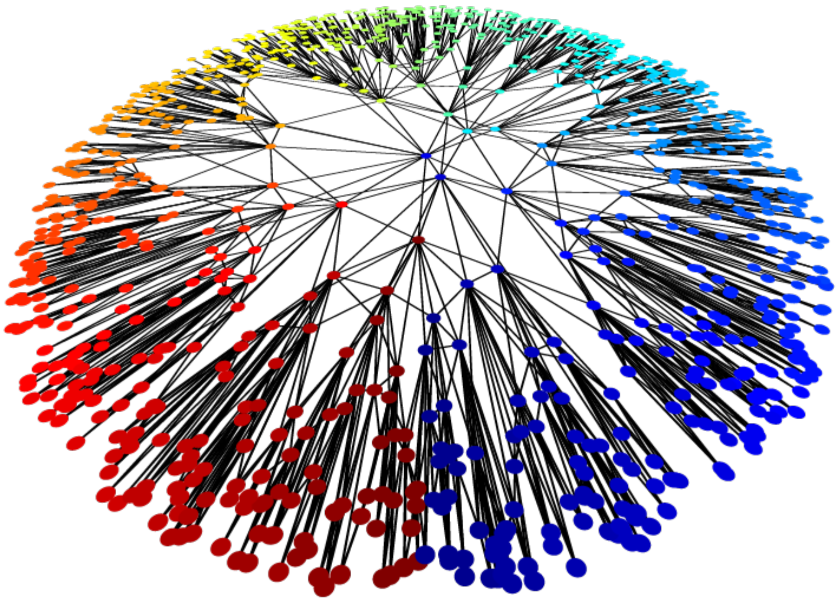
Complex systems and networks

Dr. Michael Lenz

Computational Biology and Data Mining Research Group
Institute of Organismic and Molecular Evolution
Johannes Gutenberg Universität
Mainz, Germany



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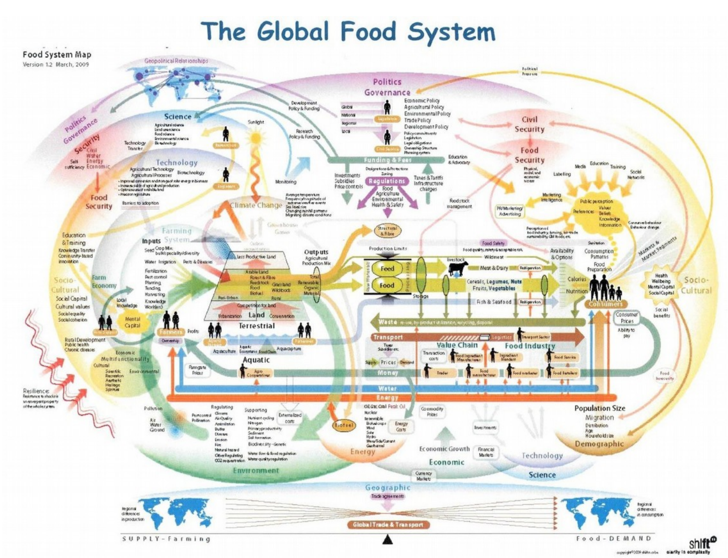
Michael Lenz
mlenz@uni-mainz.de

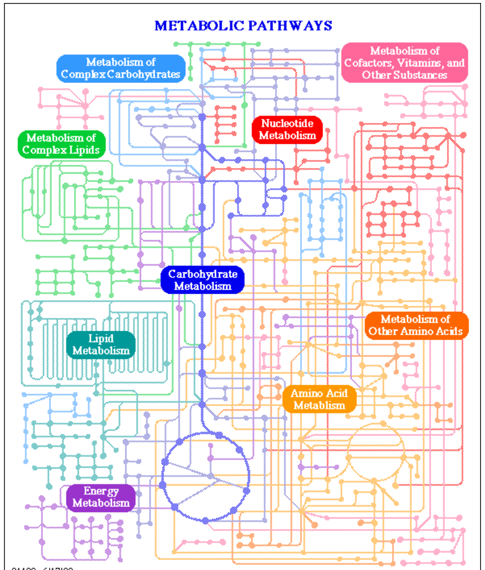
What is a complex system?

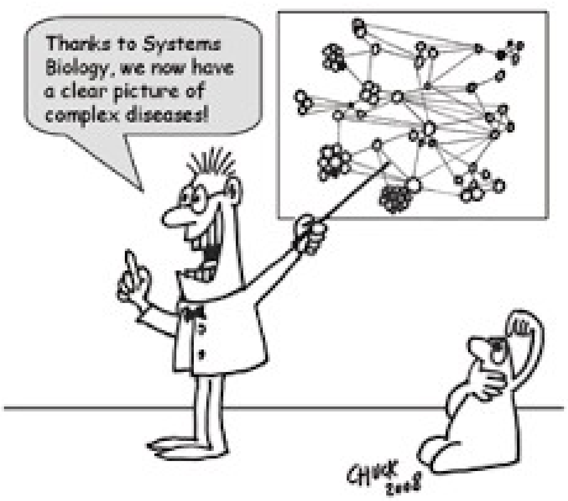
No generally accepted definition so far

Complex systems typically have several of the following properties:

- They are composed of many components
- Show emergent behavior
- Contain nonlinearities
- Are open systems
- Evolve far from equillibrium
- Show chaotic behavior



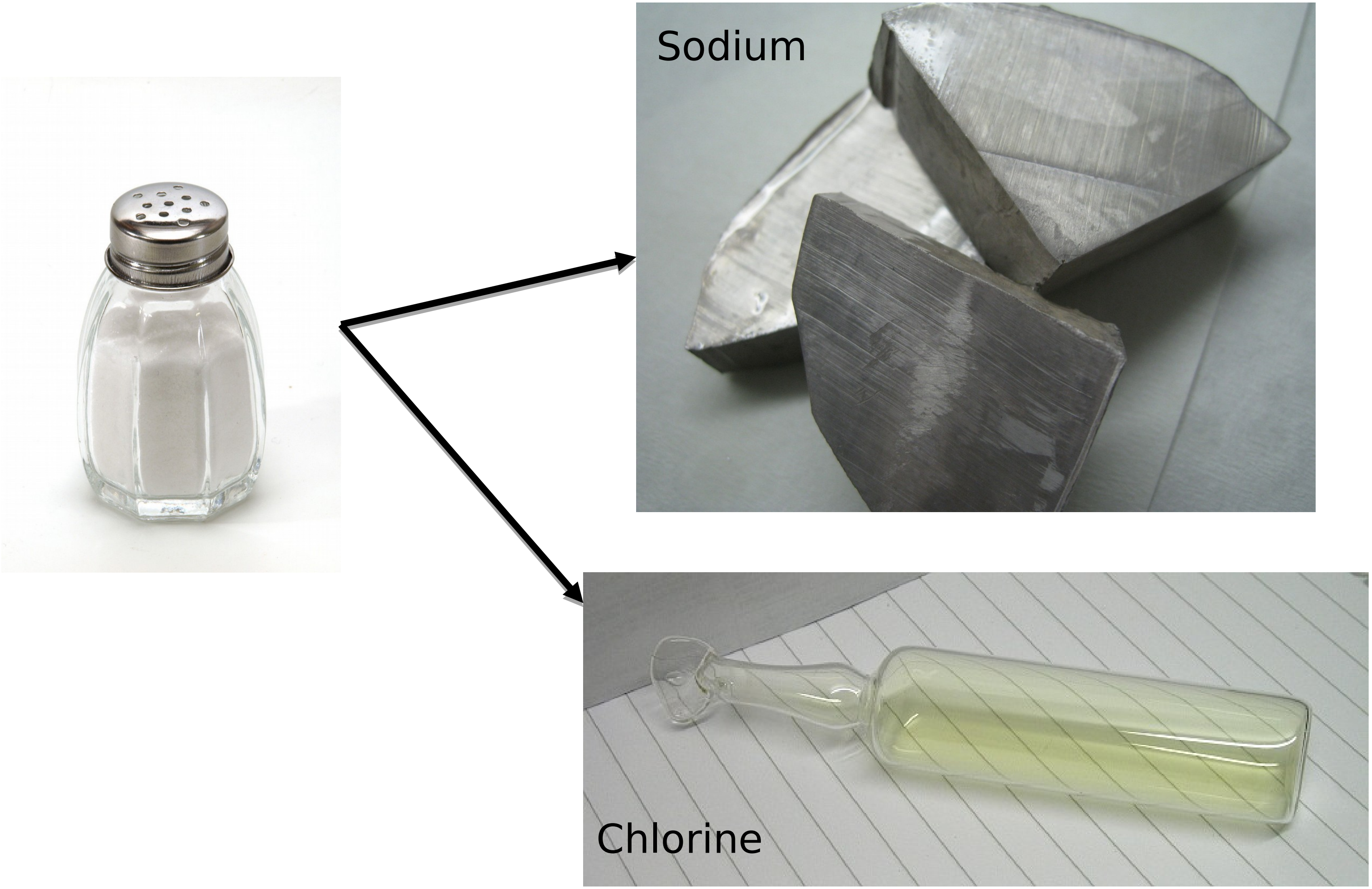




Emergent properties

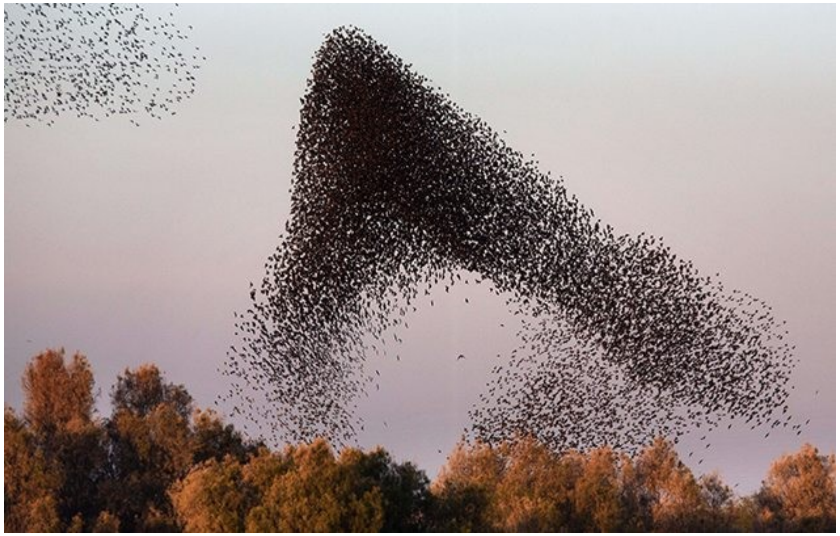
Figures from ForceChange, WikiMedia Commons and the Huffington Post

The fallacy of division



Figures from WikiMedia Commons

Complex behaviours, simple rules



NatGeo

Flocking

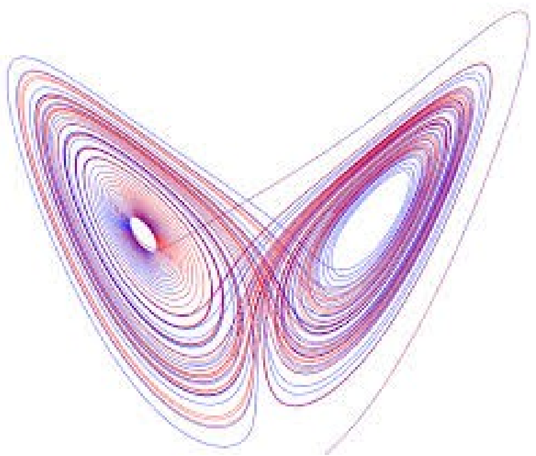
Bored Panda

Complexity & Chaos

Chaotic systems:
- Difficult to predict, despite being deterministic
- Exact knowledge of equations and starting conditions allows exact simulation
- Slight differences in starting conditions or model errors can result in huge simulation errors

Chaotic vs. complex systems:
- Chaotic systems can be complex, but also “simple”
- Complex systems may show chaotic behavior, but don’t have to

Example: Lorenz attractor



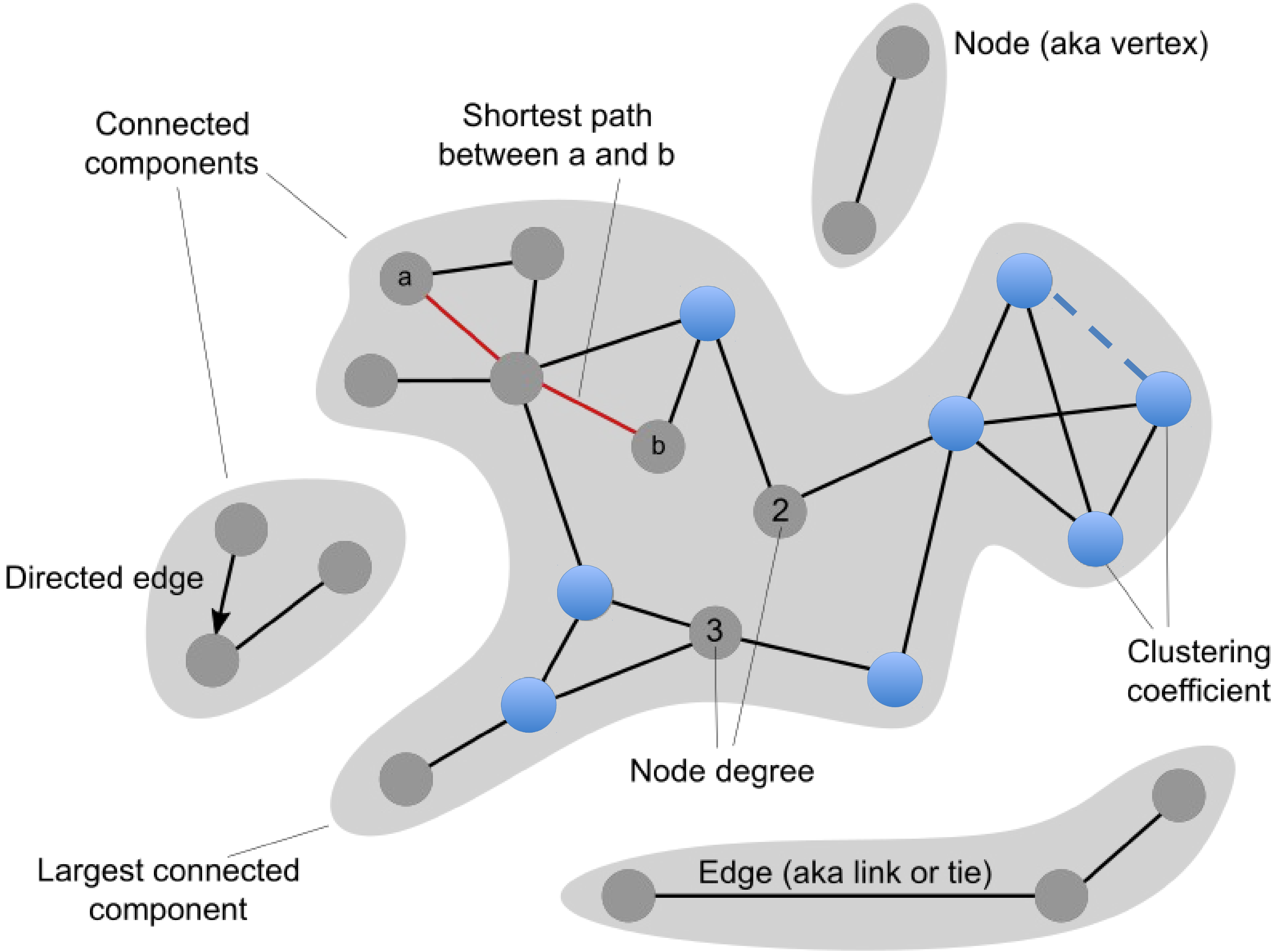
Simplified model for atmospheric convection

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sigma(y - x),$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = x(\rho - z) - y,$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = xy - \beta z.$$

Network representation of complex systems



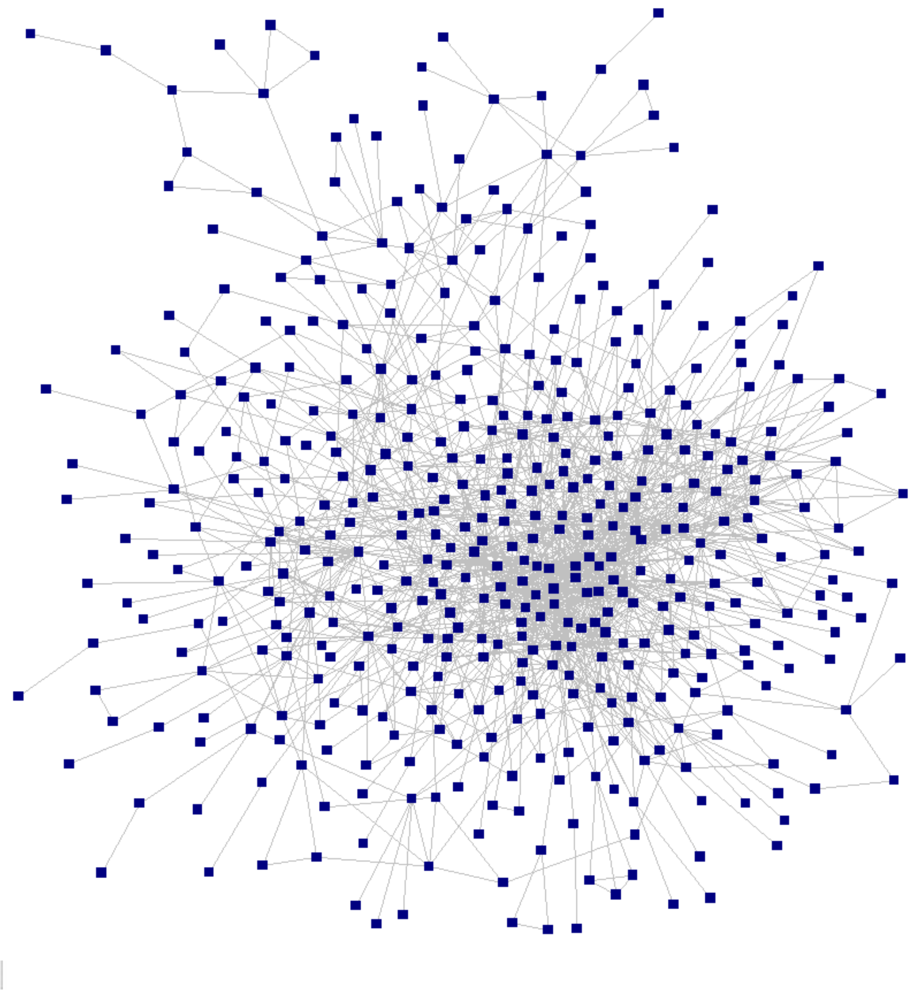
Network / Graph

Graph:

G=(V, E)

V: set of vertices

E: set of edges, each associated with 2 vertices



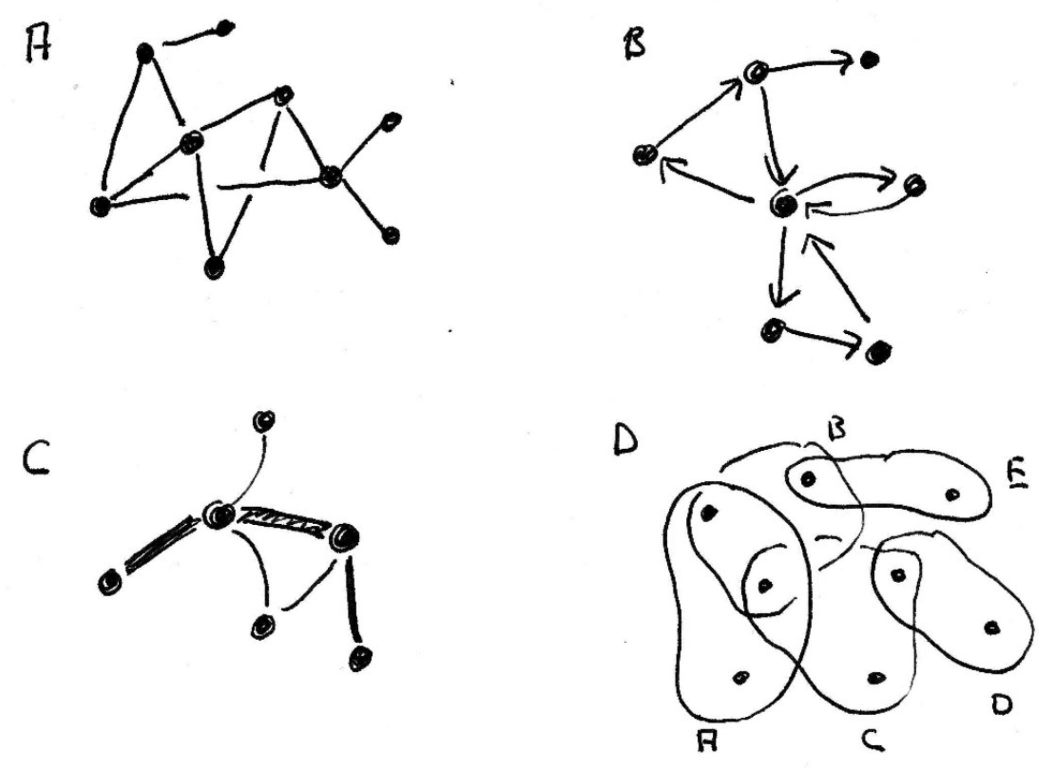
Network types

A) Homogeneous undirected network → no direction, no weights

B) Directed network

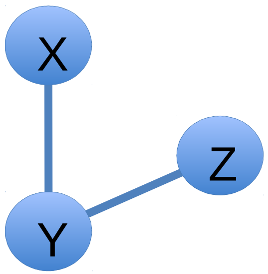
C) Weighted network

D) Hypergraphs and Bipartite network



Network representations

Drawing



Adjacency matrix

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

Link table

X	Y
Y	Z

Linked list

X: {Y}
Y: {X,Z}
Z: {Y}

What about directed networks, weighted networks, and bipartite graphs?

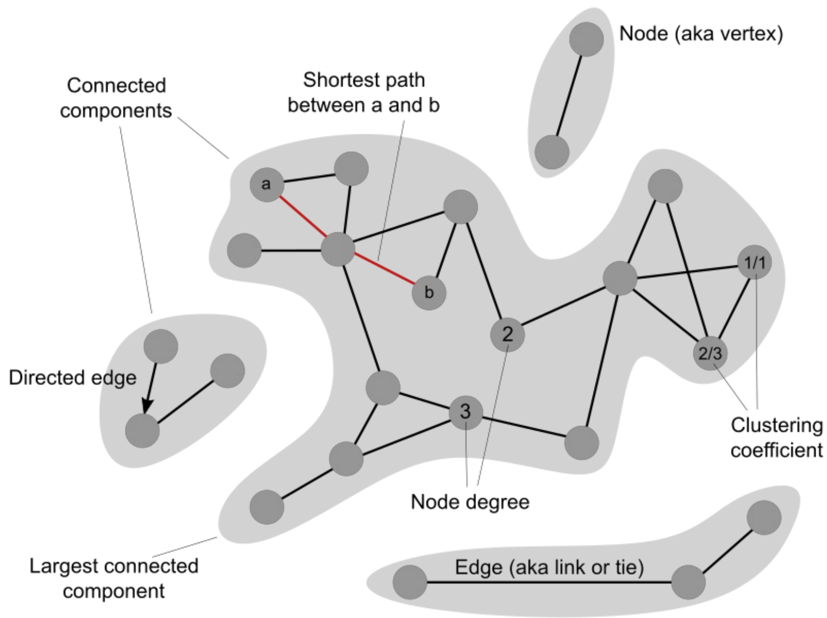
Network properties

Node degree: Number of edges connected to a node
(in-degree and out-degree for directed networks)

Path: Set of edges
Shortest path: Path with minimal amount of edges connecting two nodes

(Connected) components: Set of nodes such that a path exists that connects each pair of nodes

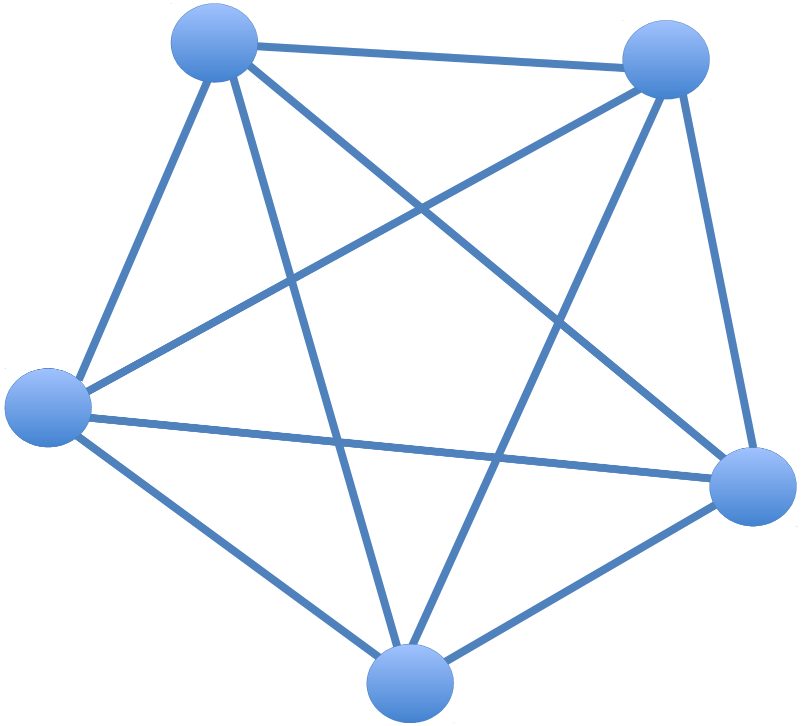
Clustering coefficient: Number of edges between neighboring nodes divided by maximum possible number of edges



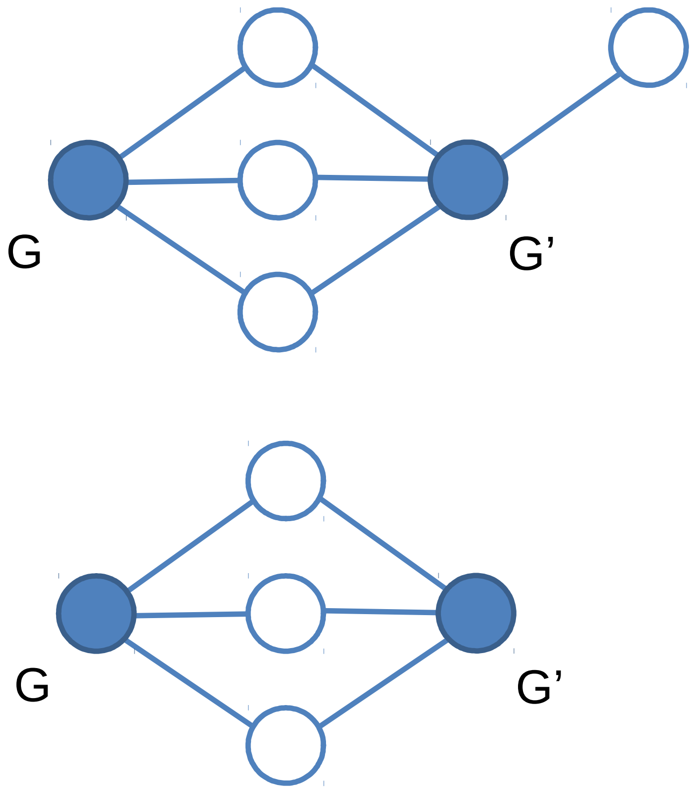
Complex networks, simple rules

Random network: Form links between nodes with probability *p*

p = 1/6

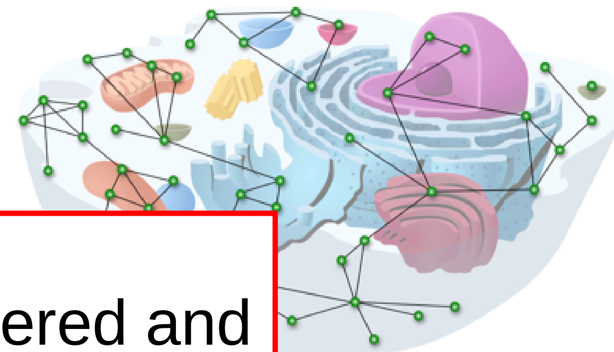


Duplication-divergence



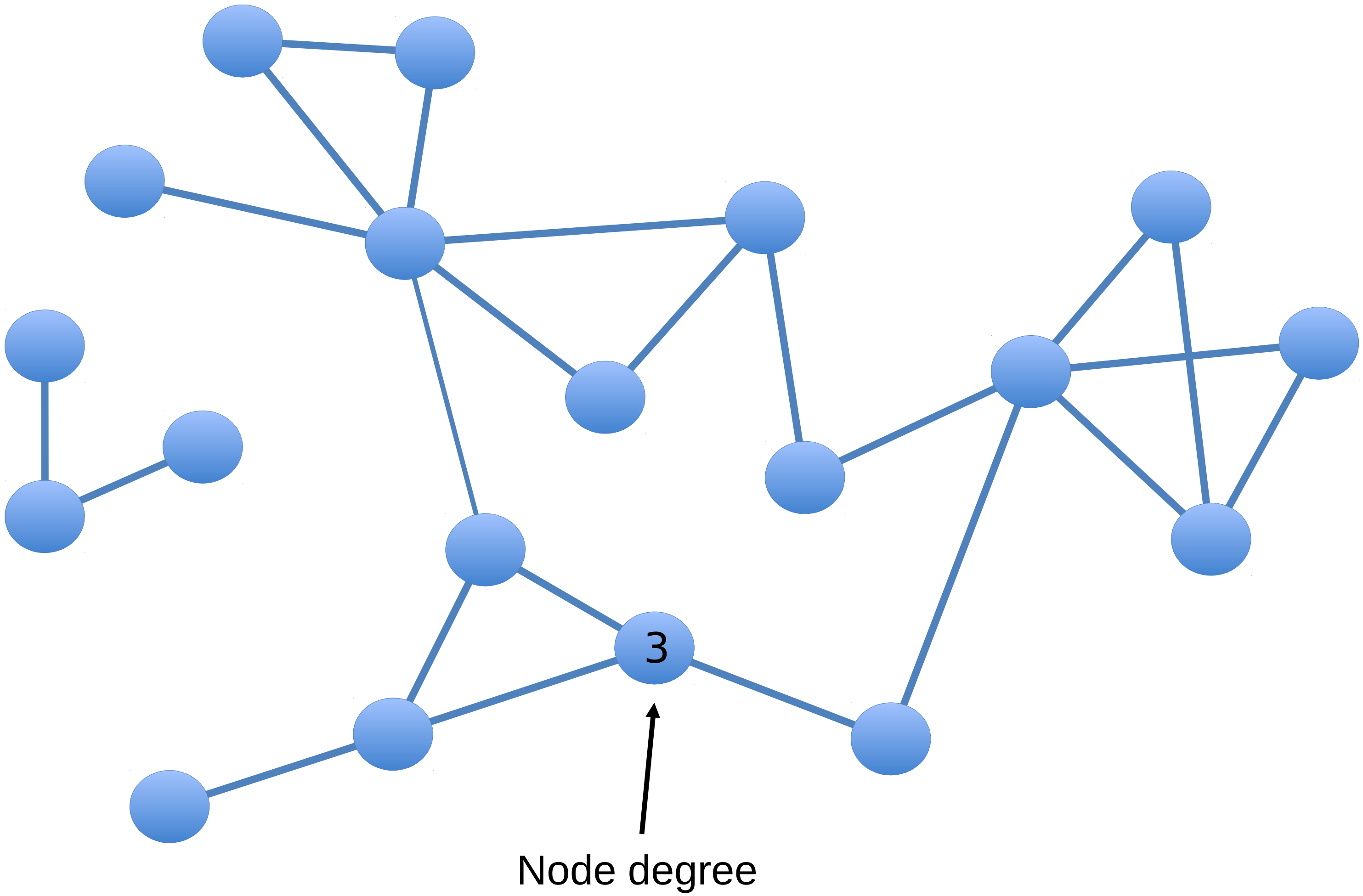
Retain links with probability *p*

Different systems, same network structural properties



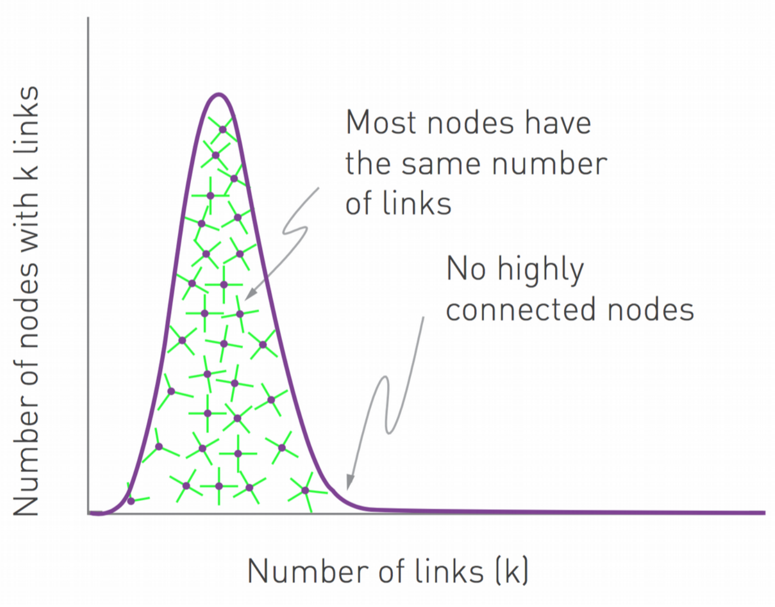
Scale-free, strongly clustered and small-world.

Complex networks are scale-free

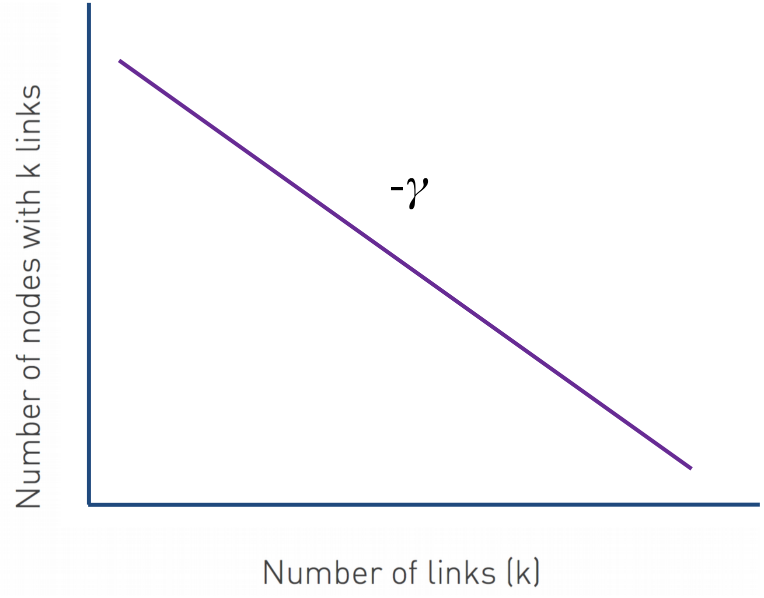


Complex networks are scale-free

Random network



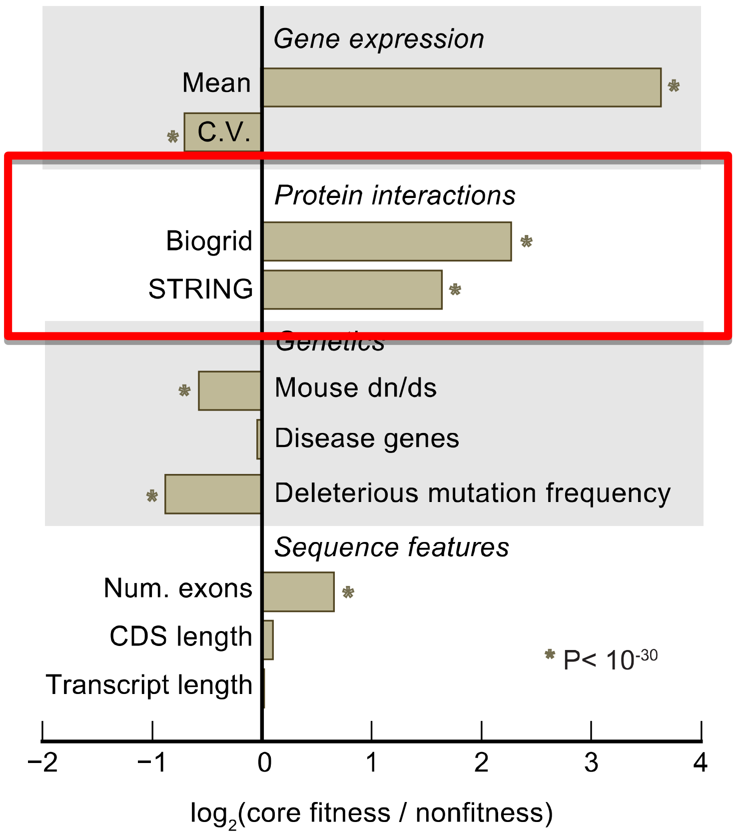
Complex network
Log-log scale



Figures from Barabasi (2015) Network Science, pp 12.

High-degree proteins: core fitness genes

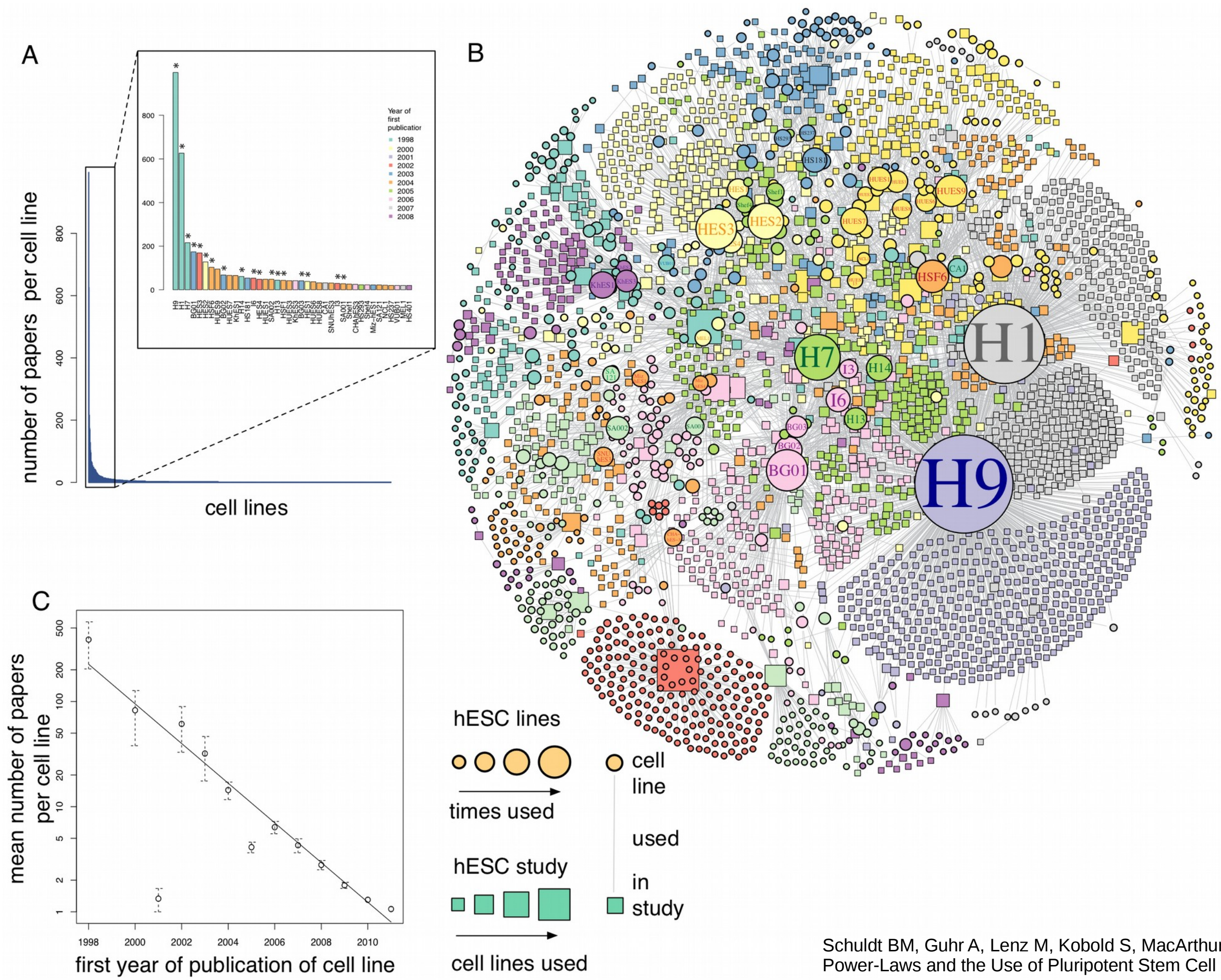
Fitness gene: Gene whose perturbation decreases cell growth and proliferation.



Hart *et al.* (2015) Cell

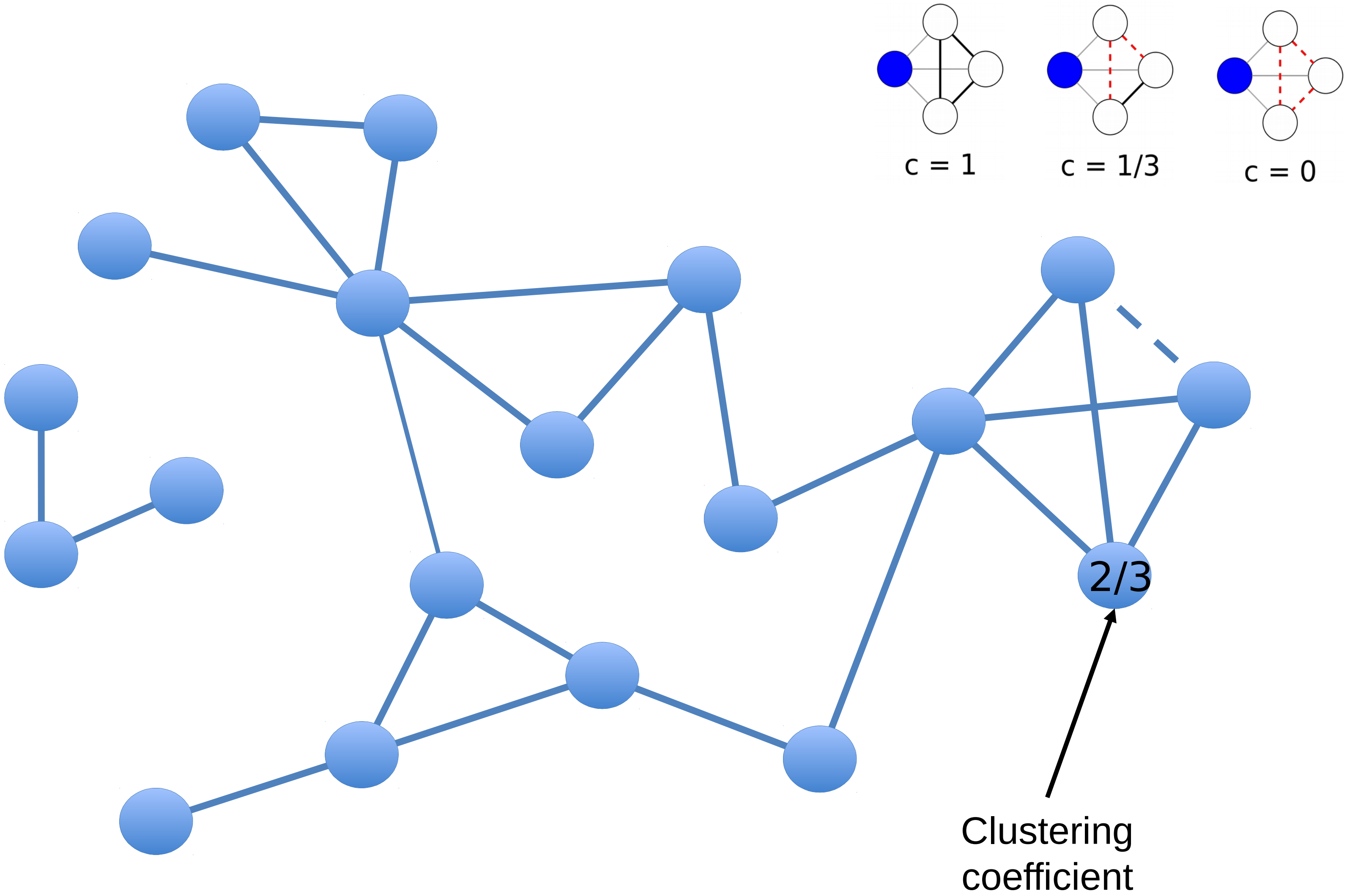
Scale free networks and preferential attachment

Example: Citation networks
Use of pluripotent stem cell lines

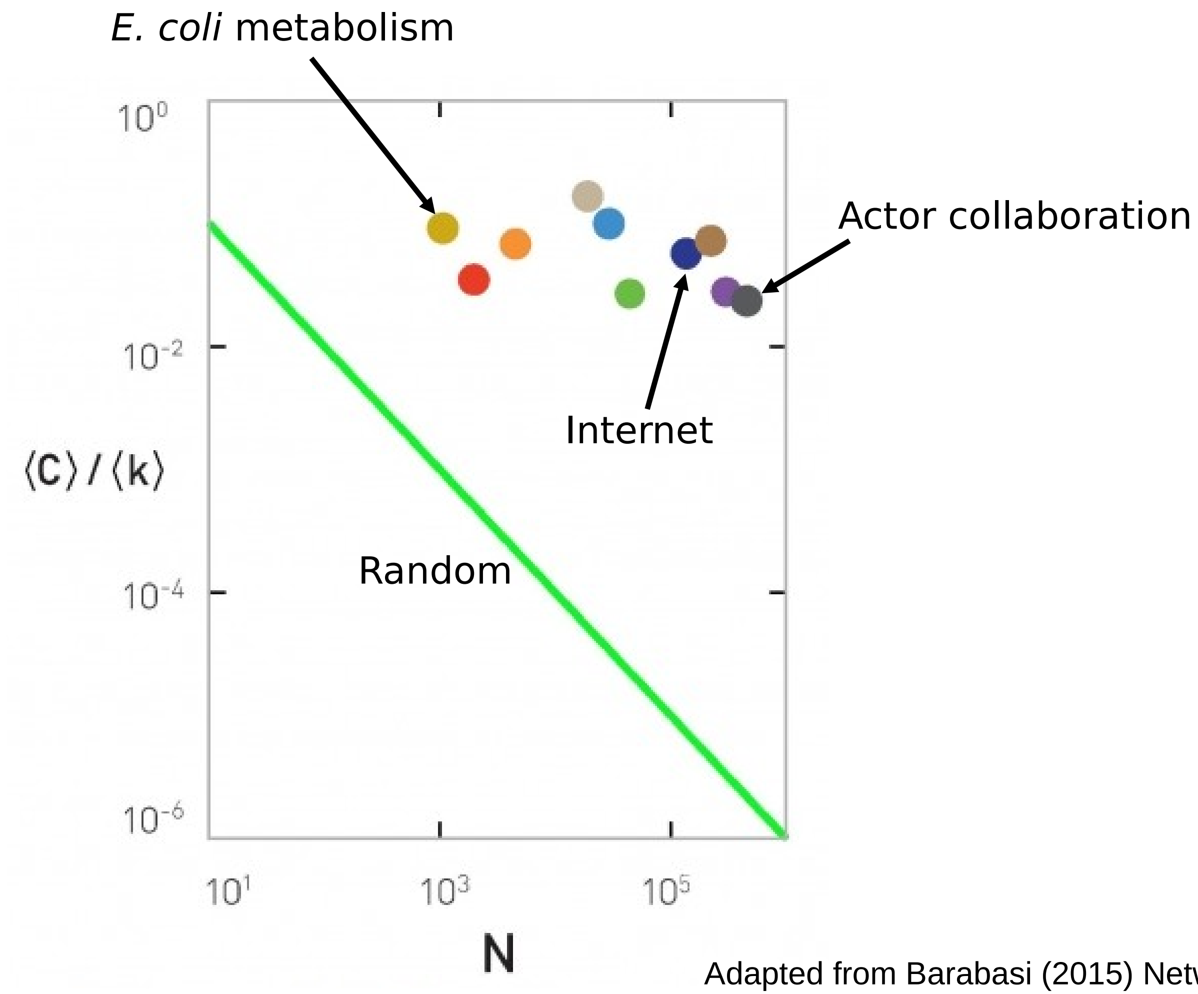


Schuldt BM, Guhr A, Lenz M, Kobold S, MacArthur BD, Schuppert A, et al. (2013) Power-Laws and the Use of Pluripotent Stem Cell Lines. PLoS ONE 8(1): e52068.

Complex networks are strongly clustered

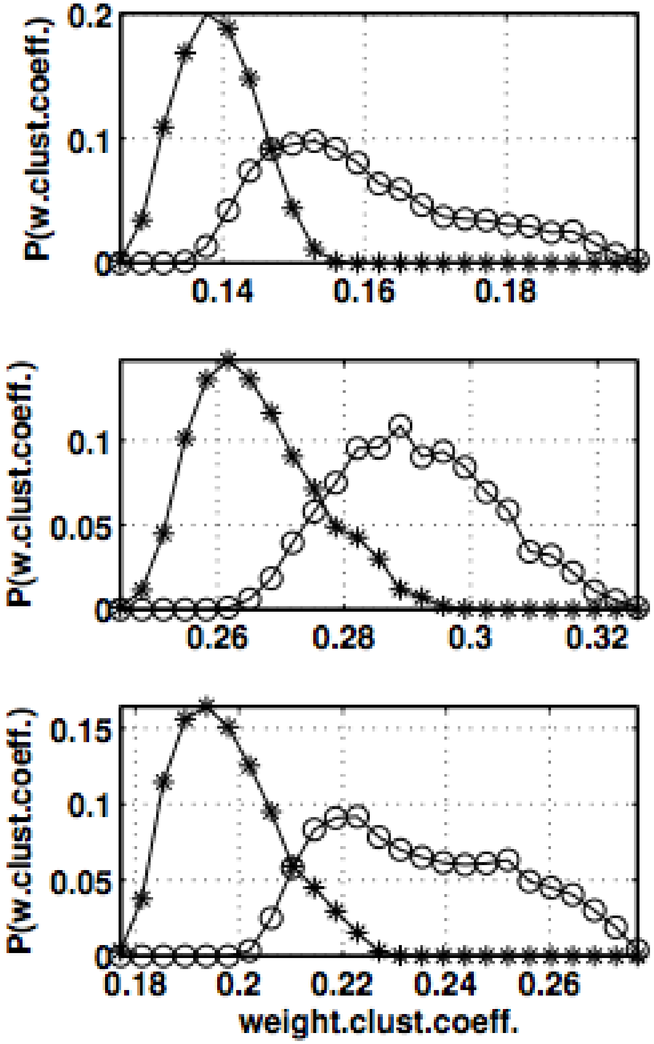


Real networks: strongly clustered



Adapted from Barabasi (2015) Network Science

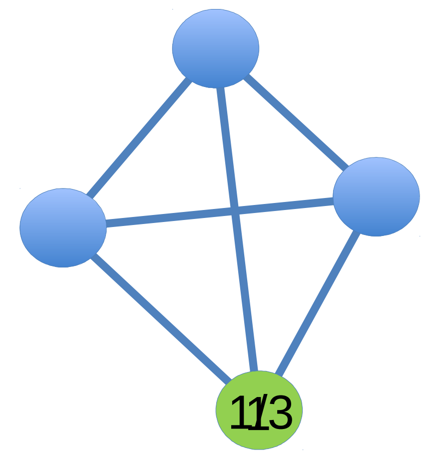
Cancer cells: reduced clustering



Liver

Breast

Lymphoma



○ Genes in normal cells

✻ Genes in cancer cells

Kalna & Higham (2007) Journal of AI Communications

Strong clustering motifs: protein complexes

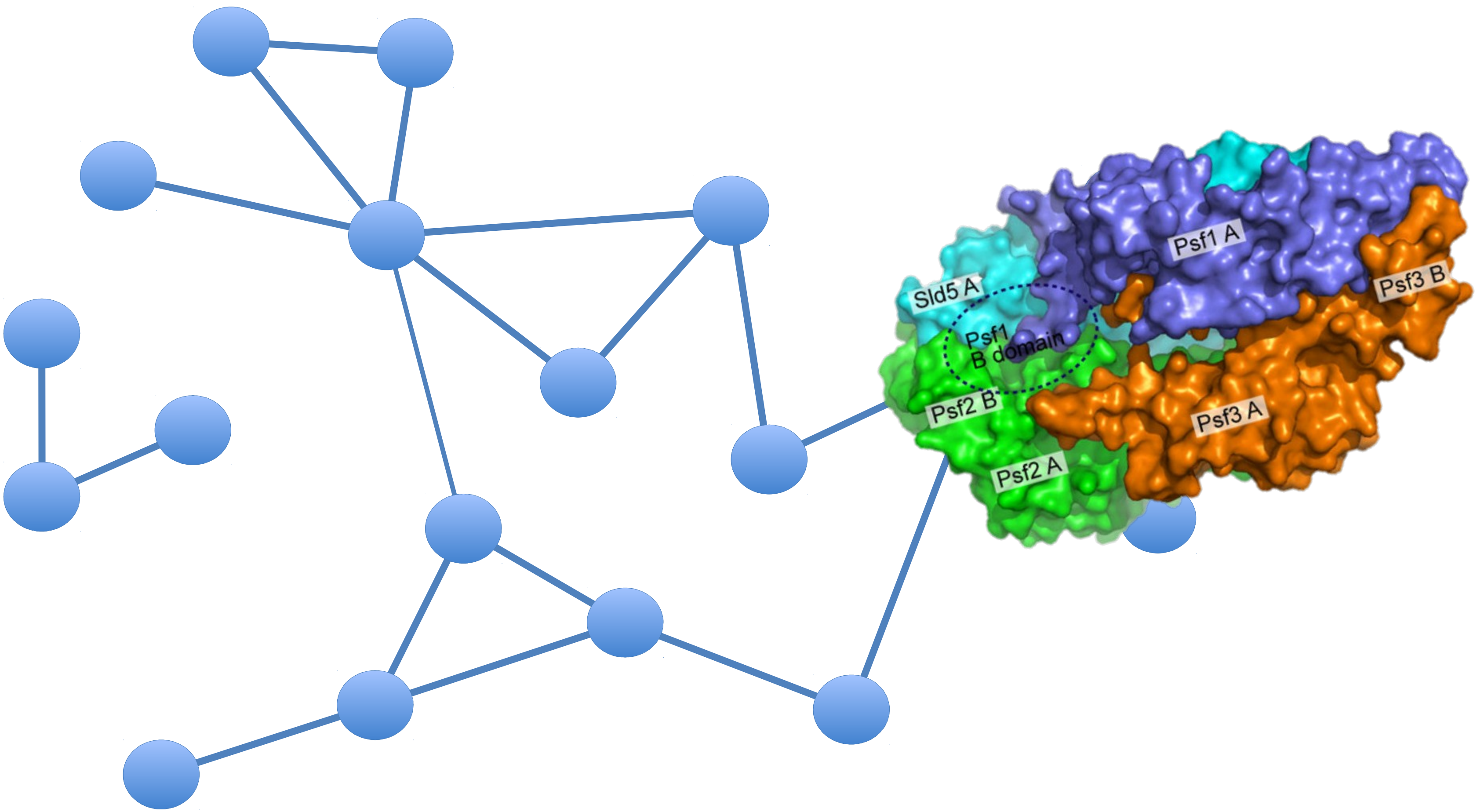
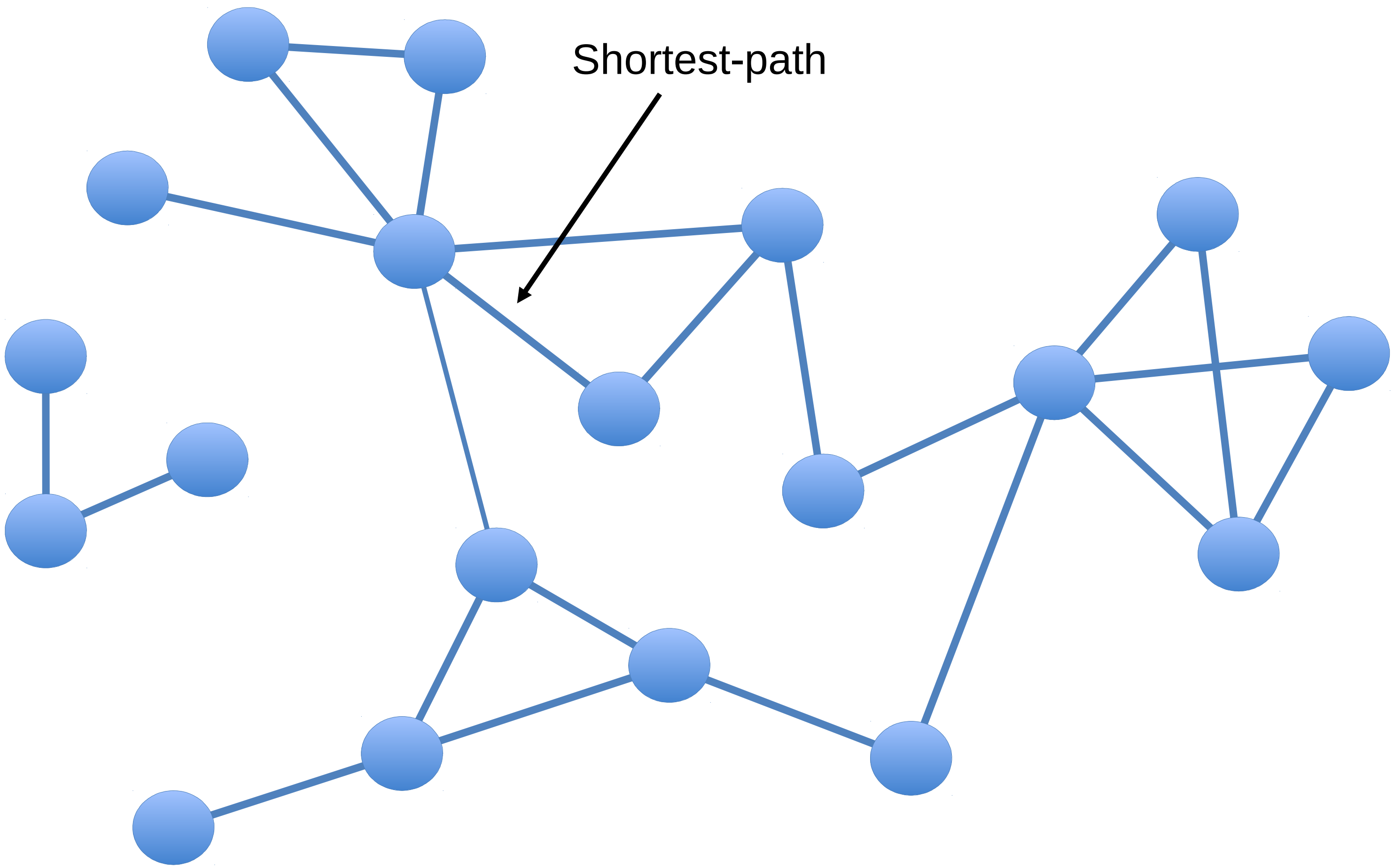
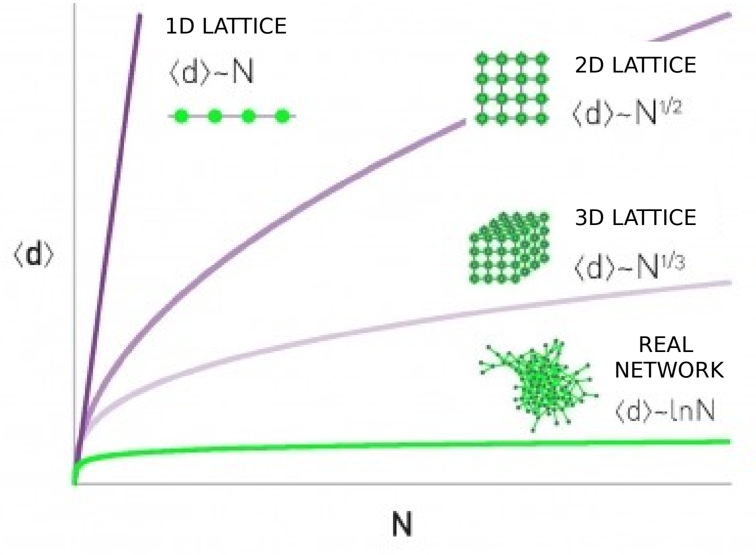


Figure from RIKEN

Complex networks are small-world

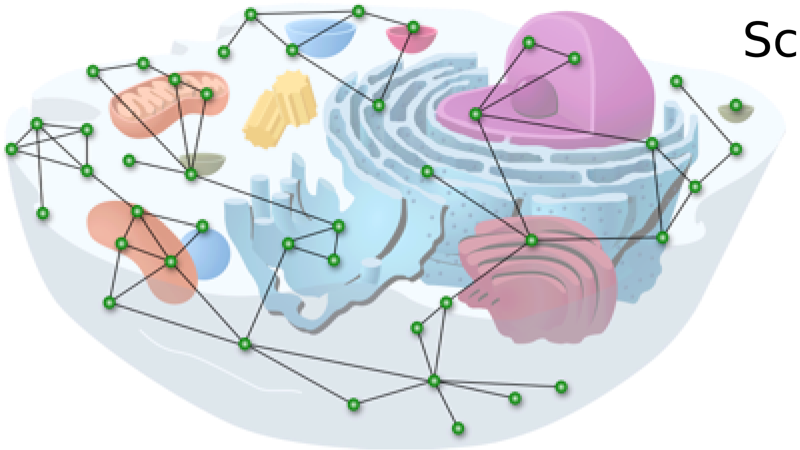


Shortest-paths and small worlds

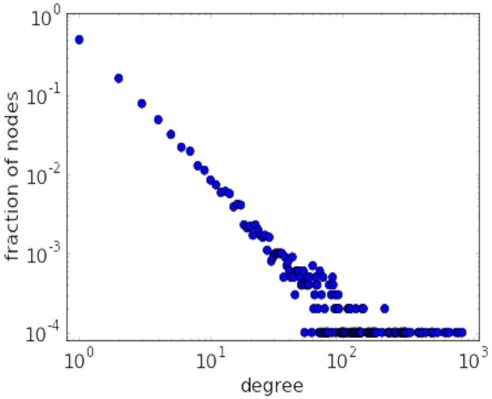


Adapted from Barabasi (2015) Network Science

Protein interaction network in the living cell



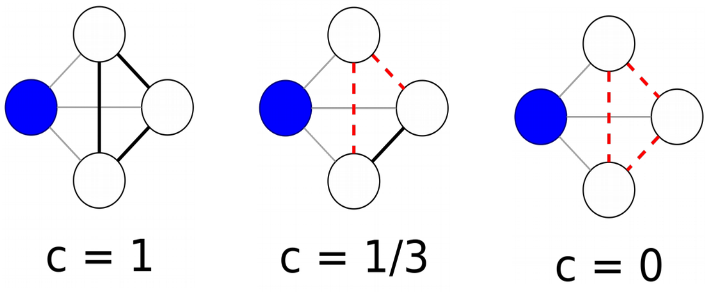
Scale-free/power law node degree distribution



Small-world property

$$L \propto \log N$$

Strong average clustering coefficient



Take-home message

A wide range of network-based approaches have been and are being developed to address problems with relevance to biology and human health. Some of the scenarios where network analysis is playing an important role are:

- Gene function prediction
- Detection of protein complexes and other modular structures
- Prediction of new interactions
- Analysis of disease modules


THANK YOU
GRACIAS
DANKE
شكراً
KÖSZÖNÖM
ви благодарам
MERCI
धन्यवाद
GRAZIE
谢谢