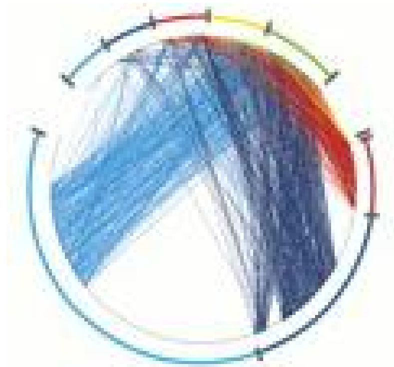
Models and Algorithms for Complex Networks

Networks and Measurements

Lecture 3

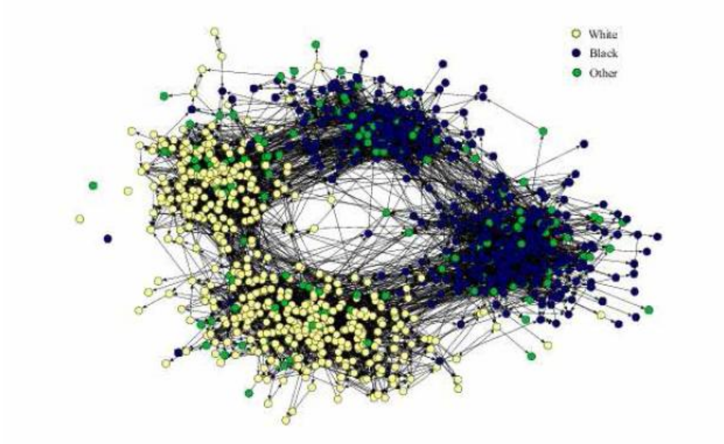


Types of networks

- Social networks
- Knowledge (Information) networks
- Technology networks
- Biological networks

Social Networks

- Links denote a social interaction
  - Networks of acquaintances
  - collaboration networks
    - actor networks
    - co-authorship networks
    - director networks
  - phone-call networks
  - e-mail networks
  - IM networks
  - Bluetooth networks
  - sexual networks
  - home page/blog networks

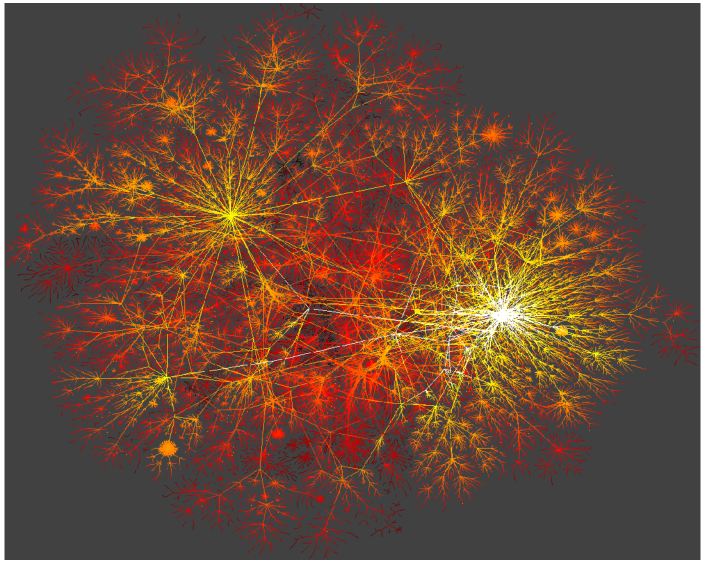


Knowledge (Information) Networks

- Nodes store information, links associate information
  - Citation network (directed acyclic)
  - The Web (directed)
  - Peer-to-Peer networks
  - Word networks
  - Networks of Trust
  - Software graphs

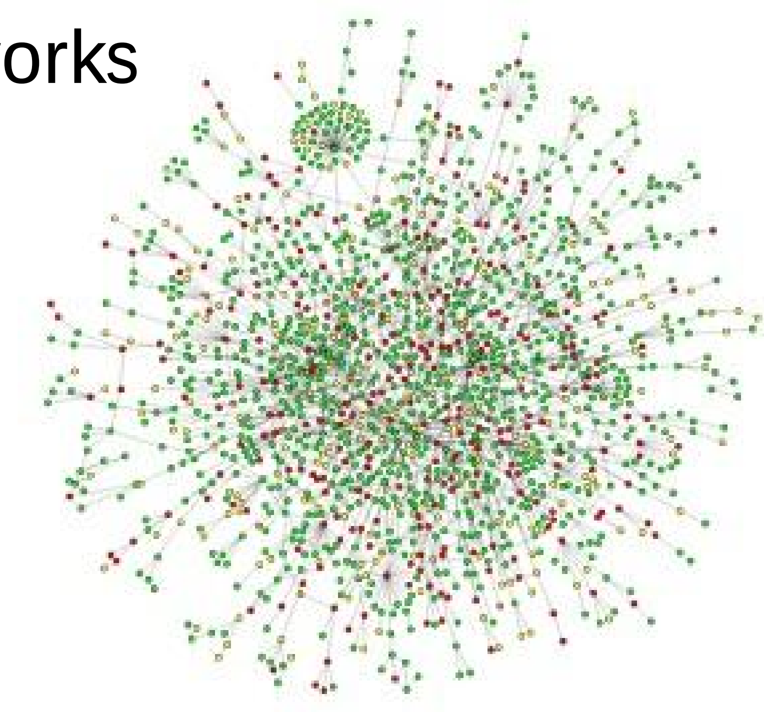
Technological networks

- Networks built for distribution of commodity
  - The Internet
    - router level, AS level
  - Power Grids
  - Airline networks
  - Telephone networks
  - Transportation Networks
    - roads, railways, pedestrian traffic



Biological networks

- Biological systems represented as networks
  - Protein-Protein Interaction Networks
  - Gene regulation networks
  - Gene co-expression networks
  - Metabolic pathways
  - The Food Web
  - Neural Networks



Measuring Networks

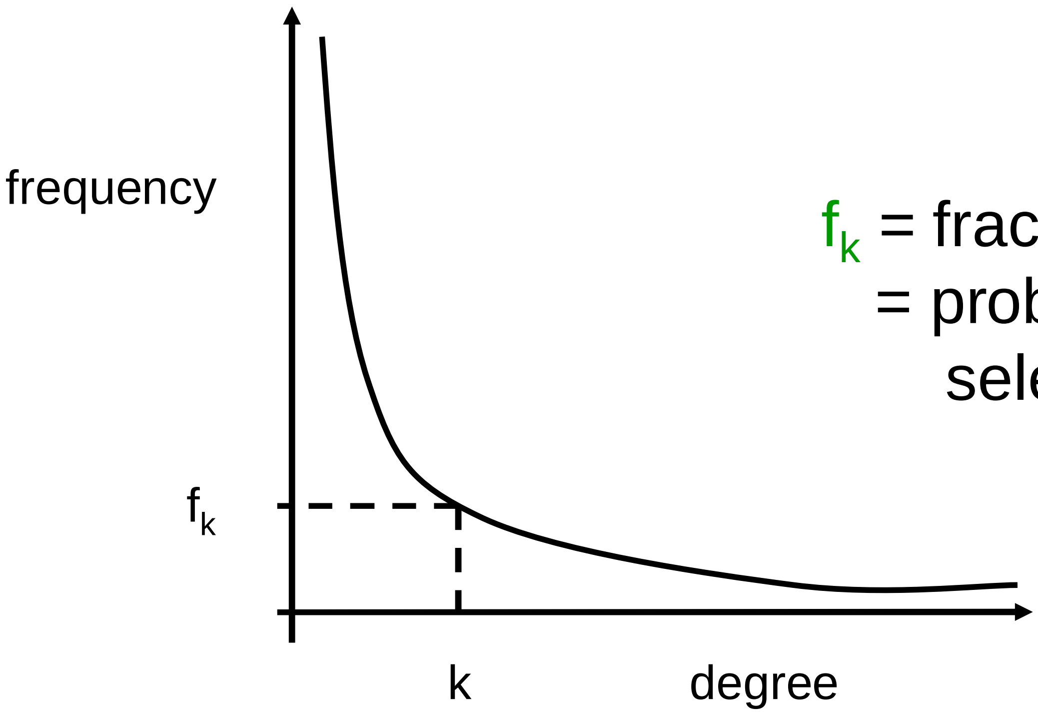
- Degree distributions
- Small world phenomena
- Clustering Coefficient
- Mixing patterns
- Degree correlations
- Communities and clusters

The basic random graph model

- The measurements on real networks are usually compared against those on “random networks”

- The basic $G_{n,p}$ (Erdös-Renyi) random graph model:
  - n : the number of vertices
  - $0 \leq p \leq 1$
  - for each pair (i,j), generate the edge (i,j) independently with probability p

Degree distributions



f_k = fraction of nodes with degree k
= probability of a randomly selected node to have degree k

- Problem: find the probability distribution that best fits the observed data

Power-law distributions

- The degree distributions of most real-life networks follow a power law

$$p(k) = Ck^{-\alpha}$$

- Right-skewed/Heavy-tail distribution
  - there is a non-negligible fraction of nodes that has very high degree (hubs)
  - scale-free: no characteristic scale, average is not informative

- In stark contrast with the random graph model!
  - Poisson degree distribution, $z=np$

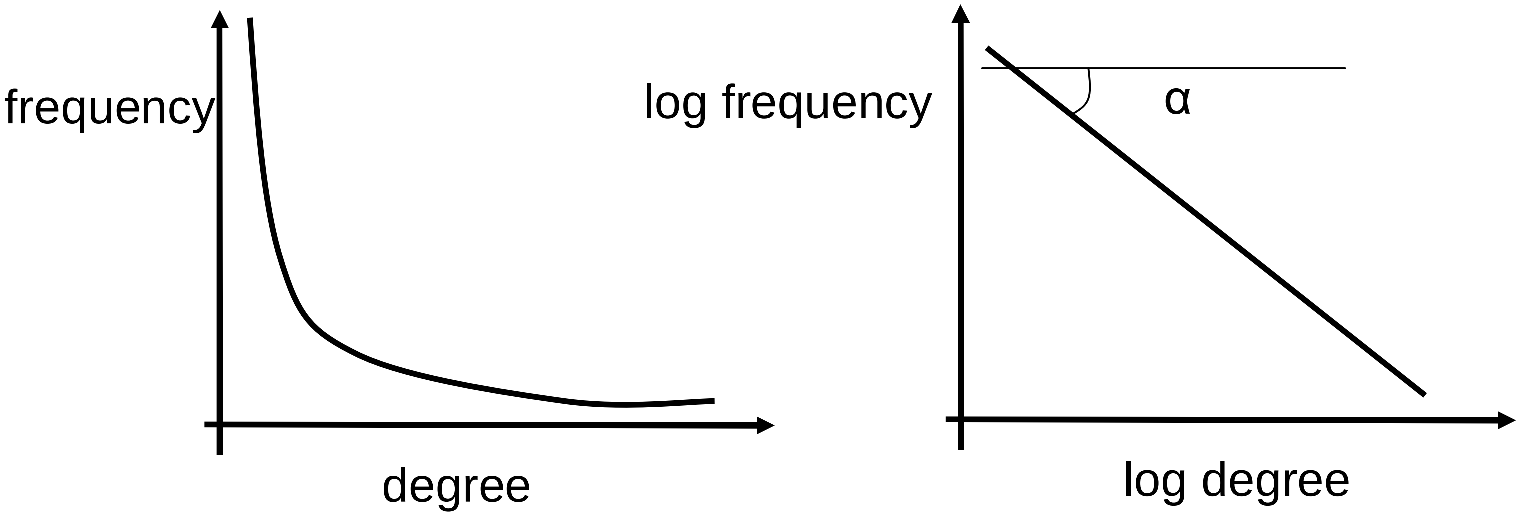
$$p(k) = P(k;z) = \frac{z^k}{k!}e^{-z}$$

  - highly concentrated around the mean
  - the probability of very high degree nodes is exponentially small

Power-law signature

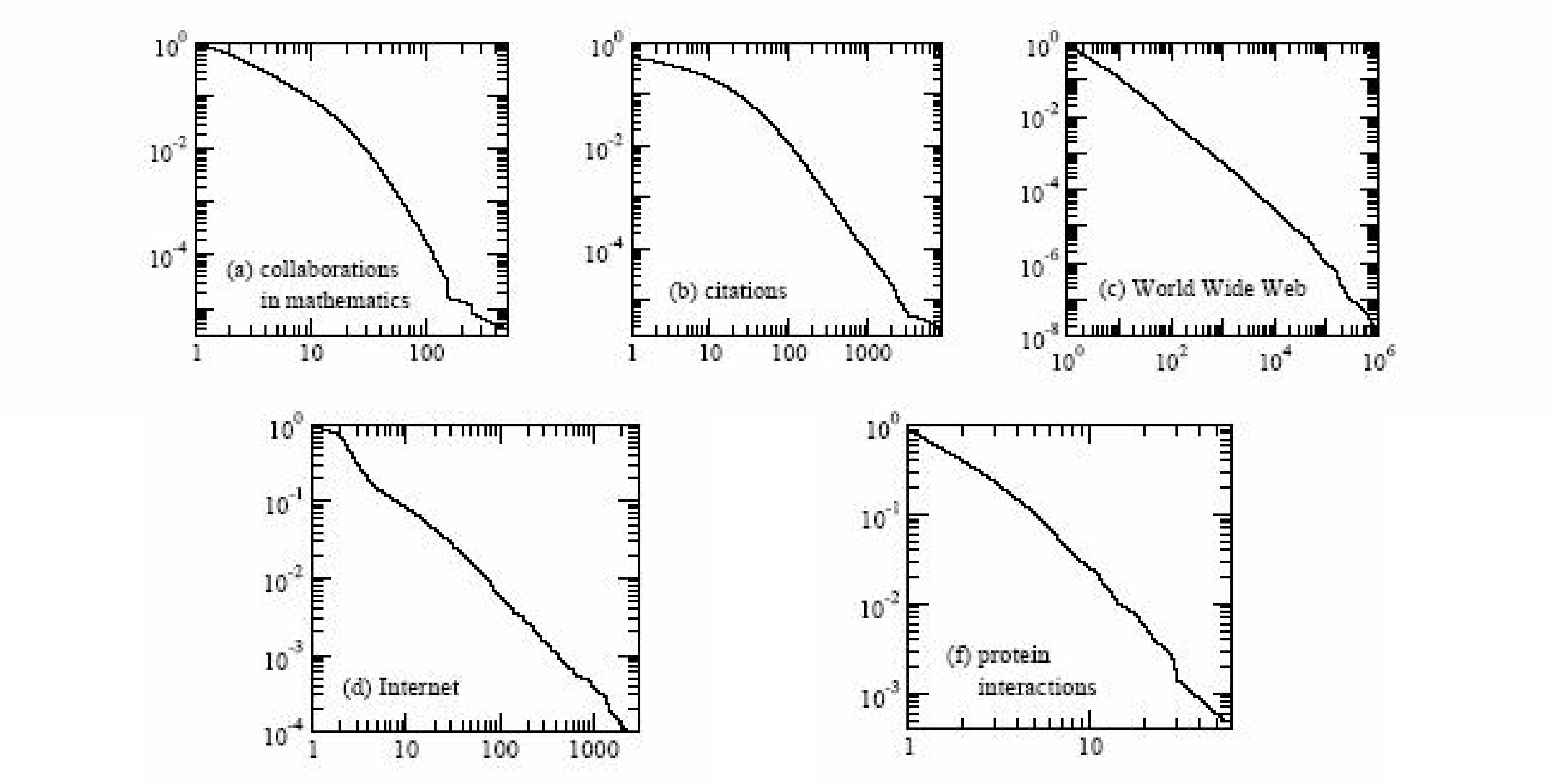
- Power-law distribution gives a line in the log-log plot

$$\log p(k) = -\alpha \log k + \log C$$



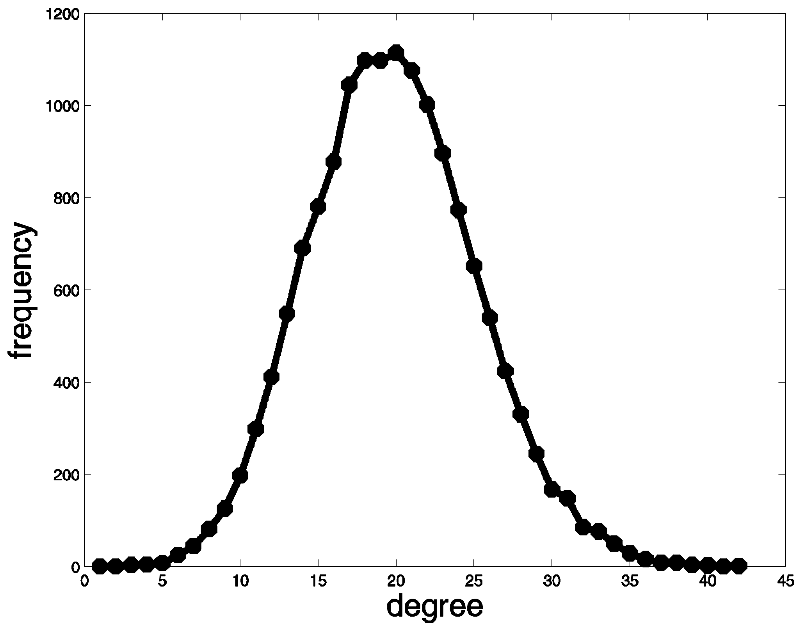
- α : power-law exponent (typically $2 \leq \alpha \leq 3$)

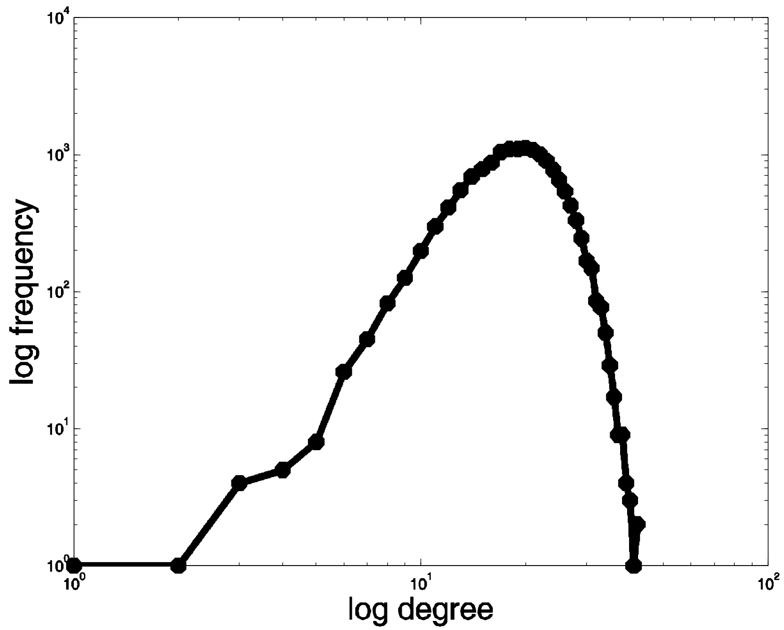
Examples



Taken from [Newman 2003]

A random graph example





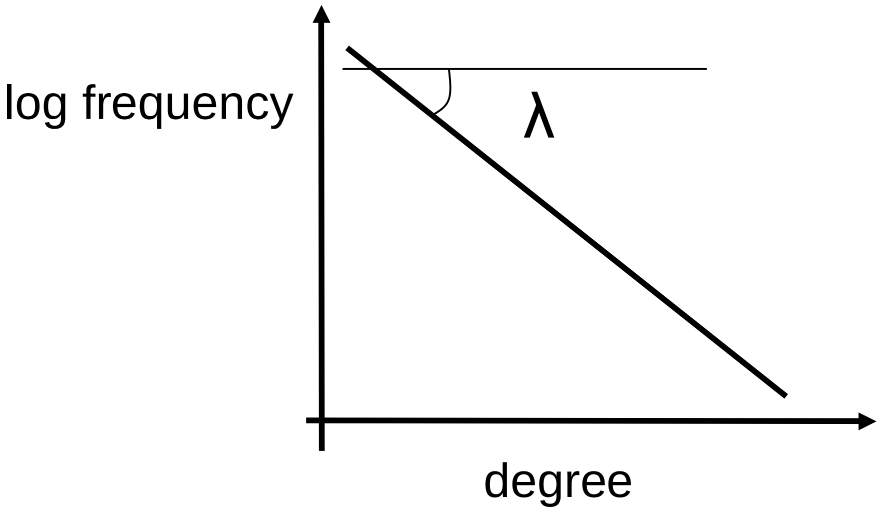
Exponential distribution

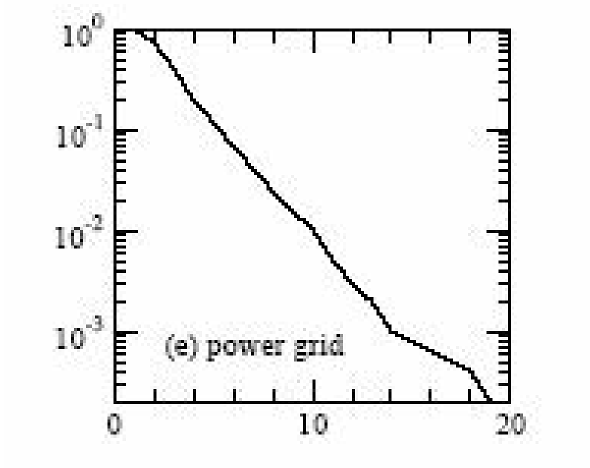
- Observed in some technological or collaboration networks

$$p(k) = \lambda e^{-\lambda k}$$

- Identified by a line in the log-linear plot

$$\log p(k) = -\lambda k + \log \lambda$$





Average/Expected degree

- For random graphs $z = np$

- For power-law distributed degree
  - if $\alpha \geq 2$, it is a constant
  - if $\alpha < 2$, it diverges

Maximum degree

- For random graphs, the maximum degree is highly concentrated around the average degree z
- For power law graphs

$$k_{max} \approx n^{1/(\alpha-1)}$$

- Rough argument: solve $nP[X \geq k] = 1$

Collective Statistics (M. Newman 2003)

	network	type	n	m	z	ℓ	α	$C^{(1)}$	$C^{(2)}$	r	Ref(s).
social	film actors	undirected	449 913	25 516 482	113.43	3.48	2.3	0.20	0.78	0.208	20, 416
	company directors	undirected	7 673	55 392	14.44	4.60	–	0.59	0.88	0.276	105, 323
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	WWW Altavista	directed	203 549 046	2 130 000 000	10.46	16.18	2.1/2.7				74
	citation network	directed	783 339	6 716 198	8.57		3.0/–				351
	Roget's Thesaurus	directed	1 022	5 103	4.99	4.87	–	0.13	0.15	0.157	244
	word co-occurrence	undirected	460 902	17 000 000	70.13		2.7		0.44		119, 157
technological	Internet	undirected	10 697	31 992	5.98	3.31	2.5	0.035	0.39	−0.189	86, 148
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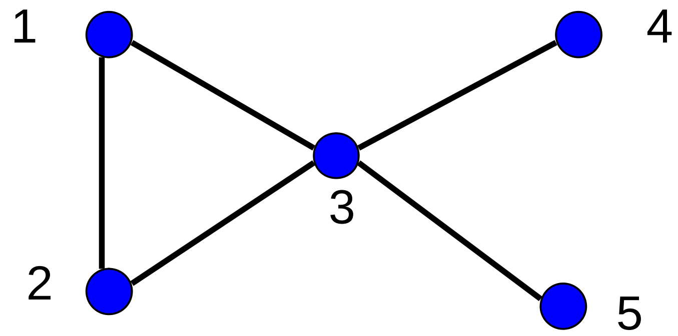
Clustering (Transitivity) coefficient

- Measures the density of triangles (local clusters) in the graph
- Two different ways to measure it:

$$C^{(1)} = \frac{\sum_i \text{triangles centered at node i}}{\sum_i \text{triples centered at node i}}$$

- The ratio of the means

Example



$$C^{(1)} = \frac{3}{1+1+6} = \frac{3}{8}$$

Clustering (Transitivity) coefficient

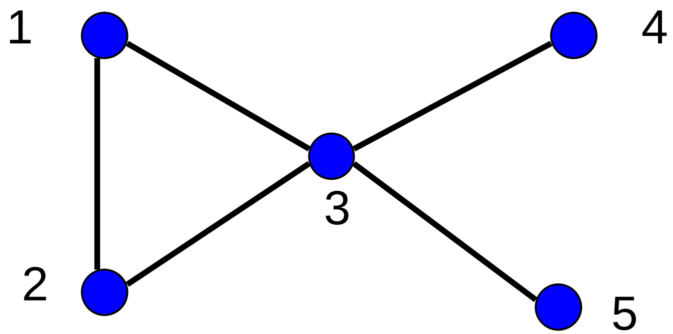
- Clustering coefficient for node i

$$C_i = \frac{\text{triangles centered at node i}}{\text{triples centered at node i}}$$

$$C^{(2)} = \frac{1}{n} C_i$$

- The mean of the ratios

Example



$$C^{(2)} = \frac{1}{5}\left(1+1+1/6\right) = \frac{13}{30}$$

$$C^{(1)} = \frac{3}{8}$$

- The two clustering coefficients give different measures
- $C^{(2)}$ increases with nodes with low degree

Collective Statistics (M. Newman 2003)

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Clustering coefficient for random graphs

- The probability of two of your neighbors also being neighbors is p, independent of local structure
  - clustering coefficient C = p
  - when z is fixed C = z/n =O(1/n)

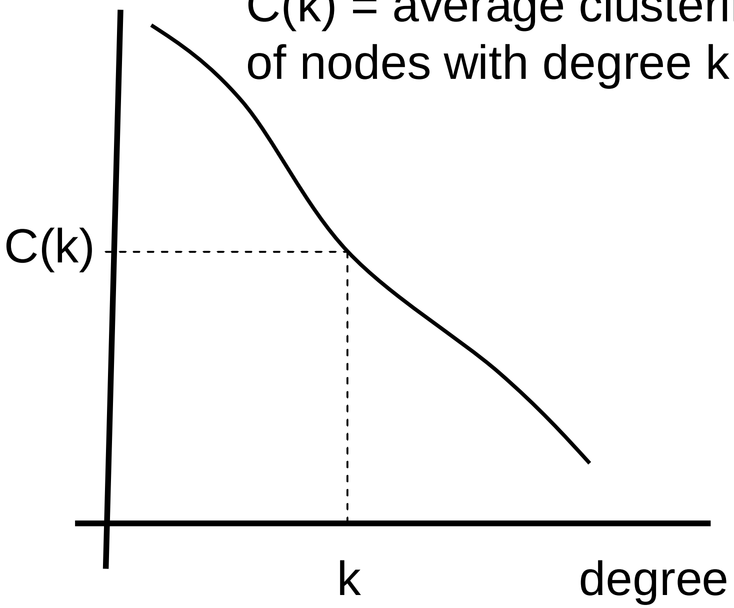
Table 1: Clustering coefficients, C, for a number of different networks; n is the number of node, z is the mean degree. Taken from [146].

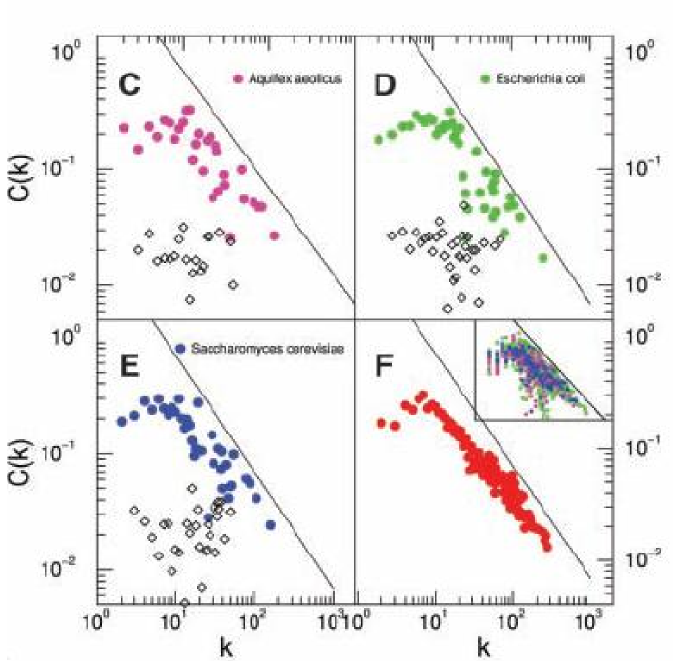
Network	n	z	C measured	C for random graph
Internet [153]	6,374	3.8	0.24	0.00060
World Wide Web (sites) [2]	153,127	35.2	0.11	0.00023
power grid [192]	4,941	2.7	0.080	0.00054
biology collaborations [140]	1,520,251	15.5	0.081	0.000010
mathematics collaborations [141]	253,339	3.9	0.15	0.000015
film actor collaborations [149]	449,913	113.4	0.20	0.00025
company directors [149]	7,673	14.4	0.59	0.0019
word co-occurrence [90]	460,902	70.1	0.44	0.00015
neural network [192]	282	14.0	0.28	0.049
metabolic network [69]	315	28.3	0.59	0.090
food web [138]	134	8.7	0.22	0.065

The C(k) distribution

- The C(k) distribution is supposed to capture the hierarchical nature of the network
  - when constant: no hierarchy
  - when power-law: hierarchy

C(k) = average clustering coefficient of nodes with degree k





Millgram’s small world experiment

- Letters were handed out to people in Nebraska to be sent to a target in Boston
- People were instructed to pass on the letters to someone they knew on first-name basis
- The letters that reached the destination followed paths of length around 6
- Six degrees of separation: (play of John Guare)

- Also:
  - The Kevin Bacon game
  - The Erdös number
- Small world project: http://smallworld.columbia.edu/index.html

Measuring the small world phenomenon

- d_{ij} = shortest path between i and j
- Diameter:

$$d = \max_{i,j} d_{ij}$$

- Characteristic path length:

$$a = \frac{1}{n(n-1)/2} \sum_{i>j} d_{ij}$$

- Harmonic mean

$$a^{-1} = \frac{1}{n(n-1)/2} \sum_{i>j} d_{ij}^{-1}$$

- Also, distribution of all shortest paths

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Is the path length enough?

- Random graphs have diameter

$$d = \frac{\log n}{\log z}$$

- $d = \log n / \log\log n$ when $z = \omega(\log n)$

- Short paths should be combined with other properties
  - ease of navigation
  - high clustering coefficient

Degree correlations

- Do high degree nodes tend to link to high degree nodes?
- Pastor Satoras et al.
  - plot the mean degree of the neighbors as a function of the degree

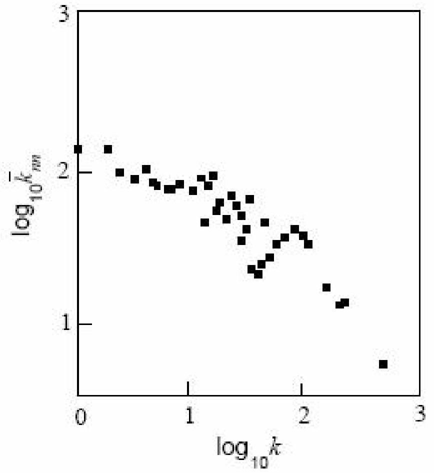

FIG. 3.13. Correlations of the degrees of nearest-neighbour vertices (autonomous systems) in the Internet at the interdomain level (after Pastor-Satorras, Vázquez, and Vespignani 2001). The empirical dependence of the average degree of the nearest neighbours of a vertex on the degree of this vertex is shown in a log–log scale. This empirical dependence was fitted by a power law with exponent approximately 0.5.

Degree correlations

- Newman
  - compute the correlation coefficient of the degrees of the two endpoints of an edge
  - assortative/disassortative

$$r = \frac{M^{-1}\sum_i j_i k_i - \left[M^{-1}\sum_i \frac{1}{2}(j_i + k_i)\right]^2}{M^{-1}\sum_i \frac{1}{2}(j_i^2 + k_i^2) - \left[M^{-1}\sum_i \frac{1}{2}(j_i + k_i)\right]^2},$$

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	student relationships	undirected	573	477	1.66	16.01	–	0.005	0.001	−0.029	45
	sexual contacts	undirected	2 810				3.2				265, 266
information	WWW nd.edu	directed	269 504	1 497 135	5.55	11.27	2.1/2.4	0.11	0.29	−0.067	14, 34
	WWW Altavista	directed	203 549 046	2 130 000 000	10.46	16.18	2.1/2.7				74
	citation network	directed	783 339	6 716 198	8.57		3.0/–				351
	Roget's Thesaurus	directed	1 022	5 103	4.99	4.87	–	0.13	0.15	0.157	244
	word co-occurrence	undirected	460 902	17 000 000	70.13		2.7		0.44		119, 157
technological	Internet	undirected	10 697	31 992	5.98	3.31	2.5	0.035	0.39	−0.189	86, 148
	power grid	undirected	4 941	6 594	2.67	18.99	–	0.10	0.080	−0.003	416
	train routes	undirected	587	19 603	66.79	2.16	–		0.69	−0.033	366
	software packages	directed	1 439	1 723	1.20	2.42	1.6/1.4	0.070	0.082	−0.016	318
	software classes	directed	1 377	2 213	1.61	1.51	–	0.033	0.012	−0.119	395
	electronic circuits	undirected	24 097	53 248	4.34	11.05	3.0	0.010	0.030	−0.154	155
	peer-to-peer network	undirected	880	1 296	1.47	4.28	2.1	0.012	0.011	−0.366	6, 354
biological	metabolic network	undirected	765	3 686	9.64	2.56	2.2	0.090	0.67	−0.240	214
	protein interactions	undirected	2 115	2 240	2.12	6.80	2.4	0.072	0.071	−0.156	212
	marine food web	directed	135	598	4.43	2.05	–	0.16	0.23	−0.263	204
	freshwater food web	directed	92	997	10.84	1.90	–	0.20	0.087	−0.326	272
	neural network	directed	307	2 359	7.68	3.97	–	0.18	0.28	−0.226	416, 421

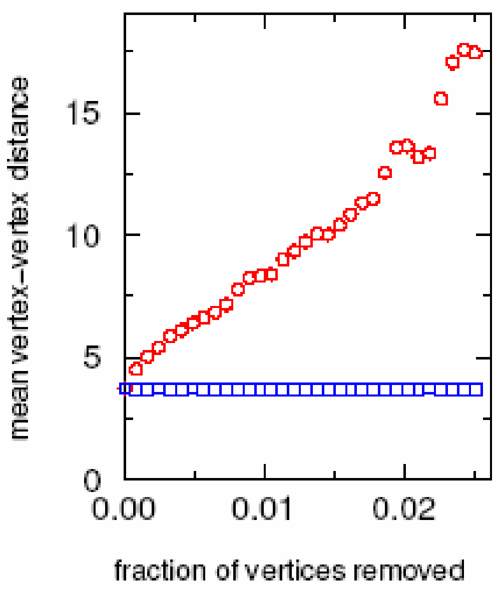
TABLE II Basic statistics for a number of published networks. The properties measured are: type of graph, directed or undirected; total number of vertices n; total number of edges m; mean degree z; mean vertex–vertex distance ℓ; exponent α of degree distribution if the distribution follows a power law (or "–" if not; in/out-degree exponents are given for directed graphs); clustering coefficient $C^{(1)}$ from Eq. (3); clustering coefficient $C^{(2)}$ from Eq. (6); and degree correlation coefficient r, Sec. III.F. The last column gives the citation(s) for the network in the bibliography. Blank entries indicate unavailable data.

Connected components

- For undirected graphs, the size and distribution of the connected components
  - is there a giant component?
- For directed graphs, the size and distribution of strongly and weakly connected components

Network Resilience

- Study how the graph properties change when performing random or targeted node deletions



Graph eigenvalues

- For random graphs
  - semi-circle law

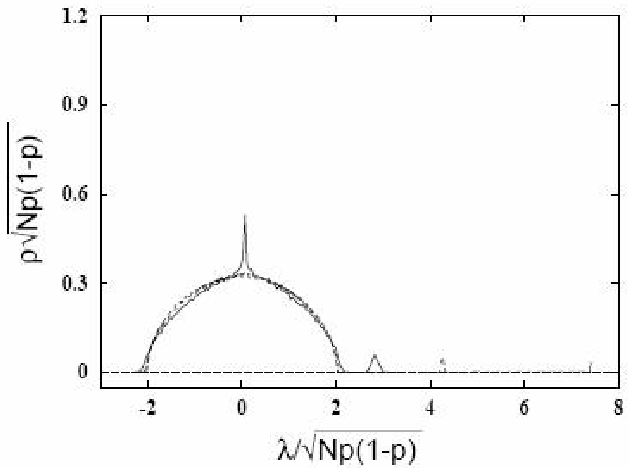
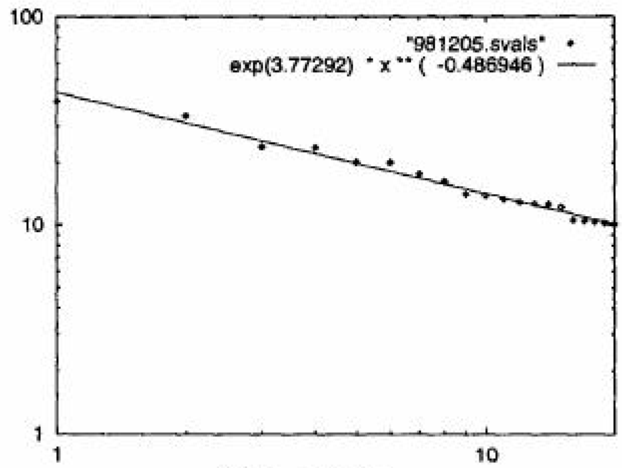


FIG. 10. Rescaled spectral density of three random graphs having $p = 0.05$ and size $N = 100$ (continuous line), $N = 300$ (dashed line) and $N = 1000$ (short-dashed line). The isolated peak corresponds to the principal eigenvalue. After Farkas *et al.* 2001.

- For the Internet (Faloutsos[3])



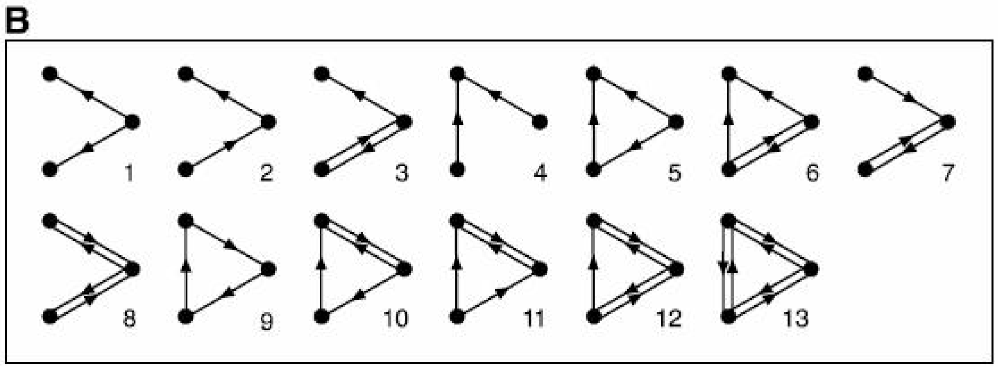
(a) Int-12-98

Motifs

- Most networks have the same characteristics with respect to global measurements
  - can we say something about the local structure of the networks?
- Motifs: Find small subgraphs that over-represented in the network

Example

- Motifs of size 3 in a directed graph

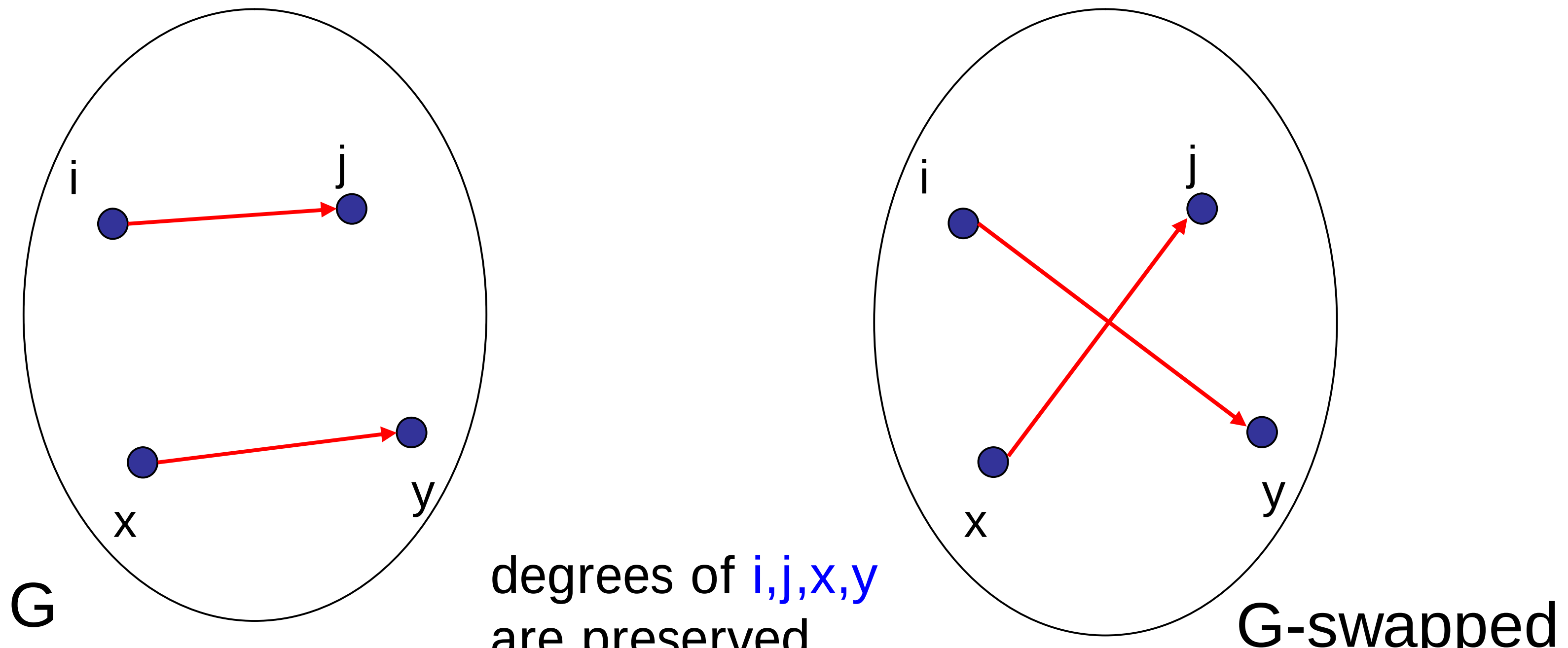


Finding interesting motifs

- Sample a part of the graph of size S
- Count the frequency of the motifs of interest
- Compare against the frequency of the motif in a random graph with the same number of nodes and the same degree distribution

Generating a random graph

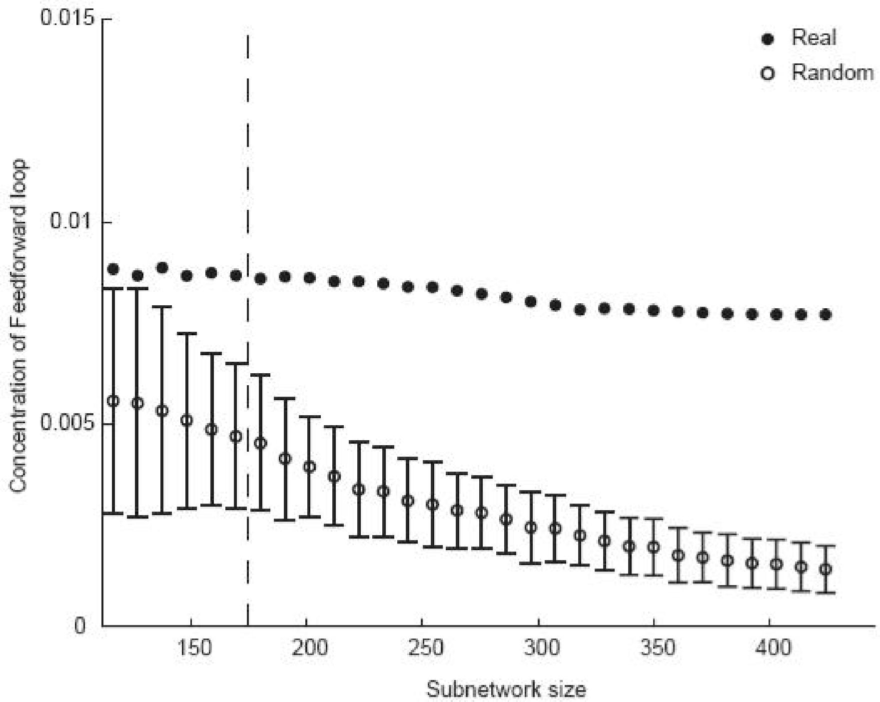
- Find edges (i,j) and (x,y) such that edges (i,y) and (x,j) do not exist, and swap them
  - repeat for a large enough number of times

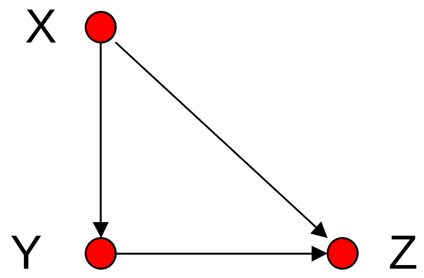


degrees of i,j,x,y are preserved

The feed-forward loop

- Over-represented in gene-regulation networks
  - a signal delay mechanism





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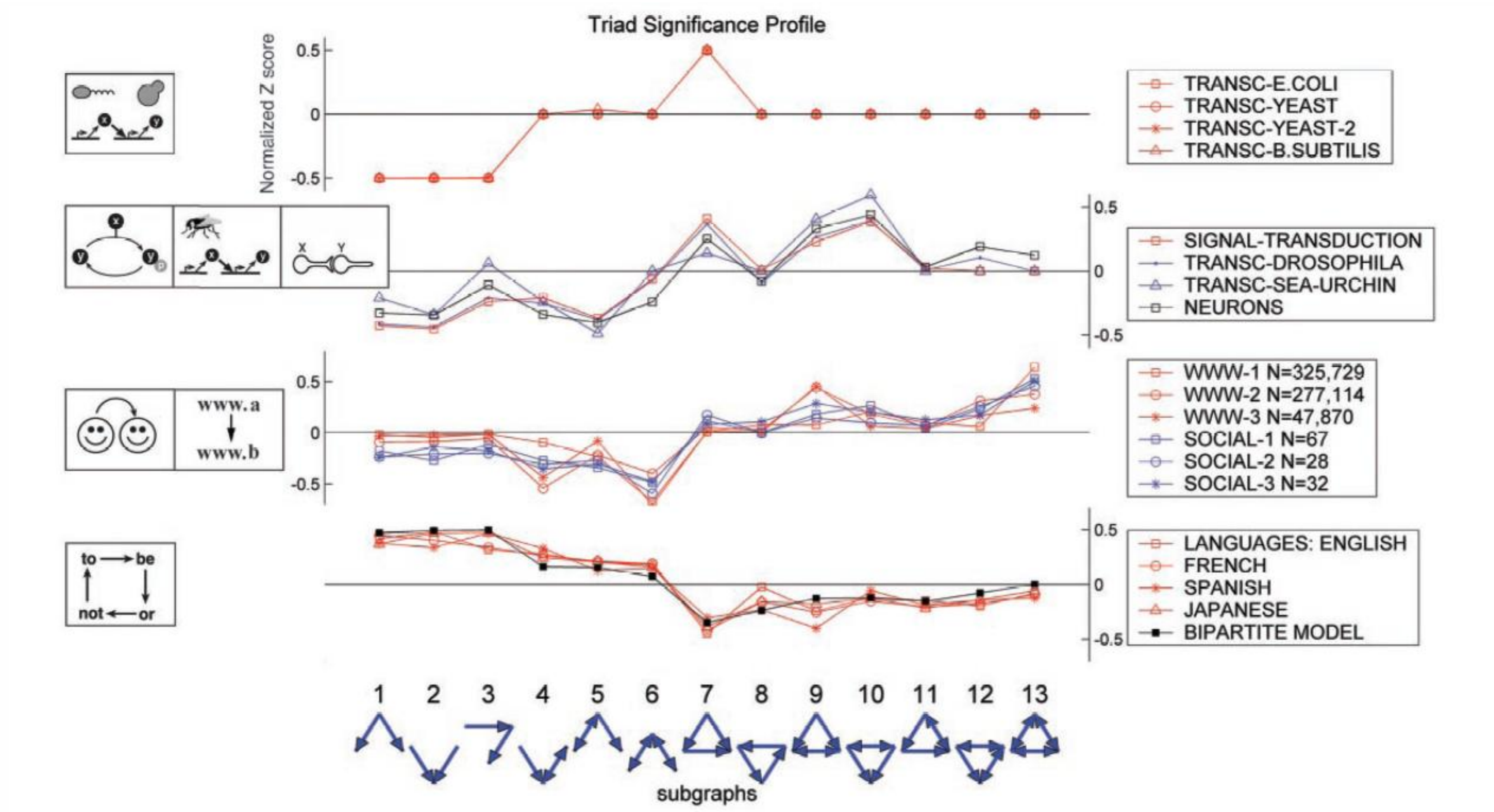
Families of networks

- Compute the relative frequency of different motifs, and group the networks if they exhibit similar frequencies

$$Z_i = (N\mathrm{real}_i - \langle N\mathrm{rand}_i \rangle)/\mathrm{std}(N\mathrm{rand}_i)$$

Experiments



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