

Overview of Complex Networks

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Principles of Complex Systems, Vols. 1, 2, & 3D
CSYS/MATH 6701, 6713, & a pretend number,
2023–2024 | @pocsvox

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Santa Fe Institute | University of Vermont



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Thesaurus deliciousness:

network
noun

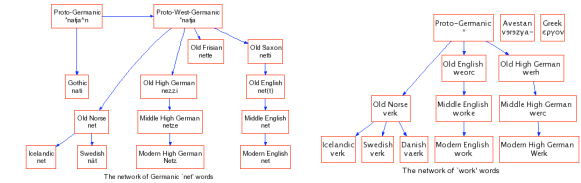
- 1 a *network of arteries* WEB, lattice, net, matrix, mesh, crisscross, grid, reticulum, reticulation; Anatomy plexus.
- 2 a *network of lanes* MAZE, labyrinth, warren, tangle.
- 3 a *network of friends* SYSTEM, complex, nexus, web, webwork.

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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.

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-mech** flavor.
- Mindboggling amount of work published on complex networks since 1998 ...
- ...largely due to your typical theoretical physicist:



- Piranha physicus*
- Hunt in packs.
- Feast on new and interesting ideas (see chaos, cellular automata, ...)
- See also: <https://xkcd.com/793/>

Popularity (according to Google Scholar)



"Collective dynamics of 'small-world' networks"
Watts and Strogatz,
Nature, **393**, 440–442, 1998. [16]

Times cited: ~ 37,460 (as of October 24, 2018)



"Emergence of scaling in random networks"
Barabási and Albert,
Science, **286**, 509–511, 1999. [2]

Times cited: ~ 32,093 (as of October 24, 2018)

Outline

Complex Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks

- Physical networks
- Interaction networks
- Relational networks

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Ancestry:

From Keith Briggs's excellent etymological investigation:



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

- Opus reticulatum:
- A Latin origin?

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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
- 1883–: distribution network of electrical cables
- 1914–: wireless broadcasting networks

net•work |ˈnetwɜːk|

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*.

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Review articles:



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

Times cited: ~ **8,533** (as of October 24, 2018)



“The structure and function of complex networks”
M. E. J. Newman,
SIAM Rev., **45**, 167–256, 2003. [12]

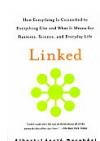
Times cited: ~ **17,782** (as of October 24, 2018)



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

Times cited: ~ **20,531** (as of October 24, 2018)

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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 [15]

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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. [9].

c.f. Wigner’s “The Unreasonable Effectiveness of Mathematics in the Natural Sciences” [17]

But:

For scientists, description is only part of the battle.

We still need to **understand**.

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Popularity according to textbooks:



“Networks”
by Mark Newman (2018). [11]



“Networks, crowds, and markets: Reasoning about a highly connected world”
by Easley and Kleinberg (2010). [7]

<http://cs.cornell.edu/home/kleinber/networks-book/>

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Numerous others ...

Complex Social Networks—F. Vega-Redondo [14]

Fractal River Basins: Chance and Self-Organization—I. Rodriguez-Iturbe and A. Rinaldo [13]

Random Graph Dynamics—R. Durrett

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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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

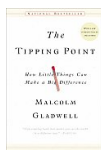
Links may be directed or undirected.

Links may be binary or weighted.

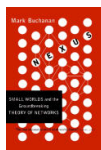
Other spiffing words: vertices and edges.

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Popularity according to books:



The Tipping Point: How Little Things can make a Big Difference—Malcolm Gladwell [8]



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

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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.

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

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Super Basic definitions

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 = $\langle k \rangle$ (and sometimes z)

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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Super Basic definitions

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.,

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

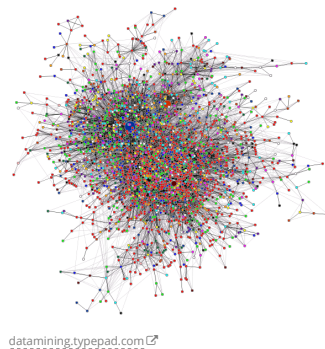
(n.b., for numerical work, we always use sparse matrices.)

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Examples

Interaction networks

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

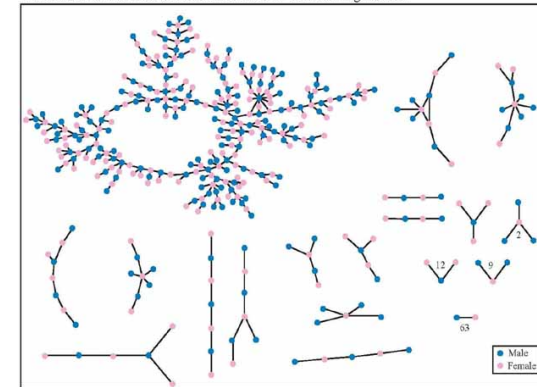


datamining.typepad.com

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Examples

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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Examples

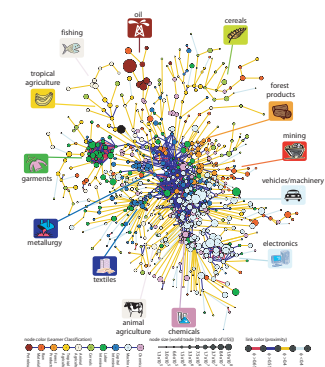
So what passes for a complex network?

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

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topics:

- Hidalgo et al.'s "The Product Space Conditions the Development of Nations" [10]
- 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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Examples

Relational networks

- Consumer purchases (Walmart, Target, Amazon, ...)
- Thesauri: Networks of words generated by meanings
- Knowledge/Databases/Ideas
- Metadata—Tagging: bit.ly [flickr](http://flickr.com)

common tags [cloud](#) | [list](#)

[community](#) [daily](#) [dictionary](#) [education](#) [encyclopedia](#)
[english](#) [free](#) [imported](#) [info](#) [information](#) [internet](#) [knowledge](#)
[learning](#) [news](#) [reference](#) [research](#) [resource](#)
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[wikipedia](#)

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Examples

Physical networks

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



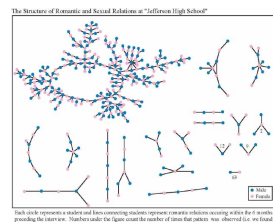
Distribution (branching) versus redistribution (cyclical)

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Examples

Interaction networks: social networks

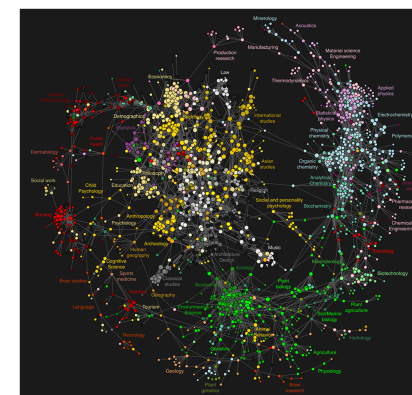
- Snogging
- Friendships
- Acquaintances
- Boards and directors
- Organizations
- [facebook](#) [twitter](#)



(Bearman et al., 2004)

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Clickworthy Science:



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

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- [7] D. Easley and J. Kleinberg. **Networks, crowds, and markets: Reasoning about a highly connected world.** Cambridge University Press, 2010.
- [8] M. Gladwell. **The Tipping Point.** Little, Brown and Company, New York, 2000.
- [9] A. Halevy, P. Norvig, and F. Pereira. **The unreasonable effectiveness of data.** *IEEE Intelligent Systems*, 24:8–12, 2009. [pdf](#)
- [10] C. A. Hidalgo, B. Klinger, A.-L. Barabási, and R. Hausman. **The product space conditions the development of nations.** *Science*, 317:482–487, 2007. [pdf](#)

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- [17] E. Wigner. **The unreasonable effectiveness of mathematics in the natural sciences.** *Communications on Pure and Applied Mathematics*, 13:1–14, 1960. [pdf](#)

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- [5] S. Bornholdt and H. G. Schuster, editors. **Handbook of Graphs and Networks.** Wiley-VCH, Berlin, 2003.
- [6] S. N. Dorogovtsev and J. F. F. Mendes. **Evolution of Networks.** Oxford University Press, Oxford, UK, 2003.

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References IV

- [11] M. Newman. **Networks.** Oxford university press, 2nd edition, 2018.
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