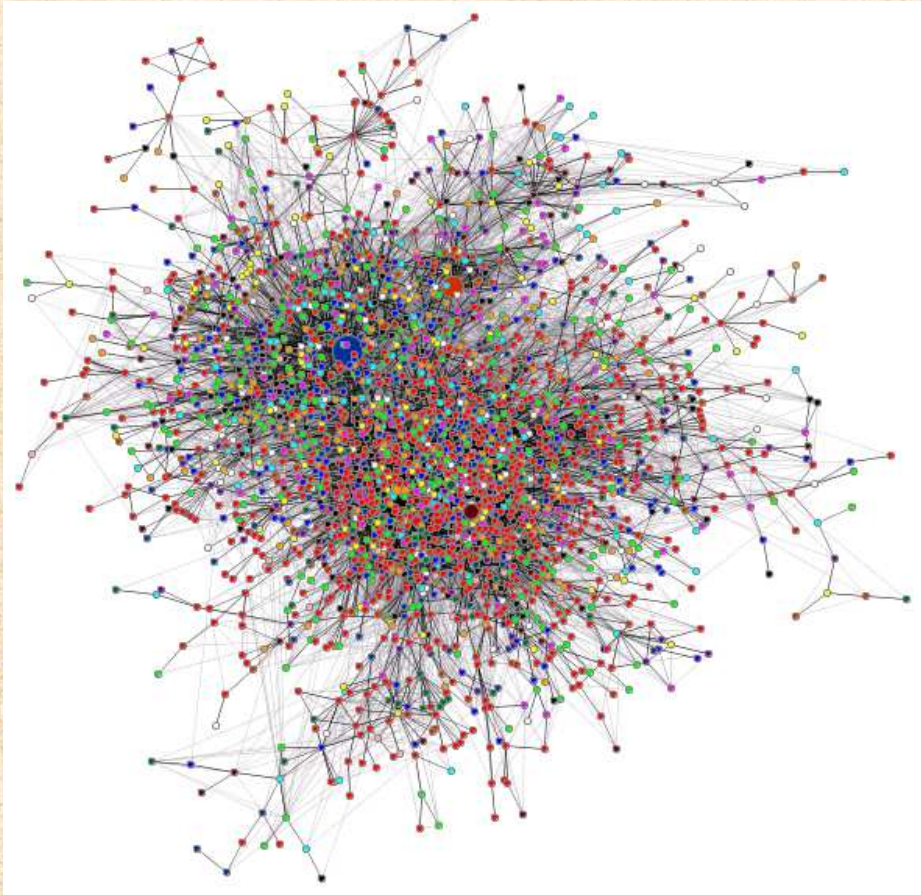

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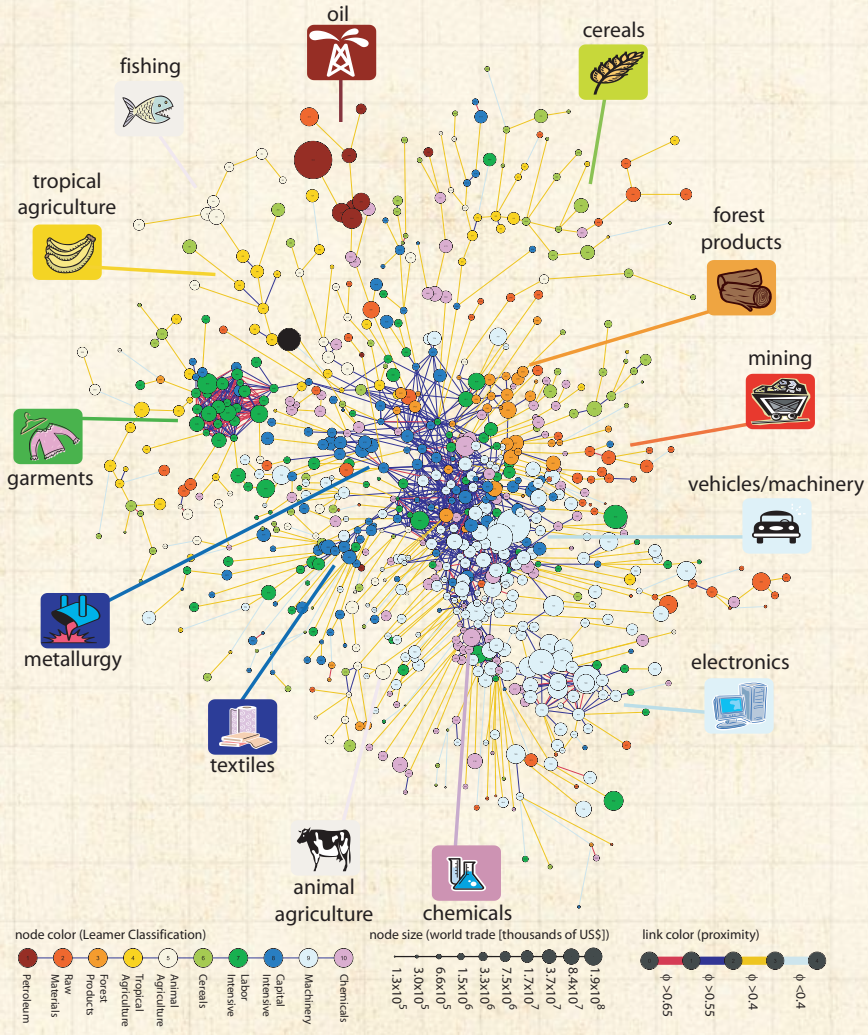
topics:

- Hidalgo et al.'s "The Product Space Conditions the Development of Nations" [9]
- How do products depend on each other, and how does this network evolve?
- How do countries depend on each other for water, energy, people (immigration), investments?



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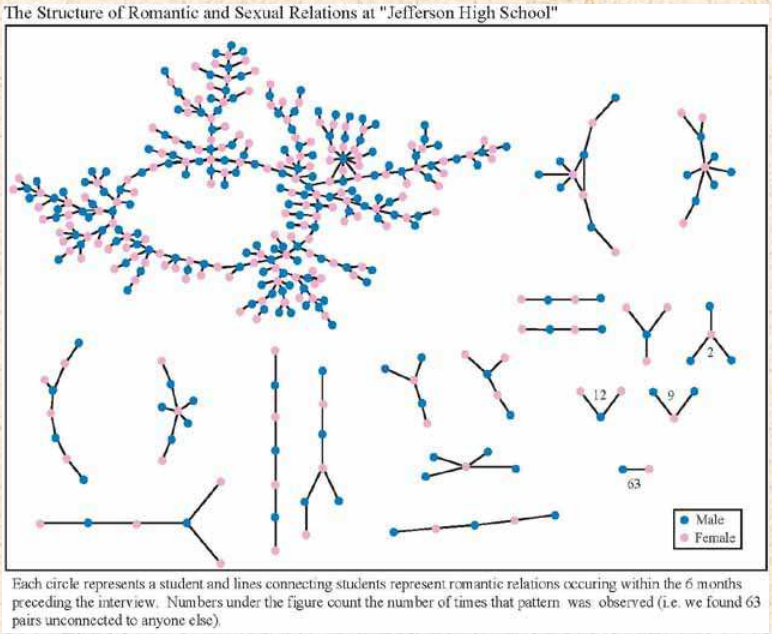
- Friendships
- Acquaintances
- Boards and directors
- Organizations
- facebook, twitter, ...



(Bearman *et al.*, 2004)

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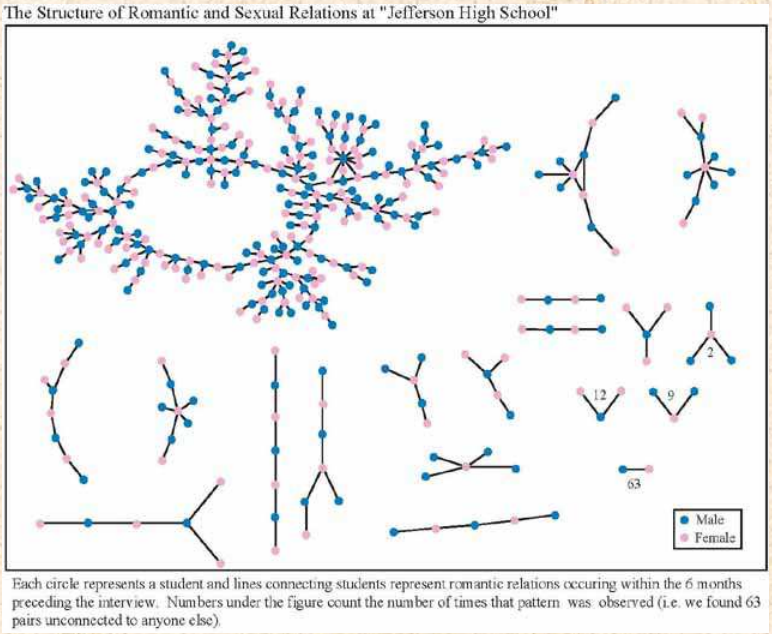

Each circle represents a student and lines connecting students represent romantic relations occuring within the 6 months preceding the interview. Numbers under the figure count the number of times that pattern was observed (i.e. we found 63 pairs unconnected to anyone else).

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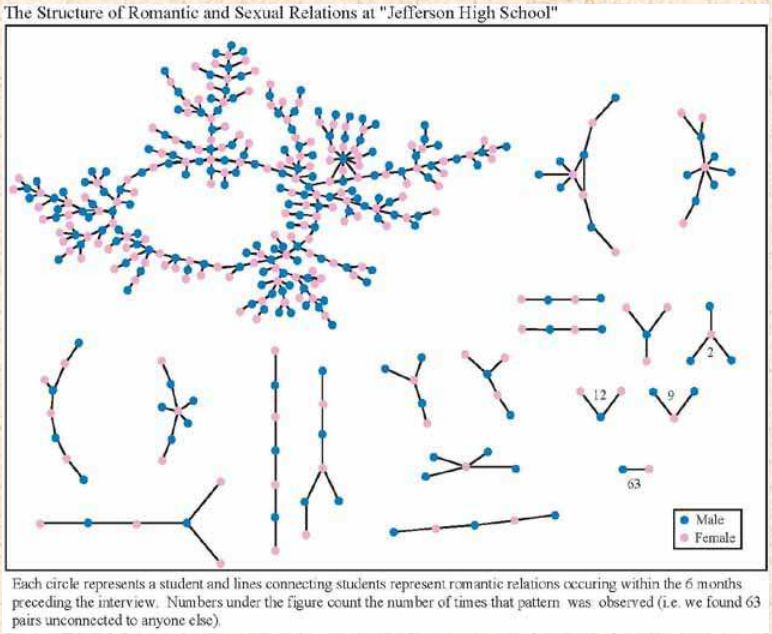

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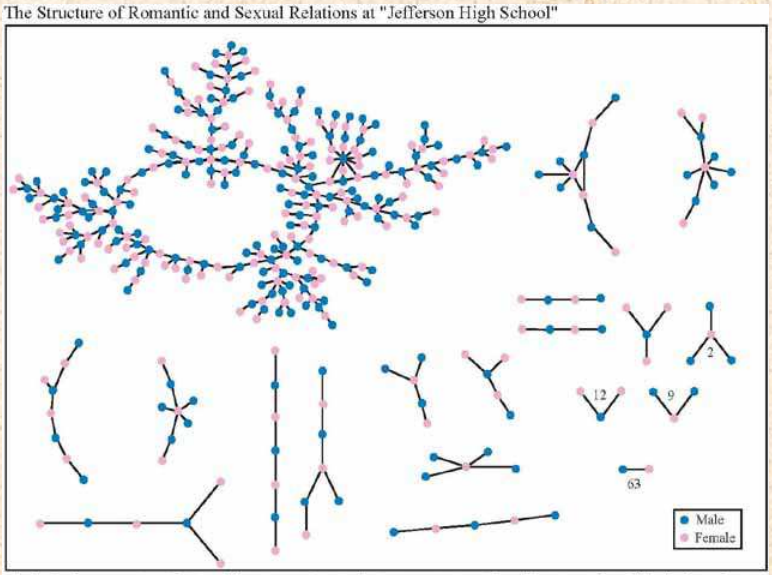

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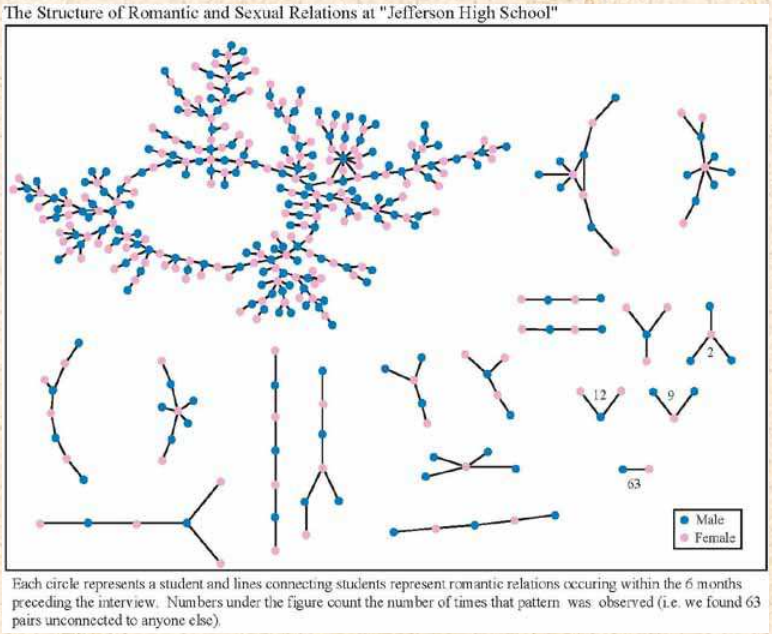

(Bearman *et al.*, 2004)

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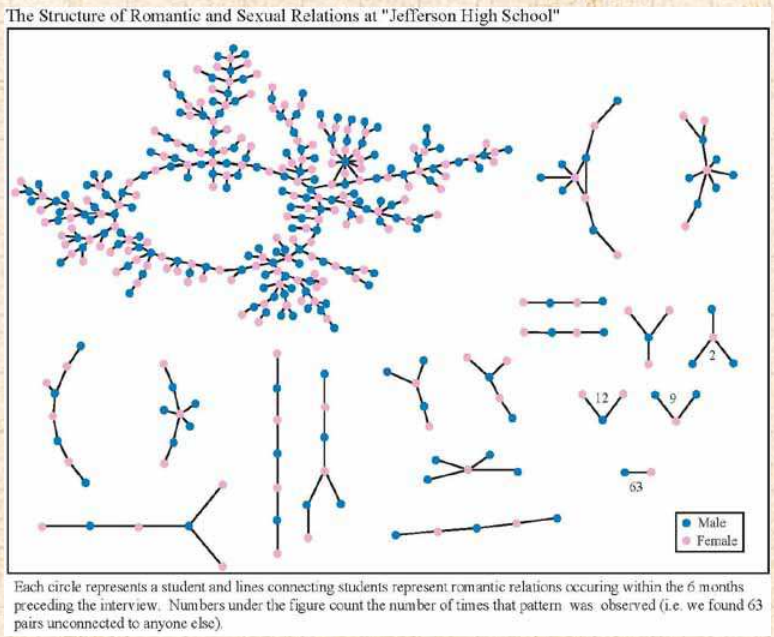

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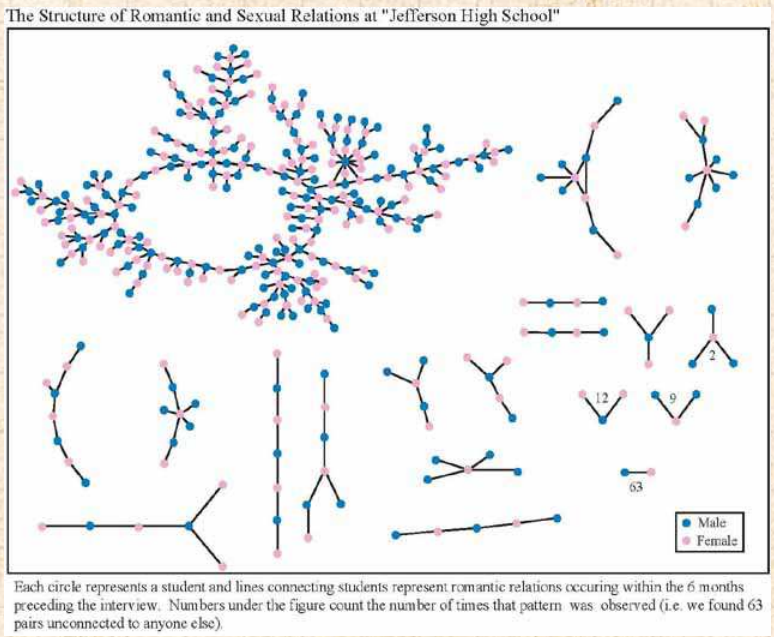

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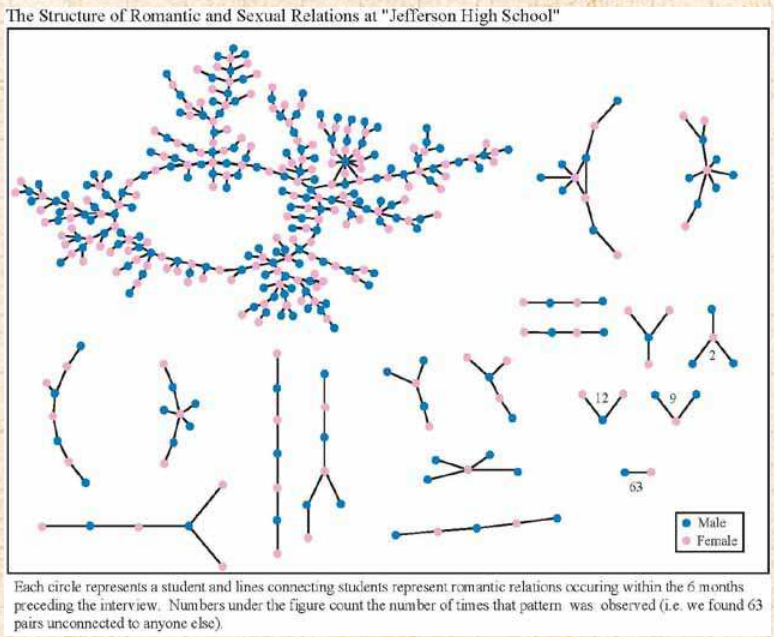

Each circle represents a student and lines connecting students represent romantic relations occuring within the 6 months preceding the interview. Numbers under the figure count the number of times that pattern was observed (i.e. we found 63 pairs unconnected to anyone else).

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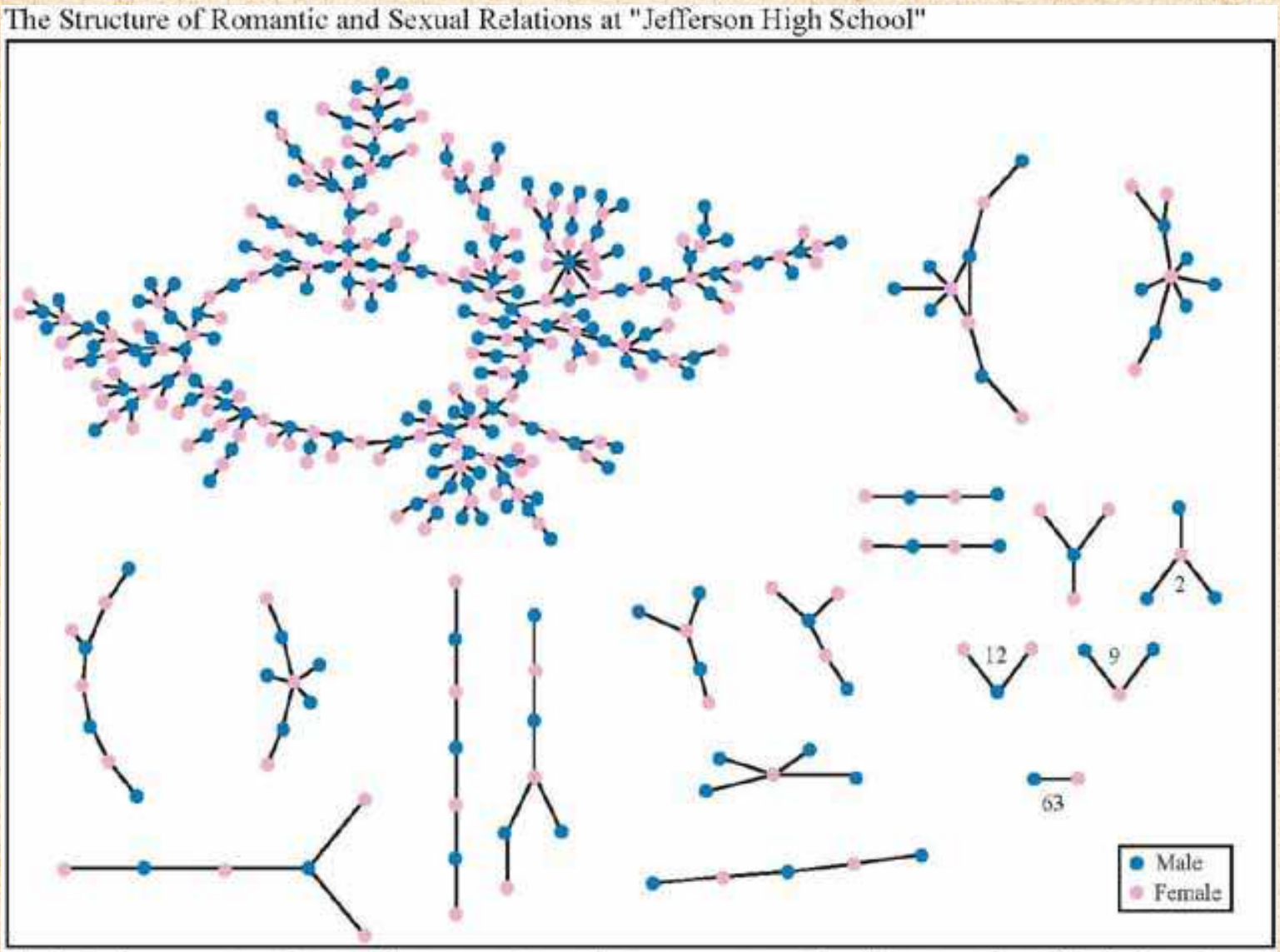

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Outline

Examples

Relational networks

- Consumer purchases
- Thesauri: Networks of words generated by meanings
- Knowledge/Databases/Ideas
- Metadata—Tagging: bit.ly flickr

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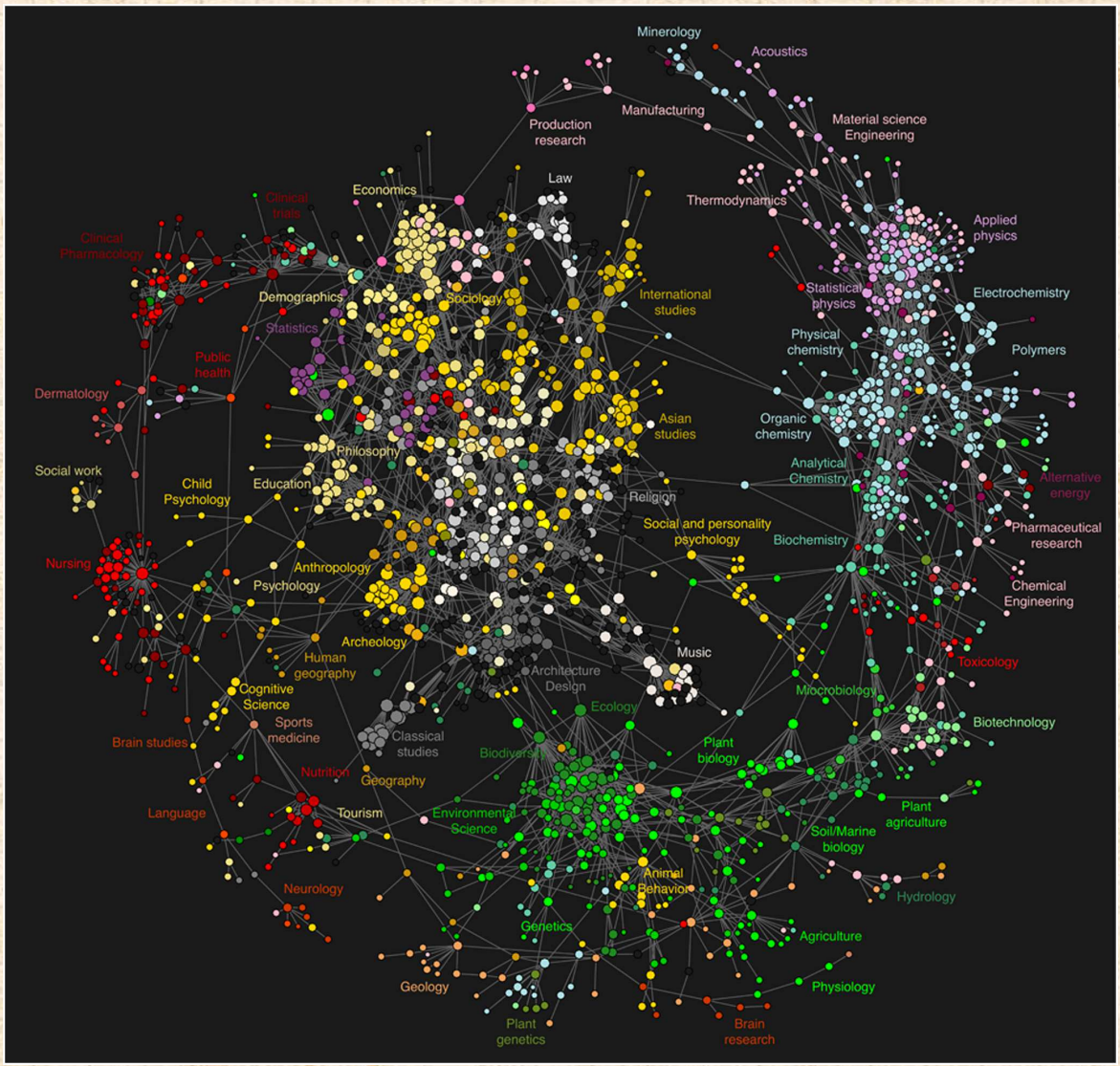
common tags cloud | list

community daily dictionary education **encyclopedia**
english free imported info information internet knowledge
learning news **reference** research resource
resources search tools useful web web2.0 **wiki**
wikipedia

Clickworthy Science:



"Clickstream Data Yields High-Resolution Maps of Science", Bollen et al. [4], 2009.

Neural reboot (NR):

Dog has fun.

https://www.youtube.com/v/7xEX-48RHCY?rel=0

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