

Overview of Complex Networks

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Principles of Complex Systems, Vols. 1 & 2
CSYS/MATH 300 and 303, 2021-2022 | @pocsvox

Prof. Peter Sheridan Dodds | @peterdodds

Computational Story Lab | Vermont Complex Systems Center
Vermont Advanced Computing Core | University of Vermont



The PoCVerse
Overview of
Complex
Networks
1 of 43

Complex
Networks Basics

Etymology
Popularity
Graph theory?
Basic definitions

Examples of
Complex
Networks

Physical networks
Interaction networks
Relational networks

References



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The PoCverse
Overview of
Complex
Networks
2 of 43

Complex
Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of
Complex
Networks

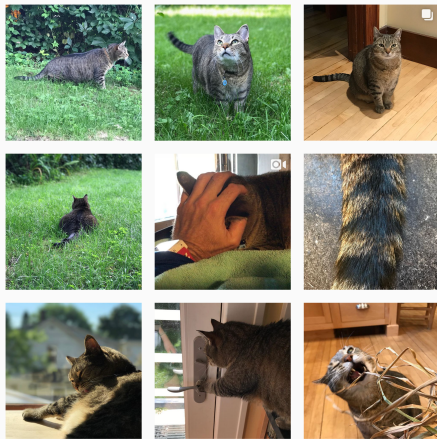
- Physical networks
- Interaction networks
- Relational networks

References



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The PoCverse
Overview of
Complex
Networks
3 of 43

Complex
Networks Basics



- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of
Complex
Networks

- Physical networks
- Interaction networks
- Relational networks

References



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

Outline

The PoCverse
Overview of
Complex
Networks
4 of 43

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References

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
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.*



Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References

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/>]

The PoCverse
Overview of
Complex
Networks
9 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).'

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




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The PoCverse
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





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The PoCverse
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






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The PoCverse
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







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The PoCverse
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








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-  1658–: reticulate structures in animals
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-  1869–: railways
-  1883–: distribution network of electrical cables
-  1914–: wireless broadcasting networks

The PoCverse
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

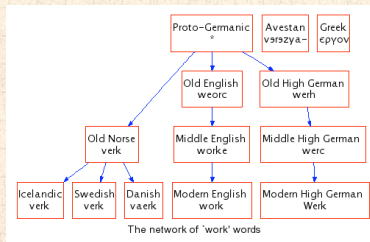
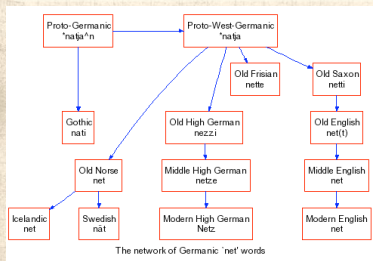


Ancestry:

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.

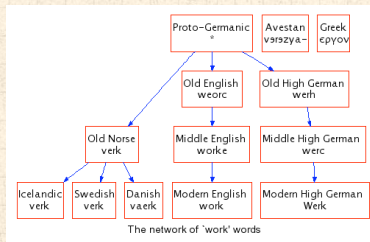
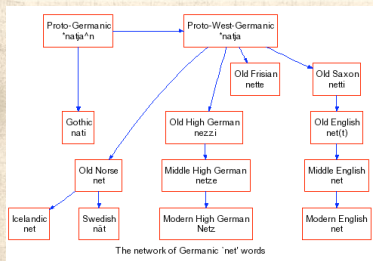



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 **'Network'** = something built based on the idea of natural, flexible lattice or web.

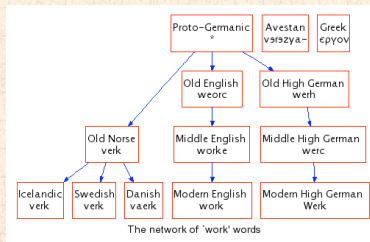
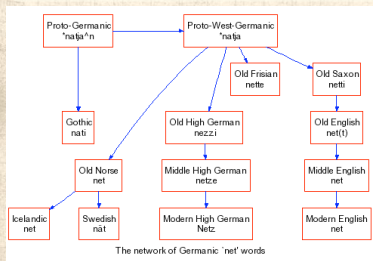



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 **'Network'** = something built based on the idea of natural, flexible lattice or web.

 c.f., ironwork, stonework, fretwork.



Key Observation:



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

The PoCSverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Key Observation:



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Opens door to mathematical and numerical analysis.

The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Key Observation:

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The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



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The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



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The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks

References



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 *Piranha physicist*



The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks


References



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 *Piranha physicus*

 Hunt in packs.



The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks




References



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The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks






References



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-  See also: <https://xkcd.com/793/> 

The PoCverse
Overview of
Complex
Networks
12 of 43

Complex
Networks Basics

Etymology

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
13 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

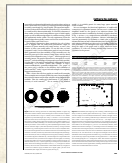
Relational networks

References



Popularity (according to Google Scholar)

The PoCSverse
Overview of
Complex
Networks
14 of 43

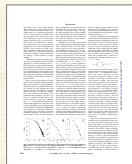


“Collective dynamics of ‘small-world’ networks” [↗](#)

Watts and Strogatz,
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Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

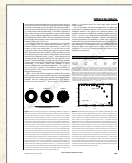
Relational networks


References




Popularity (according to Google Scholar)

The PoCSverse
Overview of
Complex
Networks
14 of 43




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
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Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

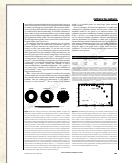
Relational networks

References



Popularity (according to Google Scholar)

The PoCSverse
Overview of
Complex
Networks
14 of 43



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Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



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The PoCverse
Overview of
Complex
Networks
15 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 textbooks:

The PoCverse
Overview of
Complex
Networks
16 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 textbooks:

The PoCverse
Overview of
Complex
Networks
16 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

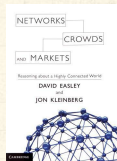
Interaction networks

Relational networks

References



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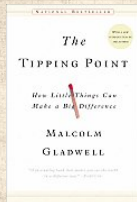


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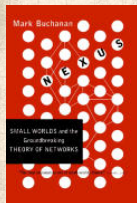
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Popularity according to books:



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



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The PoCVerse
Overview of
Complex
Networks
17 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

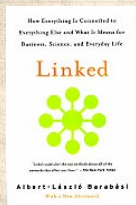
Interaction networks

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

Etymology

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]

The PoCverse
Overview of
Complex
Networks
19 of 43

Complex
Networks Basics

Etymology

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
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

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** ...

 Graph theory is well established ...

The PoCVerse
Overview of
Complex
Networks
21 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



More observations

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- 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

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



More observations

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- So why all this 'new' research on networks?

The PoCverse
Overview of
Complex
Networks
21 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



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- Answer:** Oodles of Easily Accessible Data.

The PoCverse
Overview of
Complex
Networks
21 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



More observations

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- We can now inform (alas) our theories with a much more measurable reality.*



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- 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

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- 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

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks


Interaction networks

Relational networks



References



More observations

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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

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks


Interaction networks

Relational networks



References





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The PoCverse
Overview of
Complex
Networks
22 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks


Interaction networks

Relational networks



References





More observations

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But:

 For scientists, description is only part of the battle.

The PoCverse
Overview of
Complex
Networks
22 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks


References



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But:

For scientists, description is only part of the battle.

We still need to **understand**.

The PoCverse
Overview of
Complex
Networks
22 of 43

Complex
Networks Basics

Etymology

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
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 PoCverse
Overview of
Complex
Networks
24 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

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

The PoCSverse
Overview of
Complex
Networks
24 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks

References



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The PoCverse
Overview of
Complex
Networks
24 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks

References




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The PoCverse
Overview of
Complex
Networks
24 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks

References





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The PoCverse
Overview of
Complex
Networks
24 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks

References





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

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 **Links** may be binary or weighted.

Other spiffing words: vertices and edges.



Super Basic definitions

Node degree = Number of links per node

The PoCSverse
Overview of
Complex
Networks
25 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

Node degree = Number of links per node

 Notation: Node i 's degree = k_i .

The PoCverse
Overview of
Complex
Networks
25 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

The PoCverse
Overview of
Complex
Networks
25 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks


Physical networks


Interaction networks

Relational networks

References

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




Super Basic definitions

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 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

The PoCverse
Overview of
Complex
Networks
25 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks


Physical networks


Interaction networks


Relational networks

References

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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

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 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



Super Basic definitions

The PoCverse
Overview of
Complex
Networks
26 of 43

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) .

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks


References



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.,

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

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks


Relational networks


References




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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.)

Complex Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of Complex Networks

Physical networks

Interaction networks

Relational networks

References



Examples

So what passes for a complex network?

The PoCverse
Overview of
Complex
Networks
27 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks


Relational networks

References



Examples

So what passes for a complex network?

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

The PoCSverse
Overview of
Complex
Networks
27 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks



Relational networks

References



Examples

So what passes for a complex network?

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

The PoCverse
Overview of
Complex
Networks
27 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References



Examples

The PoCverse
Overview of
Complex
Networks
27 of 43

Complex
Networks Basics

Etymology

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)
- Complex networks are **sparse** (low edge to node ratio)
- Complex networks are usually **dynamic** and **evolving**



Examples

The PoCverse
Overview of
Complex
Networks
27 of 43

Complex
Networks Basics

Etymology

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)
-  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 PoCverse
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 PoCSverse
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



The PoCSverse
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

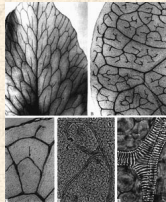
References



Examples

Physical networks

-  River networks
-  Neural networks
-  Trees and leaves



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

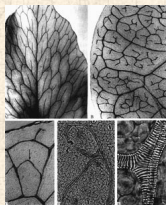
References



Examples

Physical networks

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

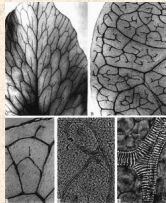
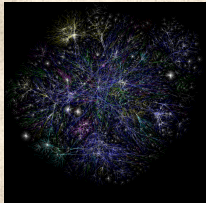


Examples

Physical networks

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

 The Internet



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



Trees and leaves



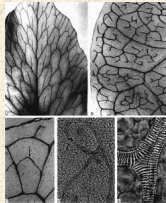
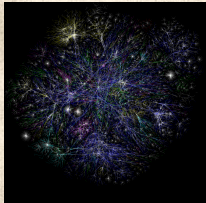
Blood networks



The Internet



Road 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

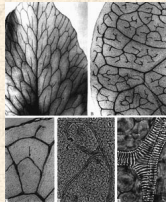
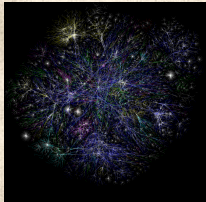


Examples

Physical networks

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

-  The Internet
-  Road networks
-  Power grids



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

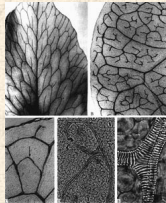
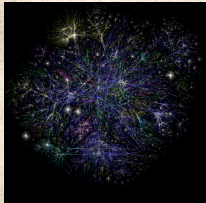



Examples

Physical networks

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

-  The Internet
-  Road networks
-  Power grids



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

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



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**
30 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

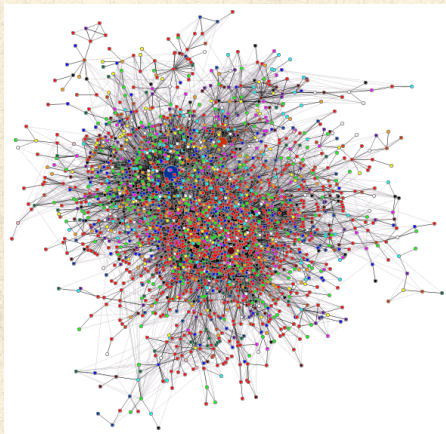
References




Examples

Interaction networks

The Blogosphere



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The PoCverse
Overview of
Complex
Networks
31 of 43

Complex
Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of
Complex
Networks

- Physical networks
- Interaction networks**
- Relational networks


References

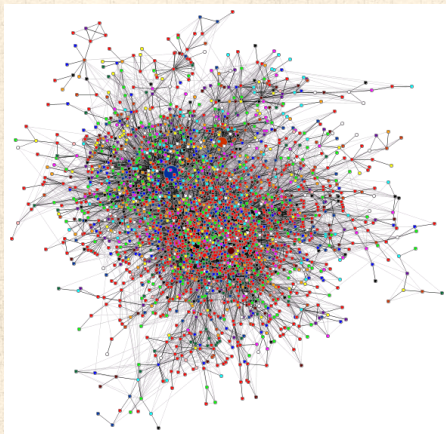



Examples

Interaction networks

 The Blogosphere

 Biochemical networks



datamining.typepad.com 

The PoCVerse
Overview of
Complex
Networks
31 of 43

Complex
Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of
Complex
Networks

- Physical networks
- Interaction networks**
- Relational networks


References




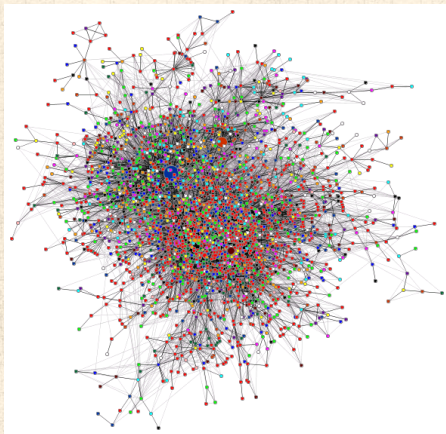
Examples


Interaction networks

 The Blogosphere

 Biochemical networks

 Gene-protein networks



datamining.typepad.com 

The PoCverse
Overview of
Complex
Networks
31 of 43

Complex
Networks Basics

Etymology
Popularity
Graph theory?
Basic definitions

Examples of
Complex
Networks

Physical networks
Interaction networks
Relational networks


References





Examples

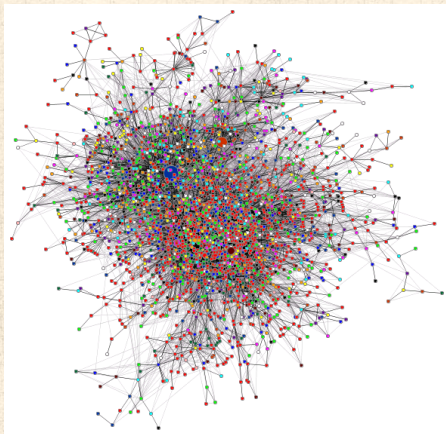
Interaction networks


 The Blogosphere

 Biochemical networks

 Gene-protein networks

 Food webs: who eats whom



datamining.typepad.com 

The PoCverse
Overview of
Complex
Networks
31 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

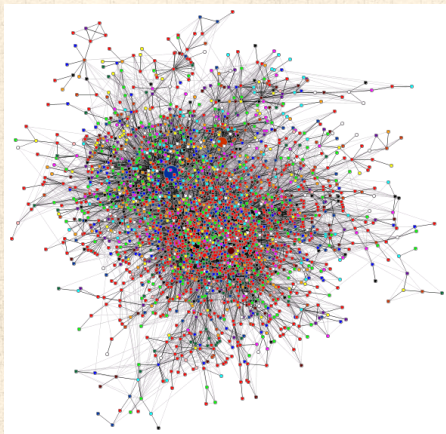
 The Blogosphere


 Biochemical networks

 Gene-protein networks

 Food webs: who eats whom

 The World Wide Web (?)



datamining.typepad.com 

The PoCVerse
Overview of
Complex
Networks
31 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

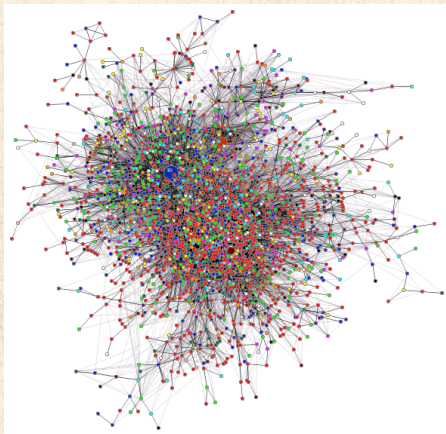
 Biochemical networks


 Gene-protein networks

 Food webs: who eats whom

 The World Wide Web (?)

 Airline networks



datamining.typepad.com 

The PoCVerse
Overview of
Complex
Networks
31 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


 Biochemical networks

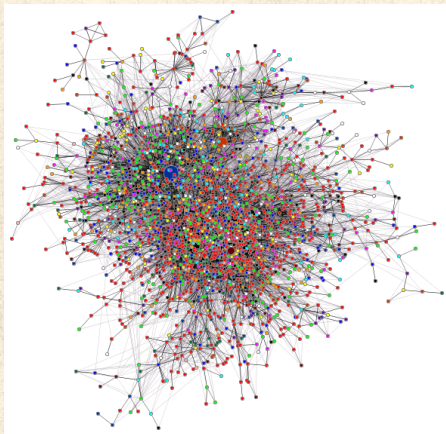
 Gene-protein networks


 Food webs: who eats whom

 The World Wide Web (?)

 Airline networks

 Call networks (AT&T)



datamining.typepad.com 

The PoCVerse
Overview of
Complex
Networks
31 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


 Biochemical networks


 Gene-protein networks

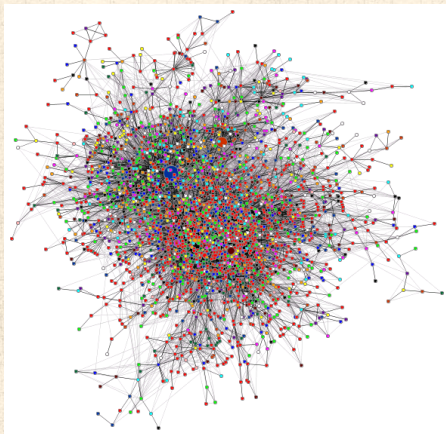
 Food webs: who eats whom


 The World Wide Web (?)

 Airline networks

 Call networks (AT&T)

 The Media



datamining.typepad.com 

The PoCVerse
Overview of
Complex
Networks
31 of 43

Complex
Networks Basics

Etymology
Popularity
Graph theory?
Basic definitions




Examples of
Complex
Networks

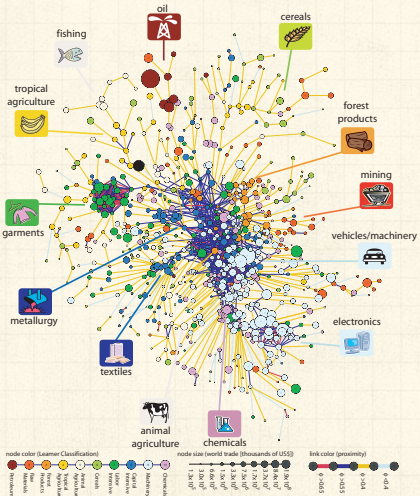
Physical networks
Interaction networks
Relational networks

References



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

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks

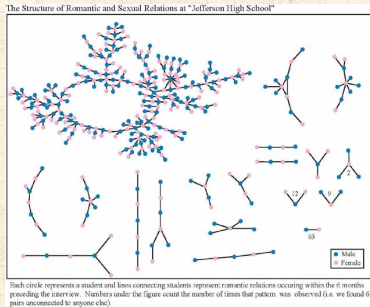
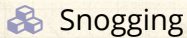
- Physical networks
- Interaction networks
- Relational networks

References



Examples

Interaction networks: social networks



(Bearman *et al.*, 2004)

The PoCSverse
Overview of
Complex
Networks
33 of 43

Complex Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks


- Physical networks
- Interaction networks**
- Relational networks


References



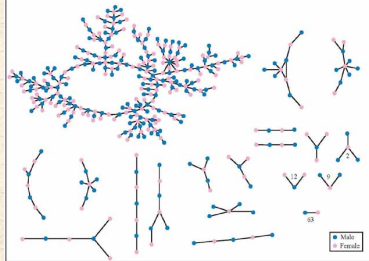
Examples

Interaction networks: 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)

The PoCVerse
Overview of
Complex
Networks
33 of 43

Complex
Networks Basics

Etymology
Popularity
Graph theory?
Basic definitions

Examples of
Complex
Networks




Physical networks
Interaction networks
Relational networks

References

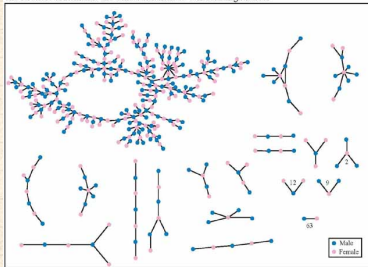


Examples

Interaction networks: 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)

The PoCverse
Overview of
Complex
Networks
33 of 43

Complex Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks





- Physical networks
- Interaction networks**
- Relational networks

References

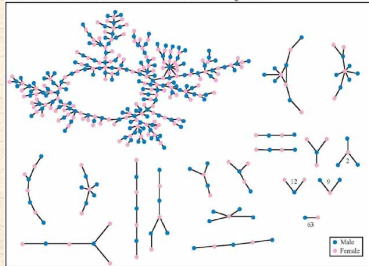


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The PoCverse
Overview of
Complex
Networks
33 of 43

Complex Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks






- Physical networks
- Interaction networks**
- Relational networks

References

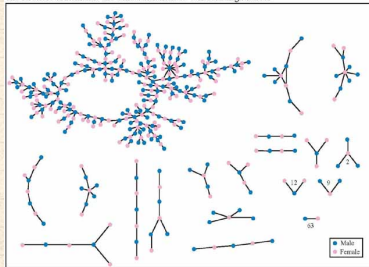


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The PoCverse
Overview of
Complex
Networks
33 of 43

Complex Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks

- Physical networks
- Interaction networks
- Relational networks

References

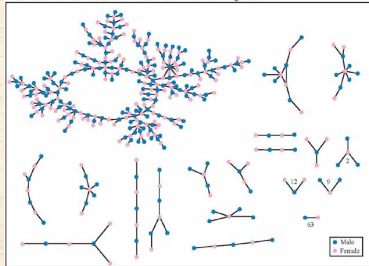


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-  [facebook](#)  [twitter](#) 

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The PoCverse
Overview of
Complex
Networks
33 of 43

Complex
Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of
Complex
Networks

- Physical networks
- Interaction networks
- Relational networks

References



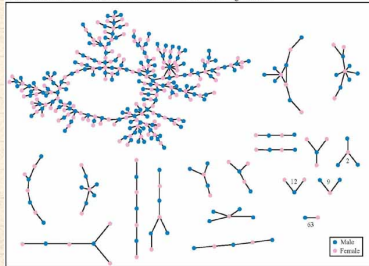
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- 🧱 Boards and directors
- 🧱 Organizations
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🧱 'Remotely sensed' by: email activity, instant messaging, phone logs

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The PoCverse
Overview of
Complex
Networks
33 of 43

Complex
Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of
Complex
Networks

- Physical networks
- Interaction networks
- Relational networks

References



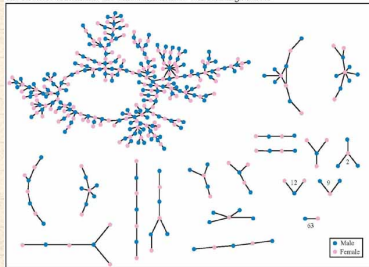
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The PoCverse
Overview of
Complex
Networks
33 of 43

Complex Networks Basics

- Etymology
- Popularity
- Graph theory?
- Basic definitions

Examples of Complex Networks

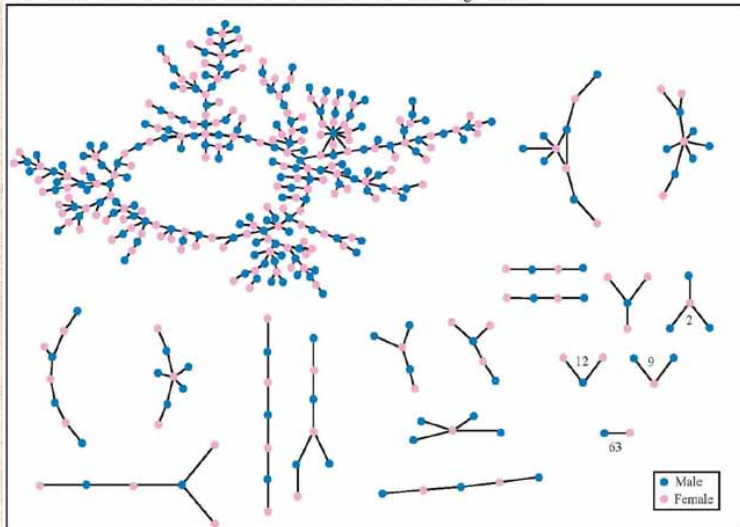
- Physical networks
- Interaction networks
- Relational networks

References



Examples

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



The PoCverse
Overview of
Complex
Networks
34 of 43

Complex
Networks Basics

Etymology
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
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

The PoCverse
Overview of
Complex
Networks
36 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
(Walmart, Target, Amazon, ...)

The PoCverse
Overview of
Complex
Networks
36 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
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Thesauri: Networks of words generated by meanings

The PoCVerse
Overview of
Complex
Networks
36 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
(Walmart, Target, Amazon, ...)



Thesauri: Networks of words generated by
meanings



Knowledge/Databases/Ideas

The PoCVerse
Overview of
Complex
Networks
36 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



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Thesauri: Networks of words generated by meanings



Knowledge/Databases/Ideas



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

The PoCverse
Overview of
Complex
Networks
36 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References

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



Neural reboot (NR):

Dog has fun.

The PoCVerse
Overview of
Complex
Networks
38 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks

Interaction networks

Relational networks

References




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The PoCSverse
Overview of
Complex
Networks
41 of 43

Complex
Networks Basics

Etymology
Popularity
Graph theory?
Basic definitions


Examples of
Complex
Networks

Physical networks
Interaction networks
Relational networks

References



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The PoCSverse
Overview of
Complex
Networks
42 of 43

Complex
Networks Basics

Etymology

Popularity

Graph theory?

Basic definitions

Examples of
Complex
Networks

Physical networks



Interaction networks

Relational networks

References



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The PoCverse
Overview of
Complex
Networks
43 of 43

Complex
Networks Basics

Etymology
Popularity
Graph theory?
Basic definitions

Examples of
Complex
Networks

Physical networks
Interaction networks
Relational networks

References

