

# Overview of Complex Networks

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Principles of Complex Systems, Vols. 1, 2, & 3D  
CSYS/MATH 300, 303, & 394, 2022-2023 | @pocsvox

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Computational Story Lab | Vermont Complex Systems Center  
Santa Fe Institute | University of Vermont



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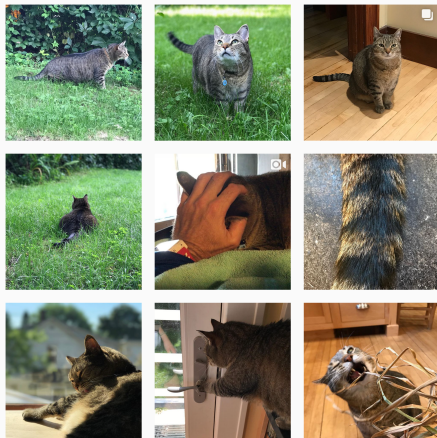
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 On Instagram at [pratchett\\_the\\_cat](https://www.instagram.com/pratchett_the_cat) 

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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.





# Ancestry:

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).'

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-  1839–: rivers and canals
-  1869–: railways
-  1883–: distribution network of electrical cables
-  1914–: wireless broadcasting networks

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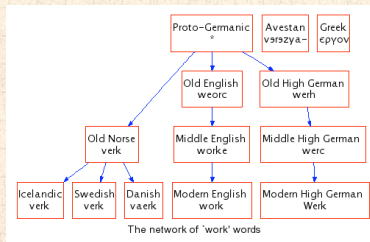
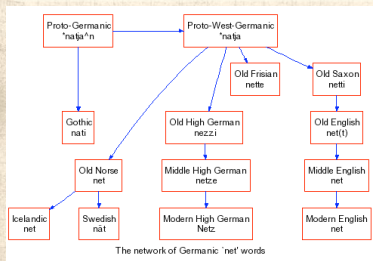


# Ancestry:

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.




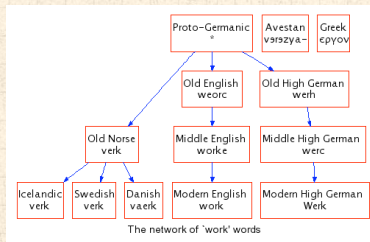
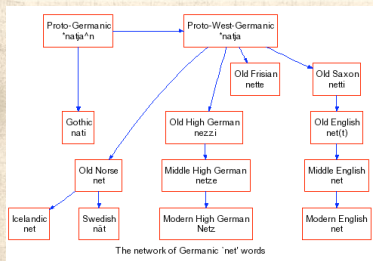



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 **'Network'** = something built based on the idea of natural, flexible lattice or web.

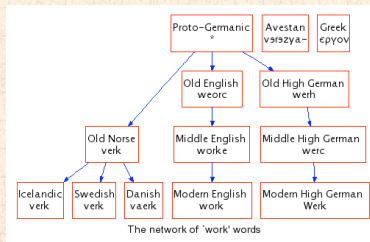
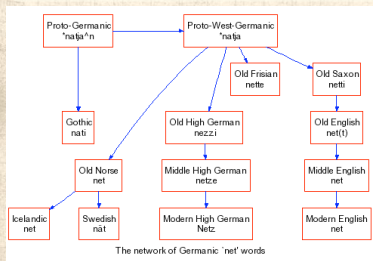



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 c.f., ironwork, stonework, fretwork.



## Key Observation:



Many **complex systems** can be viewed as **complex networks** of physical or abstract interactions.

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## Key Observation:



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Opens door to mathematical and numerical analysis.

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## Key Observation:

- Many **complex systems** can be viewed as **complex networks** of physical or abstract interactions.
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- Dominant approach of last decade of a **theoretical-physics/stat-mechish** flavor.

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 *Piranha physicist*



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 Hunt in packs.



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

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-  *Piranha physicus*
-  Hunt in packs.
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-  See also: <https://xkcd.com/793/> 

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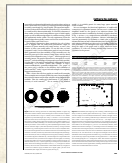
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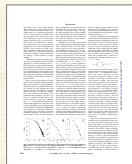


"Collective dynamics of 'small-world' networks" 

Watts and Strogatz,  
Nature, **393**, 440–442, 1998. <sup>[16]</sup>


Times cited: 

(as of October 24, 2018)



"Emergence of scaling in random networks" 

Barabási and Albert,  
Science, **286**, 509–511, 1999. <sup>[2]</sup>

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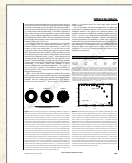
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Times cited:  ~ 37,460 (as of October 24, 2018)

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
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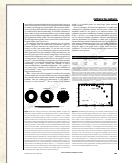
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# Popularity (according to Google Scholar)

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“Collective dynamics of ‘small-world’ networks” [↗](#)

Watts and Strogatz,  
Nature, **393**, 440–442, 1998. <sup>[16]</sup>

Times cited: [↗](#) ~ **37,460** (as of October 24, 2018)



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

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## Review articles:



“Complex Networks: Structure and Dynamics”

Boccaletti et al.,

Physics Reports, **424**, 175–308, 2006. <sup>[3]</sup>

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. <sup>[12]</sup>

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



“Statistical mechanics of complex networks”

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Rev. Mod. Phys., **74**, 47–97, 2002. <sup>[1]</sup>

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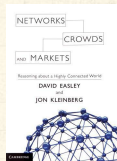
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"Networks" [a](#) [↗](#)  
by Mark Newman (2018). <sup>[11]</sup>

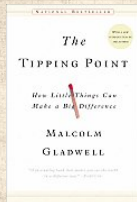


"Networks, crowds, and markets: Reasoning about a highly connected world" [a](#) [↗](#)  
by Easley and Kleinberg (2010). <sup>[7]</sup>

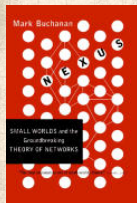
<http://cs.cornell.edu/home/kleinber/networks-book/> [↗](#)



# 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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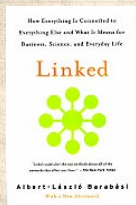
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# Popularity according to books:



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 <sup>[15]</sup>

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## Numerous others ...

-  **Complex Social Networks**—F. Vega-Redondo <sup>[14]</sup>
-  **Fractal River Basins: Chance and Self-Organization**—I. Rodríguez-Iturbe and A. Rinaldo <sup>[13]</sup>
-  **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 <sup>[5]</sup>
-  **Evolution of Networks**—S. N. Dorogovtsev and J. F. F. Mendes <sup>[6]</sup>

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# More observations



But surely **networks aren't new** ...

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 Graph theory is well established ...

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- But surely **networks aren't new** ...
- Graph theory is well established ...
- Study of social networks started in the 1930's ...

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- So why all this 'new' research on networks?
- Answer:** Oodles of Easily Accessible Data.

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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.\*



# More observations

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- A worthy goal: establish **mechanistic explanations**.



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- 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 ...*



# More observations



Web-scale data sets can be overly **exciting**.

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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) 

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But:

 For scientists, description is only part of the battle.

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But:

For scientists, description is only part of the battle.

We still need to **understand**.

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# Super Basic definitions

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

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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, ...

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# Super Basic definitions

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# Super Basic definitions

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 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.



# Super Basic definitions

Node degree = Number of links per node

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# Super Basic definitions

**Node degree** = Number of links per node

 Notation: Node  $i$ 's degree =  $k_i$ .

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




# Super Basic definitions

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 Notation: the average degree of a network =  $\langle k \rangle$




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(and sometimes  $z$ )





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 Connection between number of edges  $m$  and  
average degree:


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








# Super Basic definitions

**Node degree** = Number of links per node


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 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



# Super Basic definitions

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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  $(i, j)$ .

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

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

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So what passes for a complex network?

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# Examples

So what passes for a complex network?

 Complex networks are **large** (in node number)

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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)

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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)
-  Complex networks are usually **dynamic** and **evolving**





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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)
- Complex networks are usually **dynamic** and **evolving**
- Complex networks can be social, economic, natural, informational, abstract, ...



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## Physical networks

### River networks



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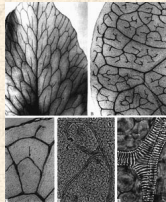
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# Examples

## Physical networks

-  River networks
-  Neural networks
-  Trees and leaves



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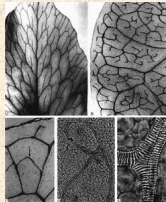
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# Examples

## Physical networks

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



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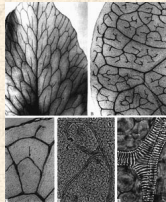
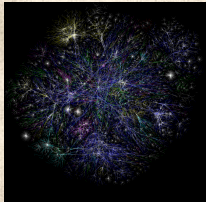


# Examples

## Physical networks

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

 The Internet



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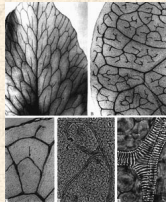
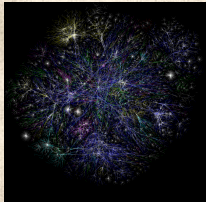


# Examples

## Physical networks

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

-  The Internet
-  Road networks



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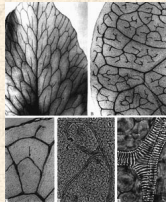
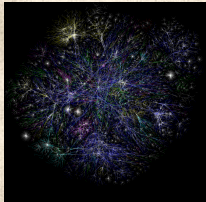


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## Physical networks

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

-  The Internet
-  Road networks
-  Power grids



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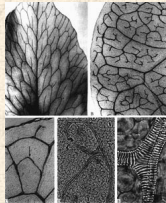
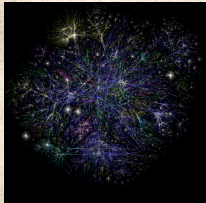



# Examples

## Physical networks

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

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-  Road networks
-  Power grids



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

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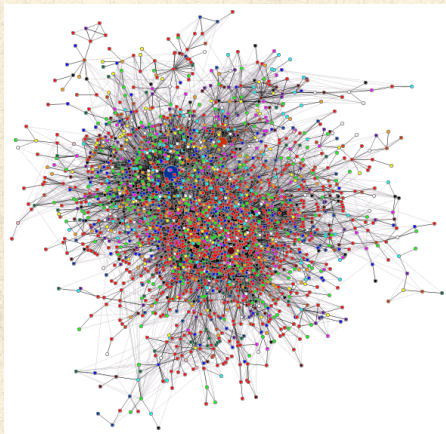
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


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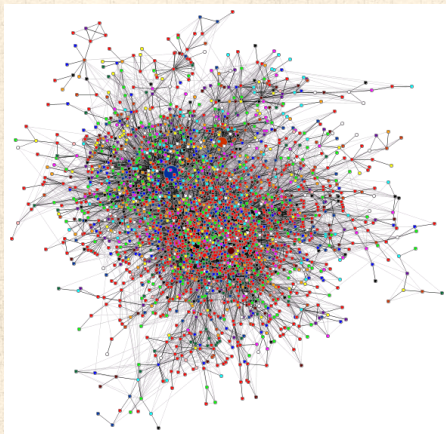



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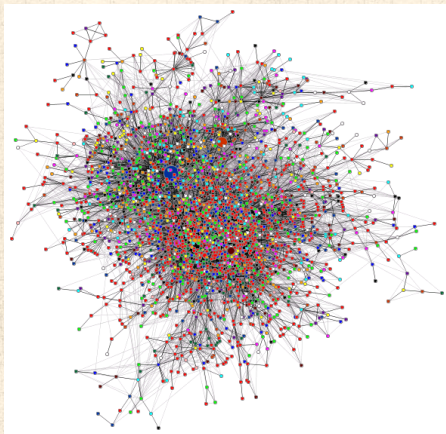
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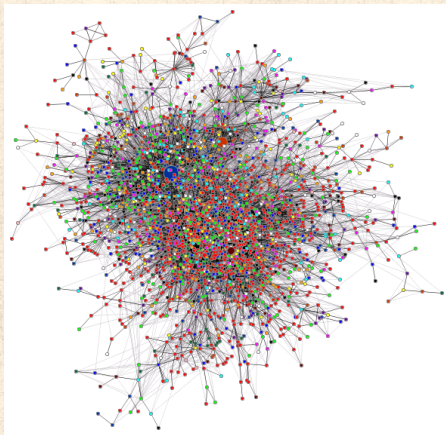
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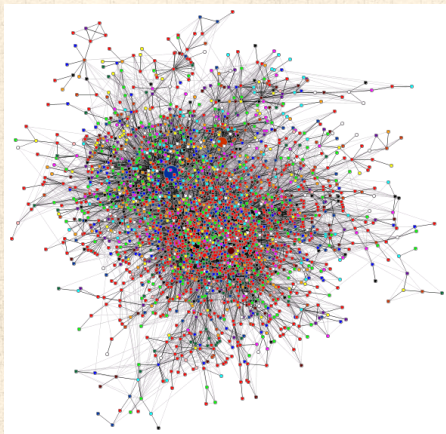
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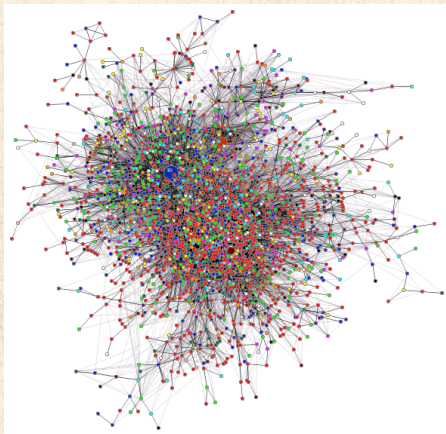
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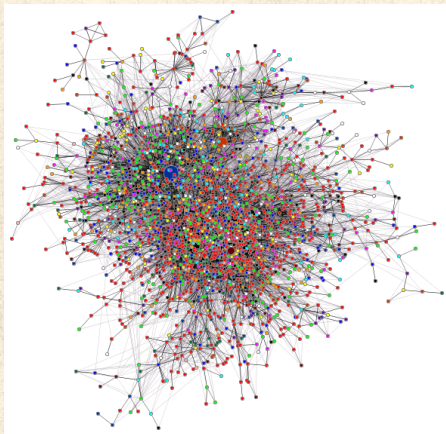
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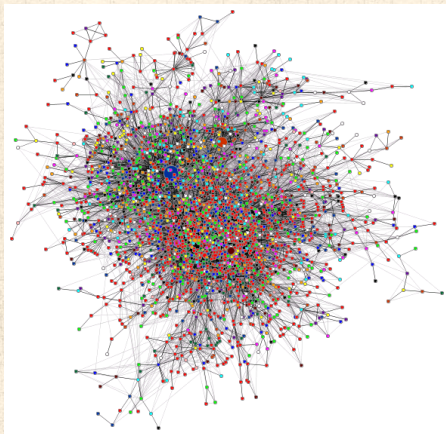
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Relational networks

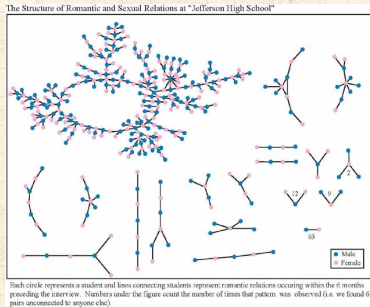
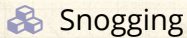
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# Examples

## Interaction networks: social networks



(Bearman *et al.*, 2004)

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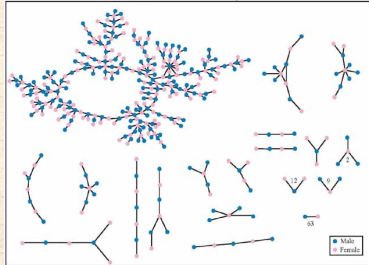
# Examples

## Interaction networks: social networks

 Snogging

 Friendships

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).

(Bearman *et al.*, 2004)

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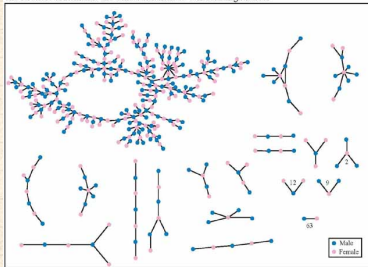


# Examples

## Interaction networks: social networks

-  Snogging
-  Friendships
-  Acquaintances

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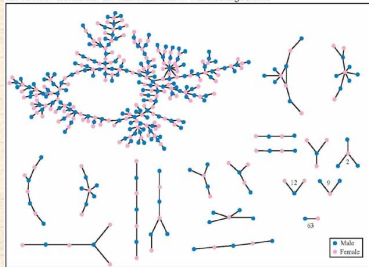


# Examples

## Interaction networks: social networks

-  Snogging
-  Friendships
-  Acquaintances
-  Boards and directors

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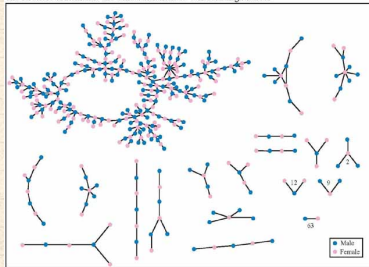


# Examples

## Interaction networks: social networks

-  Snogging
-  Friendships
-  Acquaintances
-  Boards and directors
-  Organizations

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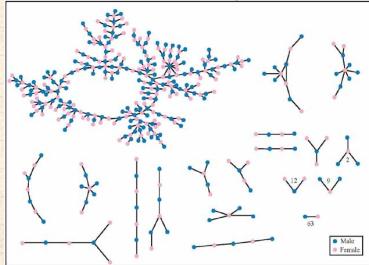


# Examples

## Interaction networks: social networks

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

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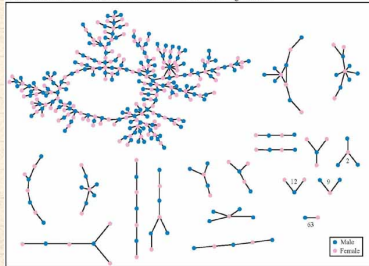
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## Interaction networks: social networks

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

🧱 'Remotely sensed' by: email activity, instant messaging, phone logs

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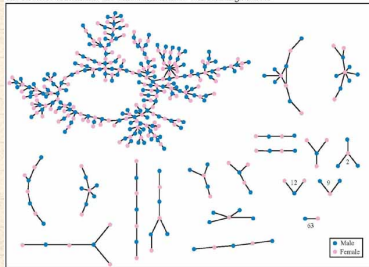
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## Interaction networks: social networks

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

-  'Remotely sensed' by: email activity, instant messaging, phone logs (**\*cough\***).

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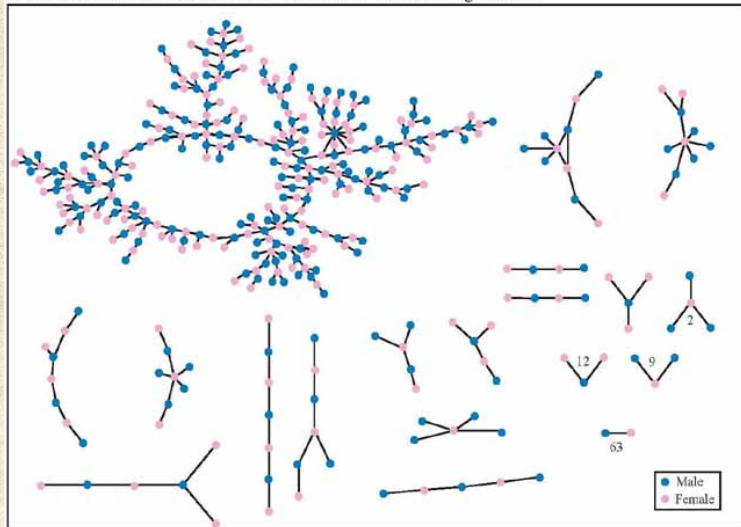
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 Consumer purchases

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## Relational networks

- Consumer purchases  
(Walmart, Target, Amazon, ...)

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## Relational networks



Consumer purchases  
(Walmart, Target, Amazon, ...)



Thesauri: Networks of words generated by meanings

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Consumer purchases  
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Consumer purchases  
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Thesauri: Networks of words generated by meanings



Knowledge/Databases/Ideas



Metadata—Tagging: [bit.ly](http://bit.ly)  [flickr](https://www.flickr.com/photos/complexnetworks/) 

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resources    search    tools    useful    web    web2.0    **wiki**  
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# Neural reboot (NR):

Dog has fun.

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

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