

Overview of Complex Networks

Last updated: 2024/11/11, 20:40:57 EST

Principles of Complex Systems, Vols. 1, 2, & 3D
CSYS/MATH 6701, 6713, & a pretend number, 2024–2025

Prof. Peter Sheridan Dodds

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



Licensed under the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/)

The PoCverse
Overview of Complex
Networks
1 of 43

Complex Networks
Basics

Eymology
Popularity
Graph theory?
Basic definitions

Examples of Complex
Networks

Physical networks
Interaction networks
Relational networks

References



These slides are brought to you by:

Sealie & Lambie
Productions



The PoCverse
Overview of Complex
Networks
2 of 43

Complex Networks
Basics

Eymology
Popularity
Graph theory?
Basic definitions

Examples of Complex
Networks

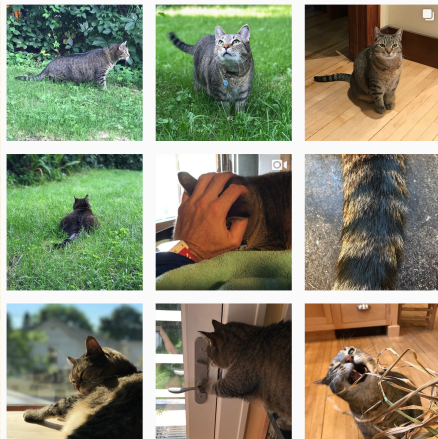
Physical networks
Interaction networks
Relational networks



References



These slides are also brought to you by:

Special Guest Executive Producer



 On Instagram at [pratchett_the_cat](https://www.instagram.com/pratchett_the_cat) 

The PoCVerse
Overview of Complex
Networks
3 of 43

Complex Networks
Basics

Eymology
Popularity
Graph theory?
Basic definitions

Examples of Complex
Networks

Physical networks
Interaction networks
Relational networks

References



Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

Etymology

Popularity

Graph theory?

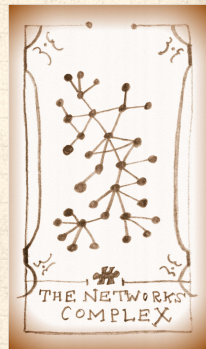
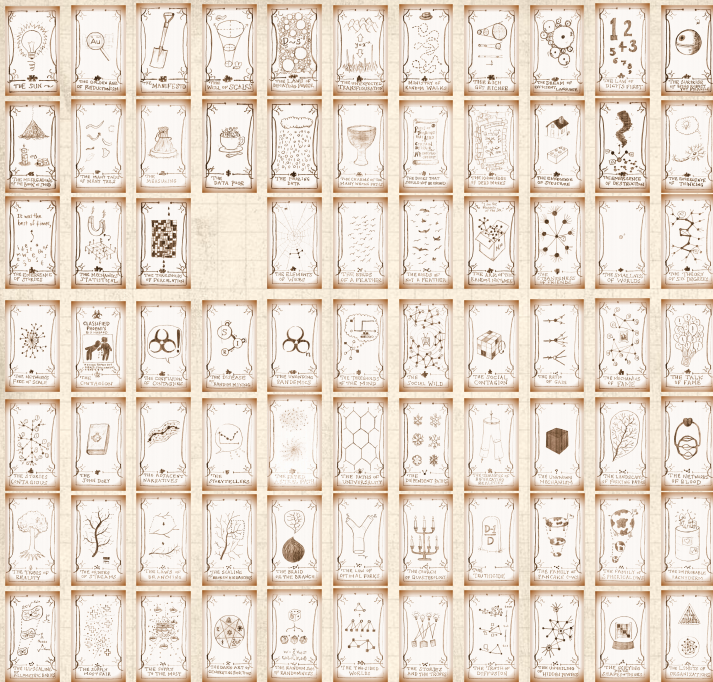
Basic definitions

Physical networks

Interaction networks

Relational networks





Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

The PoCverse
Overview of Complex
Networks

6 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



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.



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).’

The PoCSverse
Overview of Complex
Networks

10 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References




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





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





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







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








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

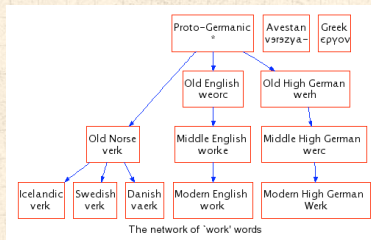
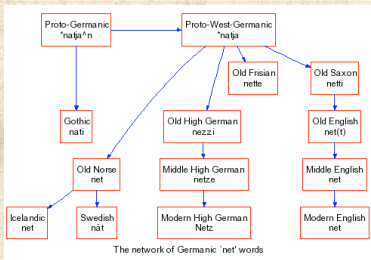


Ancestry:

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.

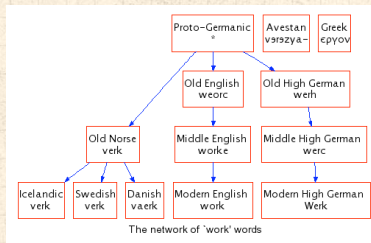
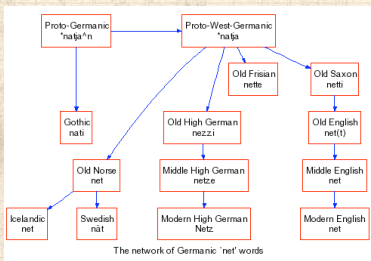



Ancestry:

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.

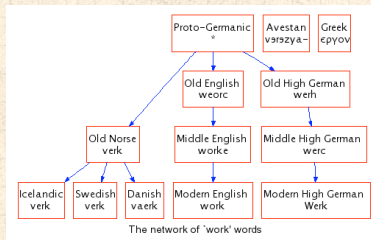
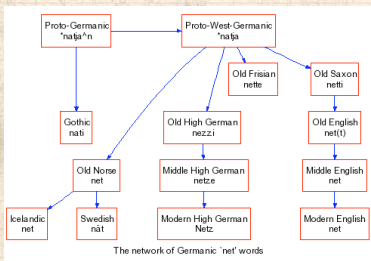



Ancestry:


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.



Key Observation:



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



Opens door to mathematical and numerical analysis.



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.



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 ...




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:



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:


 *Piranha physicus*



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:

 *Piranha physicus*

 Hunt in packs.



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:








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



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:



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



Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

The PoCSverse
Overview of Complex
Networks

13 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

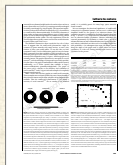
Interaction networks


Relational networks


References



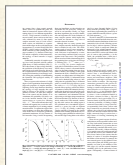
Popularity (according to Google Scholar)





“Collective dynamics of ‘small-world’ networks” 
Watts and Strogatz,
Nature, **393**, 440–442, 1998. ^[16]

Times cited: 

(as of October 24, 2018)



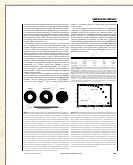
“Emergence of scaling in random networks” 
Barabási and Albert,
Science, **286**, 509–511, 1999. ^[2]


Times cited: 

(as of October 24, 2018)

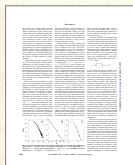



Popularity (according to Google Scholar)



“Collective dynamics of ‘small-world’ networks” 
Watts and Strogatz,
Nature, **393**, 440–442, 1998. ^[16]

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

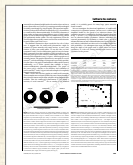



“Emergence of scaling in random networks” 
Barabási and Albert,
Science, **286**, 509–511, 1999. ^[2]

Times cited:  (as of October 24, 2018)

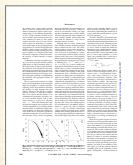



Popularity (according to Google Scholar)



“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)




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)

The PoCverse
Overview of Complex
Networks

15 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Popularity according to textbooks:

The PoCSverse
Overview of Complex
Networks
16 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks


Relational networks

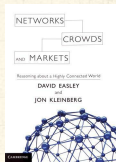
References





Popularity according to textbooks:



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



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

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

The PoCVerse
Overview of Complex
Networks
16 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

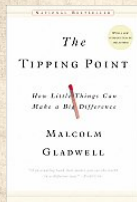
Interaction networks

Relational networks

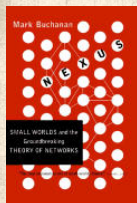
References



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

The PoCVerse
Overview of Complex
Networks
17 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

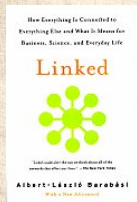
Interaction networks

Relational networks

References



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 ^[15]

The PoCVerse
Overview of Complex
Networks
18 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Numerous others ...

- Complex Social Networks—F. Vega-Redondo ^[14]
- Fractal River Basins: Chance and Self-Organization—I. Rodríguez-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]



Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

The PoCSverse
Overview of Complex
Networks
20 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



More observations



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

The PoCSverse
Overview of Complex
Networks

21 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks


Interaction networks


Relational networks

References



More observations

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

 Graph theory is well established ...

The PoCSverse
Overview of Complex
Networks
21 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



More observations



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



Graph theory is well established ...



Study of social networks started in the 1930's ...

The PoCVerse
Overview of Complex
Networks
21 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



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?

Eymology

Popularity

Graph theory?

Basic definitions

Physical networks

Interaction networks

Relational networks



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.



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

- 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**.



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 ...*



More observations



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

The PoCSverse
Overview of Complex
Networks
22 of 43

Complex Networks
Basics

Erymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks


Interaction networks

Relational networks



References



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 PoCSverse
Overview of Complex
Networks
22 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks


Interaction networks

Relational networks



References





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]





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.





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**.



Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

The PoCSverse
Overview of Complex
Networks

23 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Super Basic definitions

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

The PoCSverse
Overview of Complex
Networks

24 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Super Basic definitions

The PoCSverse
Overview of Complex
Networks
24 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks


Physical networks

Interaction networks

Relational networks

References


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

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



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




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.





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.





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.



Super Basic definitions

Node degree = Number of links per node

The PoCverse
Overview of Complex
Networks
25 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks


Relational networks

References



Super Basic definitions

Node degree = Number of links per node

 Notation: Node i 's degree = k_i .

The PoCSverse
Overview of Complex
Networks

25 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks


Relational networks


References



Super Basic definitions

Node degree = Number of links per node


 Notation: Node i 's degree = k_i .


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




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 = $\langle k \rangle$




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)





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:


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





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: N_i = the set of i 's k_i neighbors



Super Basic definitions

The PoCverse
Overview of Complex
Networks
26 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References

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) .



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.,


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




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.)



Examples

So what passes for a complex network?

The PoCSverse
Overview of Complex
Networks
27 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Examples

The PoCSverse
Overview of Complex
Networks
27 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks


Physical networks

Interaction networks

Relational networks



References

So what passes for a complex network?

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






So what passes for a complex network?

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







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**



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, ...



Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

The PoCSverse
Overview of Complex
Networks
28 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Examples

Physical networks

River networks



The PoCverse
Overview of Complex
Networks
29 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks


Relational networks


References



Examples

Physical networks

 River networks

 Neural networks



Complex Networks Basics

[Etymology](#)

[Popularity](#)

[Graph theory?](#)

[Basic definitions](#)

Examples of Complex Networks

[Physical networks](#)

[Interaction networks](#)


[Relational networks](#)


References




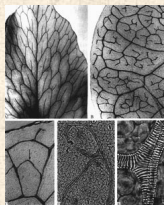
Examples

Physical networks

 River networks

 Neural networks

 Trees and leaves



Etymology

Popularity

Graph theory?

Basic definitions

Physical networks





Interaction networks

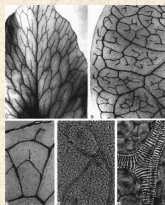
Relational networks



Examples

Physical networks

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



Complex Networks Basics

- Eymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks


- Physical networks
- Interaction networks
- Relational networks


References





Examples


Physical networks

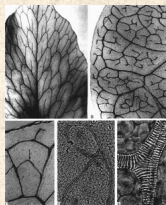
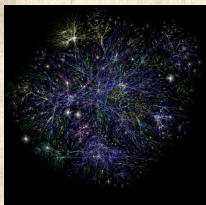
 River networks

 Neural networks

 Trees and leaves

 Blood networks

 The Internet



[Etymology](#)

[Popularity](#)

[Graph theory?](#)

[Basic definitions](#)

[Physical networks](#)





[Interaction networks](#)


[Relational networks](#)




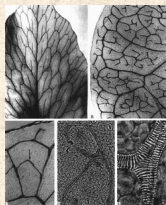
Examples

Physical networks

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





 The Internet


 Road networks





Examples

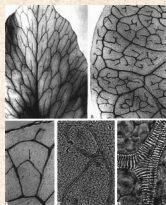
Physical networks

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

 The Internet

 Road networks

 Power grids



[Etymology](#)

[Popularity](#)

[Graph theory?](#)

[Basic definitions](#)

[Physical networks](#)





[Interaction networks](#)




[Relational networks](#)

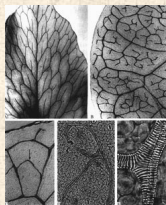
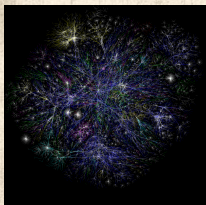



Examples

Physical networks

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

-  The Internet
-  Road networks
-  Power grids



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

Complex Networks Basics

- Eymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks

- Physical networks
- Interaction networks
- Relational networks

References



Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

The PoCSverse
Overview of Complex
Networks

30 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks










Relational networks

References




Examples

Interaction networks

-  The Blogosphere (RIP)
-  Biochemical networks
-  Gene-protein networks
-  Food webs: who eats whom
-  The internet¹
-  Airline networks
-  Call networks (AT&T)
-  The Media
-  Social Media





datamining.typepad.com 




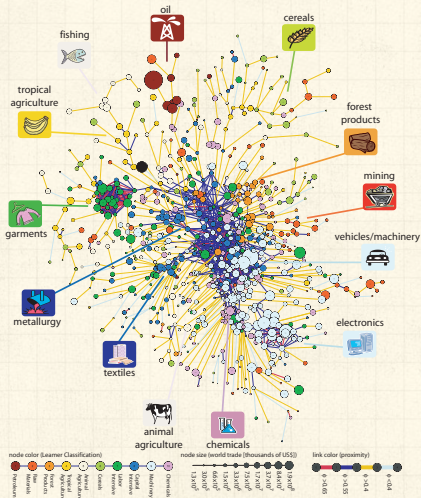
¹What was the World Wide Web, then the Internet, then the internet

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?



Complex Networks Basics

- Erymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks

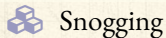
- Physical networks
- Interaction networks
- Relational networks

References

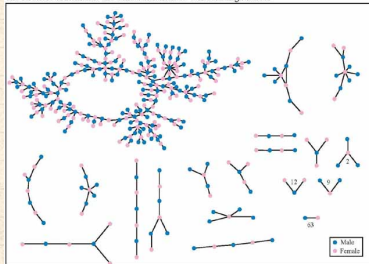


Examples

Interaction networks: social networks



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)


Erymology
Popularity
Graph theory?
Basic definitions


Physical networks
Interaction networks
Relational networks



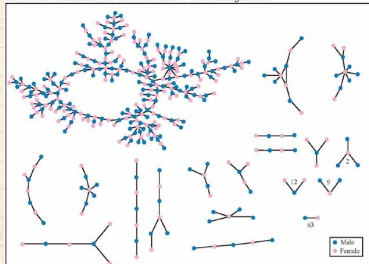
Examples

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)

Erymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks




Relational networks

References

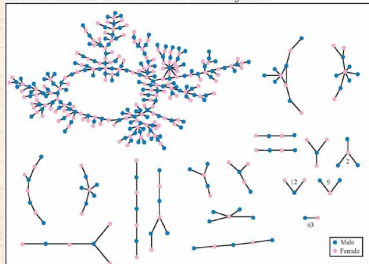


Examples

Interaction networks: social networks

-  Snogging
-  Friendships
-  Acquaintances

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)

Erymology
Popularity
Graph theory?
Basic definitions

Physical networks
Interaction networks
Relational networks

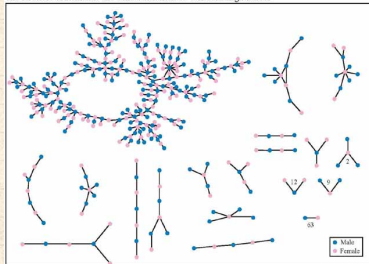


Examples

Interaction networks: social networks

- Snogging
- Friendships
- Acquaintances
- Boards and directors

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)

Erymology
Popularity
Graph theory?
Basic definitions

Physical networks
Interaction networks
Relational networks

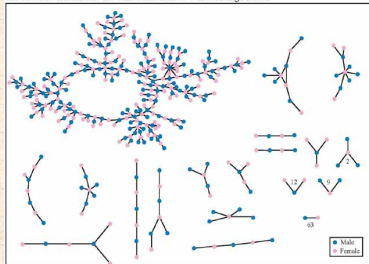


Examples

Interaction networks: social networks

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

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)

Erymology
Popularity
Graph theory?
Basic definitions

Physical networks
Interaction networks
Relational networks



Examples

Interaction networks: social networks

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

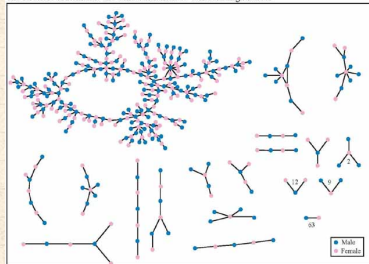
Erymology
Popularity
Graph theory?
Basic definitions

Examples of Complex Networks

Physical networks
Interaction networks
Relational networks

References

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)



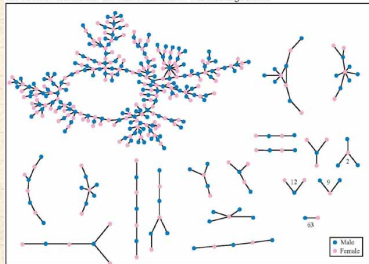
Examples

Interaction networks: social networks

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

‘Remotely sensed’ by: email activity, instant messaging, phone logs

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)

Erymology
Popularity
Graph theory?
Basic definitions

Physical networks
Interaction networks
Relational networks



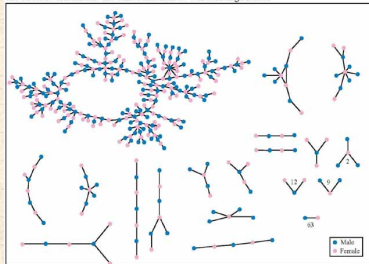
Examples

Interaction networks: social networks

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

‘Remotely sensed’ by: email activity, instant messaging, phone logs (*cough*).

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)

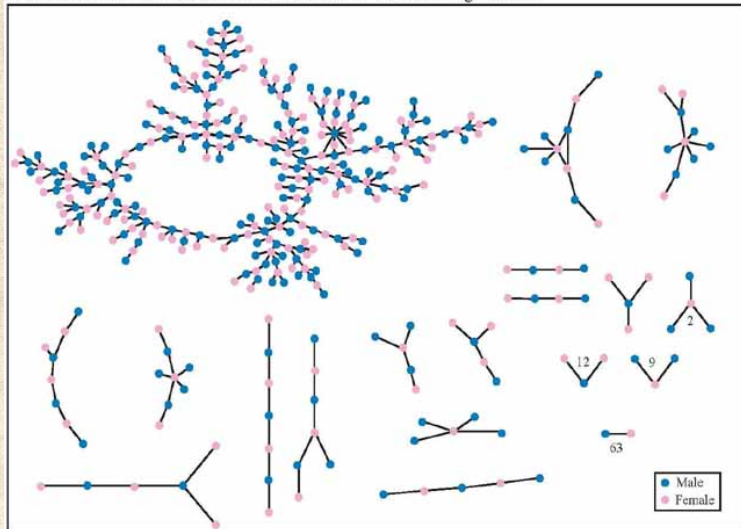
Erymology
Popularity
Graph theory?
Basic definitions

Physical networks
Interaction networks
Relational networks



Examples

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



Eymology

Popularity

Graph theory?

Basic definitions

Physical networks

Interaction networks

Relational networks



Outline

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

The PoCverse
Overview of Complex
Networks

35 of 43

Complex Networks
Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Examples

Relational networks



Consumer purchases

Eymology

Popularity

Graph theory?

Basic definitions

Physical networks

Interaction networks

Relational networks



Examples

Relational networks



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



Examples

Relational networks



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



Thesauri: Networks of words generated by meanings



Examples

Relational networks



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



Thesauri: Networks of words generated by meanings



Knowledge/Databases/Ideas

Eymology

Popularity

Graph theory?

Basic definitions

Physical networks







Interaction networks

Relational networks



Examples

Relational networks

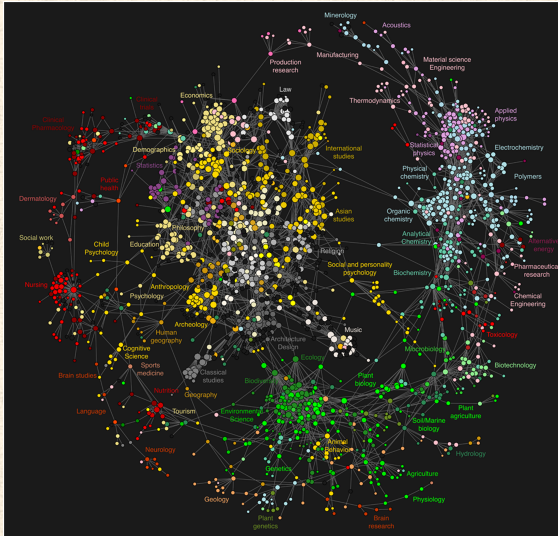
-  Consumer purchases
(Walmart, Target, Amazon, ...)
-  Thesauri: Networks of words generated by meanings
-  Knowledge/Databases/Ideas
-  Metadata—Tagging: [bit.ly](#)  [flickr](#) 

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:



The PoCVerse
Overview of Complex
Networks

37 of 43

Complex Networks
Basics

- Erymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex
Networks

- Physical networks
- Interaction networks
- Relational networks

References



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

Neural reboot (NR):

Dog has fun.

The PoCverse
Overview of Complex
Networks

38 of 43

Complex Networks
Basics

Eymology

Popularity

Graph theory?

Basic definitions

Examples of Complex
Networks

Physical networks

Interaction networks





Relational networks

References

<https://www.you>



References I

- [1] R. Albert and A.-L. Barabási.
Statistical mechanics of complex networks.
Rev. Mod. Phys., 74:47–97, 2002. [pdf](#) 
- [2] A.-L. Barabási and R. Albert.
Emergence of scaling in random networks.
Science, 286:509–511, 1999. [pdf](#) 
- [3] S. Boccaletti, V. Latora, Y. Moreno, M. Chavez, and D.-U. Hwang.
Complex networks: Structure and dynamics.
Physics Reports, 424:175–308, 2006. [pdf](#) 
- [4] J. Bollen, H. Van de Sompel, A. Hagberg, L. Bettencourt, R. Chute, M. A. Rodriguez, and B. Lyudmila.
Clickstream data yields high-resolution maps of science.
PLoS ONE, 4:e4803, 2009. [pdf](#) 






References II

- [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.
- [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.




References III

- [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](#) 
- [11] M. Newman.
Networks.
Oxford university press, 2nd edition, 2018.
- [12] M. E. J. Newman.
The structure and function of complex networks.
SIAM Rev., 45(2):167–256, 2003. [pdf](#) 



References IV

- [13] I. Rodríguez-Iturbe and A. Rinaldo.
Fractal River Basins: Chance and Self-Organization.
Cambridge University Press, Cambridge, UK, 1997.
- [14] F. Vega-Redondo.
Complex Social Networks.
Cambridge University Press, 2007.
- [15] D. J. Watts.
Six Degrees.
Norton, New York, 2003.
- [16] D. J. Watts and S. J. Strogatz.
Collective dynamics of ‘small-world’ networks.
Nature, 393:440–442, 1998. [pdf](#) 



[17] E. Wigner.

The unreasonable effectiveness of mathematics in the natural sciences.

[Communications on Pure and Applied Mathematics,](#)

13:1–14, 1960. pdf 