The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

World Year of PHYSICS 2005

SMR.1656 - 36

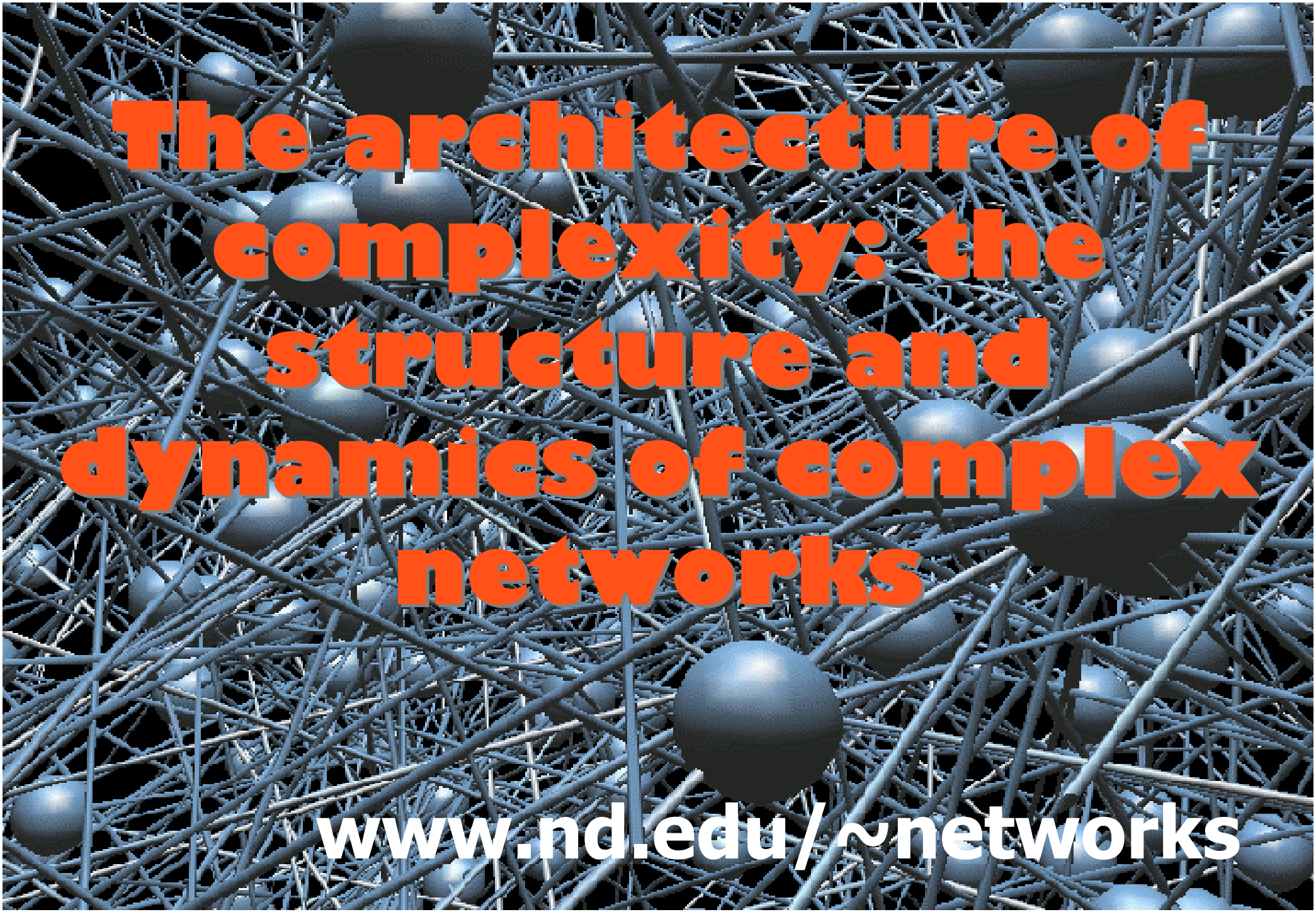
School and Workshop on
Structure and Function of Complex Networks

16 - 28 May 2005

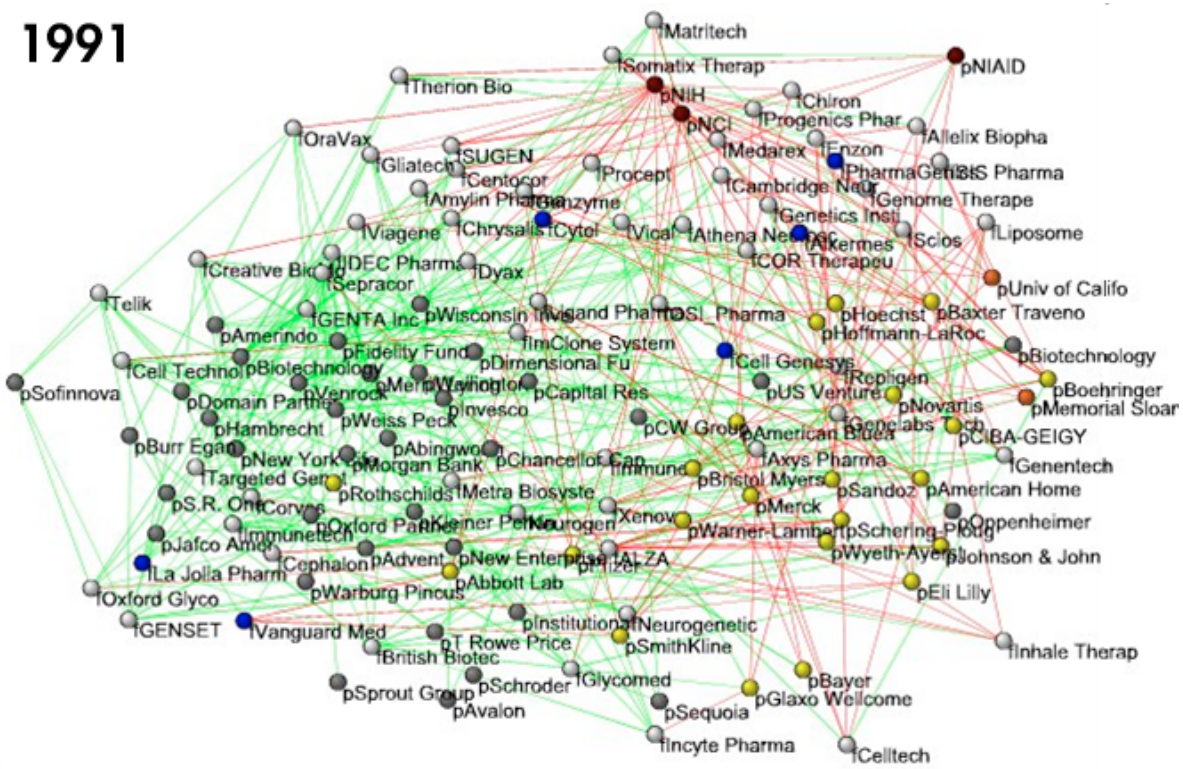
The Architecture of Complexity: The Structure and Dynamics of Complex Networks

(Public Lecture)

Albert-Laszlo BARABASI
University of Notre Dame
Department of Physics
IN 46556 Notre Dame
U.S.A.


The architecture of complexity: the structure and dynamics of complex networks
www.nd.edu/~networks

Business ties in US biotech-industry

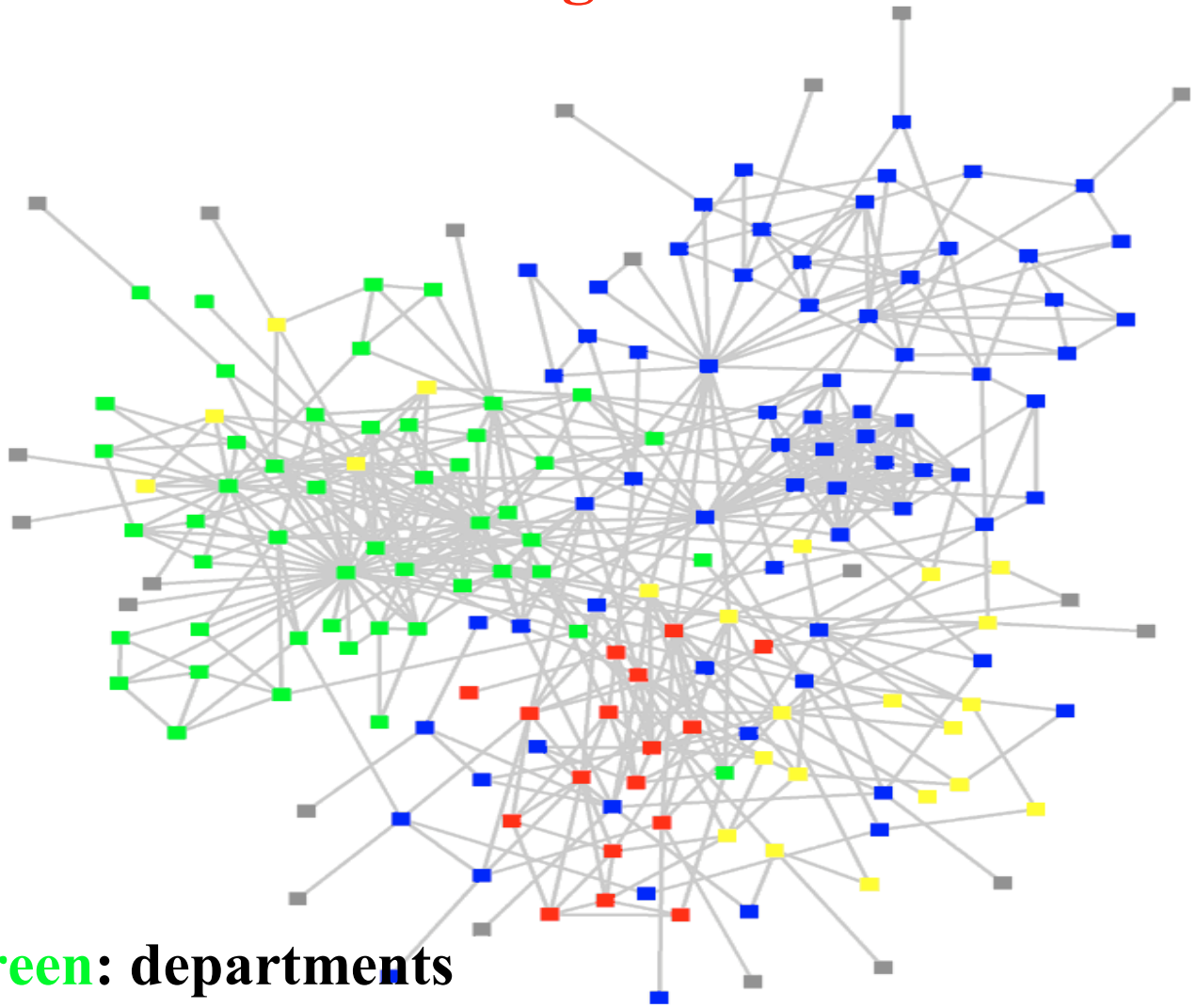


Nodes: companies: investment
pharma
research labs
public
biotechnology

Links: financial
R&D collaborations

http://ecclectic.ss.uci.edu/~drwhite/Movie

Structure of an organization



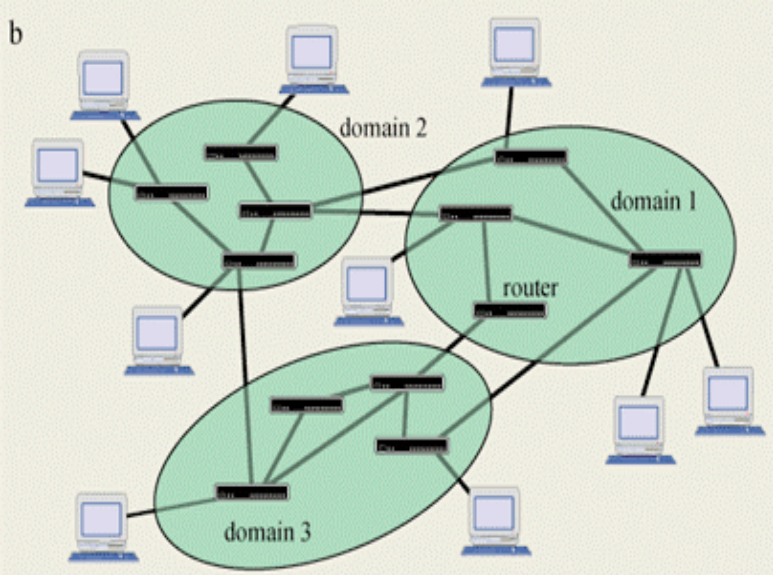
Red, blue, or green: departments

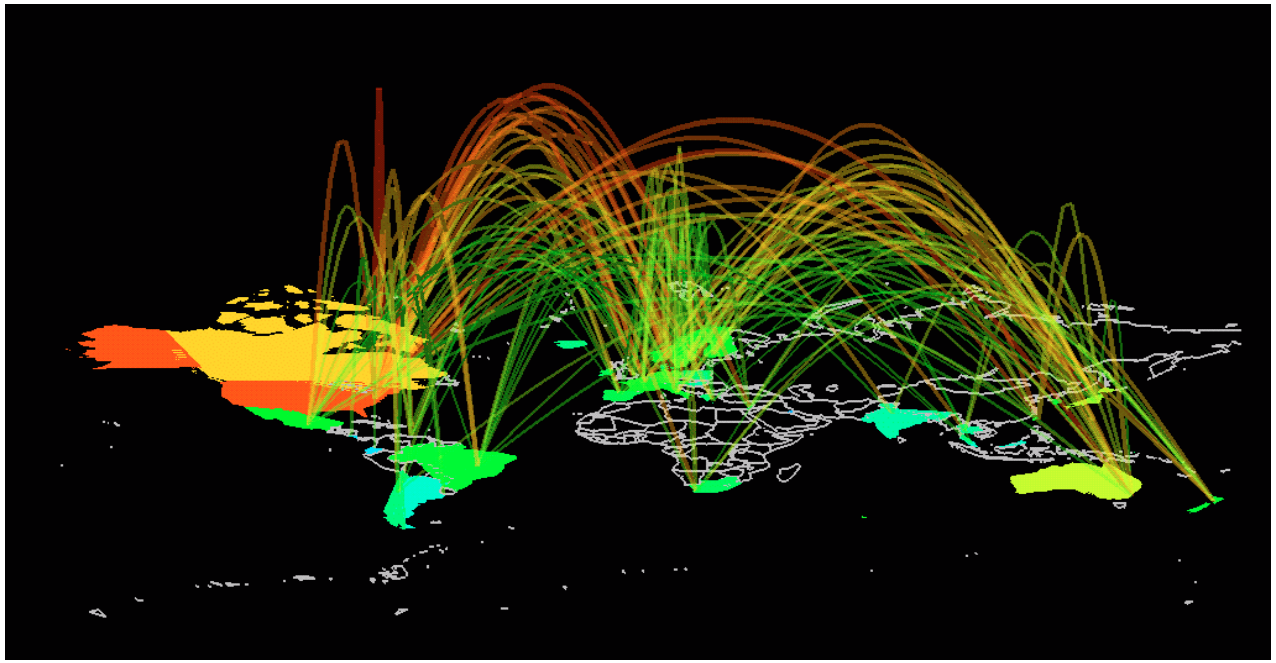
Yellow: consultants

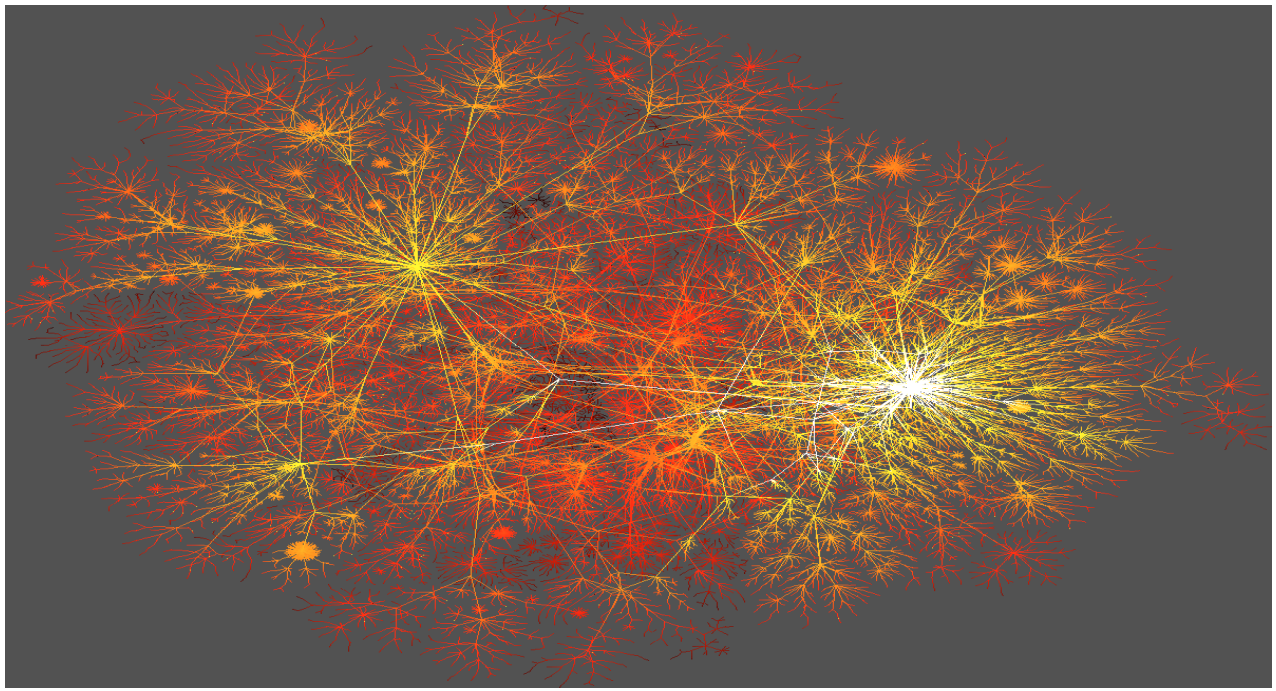
Grey: external experts

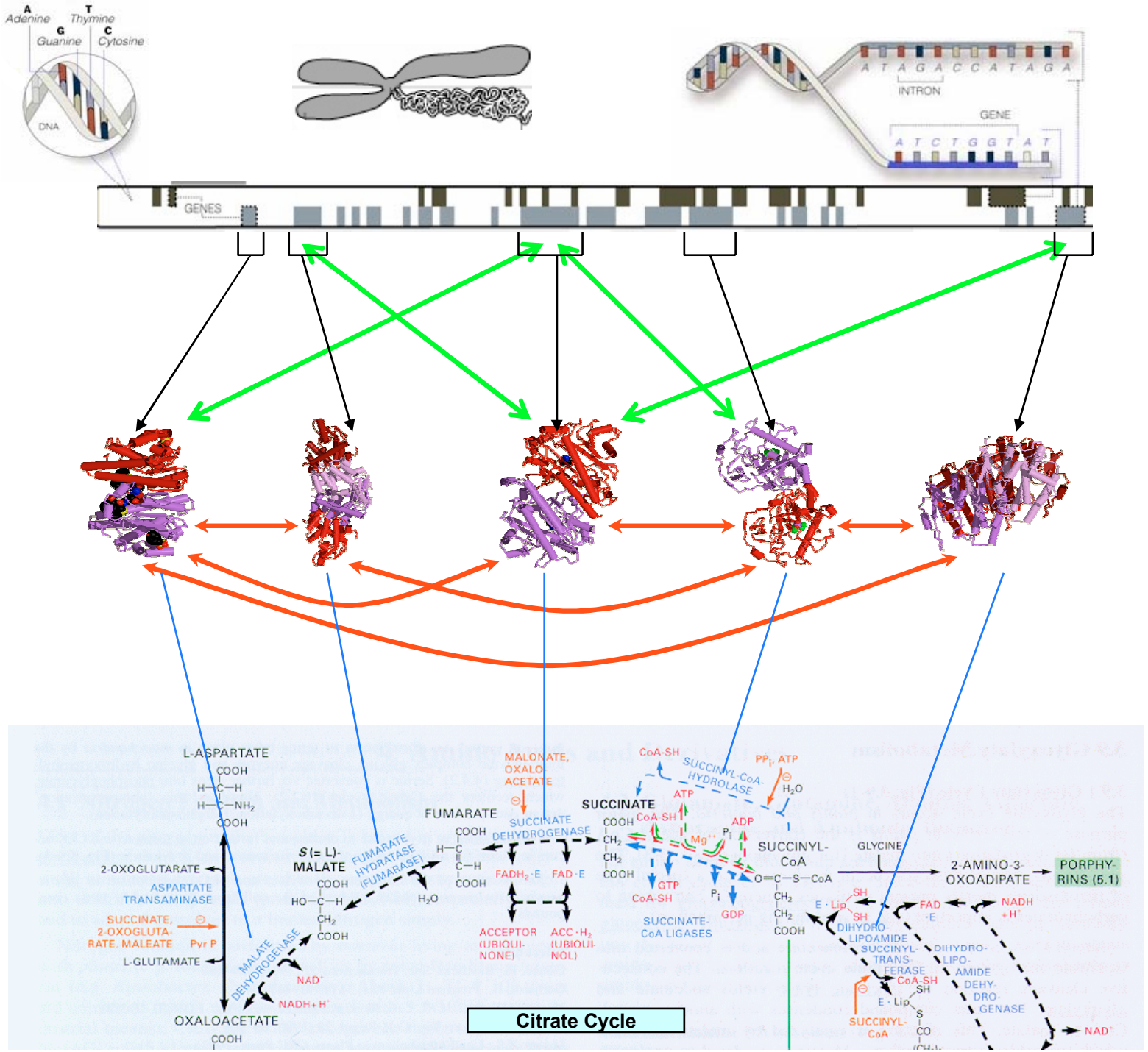
www.orgnet.com

Internet









GENOME

protein-gene interactions

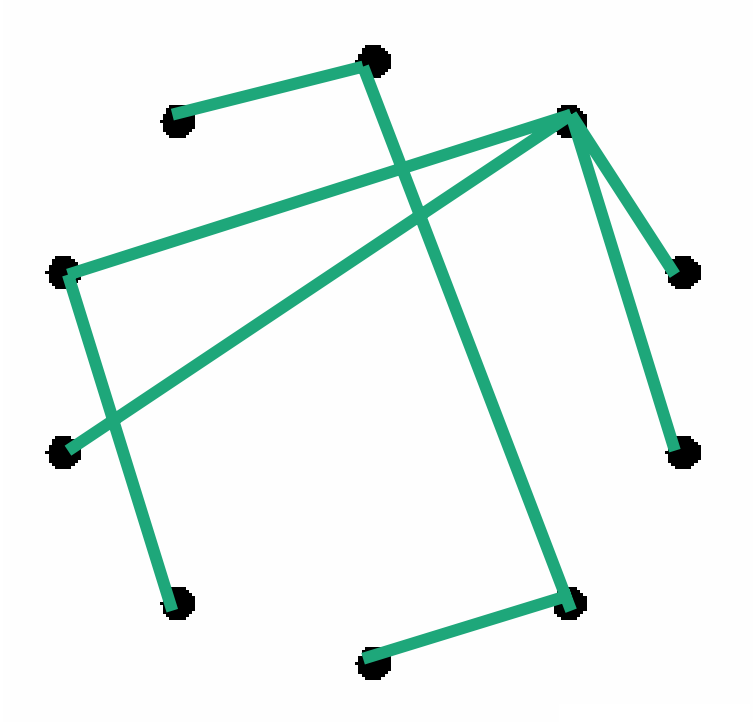
PROTEOME

protein-protein interactions

METABOLISM

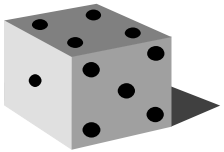
Bio-chemical reactions

Erdös-Rényi model
(1960)

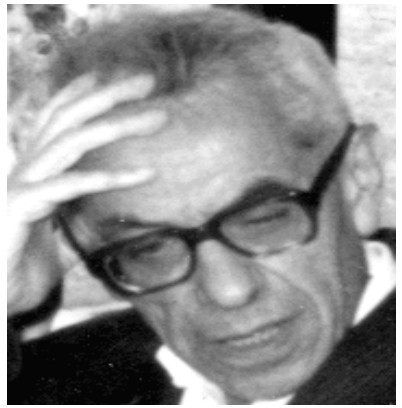


Connect with probability p

p=1/6
N=10 ⟨k⟩
~ 1.5

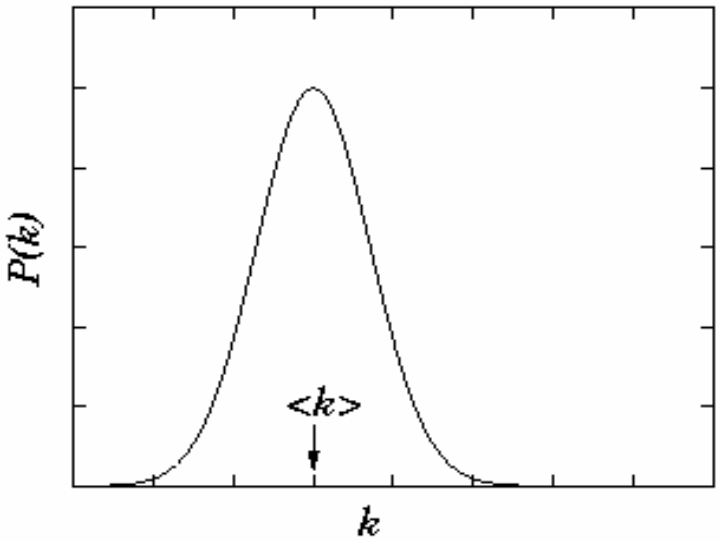


- **Democratic**
- **Random**



Pál Erdös
(1913-1996)

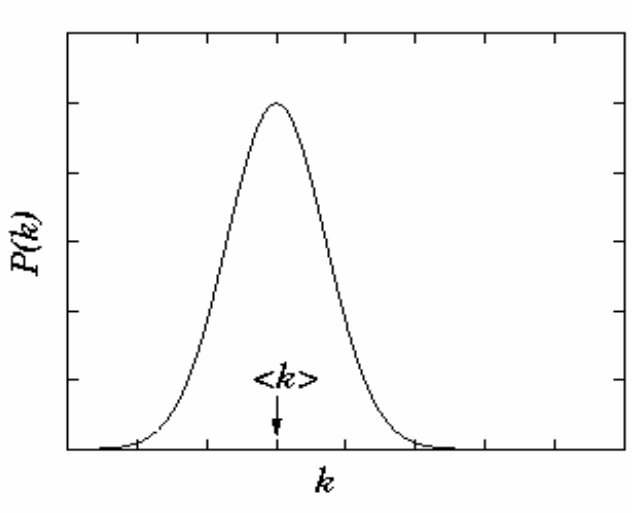
Poisson distribution



World Wide Web

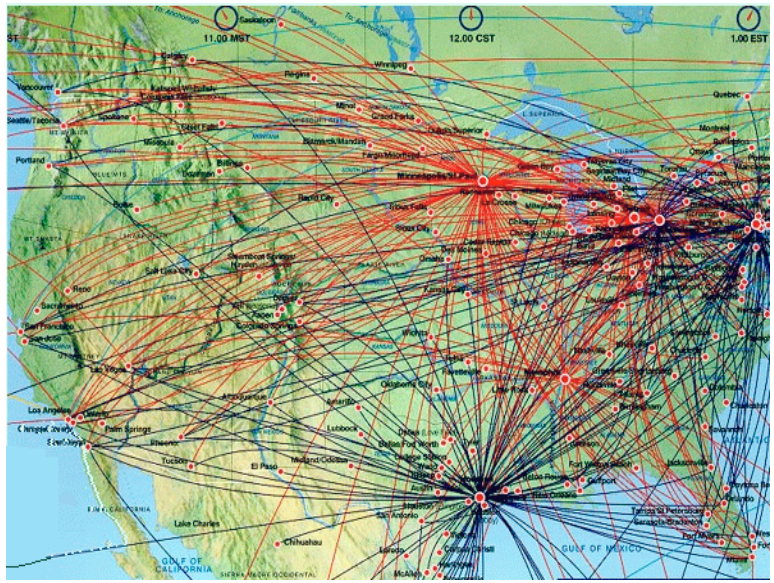
Exponential Network

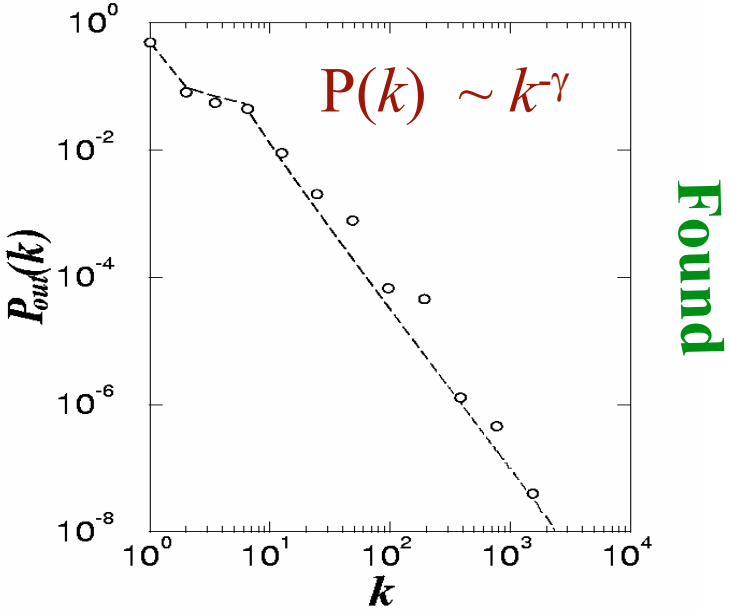
ound
em



Expected

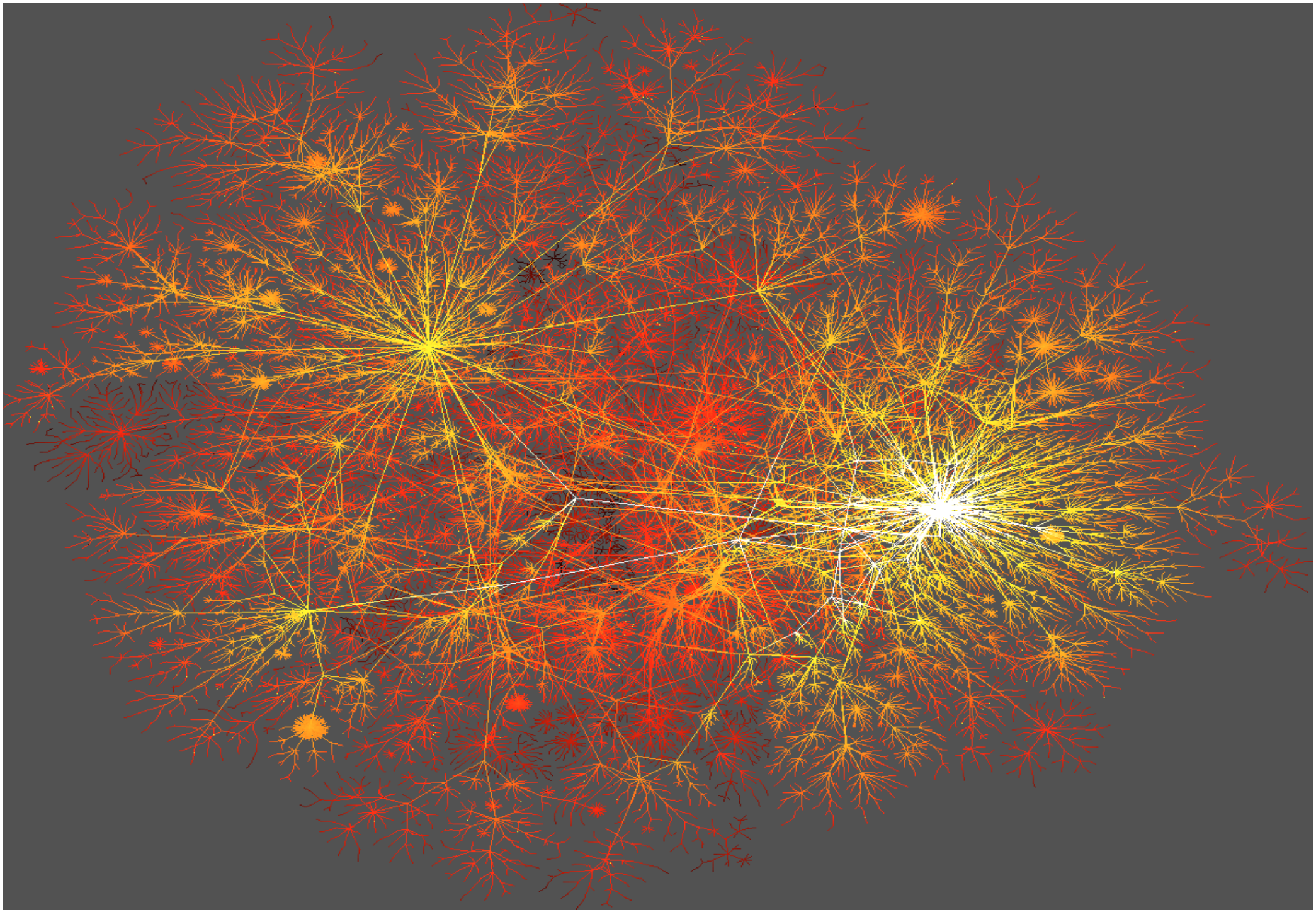
Scale-free Network

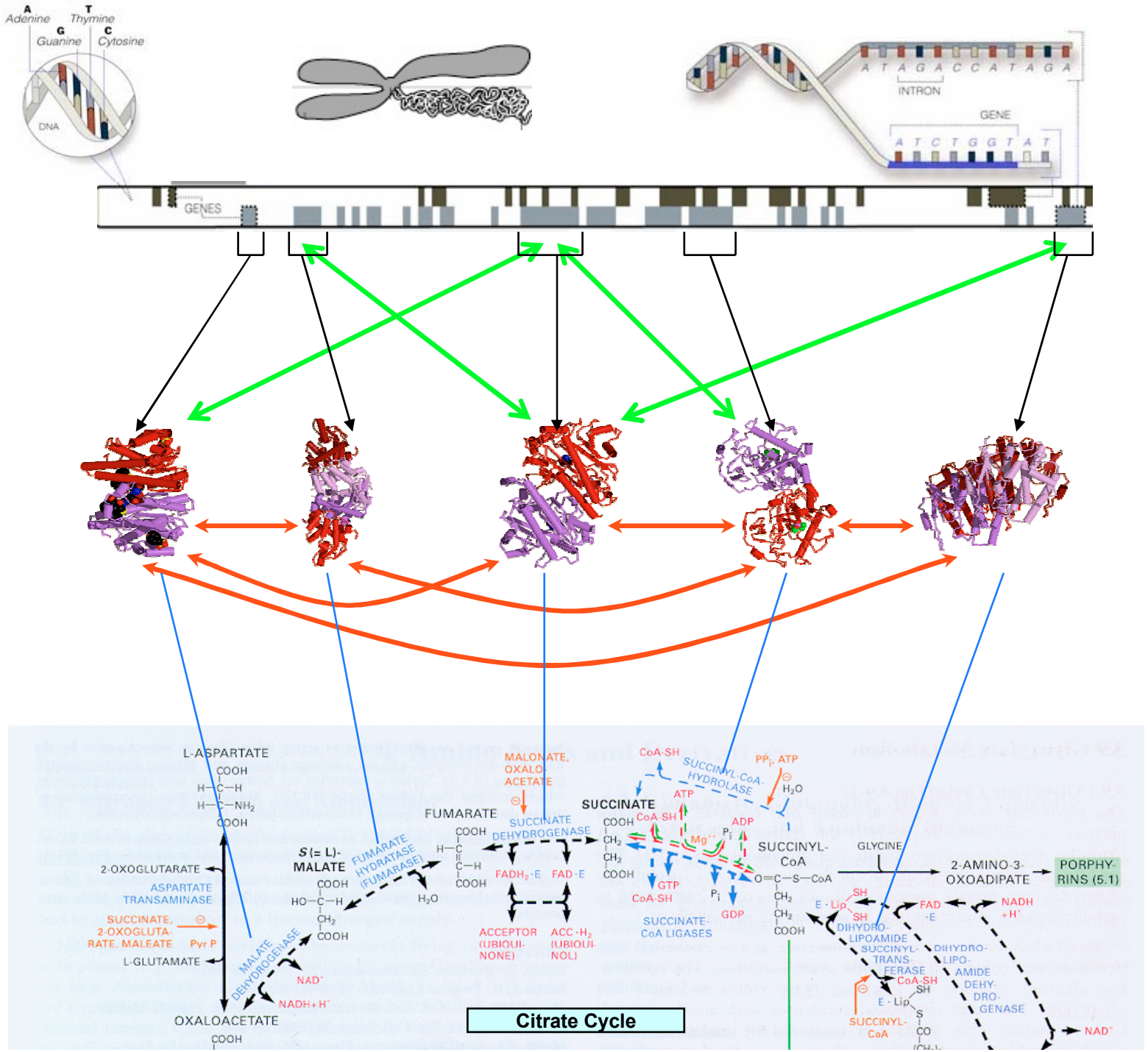




Found

R. Albert, H. Jeong, A-L Barabasi, *Nature*, **401** 130 (1999).





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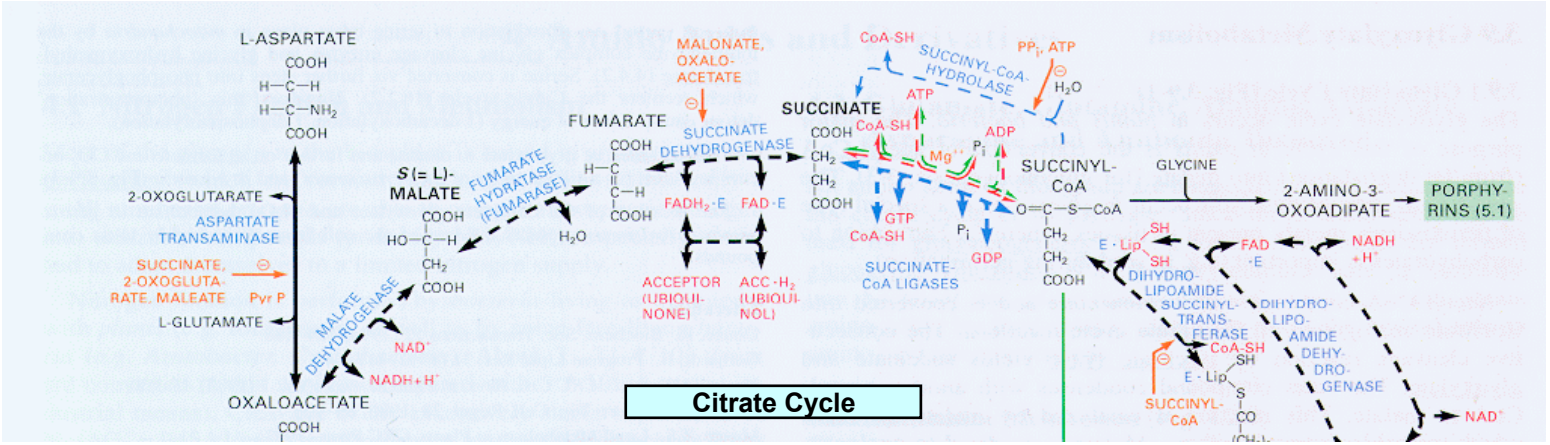
METABOLISM

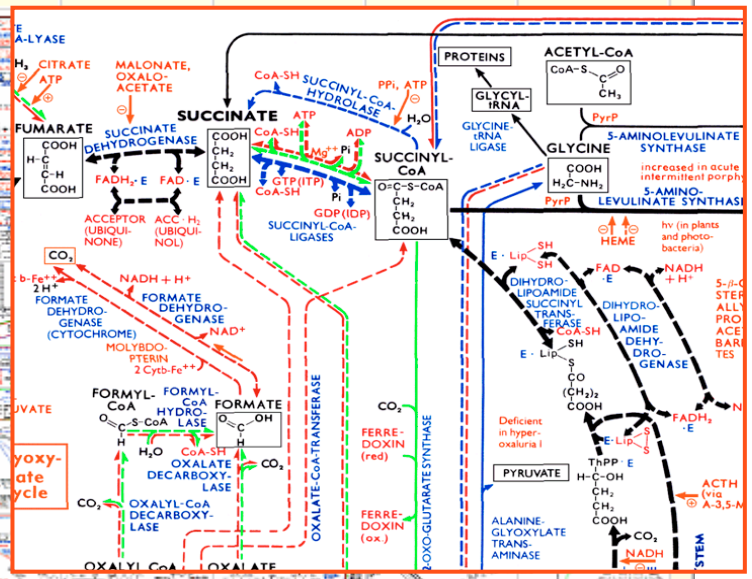
Bio-chemical reactions



METABOLISM

Bio-chemical reactions

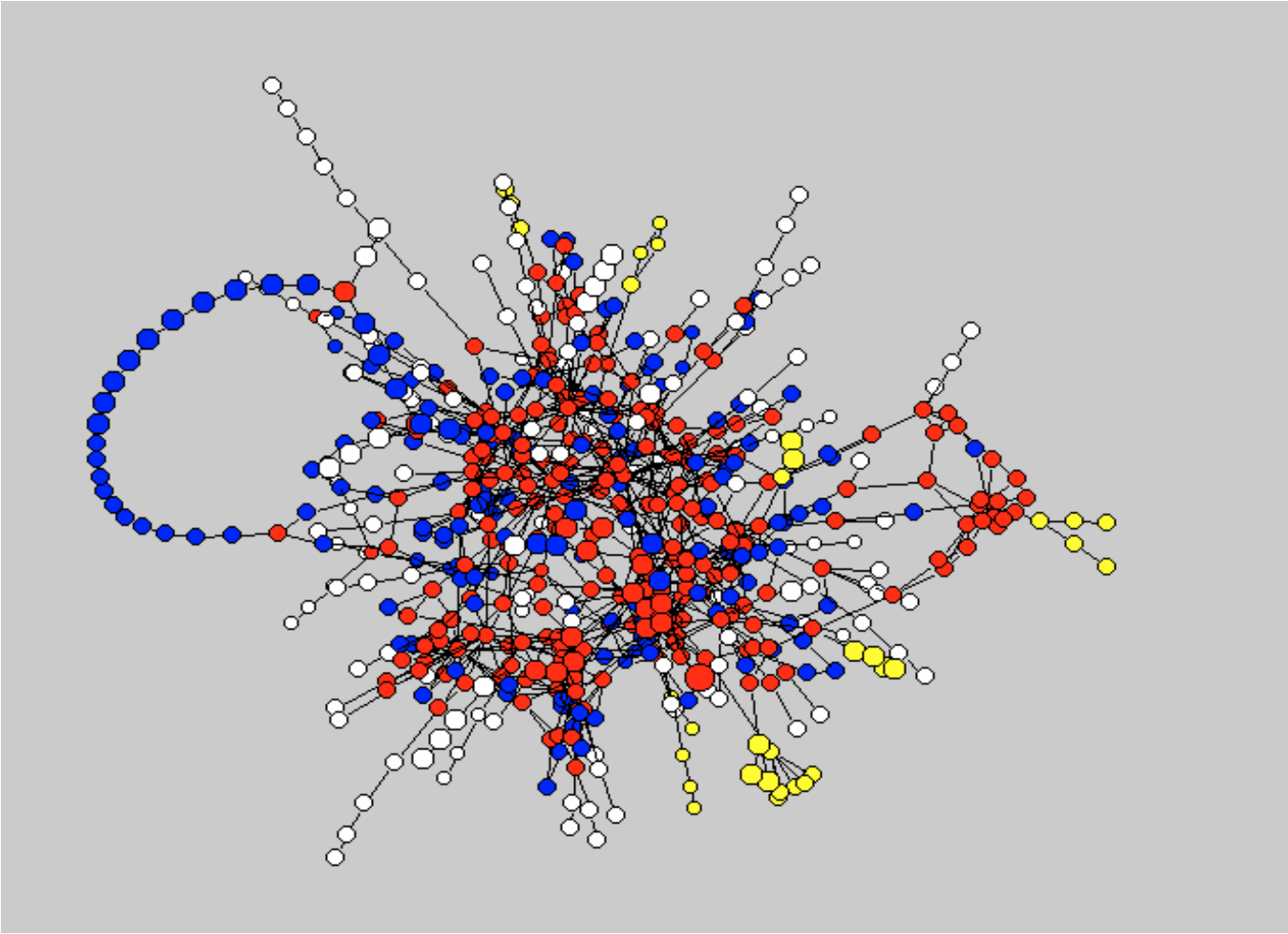
Biochemical Pathways



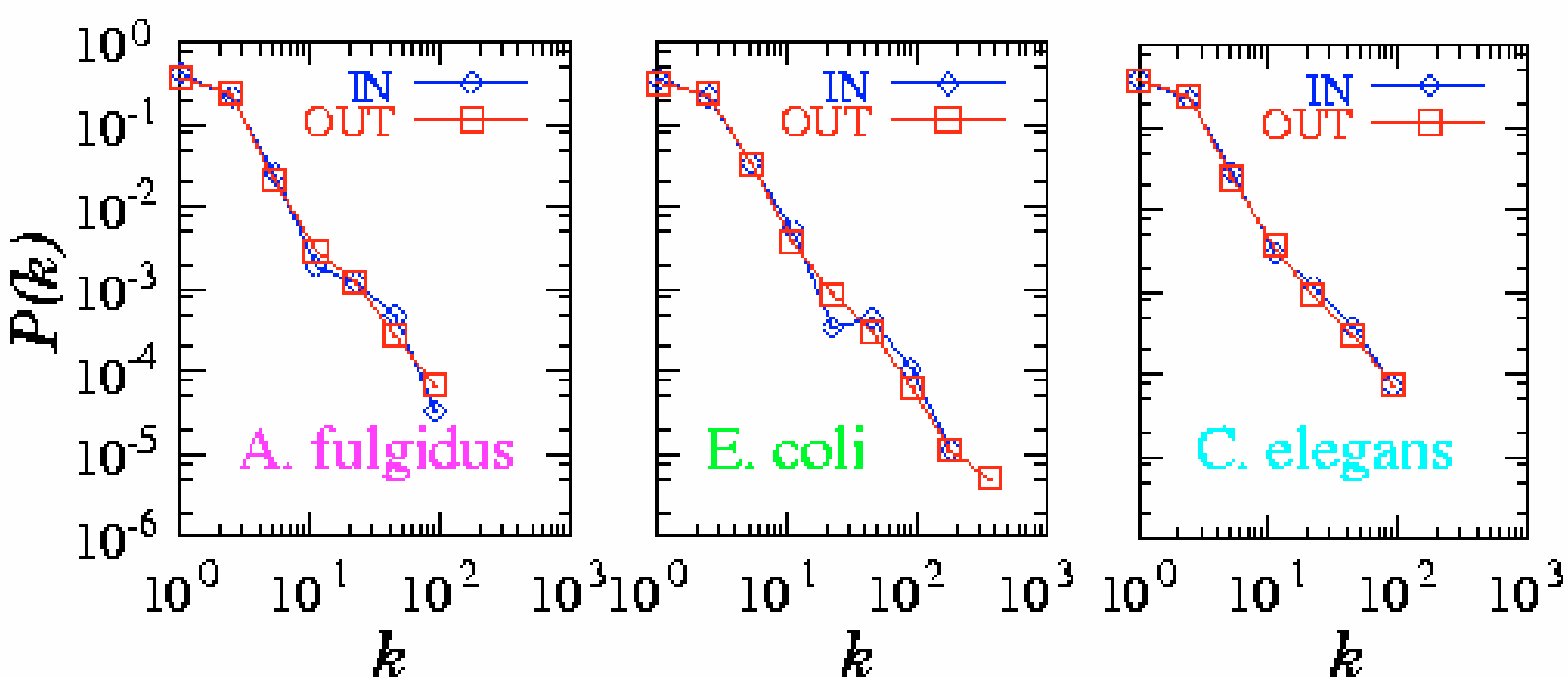
Metabolic Network

Nodes: chemicals (substrates)

Links: bio-chemical reactions



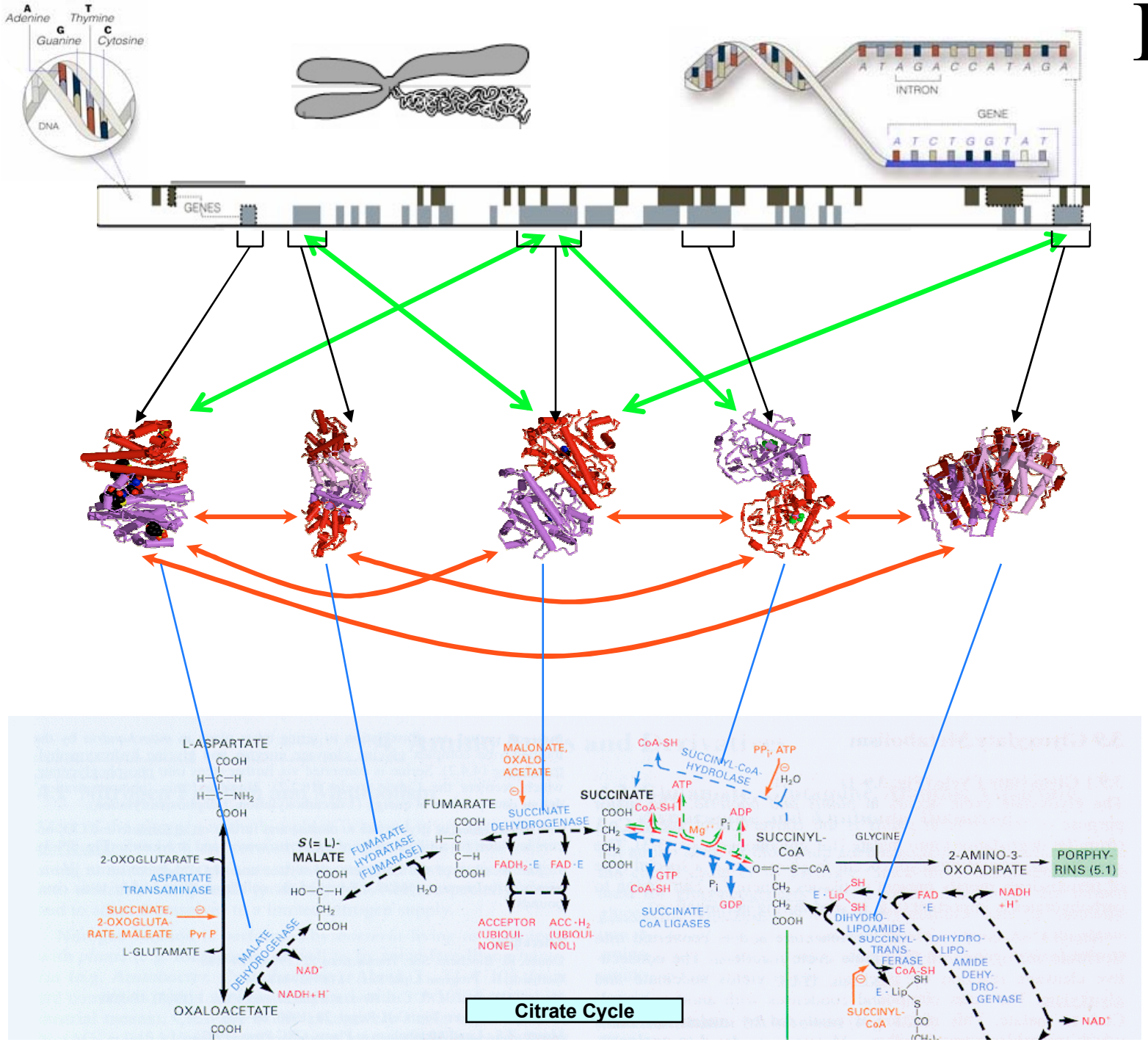
Metabolic network



Organisms from all three domains of life have a scale-free topology!

H. Jeong, B. Tombor, R. Albert, Z.N. Oltvai, and A.L. Barabasi, Nature, **407** 651 (2000)

Bio-Map



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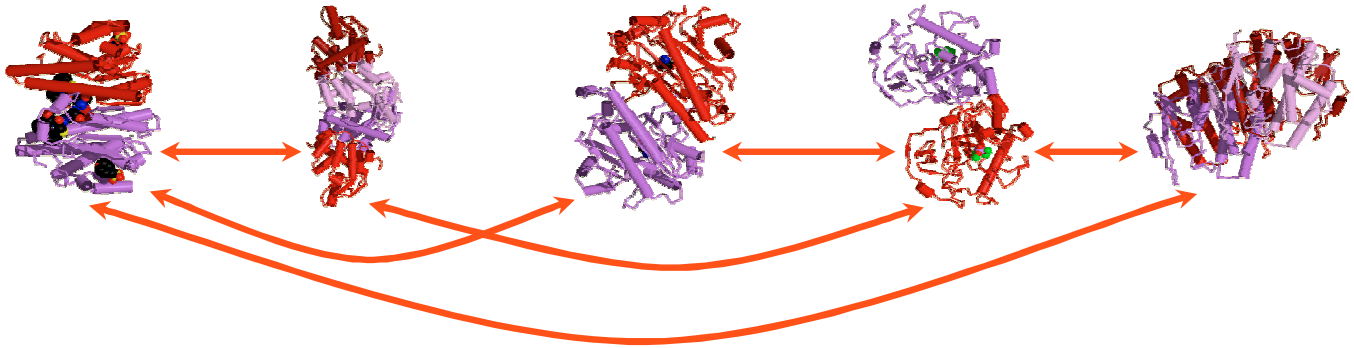
METABOLISM

Bio-chemical reactions



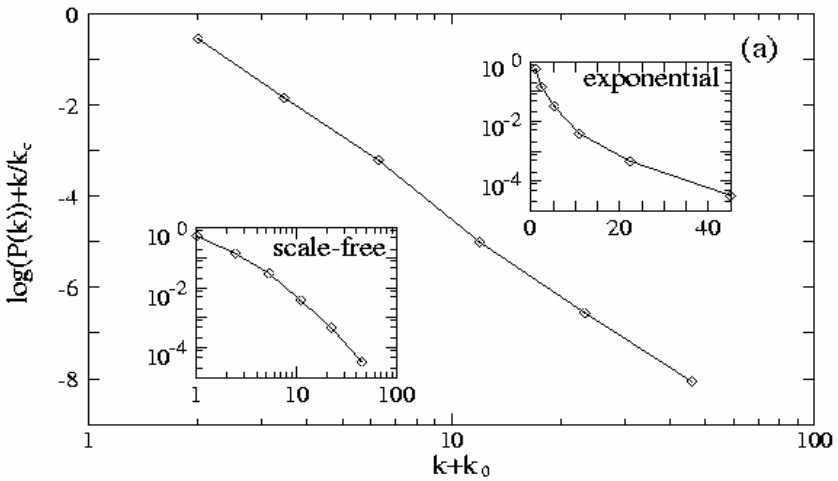
PROTEOME

protein-protein interactions

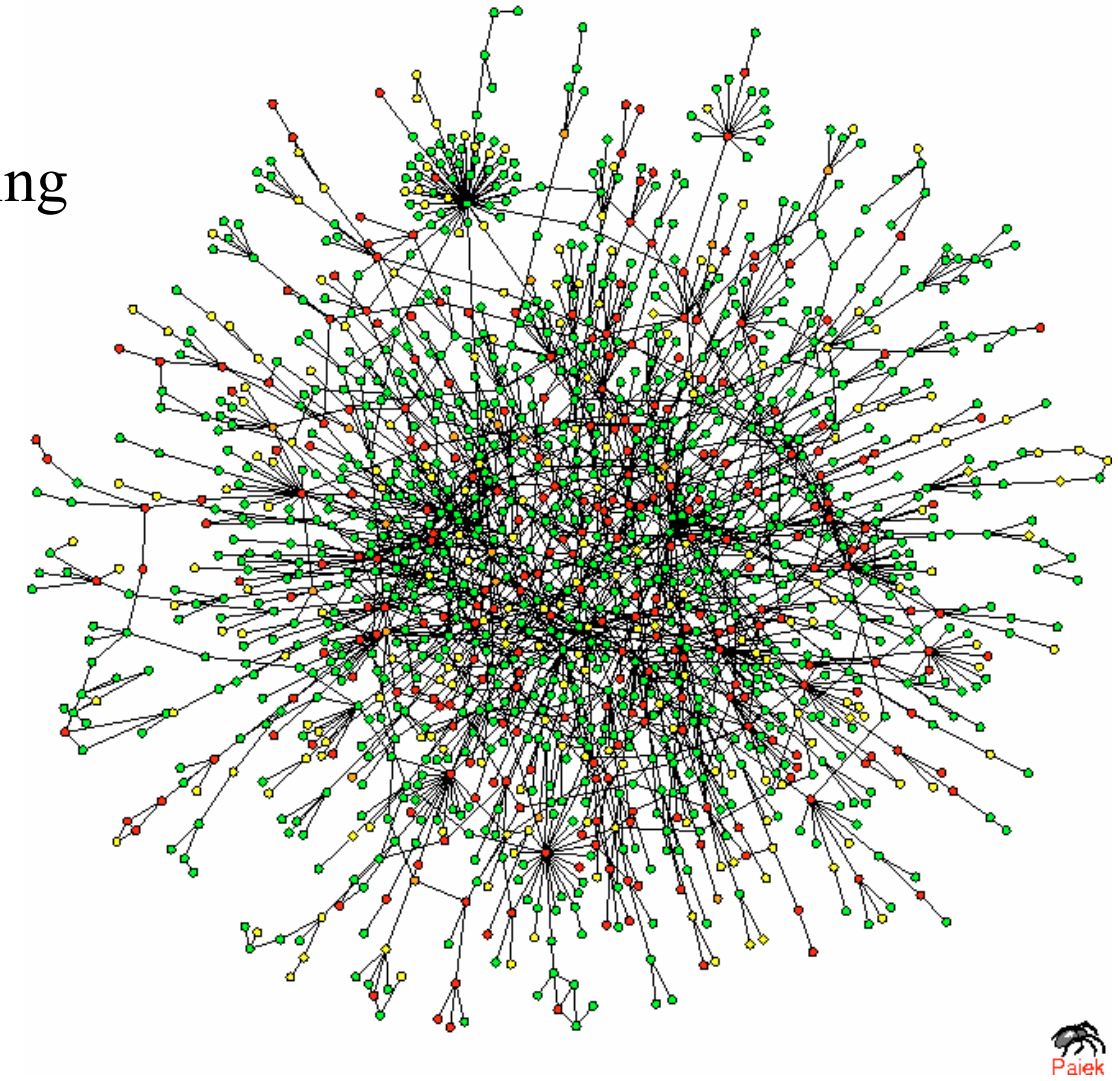
Topology of the protein network

Nodes: proteins

Links: physical interactions-binding



$$P(k) \sim (k + k_0)^{-\gamma} \exp(-\frac{k + k_0}{k_\tau})$$



H. Jeong, S.P. Mason, A.-L. Barabasi, Z.N. Oltvai, Nature 411, 41-42 (2001)

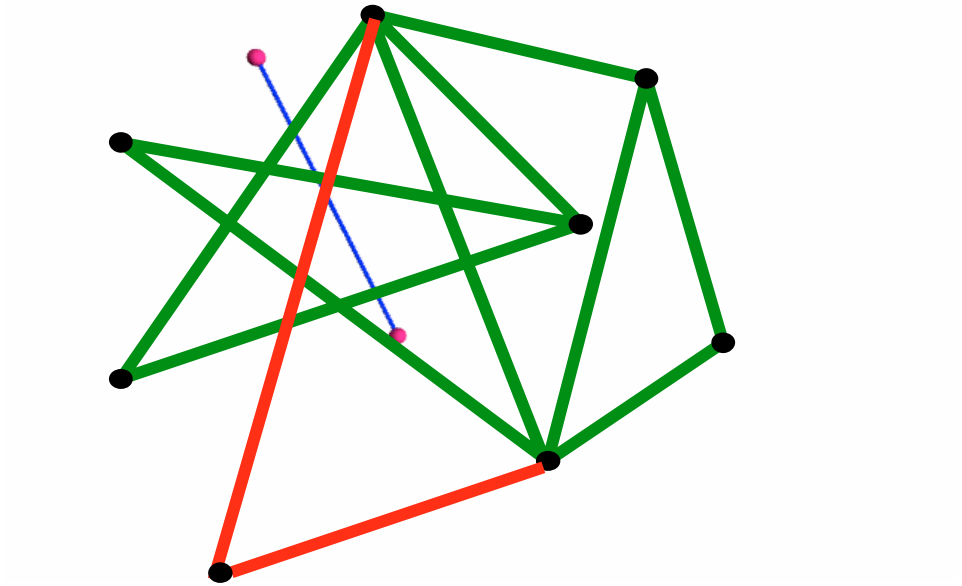
Origin of SF networks: Growth and preferential attachment

(1) Networks continuously expand by the addition of new nodes

WWW : addition of new documents

(2) New nodes prefer to link to highly connected nodes.

WWW : linking to well known sites



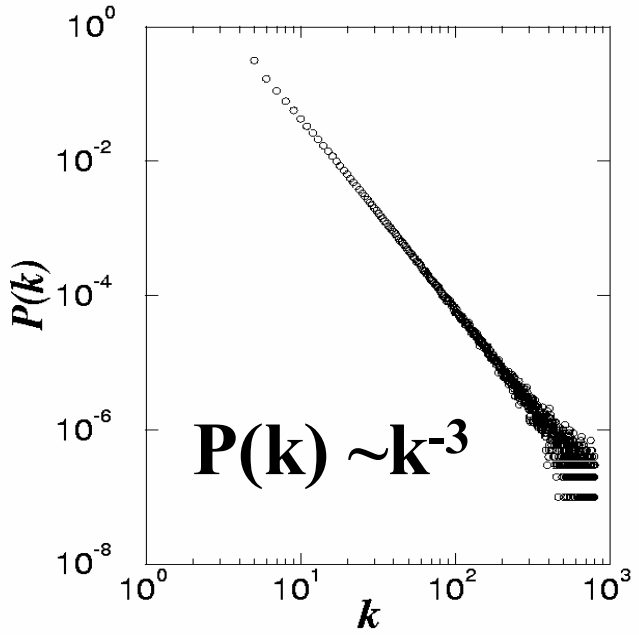
Barabási & Albert, *Science* **286,** 509 (1999)

GROWTH:

add a new node with m links

PREFERENTIAL ATTACHMENT: the probability that a node connects to a node with k links is proportional to k.

$$\Pi(k_i) = \frac{k_i}{\Sigma_j k_j}$$



Can Latecomers Make It? Fitness Model

SF model: $k(t) \sim t^{1/2}$ ⟶ (first mover advantage)

Real systems: nodes compete for links -- ***fitness***

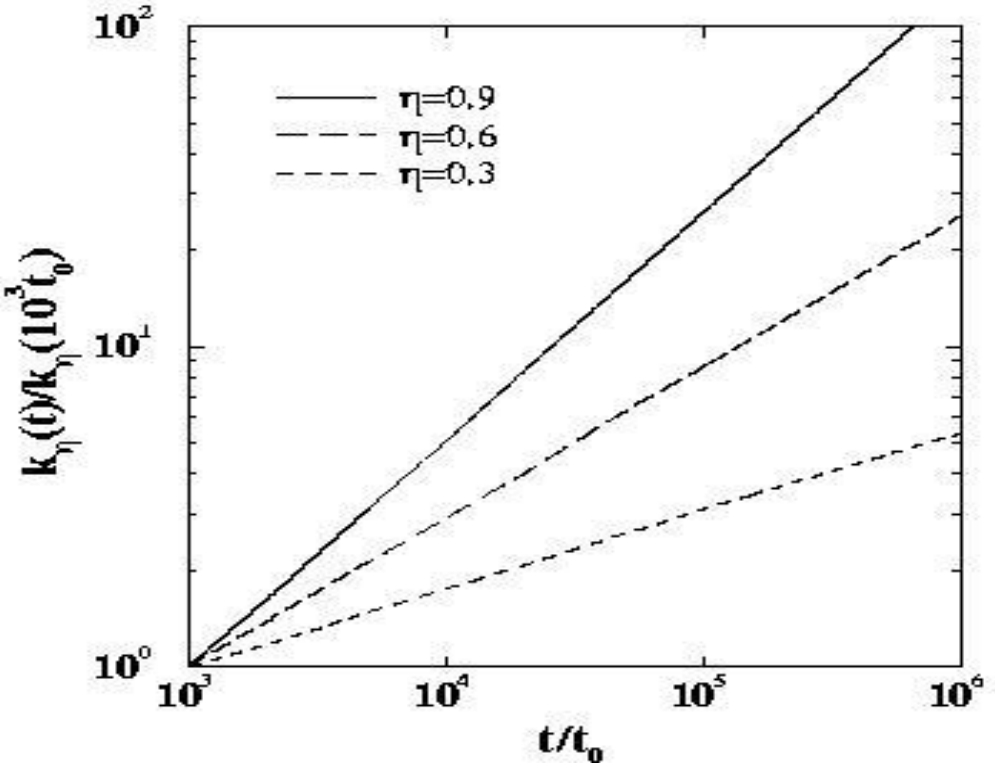
Fitness Model: fitness (η)

$$\Pi(k_i) \cong \frac{\eta_i k_i}{\sum_j \eta_j k_j}$$

$$k(\eta,t) \sim t^{\beta(\eta)}$$

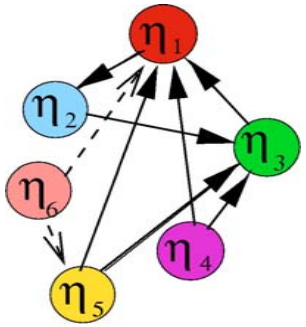
where

$$\beta(\eta) = \eta/C \qquad \int d\eta \rho(\eta) \frac{1}{C/\eta - 1} = 1$$



Bose-Einstein Condensation in Evolving Networks

Network



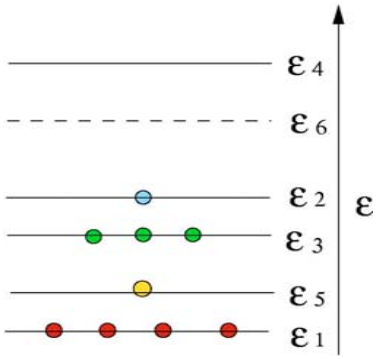
$$\Pi_i = \frac{\eta_i k_i}{\Sigma_j \eta_j k_j}$$

$$\eta \longrightarrow e^{-\beta\varepsilon}$$

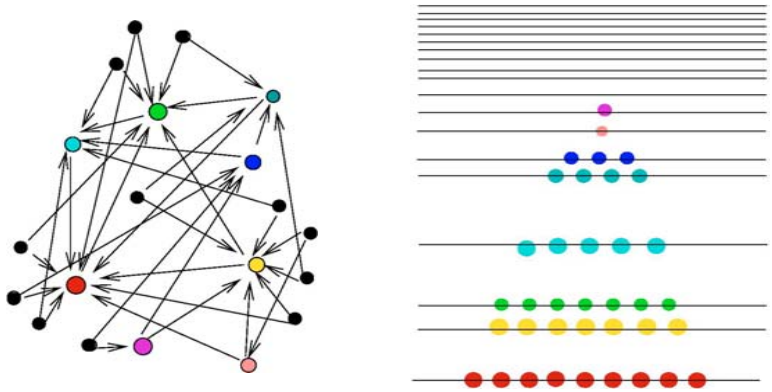
$$k_{in}(\eta) \longrightarrow n(\varepsilon) = \frac{1}{e^{-\beta\varepsilon} - 1}$$

$$\rho(\eta) \longrightarrow g(\varepsilon)$$

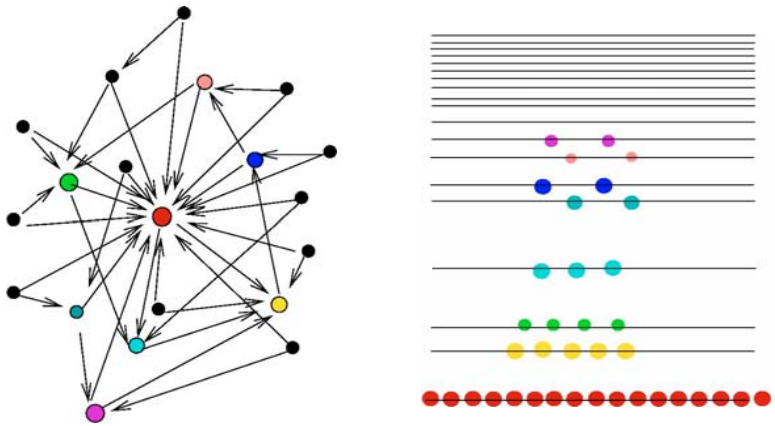
Bose gas



Fit-gets-rich

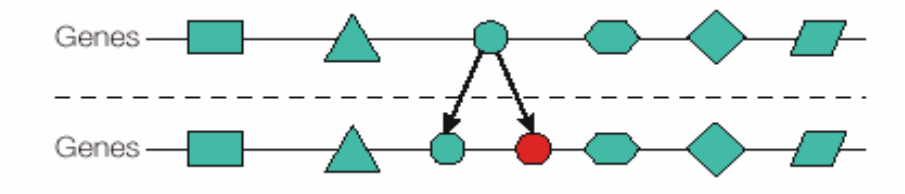


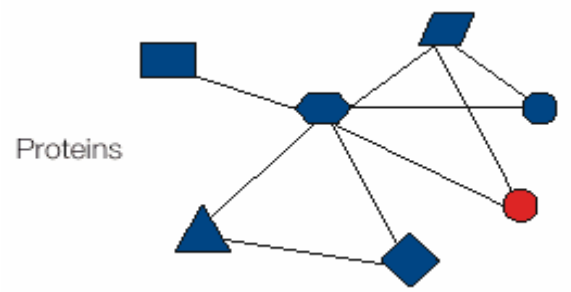
Bose-Einstein condensation



G. Bianconi and A.-L. Barabási, *Physical Review Letters* 2001; *Europhys. Lett.* 2001.

Origin of the scale-free topology in the cell: Gene Duplication





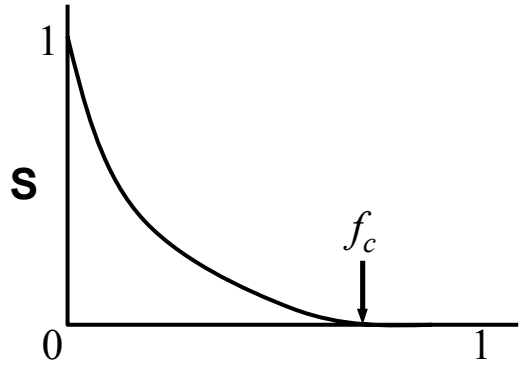
Proteins with more interactions are more likely to obtain new links:

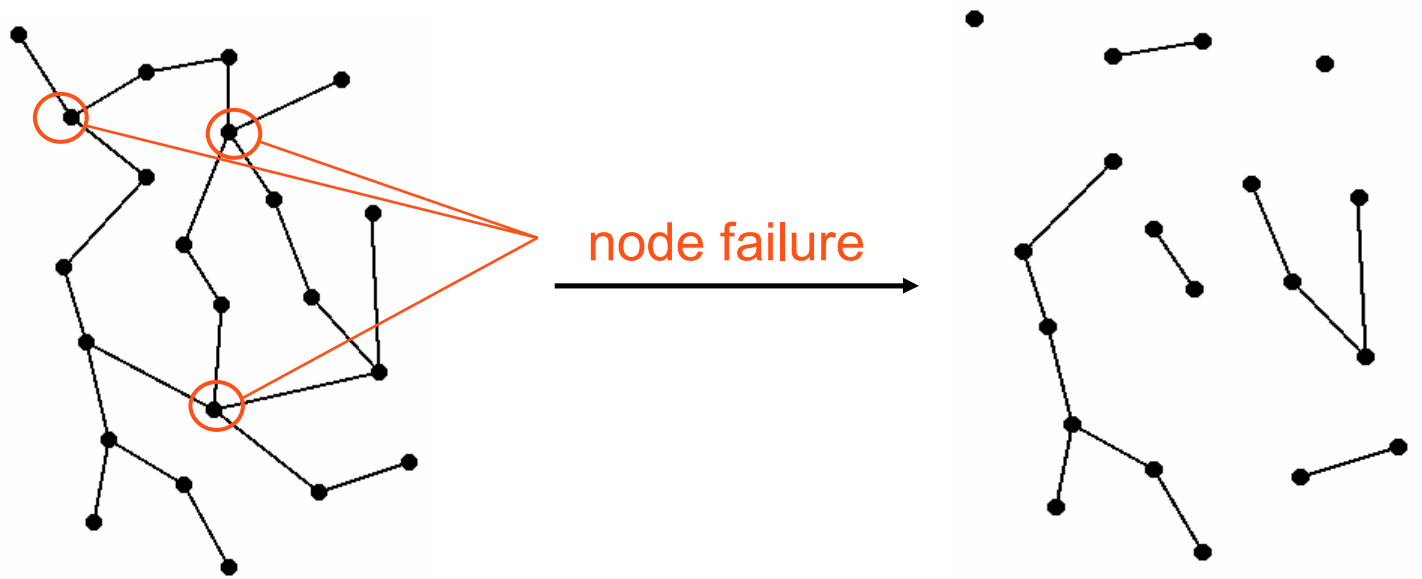
$\Pi(k) \sim k$ (preferential attachment)

Wagner 2001; Vazquez *et al.* 2003; Sole *et al.* 2001; Rzhetsky & Gomez 2001; Qian et al. 2001; Bhan *et al.* 2002.

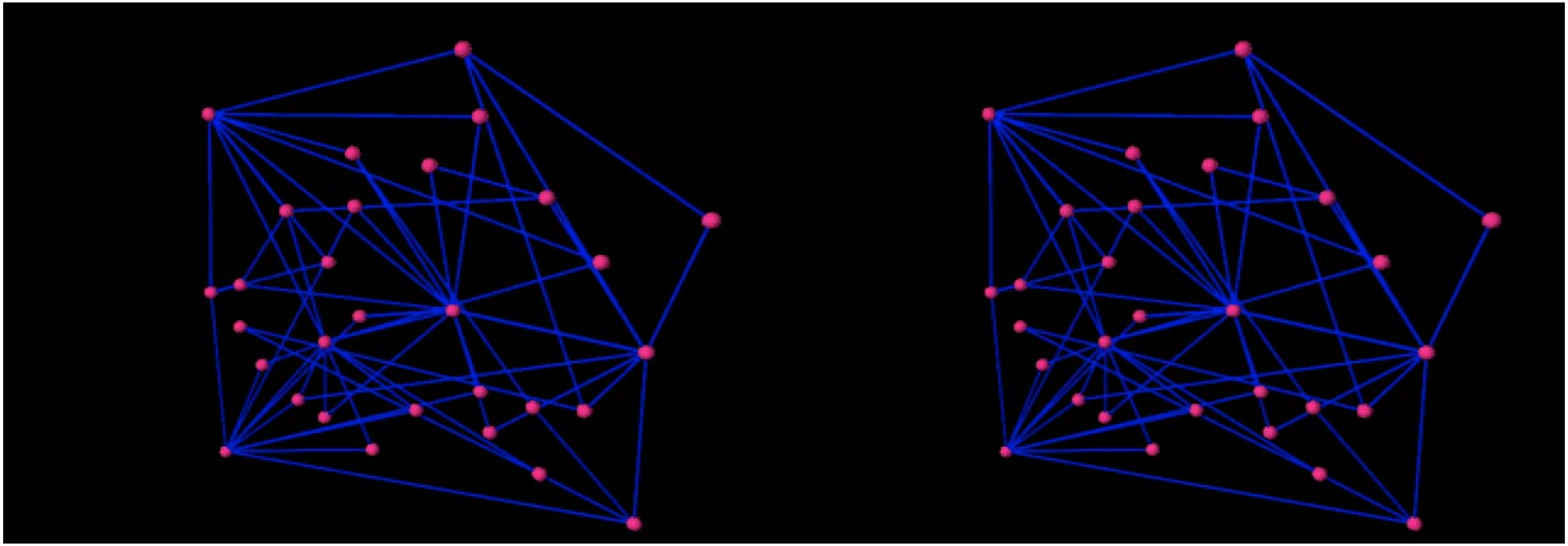
Robustness

Complex systems maintain their basic functions
even under errors and failures
(cell → mutations; Internet → router breakdowns)

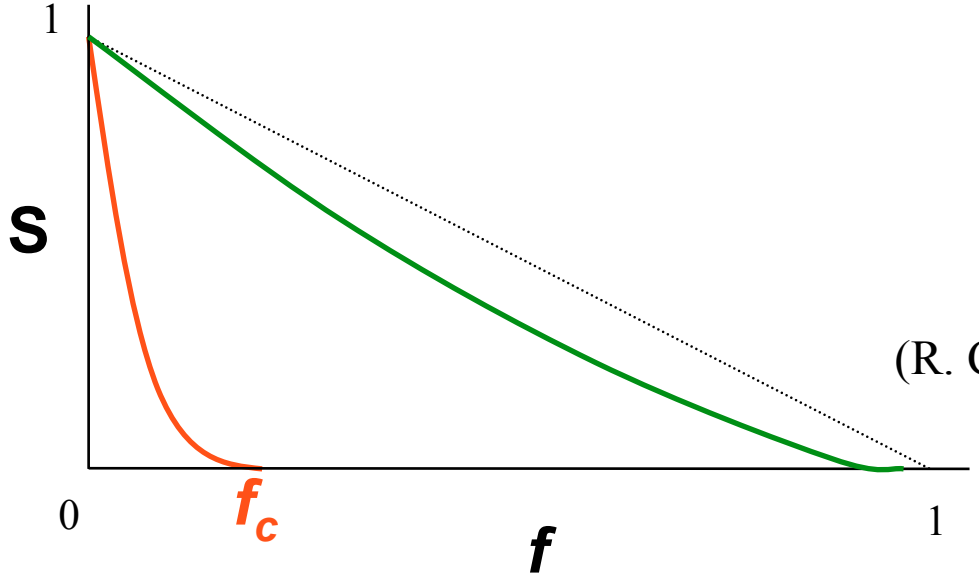




Robustness of scale-free networks



Attacks



Failures

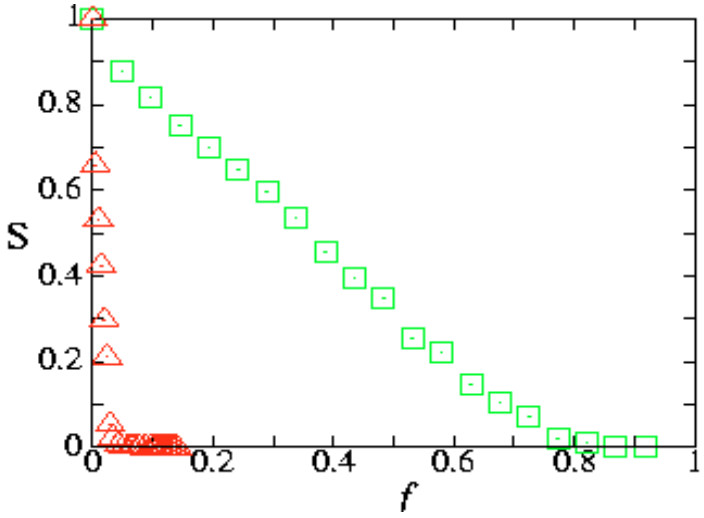
$\gamma \leq 3 : f_c=1$

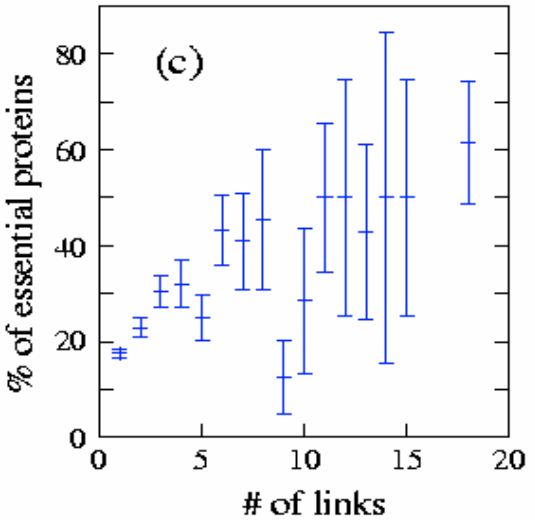
(R. Cohen et al PRL, 2000)

Albert, Jeong, Barabasi, *Nature* **406** 378 (2000); H

Yeast protein network

- lethality and topological position -





Highly connected proteins are more **essential (lethal)**...

H. Jeong, S.P. Mason, A.-L. Barabasi, Z.N. Oltvai, Nature 411, 41-42 (2001)

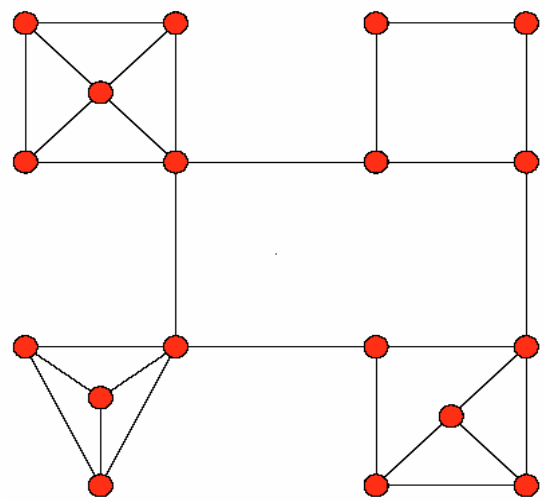
Modularity in Cellular Networks

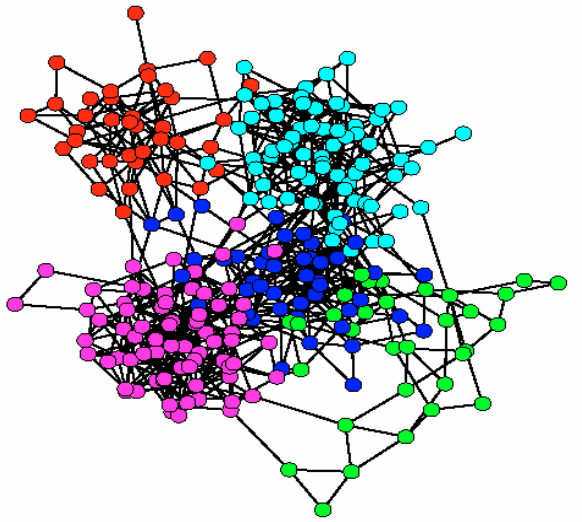
- Hypothesis:

  Biological function are carried by discrete functional modules.

❖Hartwell, L.-H., Hopfield, J. J., Leibler, S., & Murray, A. W. (1999).

- Traditional view of modularity:

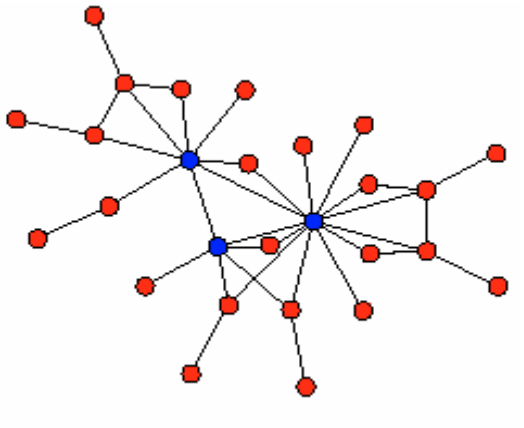




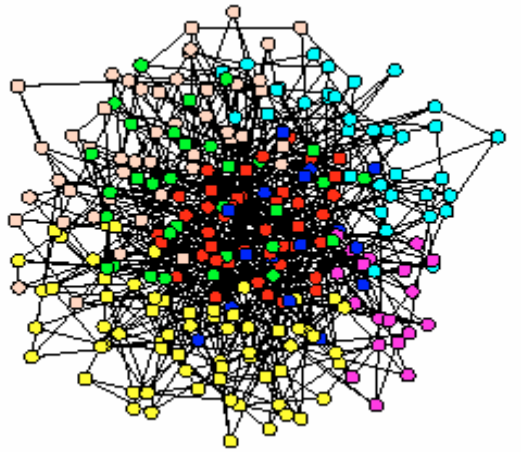
- Question: Is modularity a myth, or a structural property of biological networks?
  (are biological networks fundamentally modular?)

Modular vs. Scale-free Topology

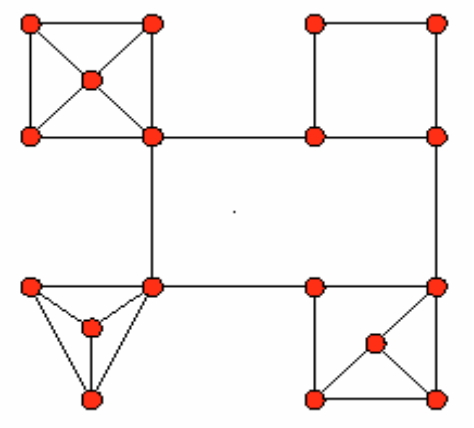
(a)



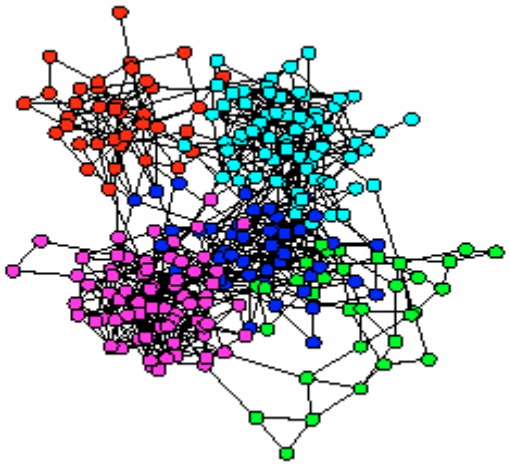
Scale-free



(b)



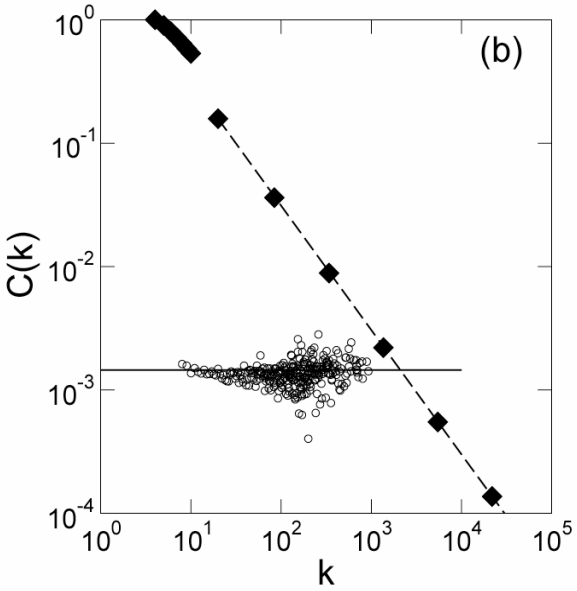
Modular

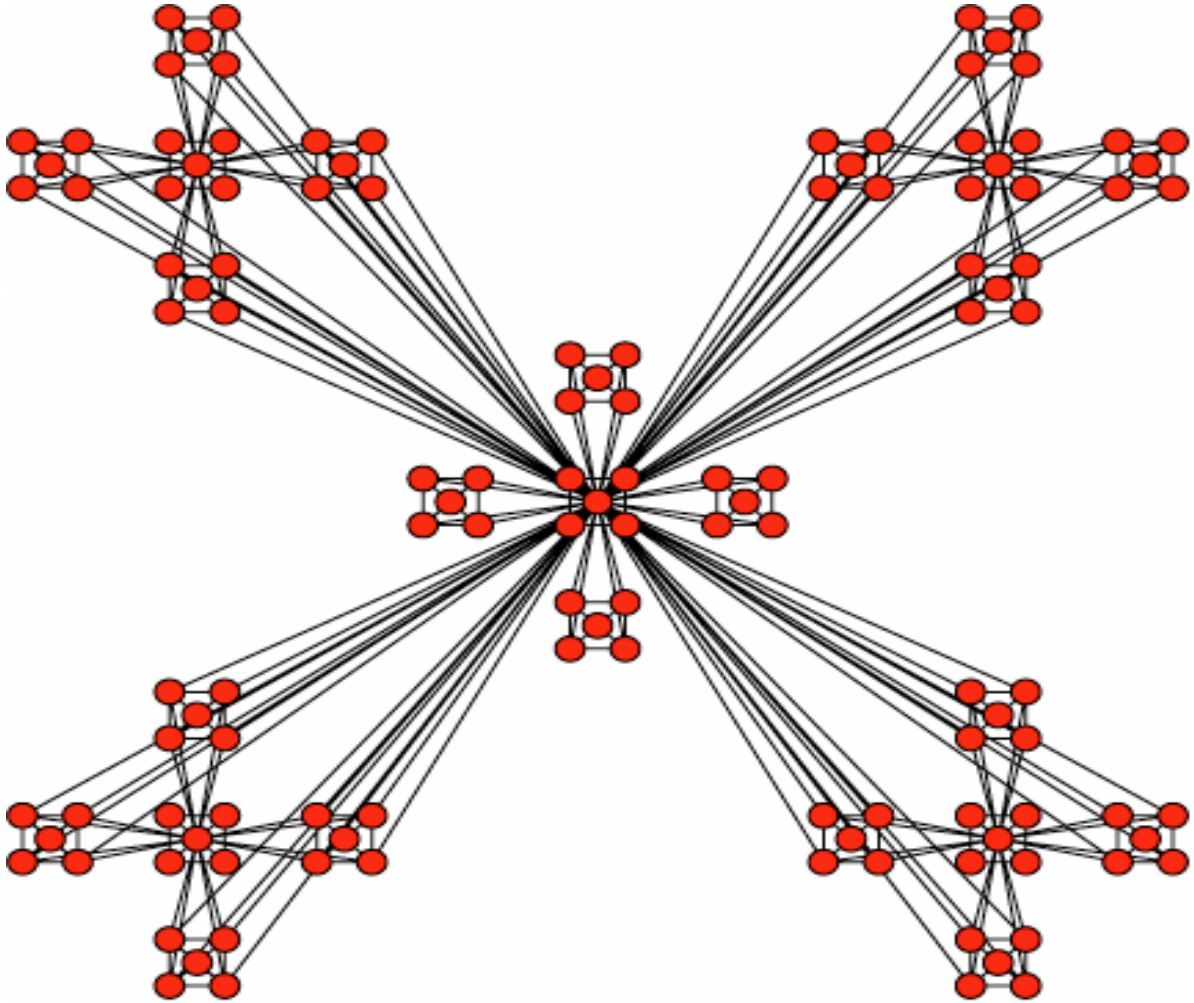


Hierarchical Networks

3. Clustering coefficient scales

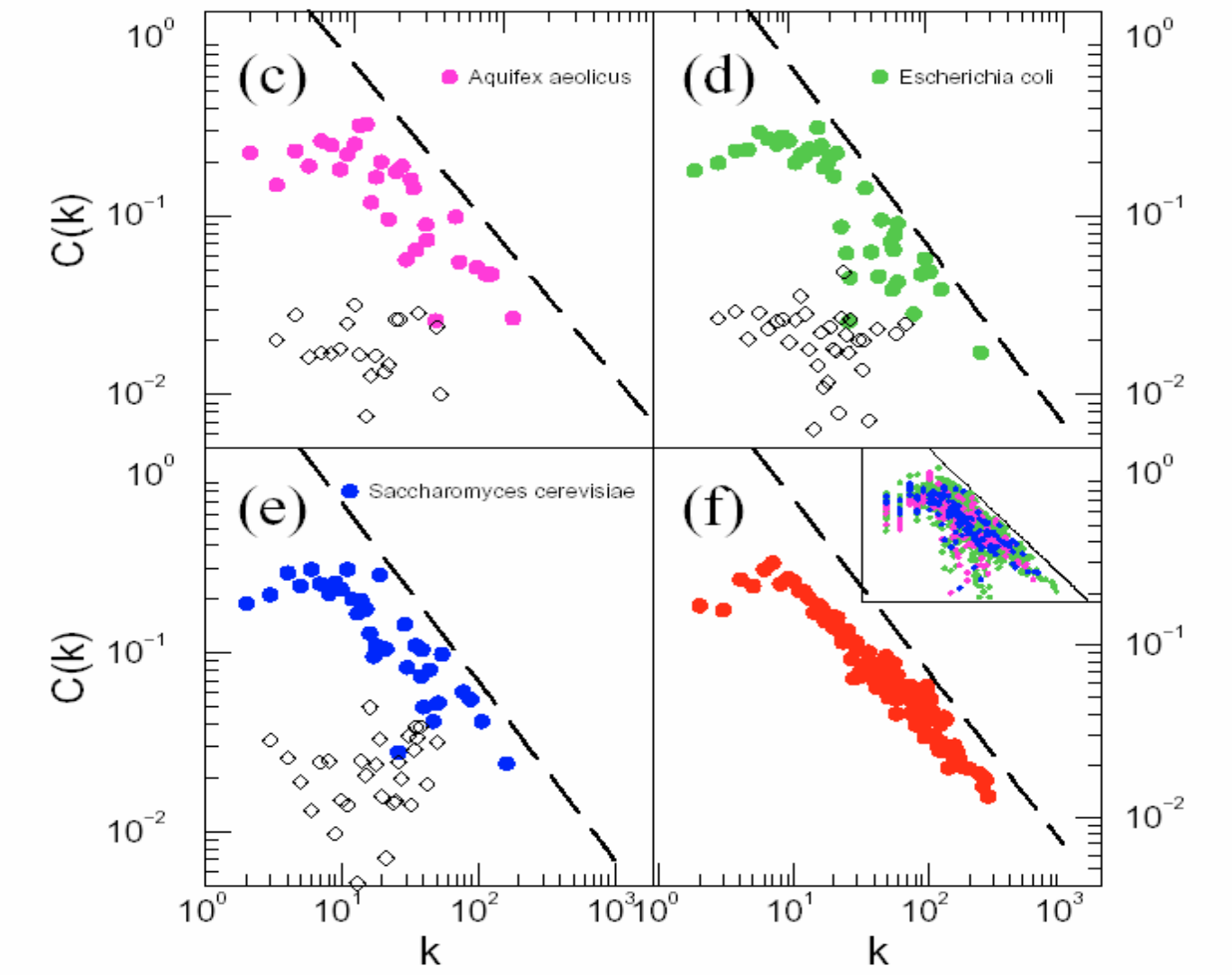
$$C(k) \sim k^{-1}$$





$$C(k) = \frac{\text{\# links between k neighbors}}{k(k-1)/2}$$

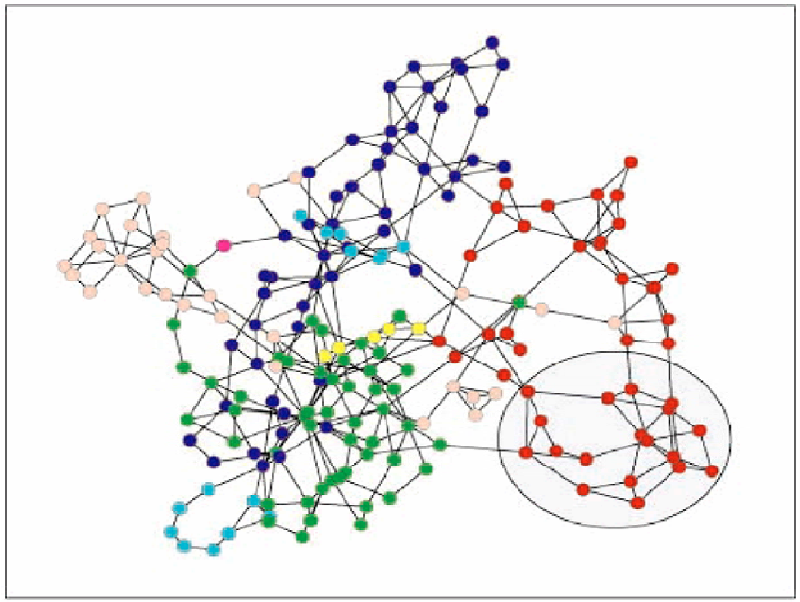
Scaling of the clustering coefficient C(k)

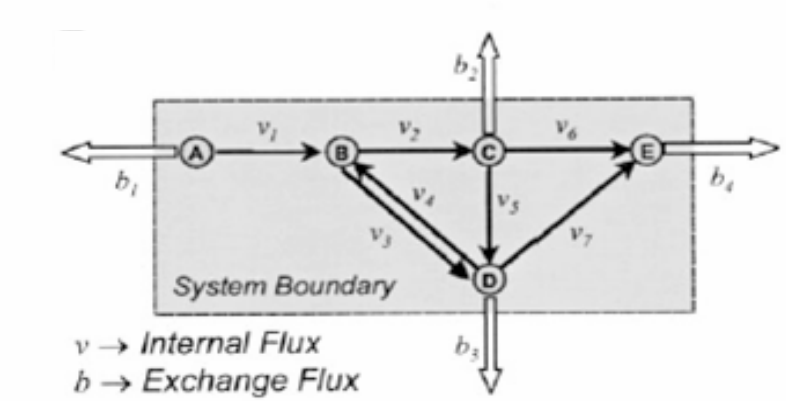


The metabolism forms a hierachical network.

Ravasz, Somera, Mongru, Oltvai, A-L. B, ***Science*** **297,** 1551 (2002).

Characterizing the links





Metabolism:
Flux Balance Analysis (Palsson)
Metabolic flux for each reaction

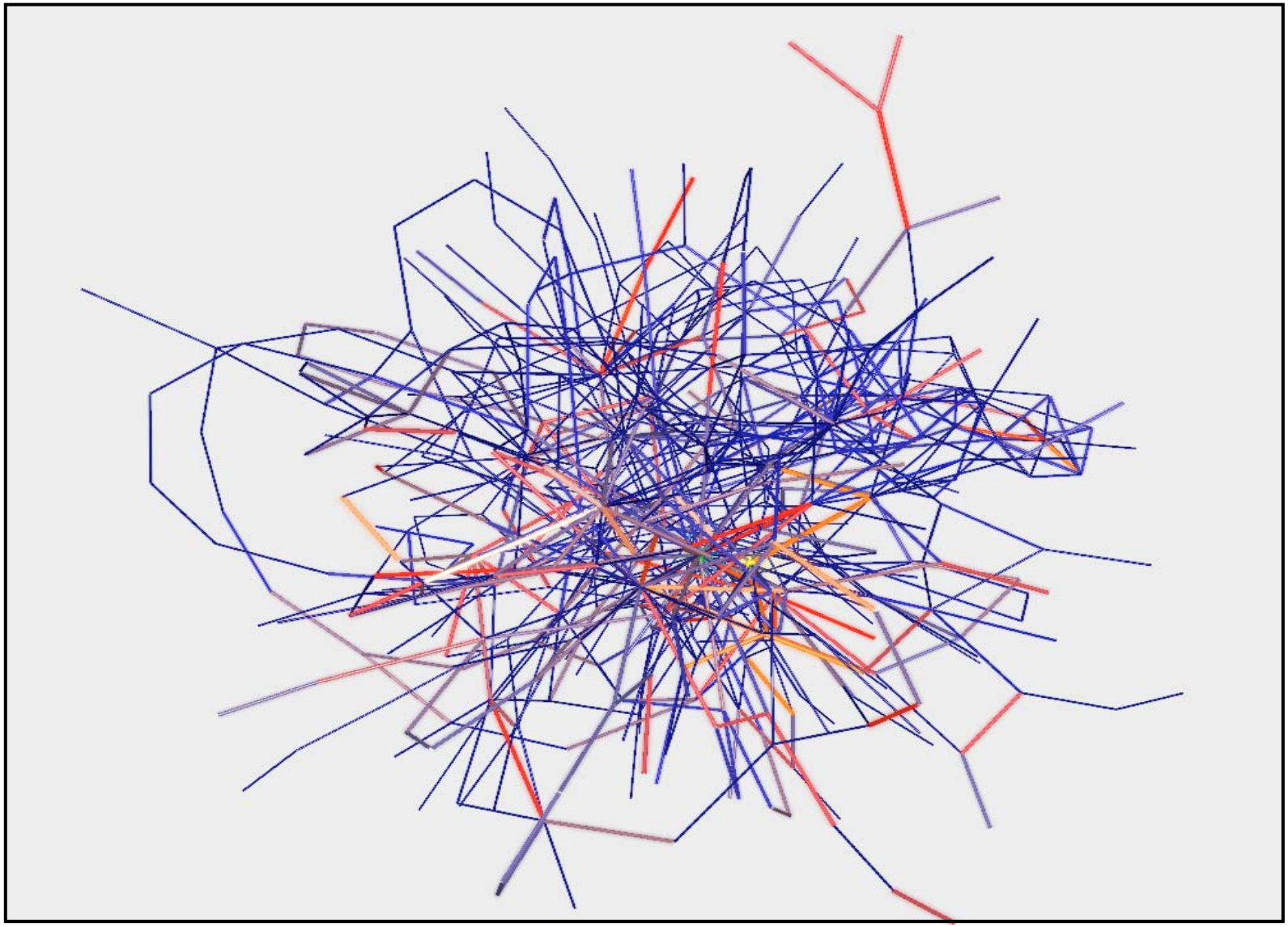
Balance Equations:

A: $-v_1 - b_1 = 0$
B: $v_1 + v_4 - v_2 - v_3 = 0$
C: $v_2 - v_5 - v_6 - b_2 = 0$
D: $v_3 + v_5 - v_4 - v_7 - b_3 = 0$
E: $v_6 + v_7 - b_4 = 0$

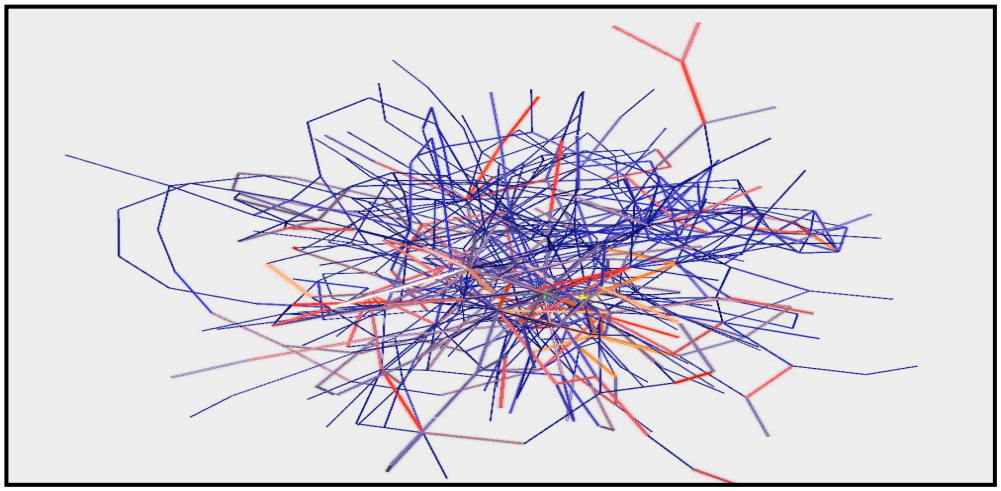
Matrix Notation
$\mathbf{S} \cdot \mathbf{v} = \mathbf{0}$

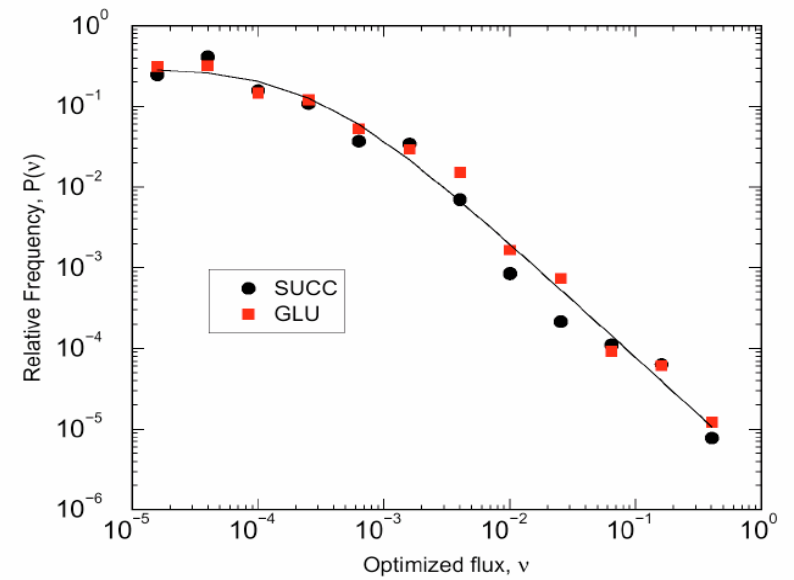
Edwards, J. S. & Palsson, B. O, *PNAS* **97**, 5528 (2000).
Edwards, J. S., Ibarra, R. U. & Palsson, B. O. *Nat Biotechnol* **19**, 125 (2001).
Ibarra, R. U., Edwards, J. S. & Palsson, B. O. *Nature* **420**, 186 (2002).

Global flux organization in the *E. coli* metabolic network

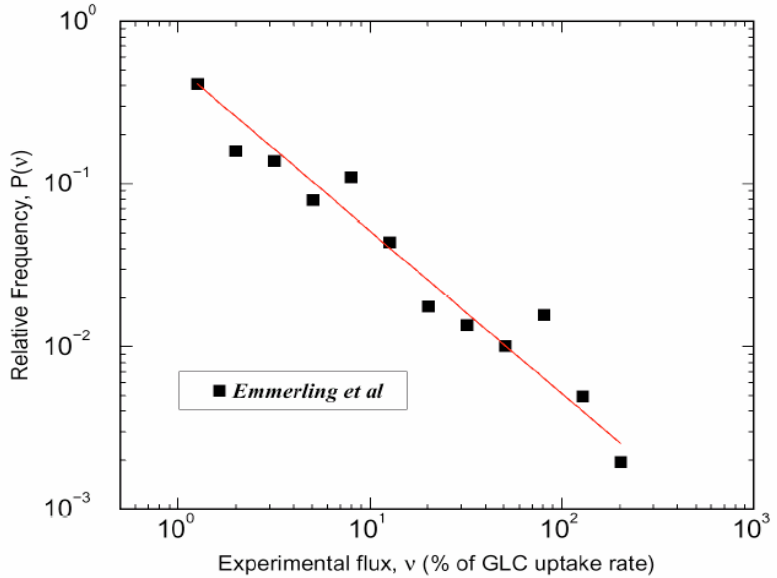


E. Almaas, B. Kovács, T. Vicsek, Z. N. Oltvai, A.-L. B. Nature, 2004.





SUCC: Succinate uptake
GLU : Glutamate uptake

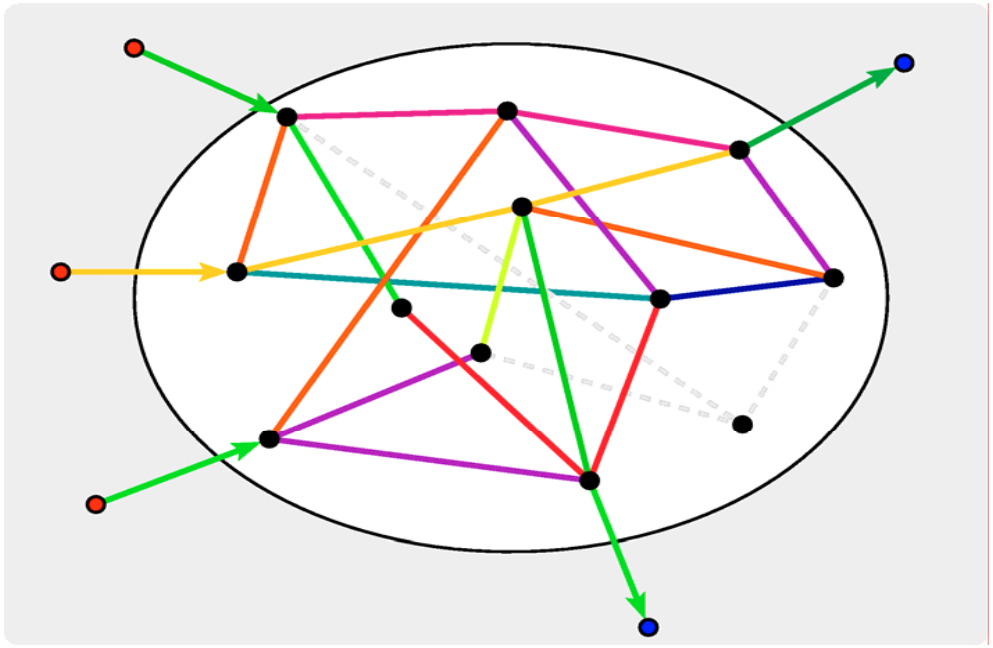


Central Metabolism,
Emmerling et. al, *J Bacteriol* **184**, 152 (2002)

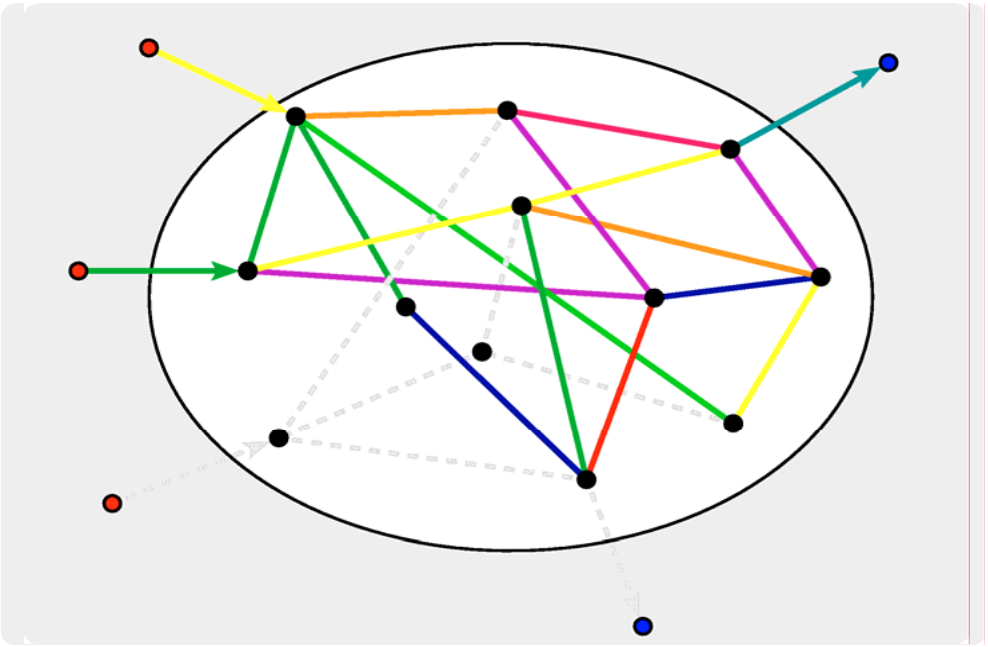
Network Plasticity

How does the metabolic network adapt to environmental changes?

Flux plasticity
(changes in flux rates)

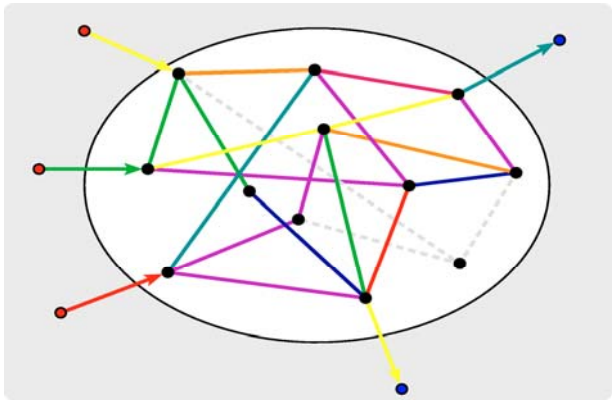


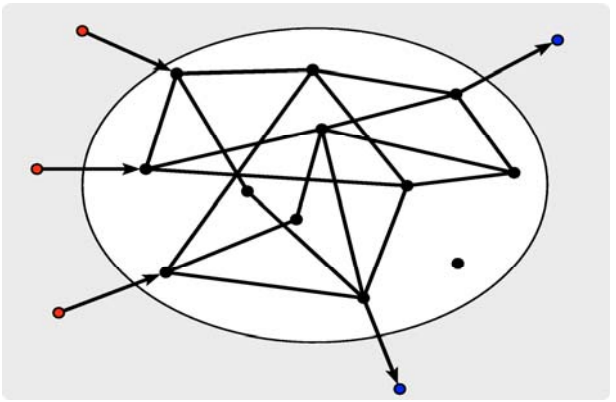
Structural plasticity
(reaction [de-] activation)



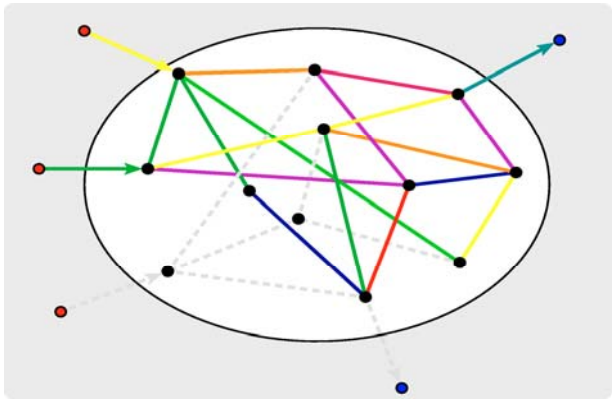
The Metabolic Core

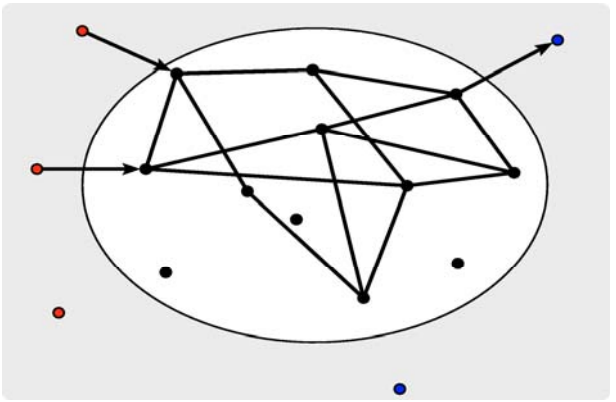
Condition 1



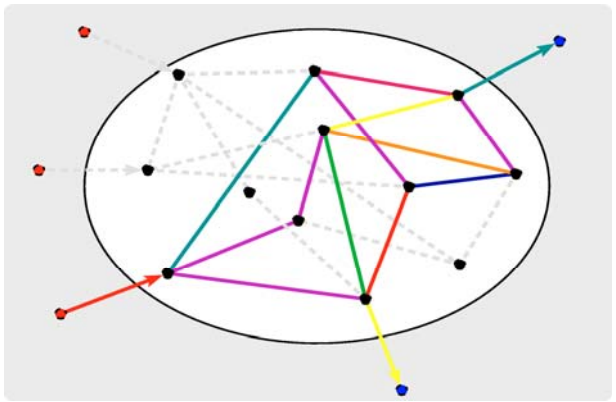


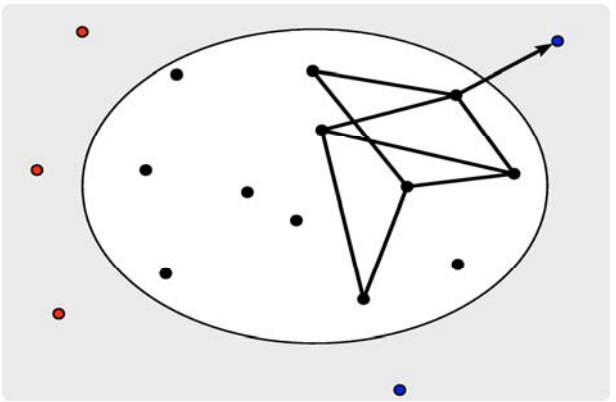
Condition 2

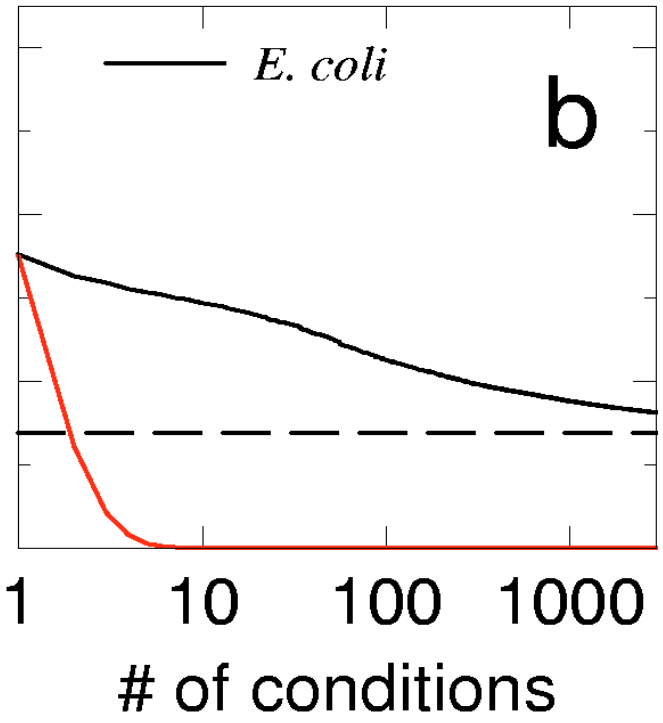




Condition 3

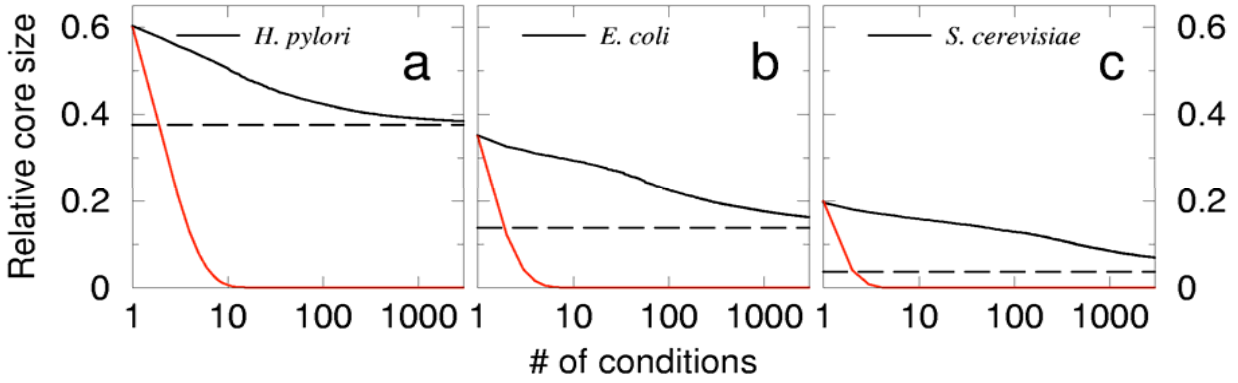




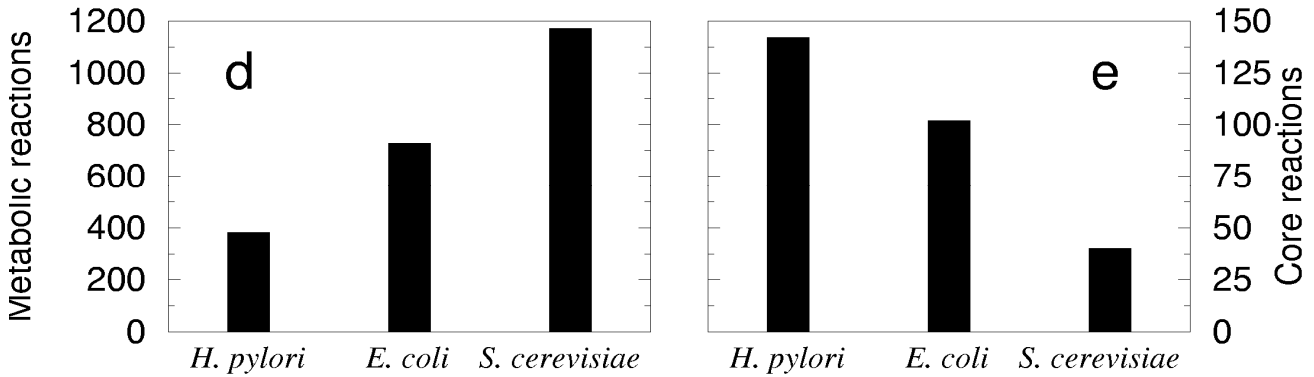


E. Almaas, Z. N. Oltvai, A.-L. Barabási, submitted 2005

The Metabolic Core



- **A connected set of reactions that are ALWAYS active**



- **The larger the network, the smaller the core**
  → a collective network effect

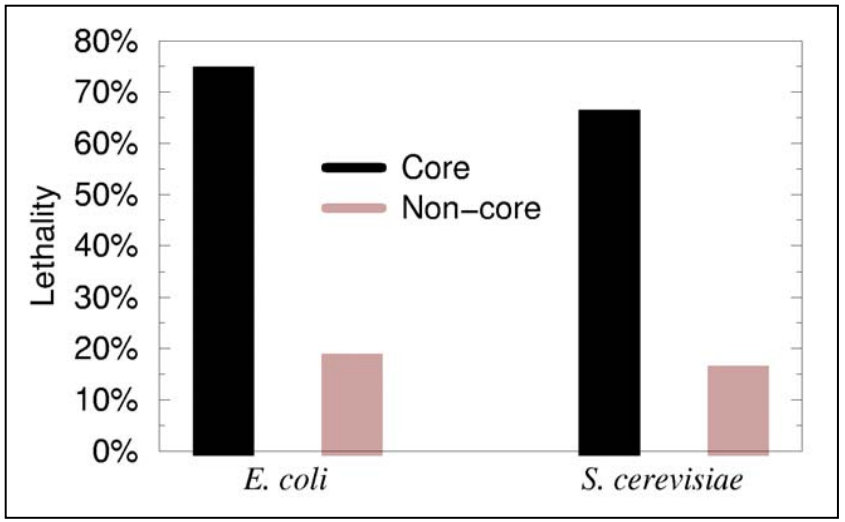
E. Almaas, Z. N. Oltvai, A.-L. Barabási, submitted 2005

Characterizing the core

The core is highly essential:

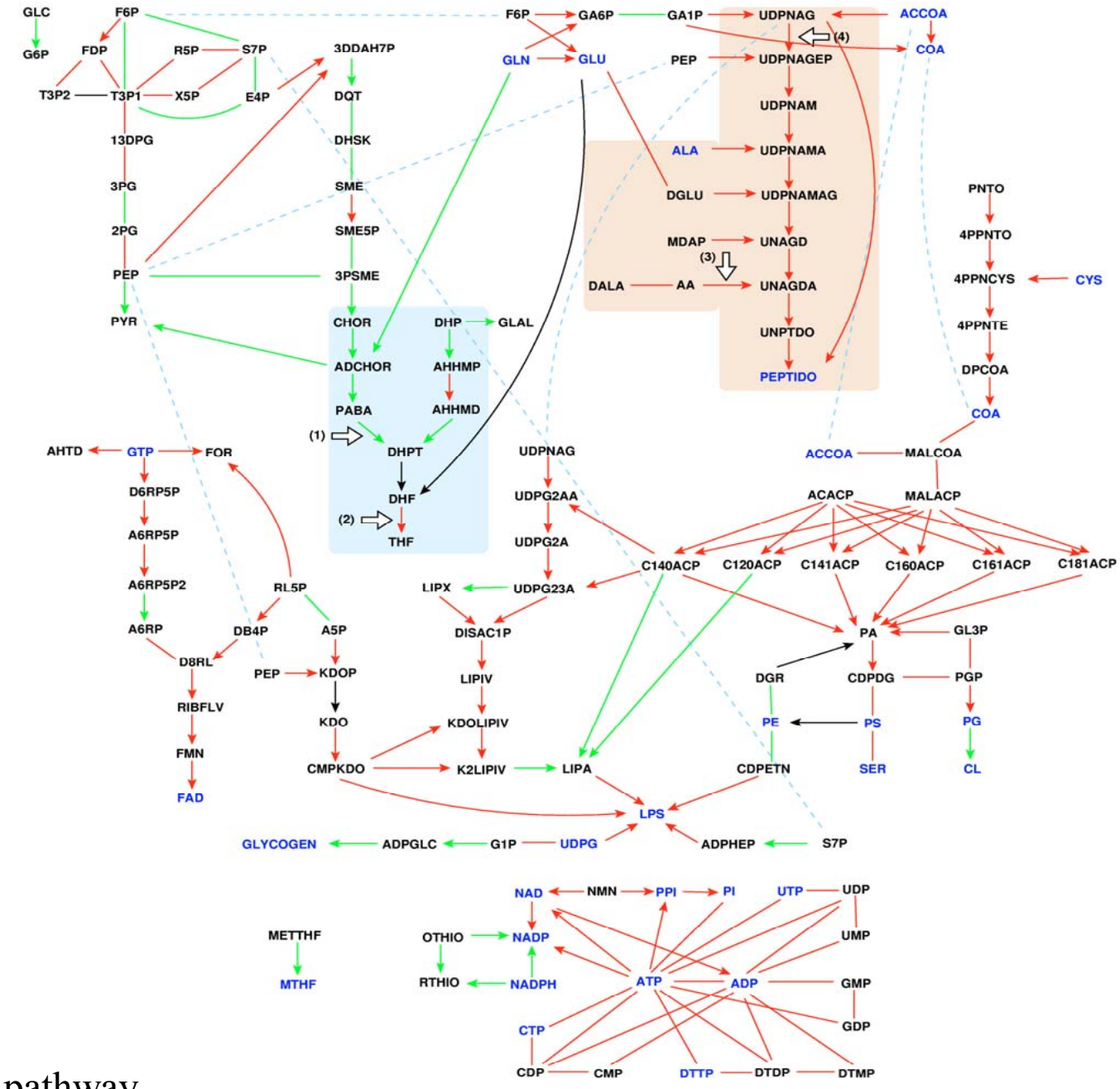
- ***E. coli*: 74% lethal (18% in non-core)**
- **Yeast: 66% lethal (16% non-core)**

- **The core is evolutionary conserved**
- ***E. coli* :**
  72% of core enzymes (47% of non-core)



E. Almaas, Z. N. Oltvai, A.-L. Barabási, submitted 2005

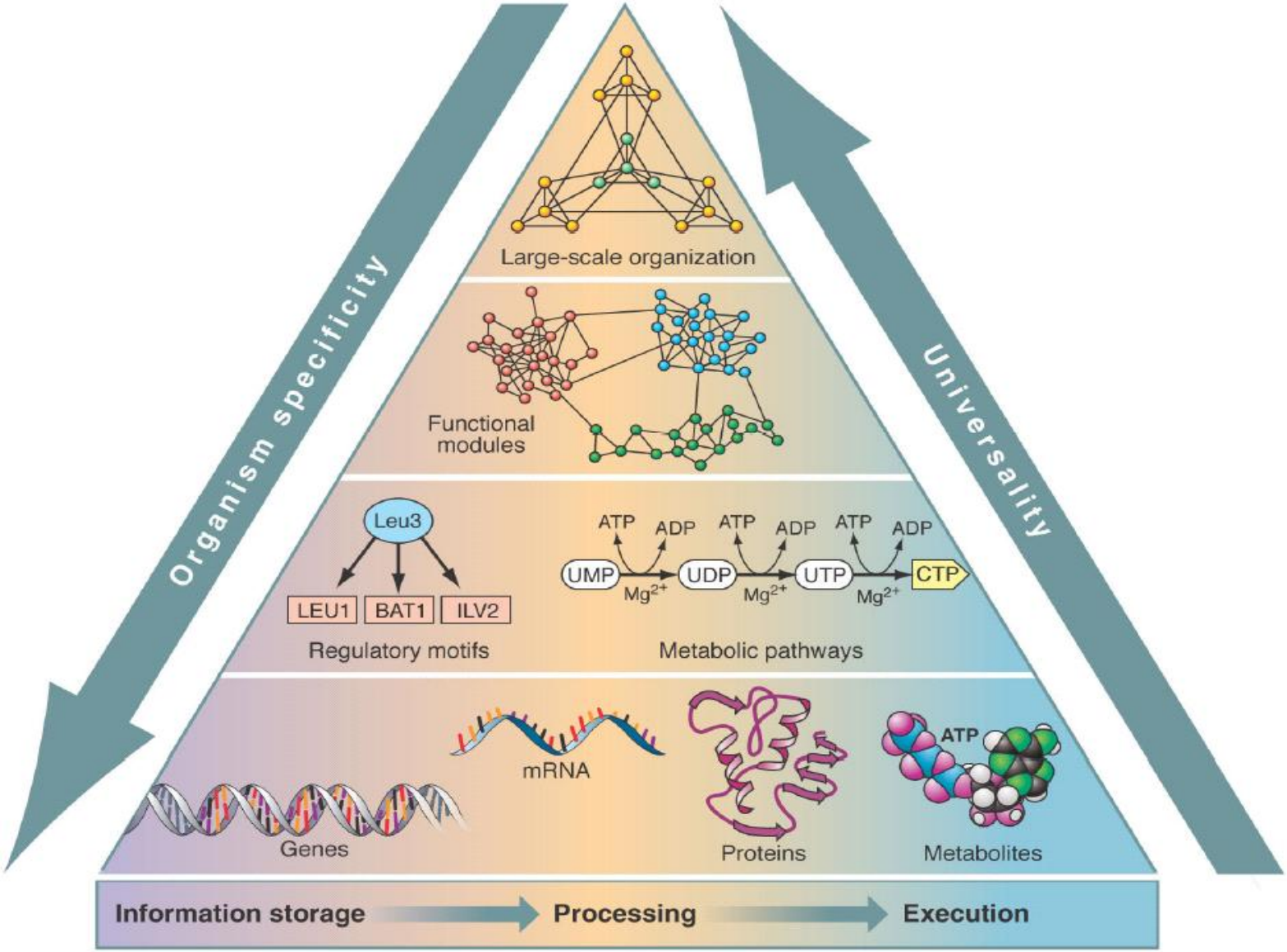
Core:
Antibiotic targets?



Blue: folate biosynthesis pathway

Brown: peptidoglycan biosynthesis pathway

Life's Complexity Pyramid



Z.N. Oltvai and A.-L. B. (2002).

Albert-László Barabási
Emil T. Hofman Professor of Physics
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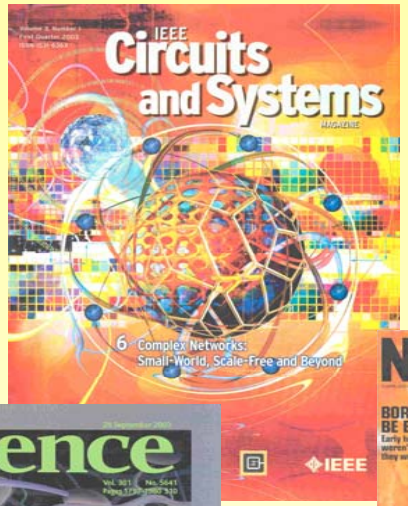

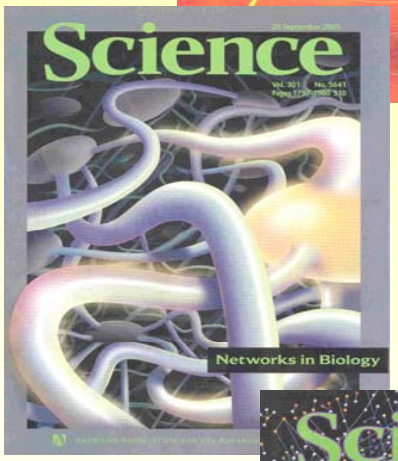

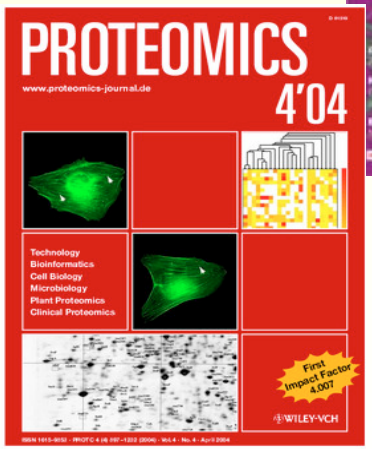

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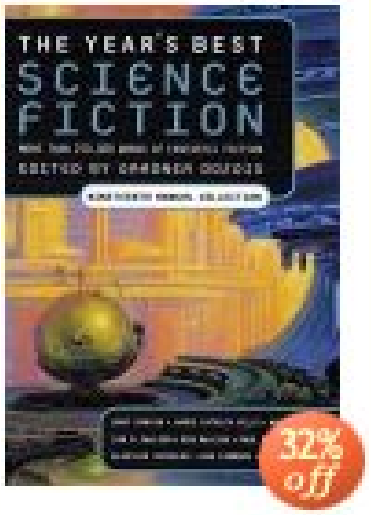
→Over
20 Books:

→Science Fiction
and Visual Arts:



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SEEING THE WORLD IN A DIFFERENT WAY

← Museum Exhibit

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Advisers to the Nation on Science, Engineering, and Medicine

NRC Panel on “Network Science”

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NRC Panel on "Network Science"

What is "network science"?

An attempt to understand networks emerging in nature, technology and society using a unified set of tools and principles.

What is new here?

A recognition that despite their individual differences, a wide range of networks emerge and evolve driven by a *fundamental set of laws and mechanism.*

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NRC Panel on "Network Science"

What is next?

Network Topology:
quite advanced—much to be learned still

Dynamics on networks:
Is there such a degree of universality as we see in the topology?

I hope so--- but still looking for the (…'s) laws here….

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Zoltán N. Oltvai, U of Pittsburgh Med. School

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