

Overview of Complex Networks

Principles of Complex Systems | @pocsvox

CSYS/MATH 300, Fall, 2016 | #FallPoCS2016

Prof. Peter Dodds | @peterdodds

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



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Sealie & Lambie Productions



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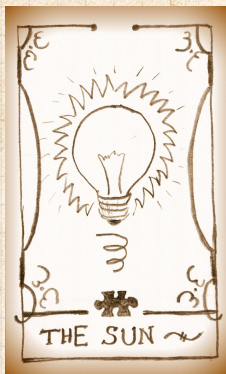
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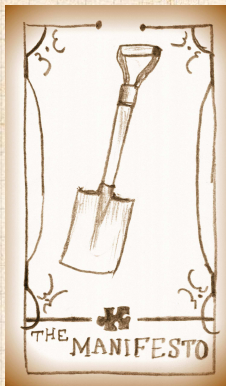
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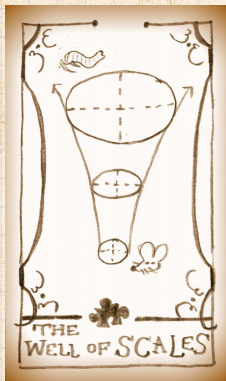
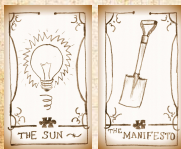
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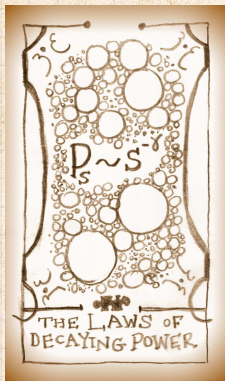
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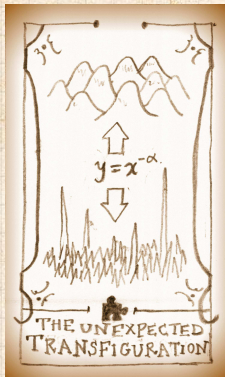
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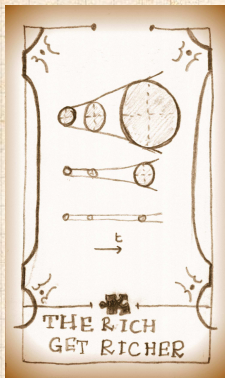
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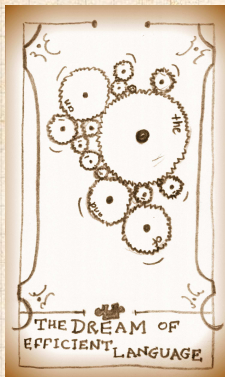
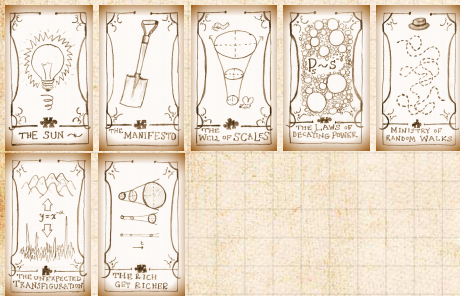
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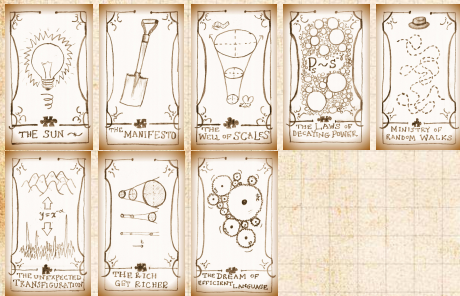
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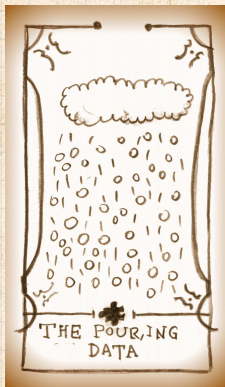
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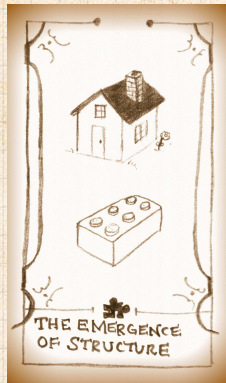
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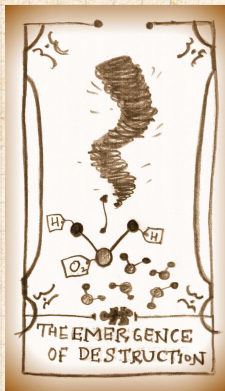
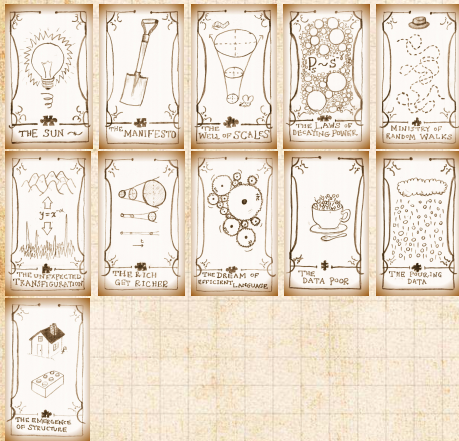
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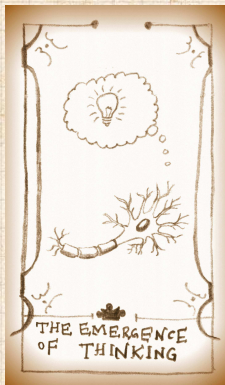
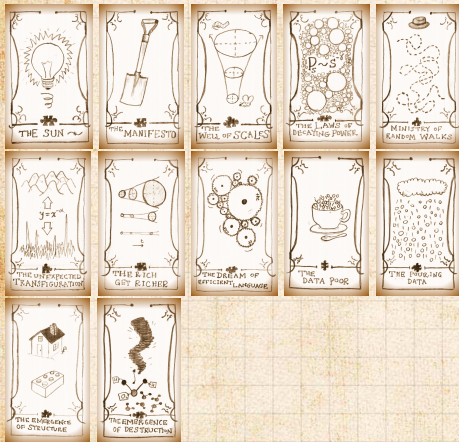
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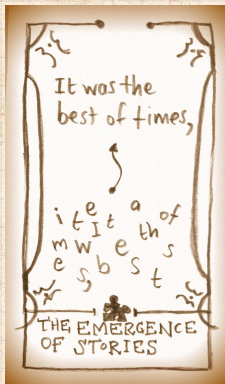
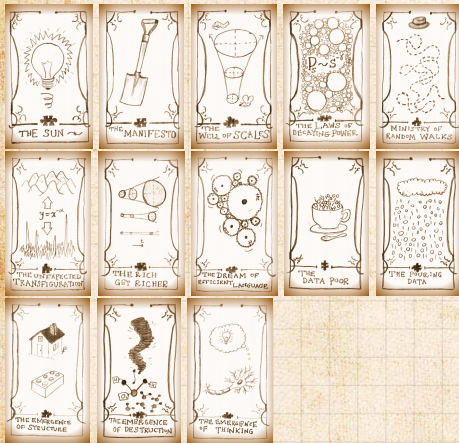
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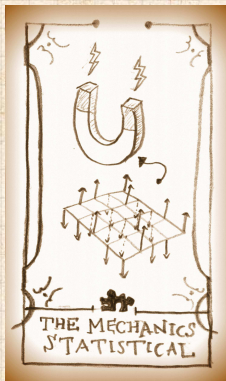
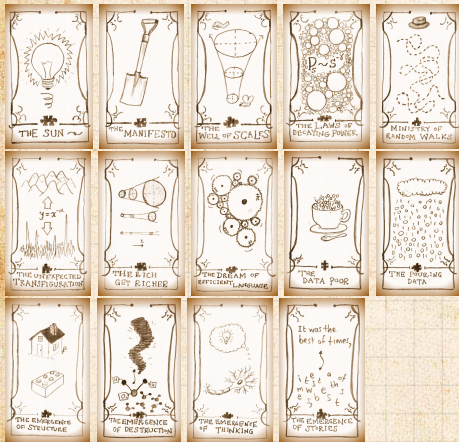
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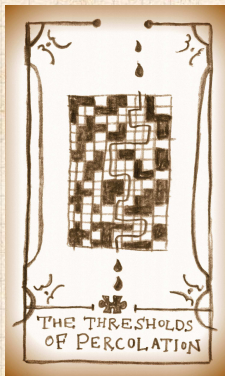
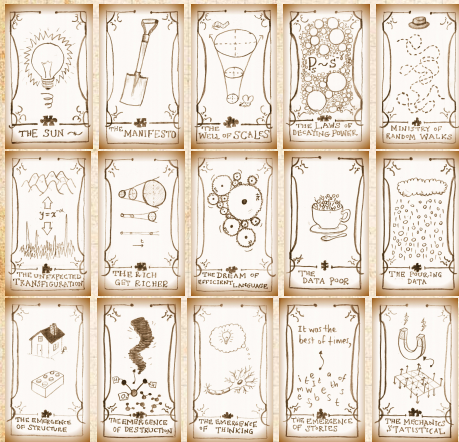
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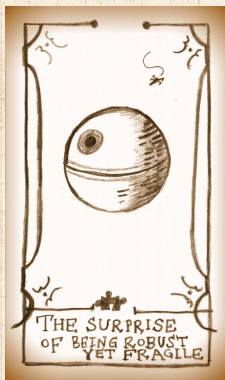
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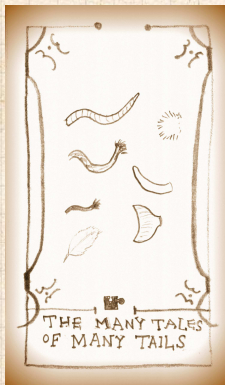
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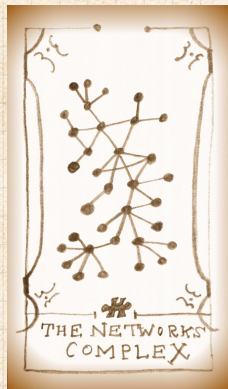
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net•work |'net,wɜrk|

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.

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From Keith Briggs's excellent etymological
investigation: 



Opus
reticulatum:



A Latin origin?



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

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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
- 1882—: distribution network of electrical cables
- 1914—: wireless broadcasting networks

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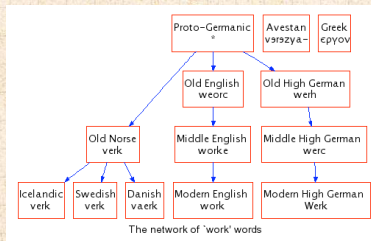
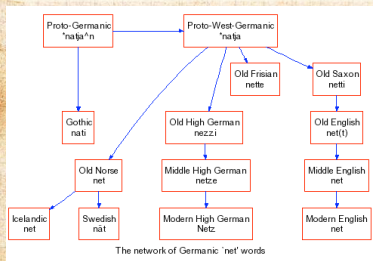


Ancestry:

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.




 'Network' = something built based on the idea of natural, flexible lattice or web.


 c.f., ironwork, stonework, fretwork.

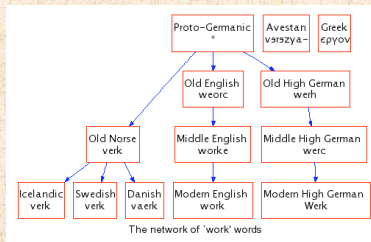
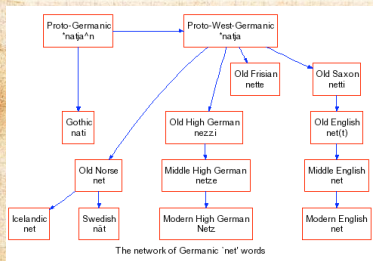



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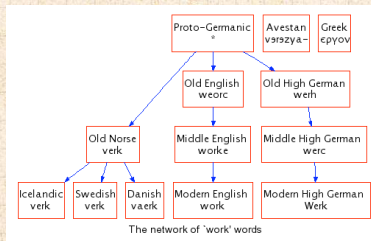
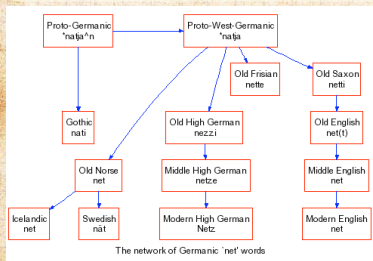



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Key Observation:



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, ...)


 See also: <https://xkcd.com/2037/>





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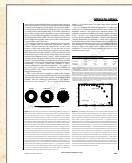
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Popularity (according to Google Scholar)



"Collective dynamics of 'small-world' networks" [↗](#)

Watts and Strogatz,
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Times cited: ~ 27,184 [↗](#) (as of October 8, 2015)



"Emergence of scaling in random networks" [↗](#)

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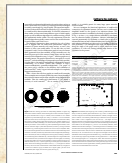
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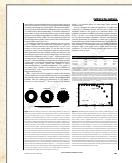
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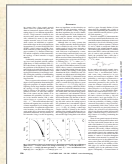
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Review articles:



“Complex Networks: Structure and Dynamics”

Boccaletti et al.,
Physics Reports, **424**, 175–308, 2006. ^[3]

Times cited: ~ **5,791** (as of October 8, 2015)



“The structure and function of complex networks”

M. E. J. Newman,
SIAM Rev., **45**, 167–256, 2003. ^[10]

Times cited: ~ **13,156** (as of October 8, 2015)



“Statistical mechanics of complex networks”

Albert and Barabási,
Rev. Mod. Phys., **74**, 47–97, 2002. ^[1]

Times cited: ~ **15,676** (as of October 8, 2015)



Popularity according to textbooks:

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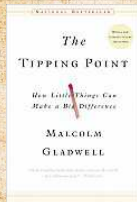
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The Tipping Point: How Little Things can
make a Big Difference—Malcolm
Gladwell ^[7]

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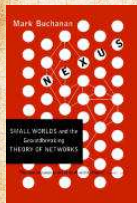
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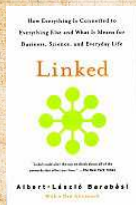
Nexus: Small Worlds and the
Groundbreaking Science of
Networks—Mark Buchanan



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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]

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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. Durrette
- 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]



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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 ...*

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 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]

But:

-  For scientists, description is only part of the battle.
-  We still need to understand.

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
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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 .

$k_i = 0, 1, 2, \dots$

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: 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.,

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

 (n.b., for numerical work, we always use sparse matrices.)

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So what passes for a complex network?

- 1. Complex networks are **large** (in node number)
- 2. Complex networks are **sparse** (low edge to node ratio)
- 3. Complex networks are usually **dynamic** and **evolving**
- 4. Complex networks can be social, economic, natural, informational, abstract, ...

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



-  Distribution (branching) versus redistribution (cyclical)

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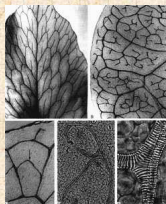


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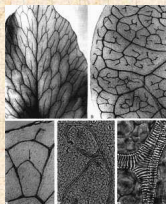
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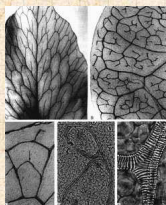
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 **Distribution** (branching) versus **redistribution** (cyclical)

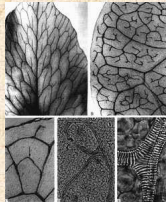
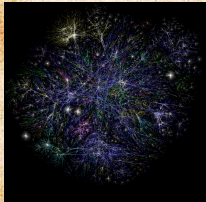


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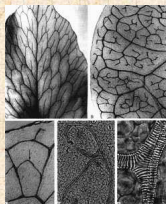


Examples

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-  River networks
-  Neural networks
-  Trees and leaves
-  Blood networks

-  The Internet
-  Road networks
-  Power grids



 **Distribution** (branching) versus **redistribution** (cyclical)

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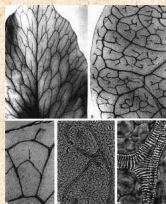
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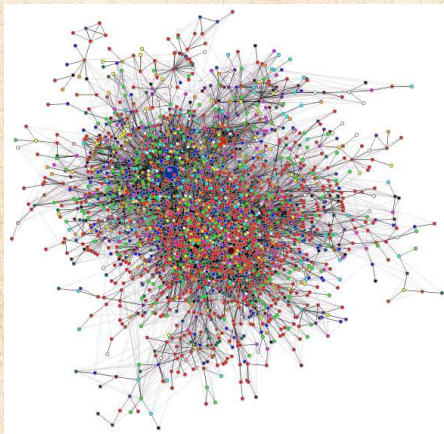
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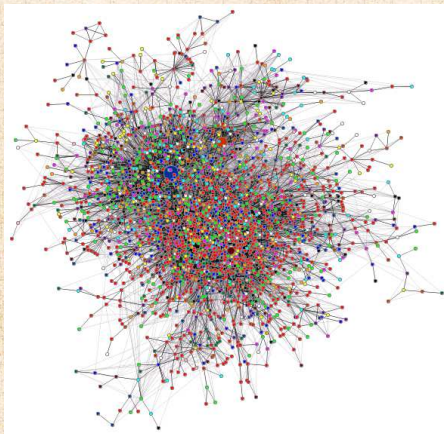
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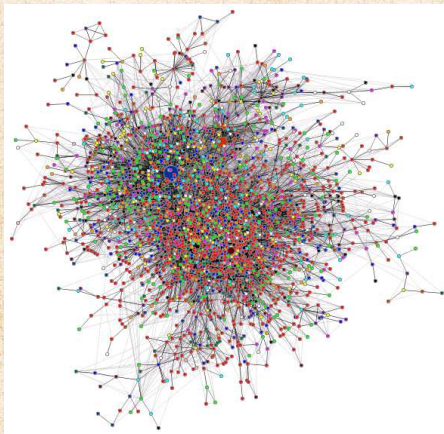
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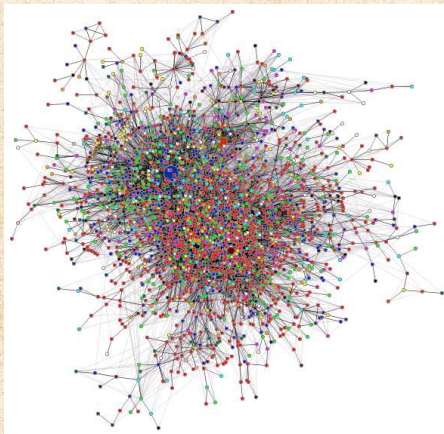
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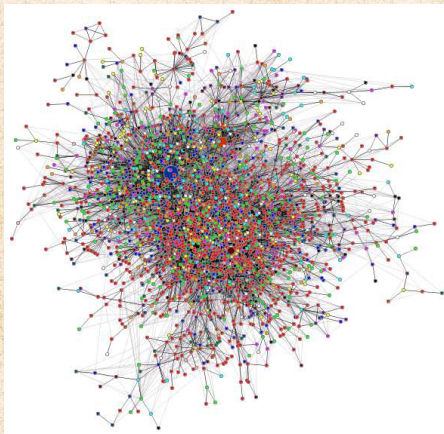
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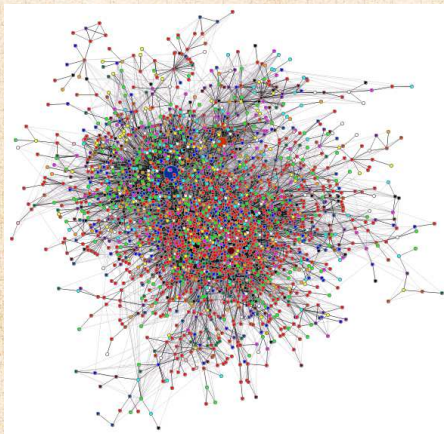
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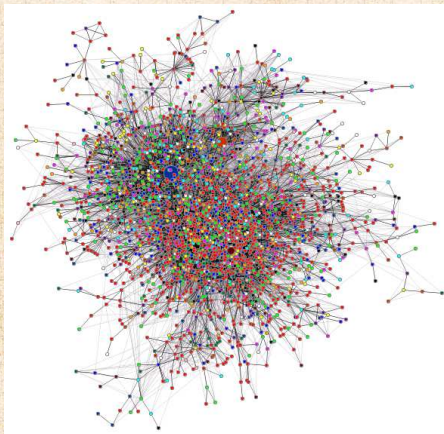
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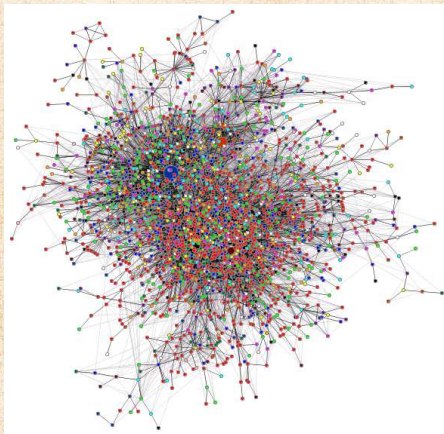
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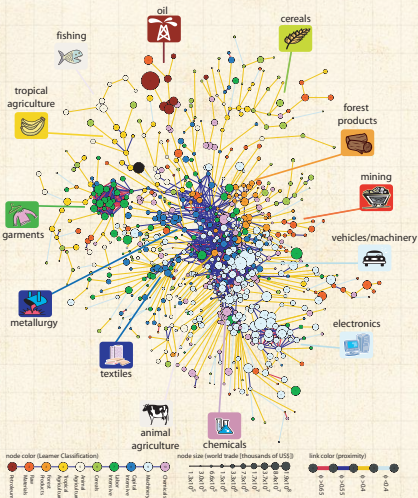
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topics:

- 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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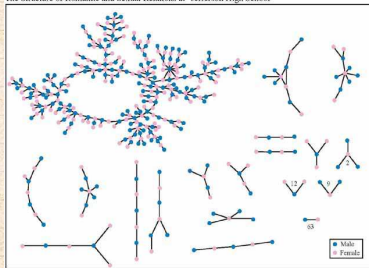


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Interaction networks: social networks

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

The Structure of Romantic and Sexual Relations at "Jefferson High School"



Each circle represents a student and lines connecting students represent romantic relations occurring 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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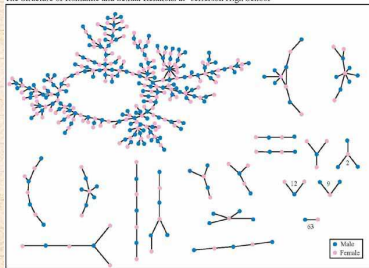
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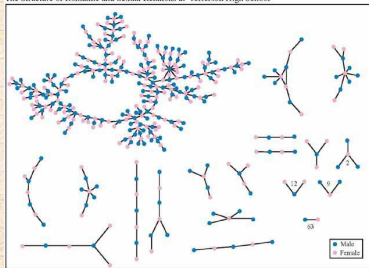
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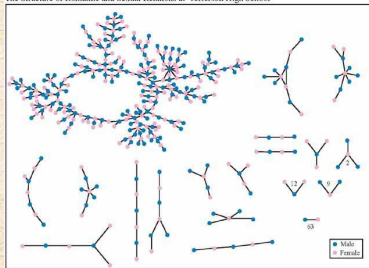
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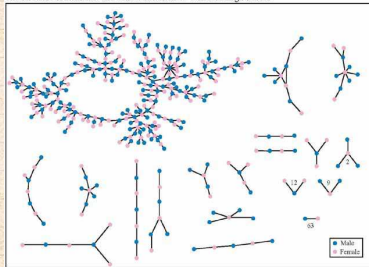
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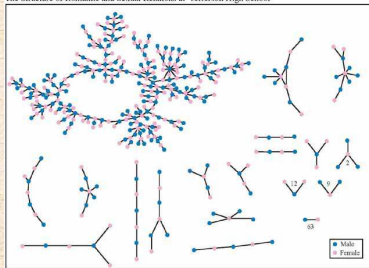
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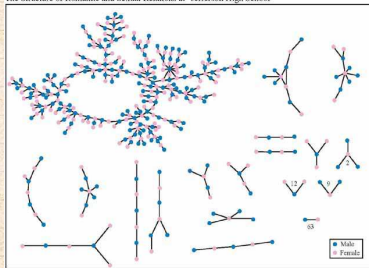
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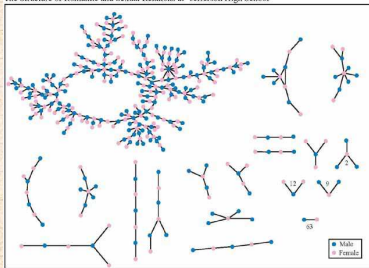
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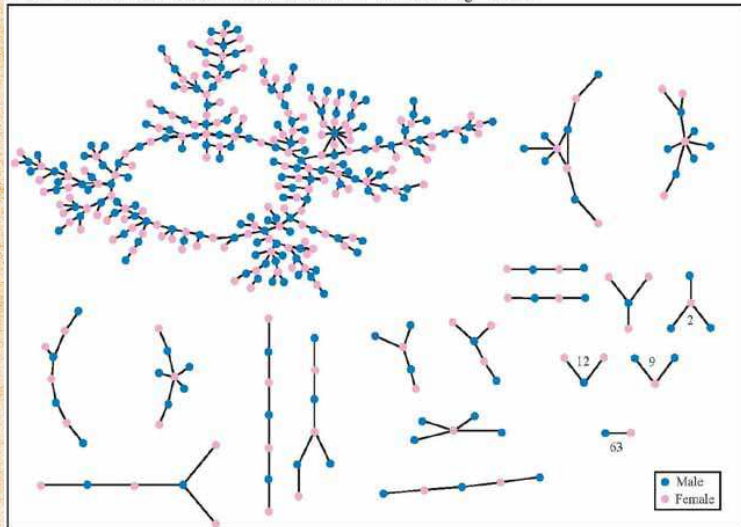
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 Thesauri: Networks of words generated by meanings

 Knowledge/Databases/Ideas

 Metadata—Tagging: [bit.ly](#)  [flickr](#) 

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common tags cloud | [list](#)

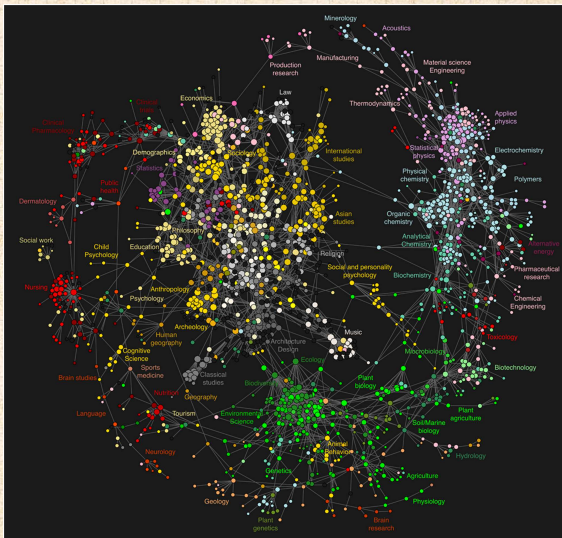
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"Clickstream Data Yields High-Resolution Maps of Science",
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Neural reboot (NR):

Dog has fun.

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