The Architecture of Complexity:

From the Topology of the WWW to the Structure of the Cell

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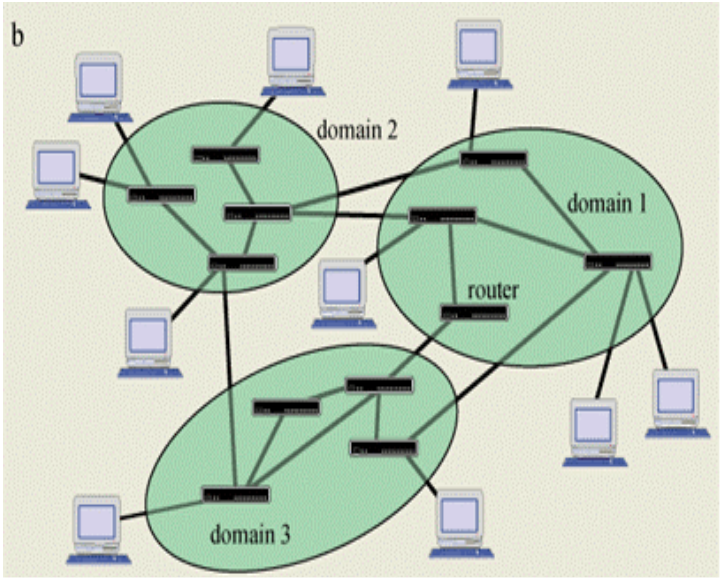
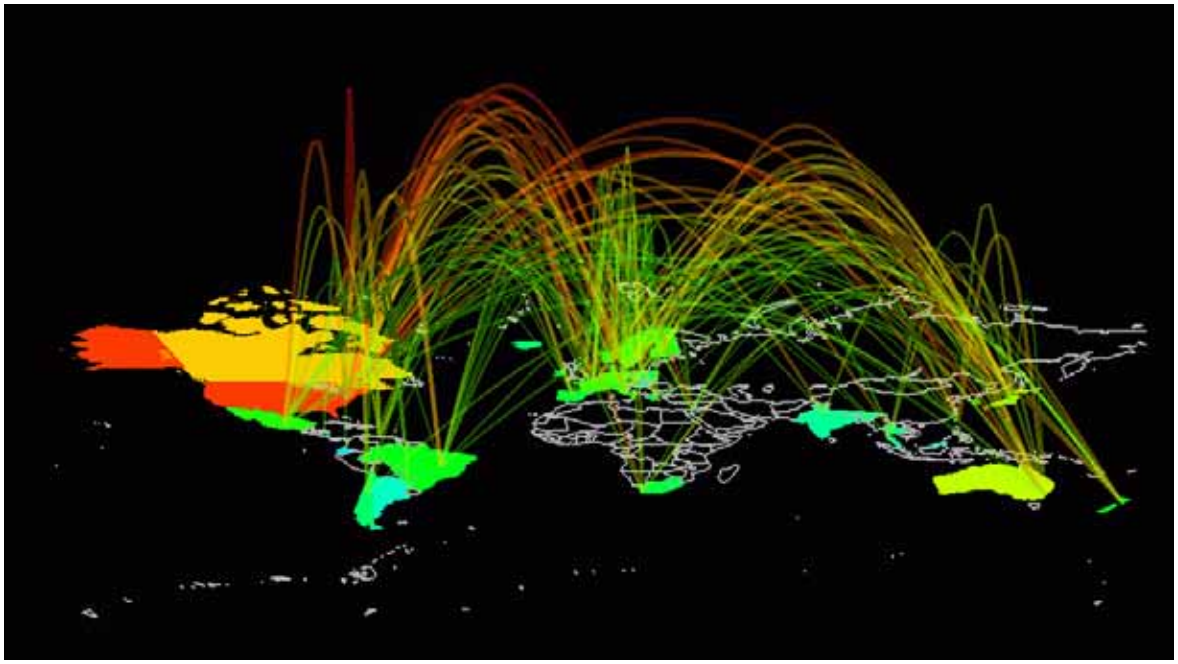
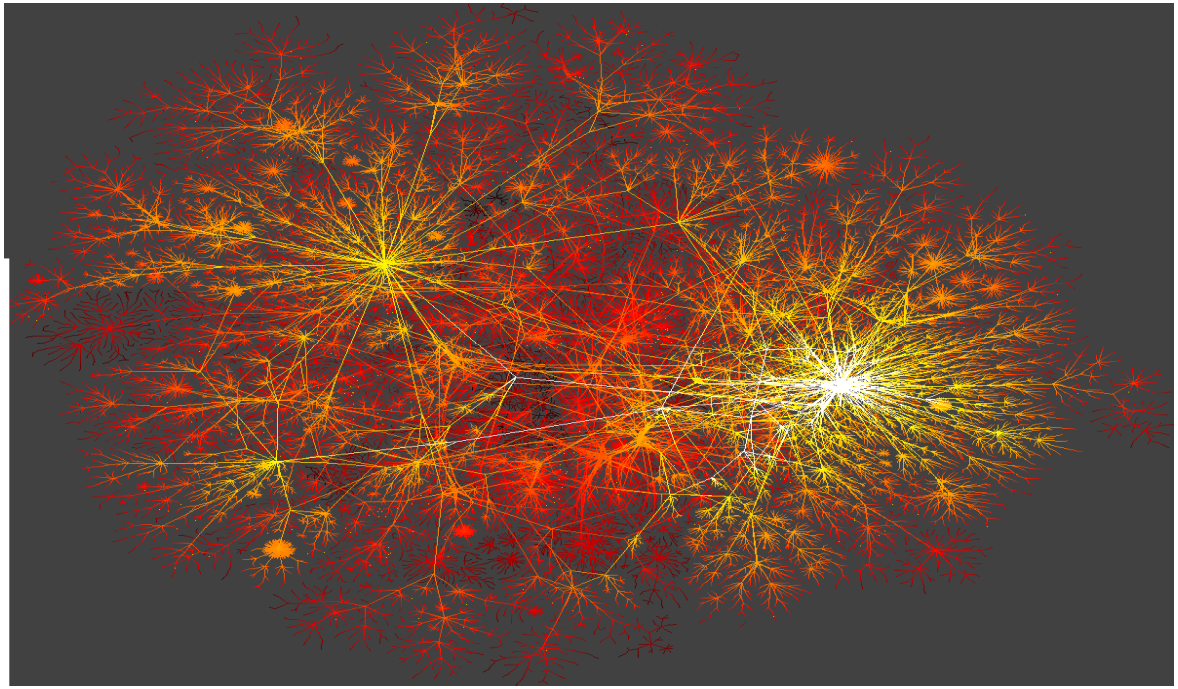
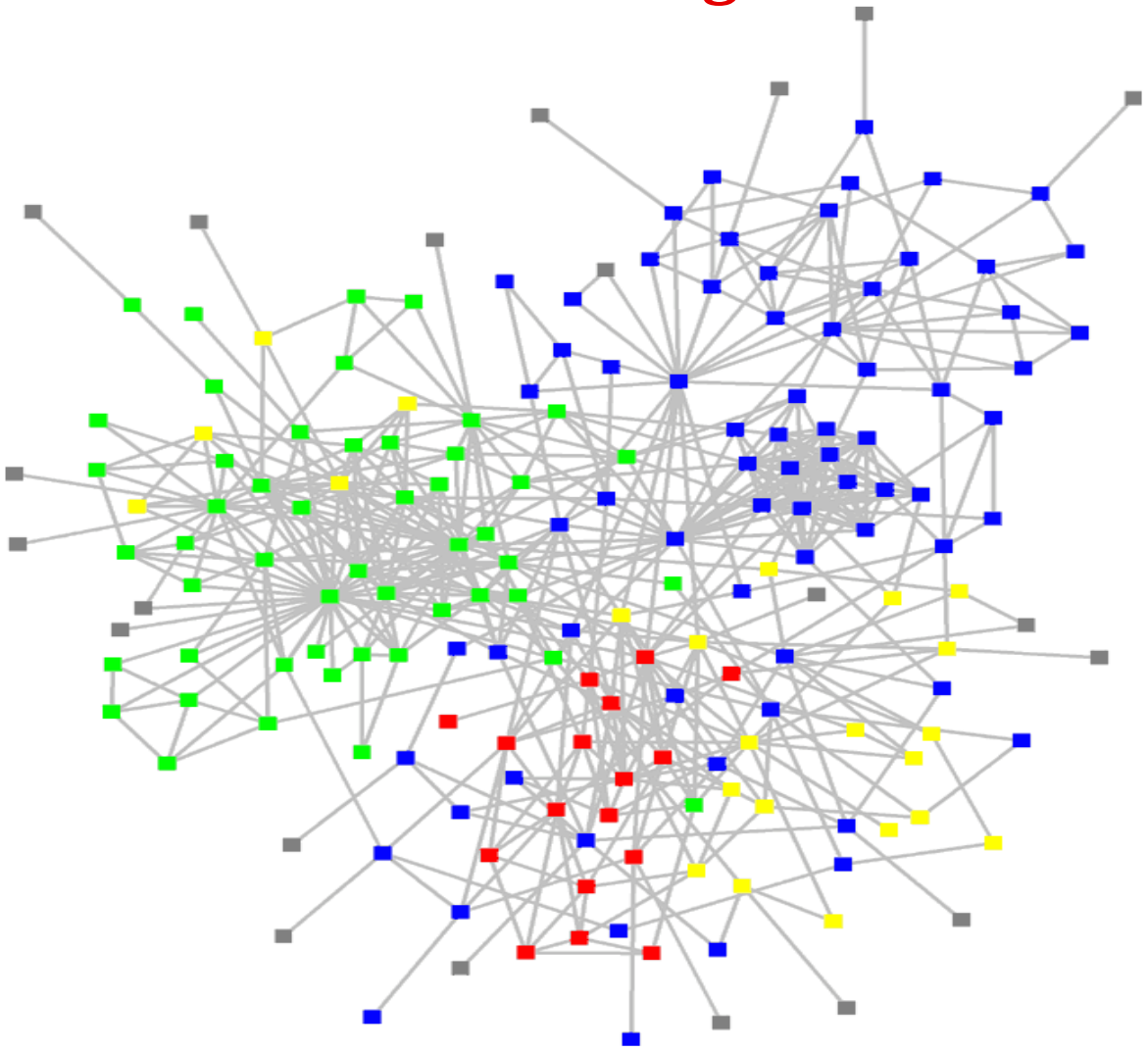
Internet







Structure of an organization



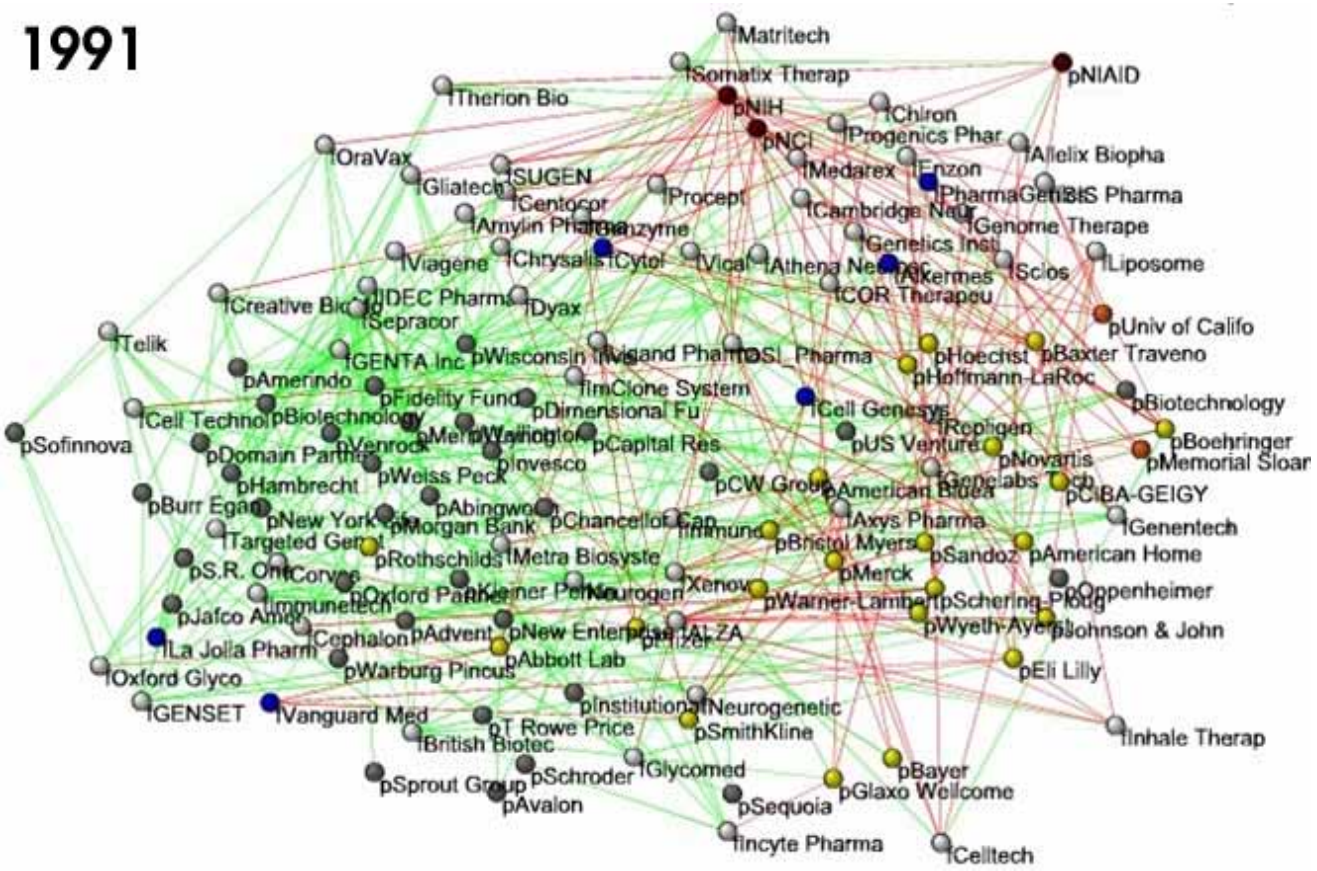
Red, **blue**, or **green**: departments

Yellow: consultants

Grey: external experts

www.orgnet.com

Business ties in US biotech-industry



Nodes: companies

investment

pharma

research labs

public

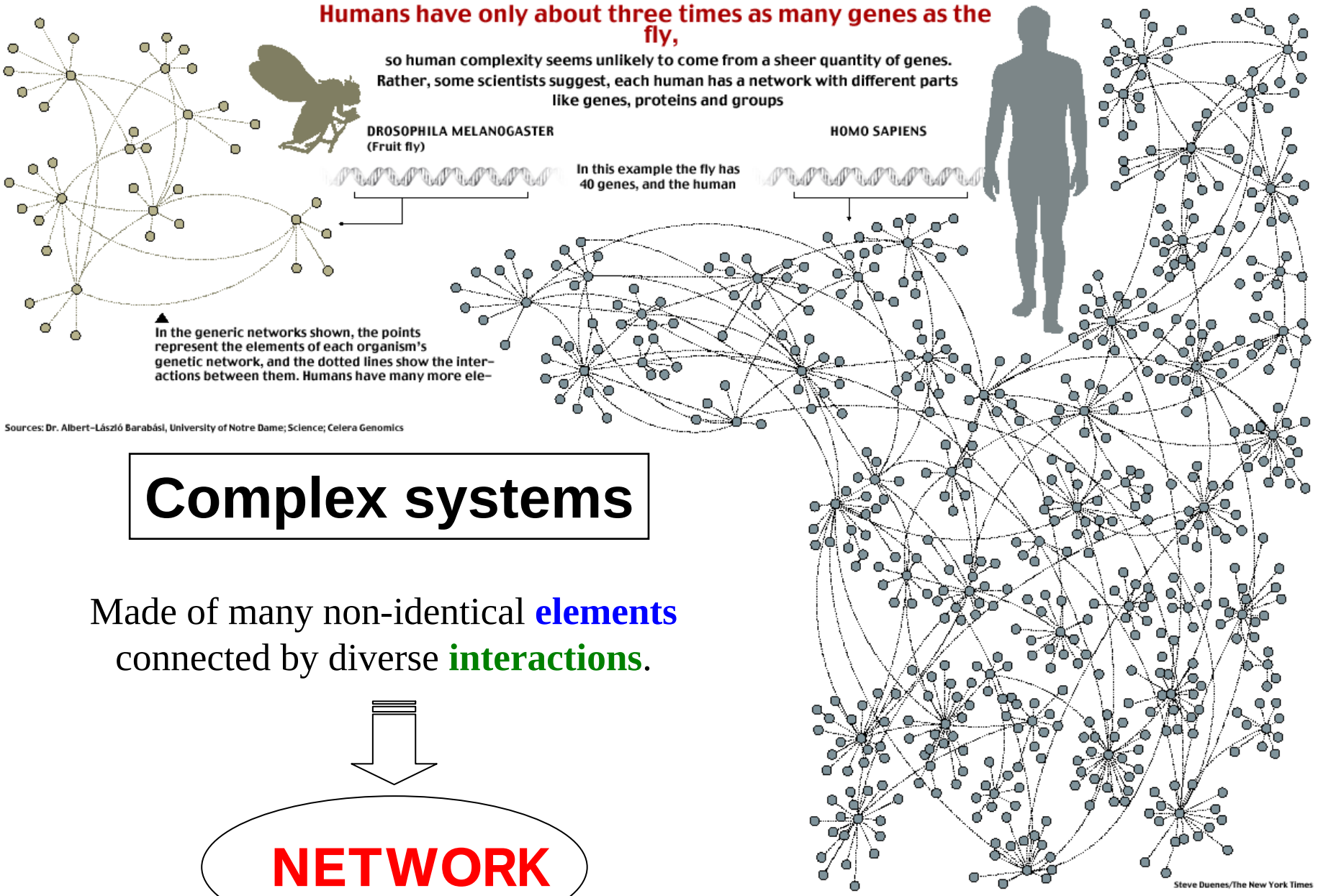
biotechnology

Links: collaborations

financial

R&D

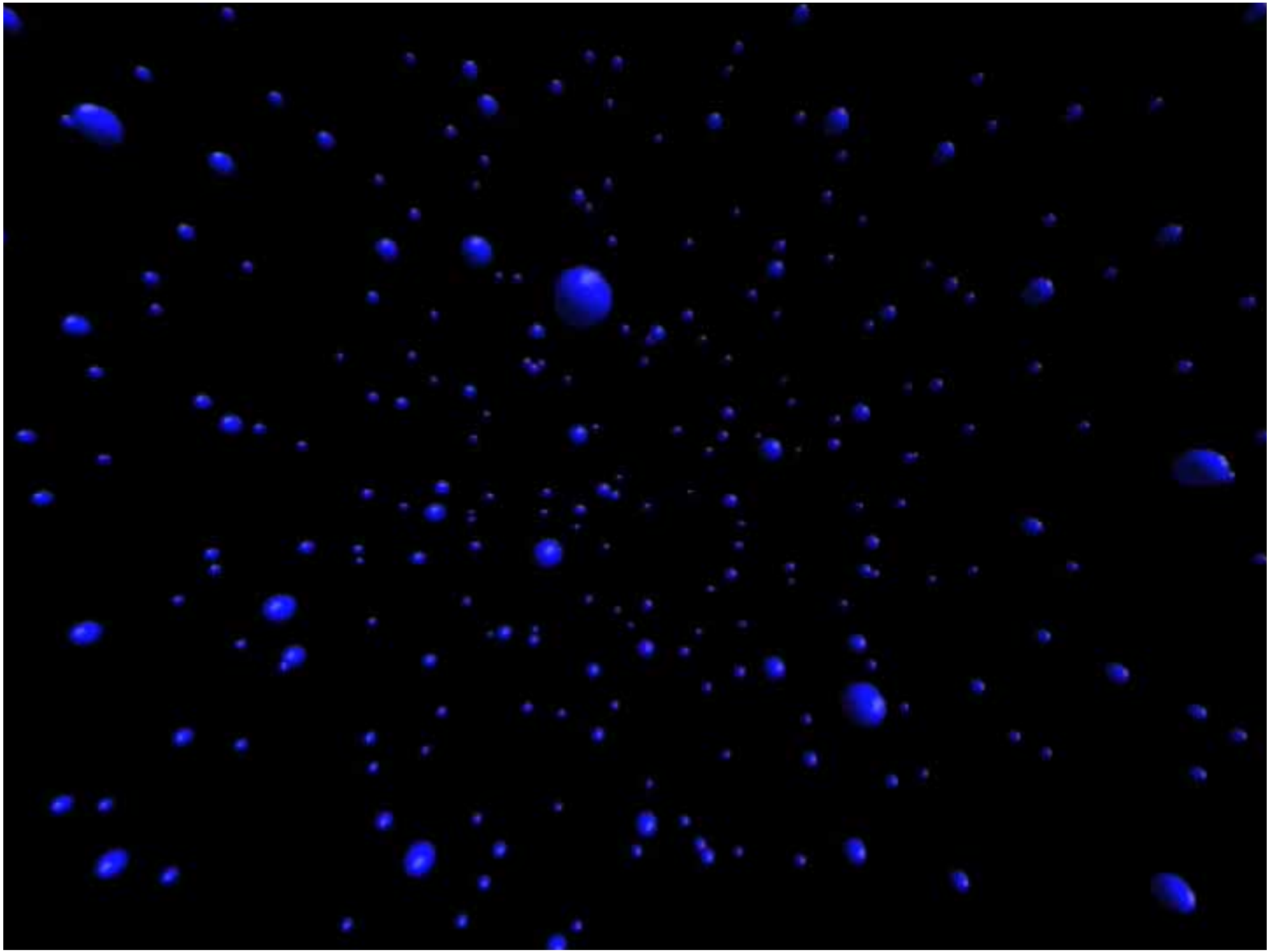
http://ecclectic.ss.uci.edu/~drwhite/Movie



Complex systems

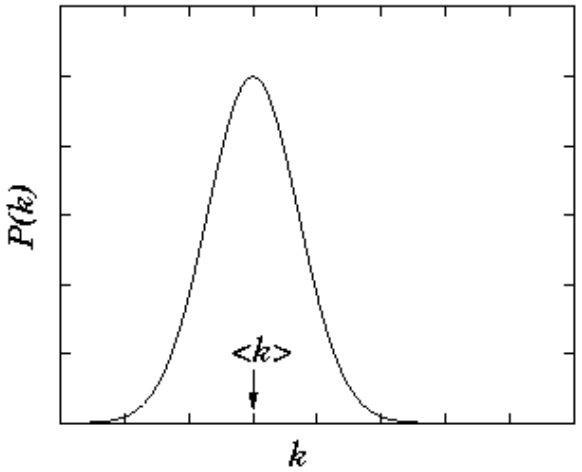
Made of many non-identical **elements** connected by diverse **interactions**.

NETWORK



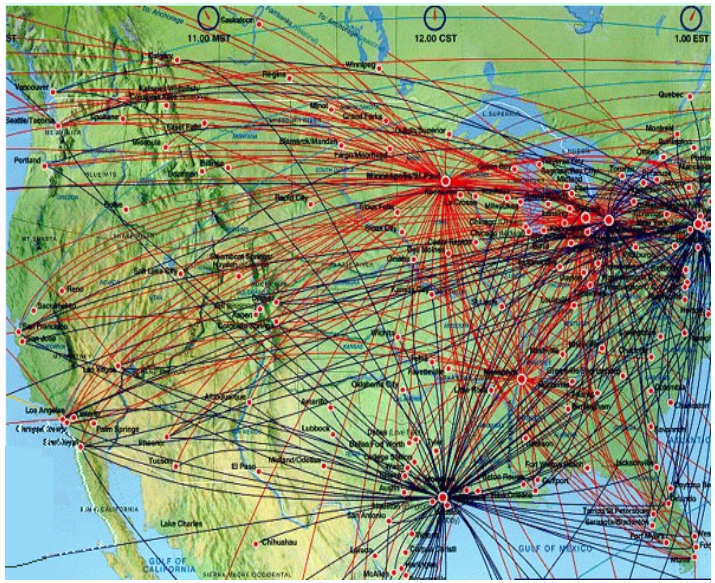
World Wide Web

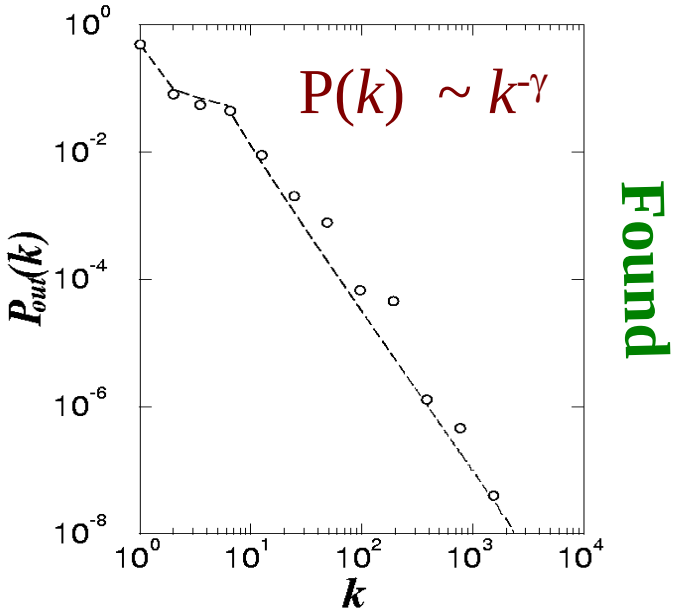
Exponential Network



Expected

Scale-free Network



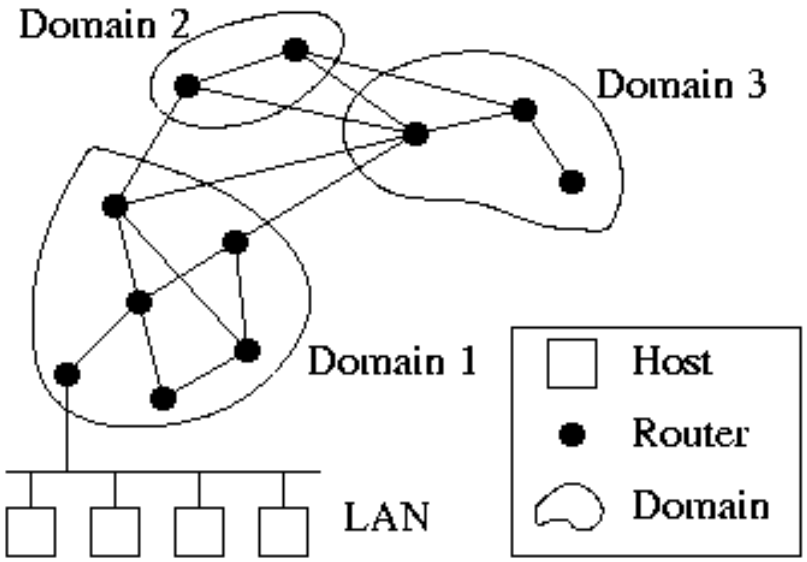


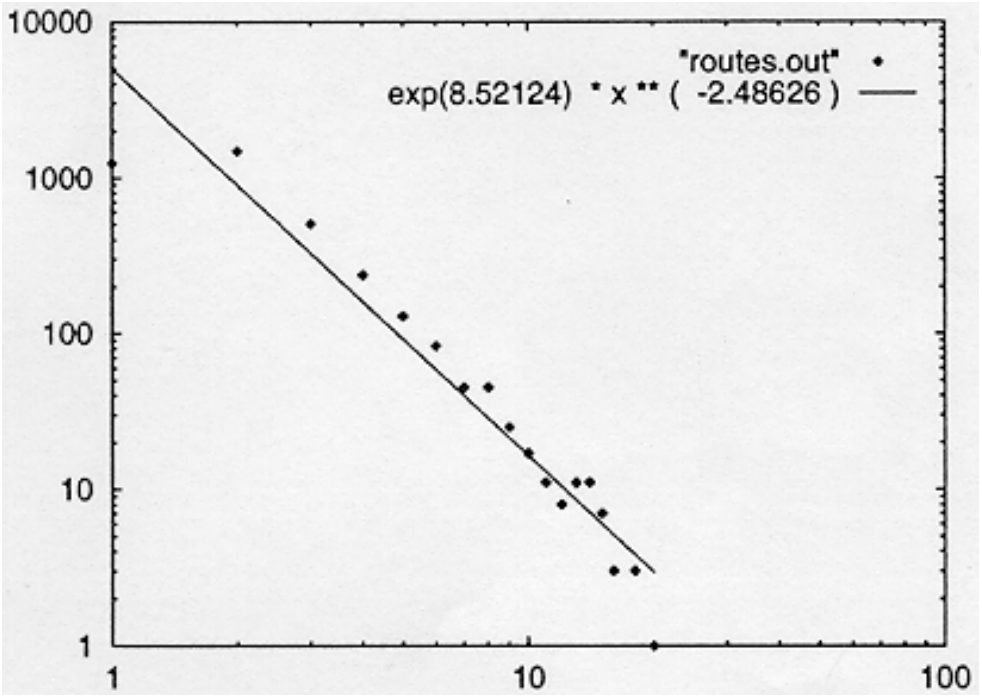
Found

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

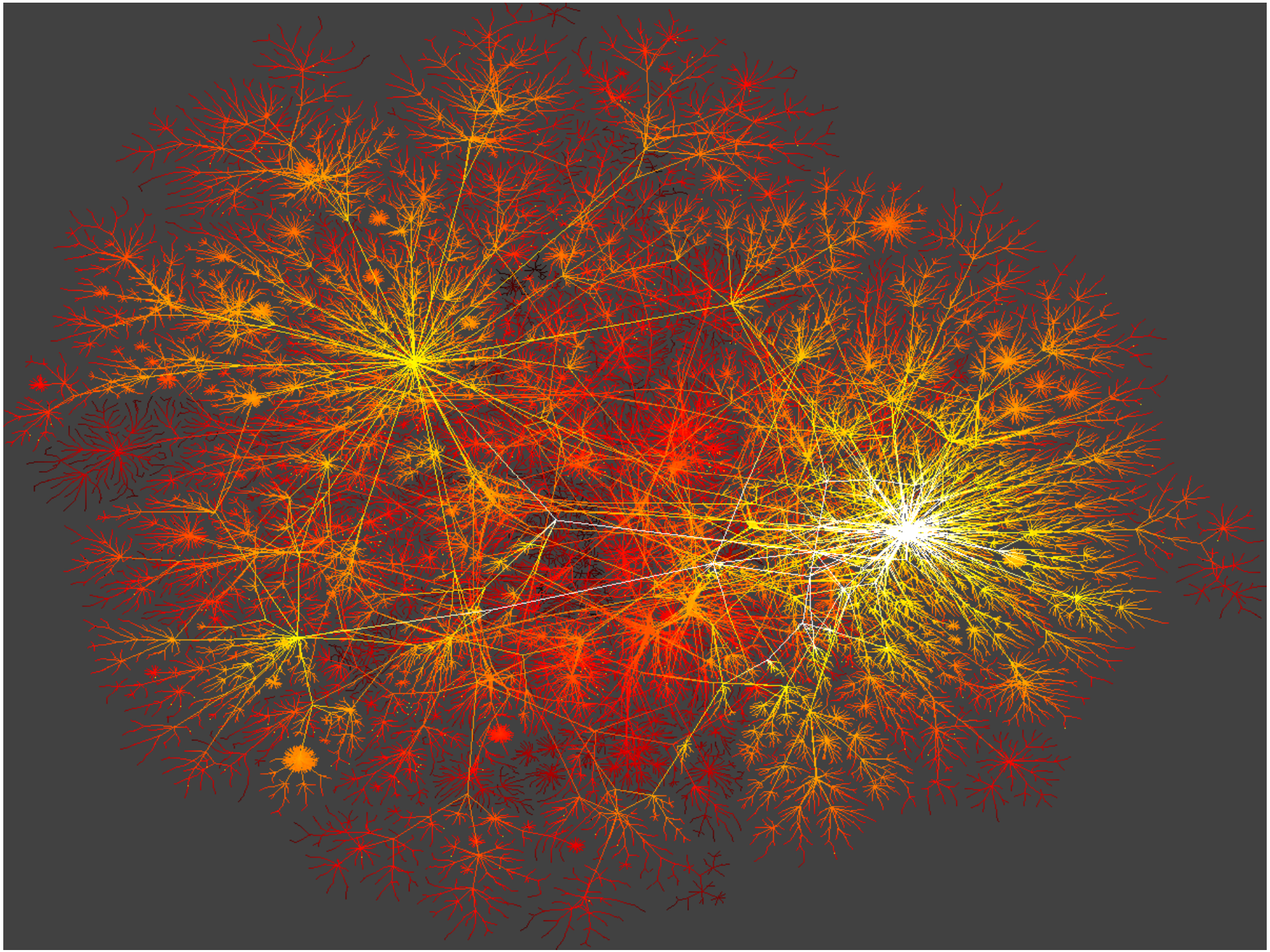
INTERNET BACKBONE

Nodes: computers, routers
Links: physical lines





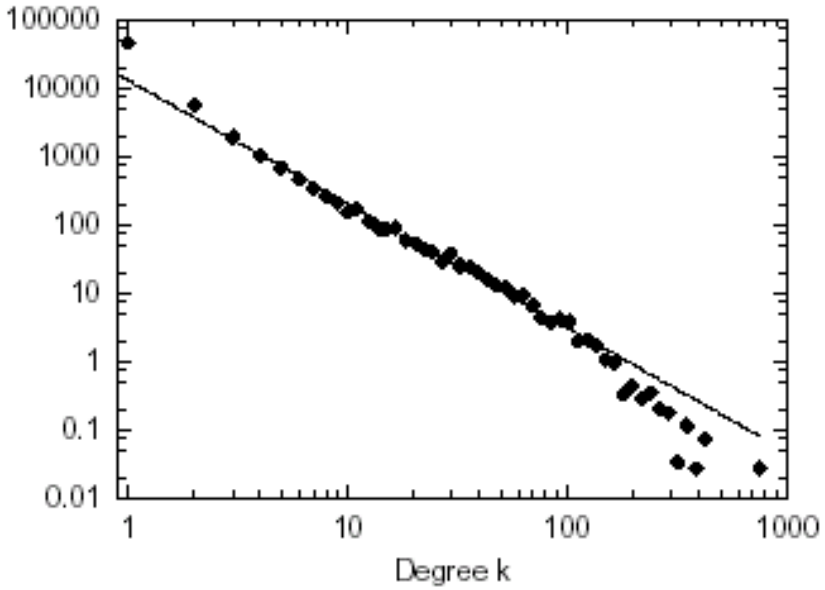
(Faloutsos, Faloutsos and Faloutsos, 1999)



Online communities

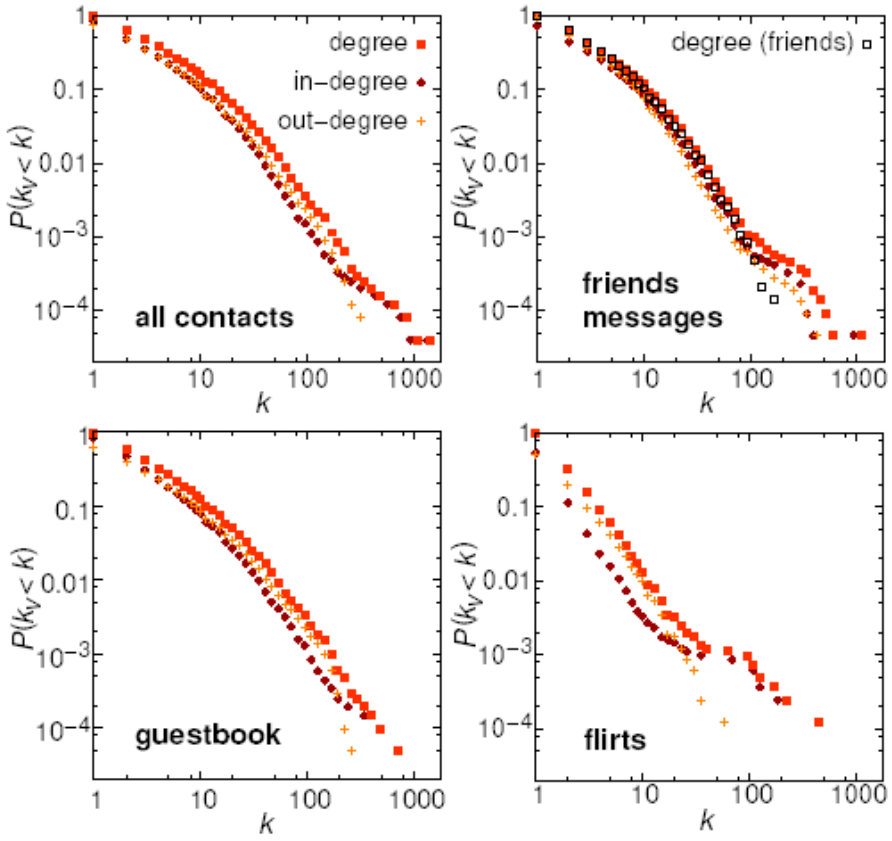
Nodes: online user
Links: email contact

Kiel University log files
112 days, N=59,912 nodes



Ebel, Mielsch, Bornholdtz, PRE 2002.

Pussokram.com online community; 512 days, 25,000 users.

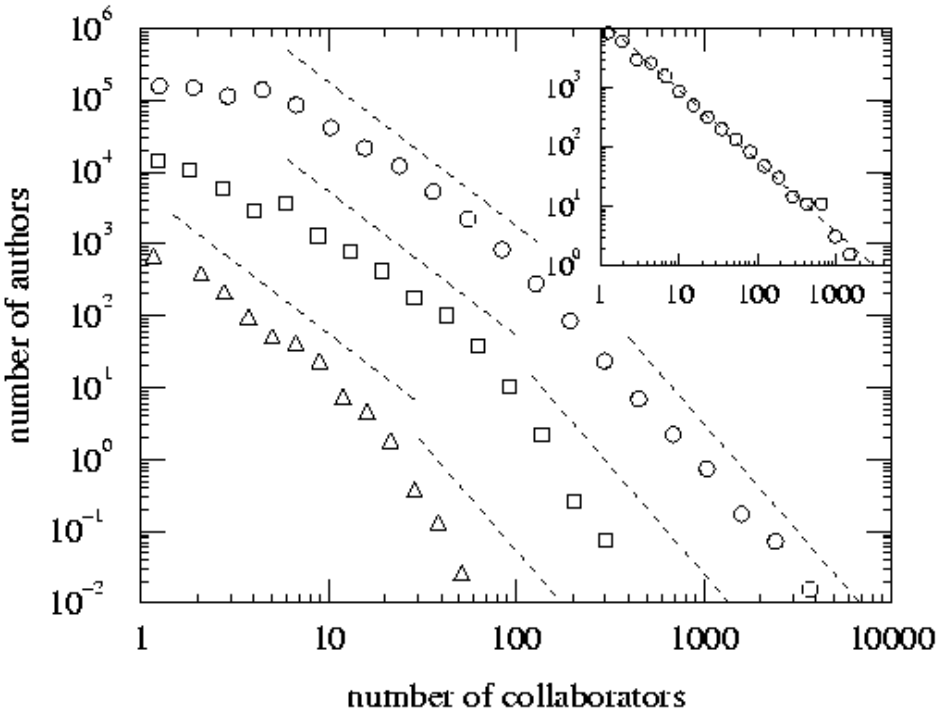


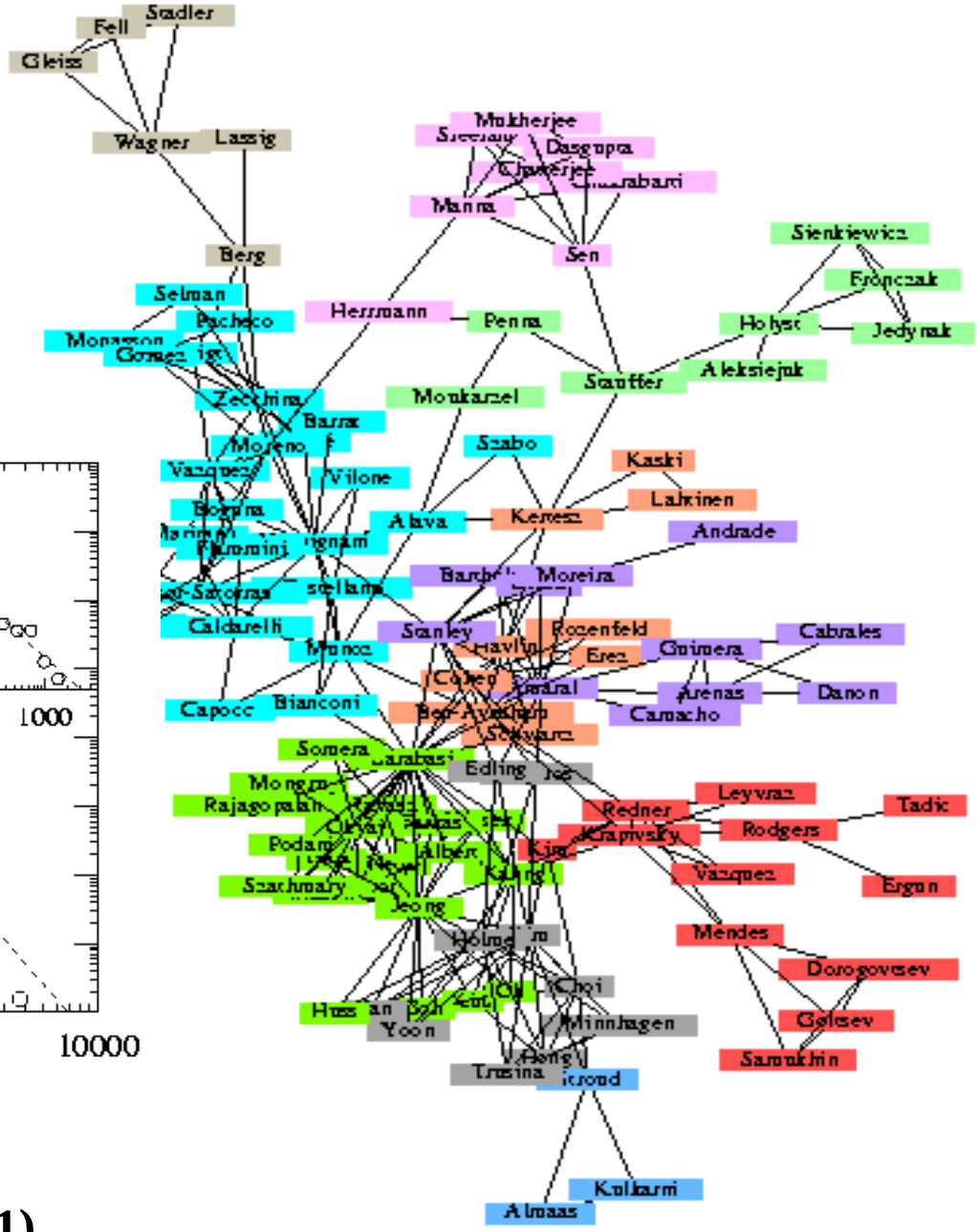
Holme, Edling, Liljeros, 2002.

SCIENCE COAUTHORSHIP

Nodes: scientist (authors)

Links: write paper together





(Newman, 2000, Barabási *et al* 2001)

SCIENCE CITATION INDEX

1,000 Most Cited Physicists, 1981-June 1997

Out of over 500,000 Examined

(see http://www.sst.nrel.gov)

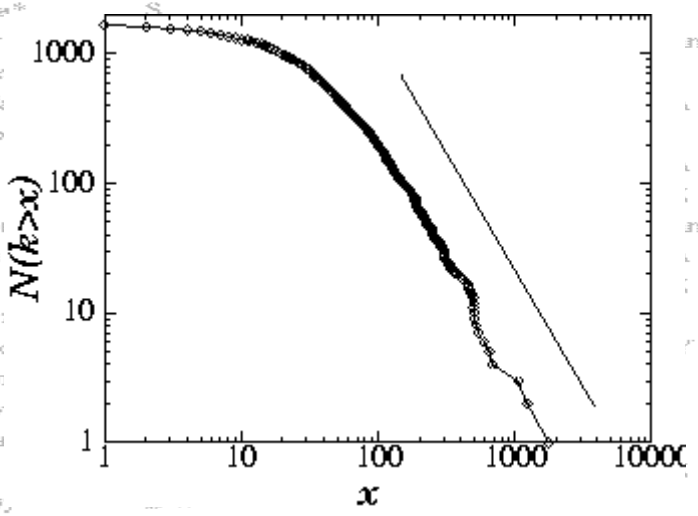
Author name		Institute	Country	Field	avg. cites	total art.	total cites	rank by total cit.
Witten	E	Princeton (U)	USA, NJ	High-energy (T)	168	138	23235	1
Gossard	AC	UCSB (U)	USA, CA	Semi				2
Cava	RJ	Bell Labs (I)	USA, NJ	Supe				3
Batlogg	B	L	USA, NJ	Supe				4
Ploog	K	Max-Planck (NL)	Germany	Semi				5
Ellis	J	t	Switzerland	Astr				6
Fisk	Z	Florida State (U)	USA, FL	Solic				7
Cardona	M	Max Planck (NL)	Germany	Semi				8
Nanopoulos	DV	Texas A&M (U)	USA, TX	High				9
Heeger	AJ	UCSB (U)	USA, CA	Poly				10
Lee*	PA							11
Suzuki*	T							12
Anderson			NJ	Solic				13
Suzuki*								14
Freeman			IL	Solic				15
Tanaka*	S							16
Muller			nd	Supe				17
Schnee				Supe				18
Chemk				Optics (E)	60	162	9668	19
Morko				Semiconductors (E)	20	477	9668	19
Miller				Semiconductors (E)	67	144	9652	21
Chu				Superconductivity (E)	73	113	9453	22
Bednor			nd	Superconductivity (E)	110	85	9311	23
Cohen				Solid State (T)	33	284	9311	23
Meng				Superconductivity (E)	86	108	9300	25
Waszc				Superconductivity (E)	57	162	9170	26
Shiran				Superconductivity (E)	34	269	8841	27
Wiegm				Semiconductors (E)	85	104	8822	28
Vando				Magnetism (E)	67	129	8686	29
Uchida					28	301	8520	30
Hor				Superconductivity (E)	72	119	8512	31
Murph				Astronomy (E)	111	76	8439	32
Birgeneau	RJ	MIT (U)	USA, MA	Superconductivity (E)	41	286	8375	33
Jorgensen	JD	Argonne (NL)	USA, IL	Superconductivity (E)	67	223	8288	34
Hinks	DG	Argonne (NL)	USA, IL	Superconductivity (E)	57	223	8263	35

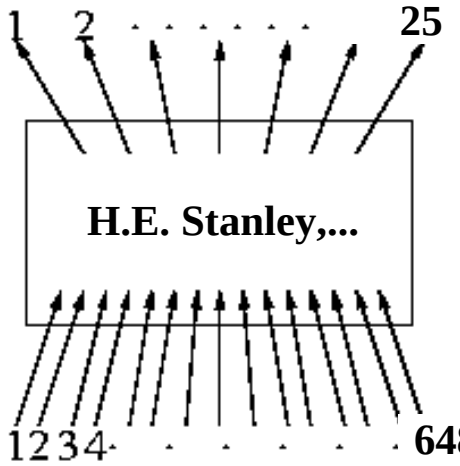
* citation total may be skewed because of multiple authors with the same name

Nodes: papers

Links: citations

1736 PRL papers (1988)





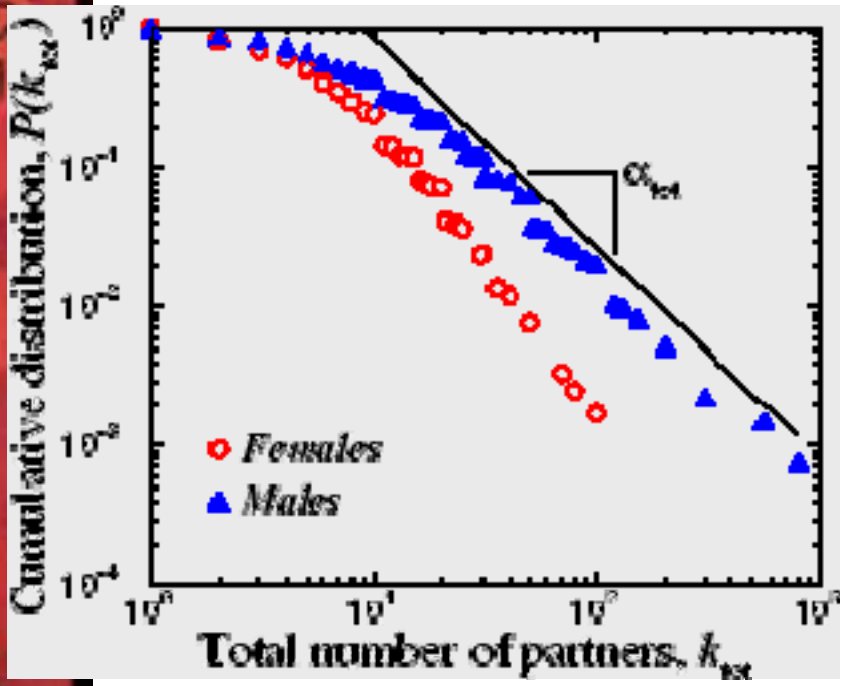
$P(k) \sim k^{-\gamma}$

$(\gamma = 3)$

(S. Redner, 1998)

Swedish sex-web

Nodes: people (Females; Males)
Links: sexual relationships



4781 Swedes; 18-74;
59% response rate.

Liljeros et al. Nature 2001

Origin of SF networks: Growth and preferential attachment

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

WWW : addition of new documents

GROWTH:

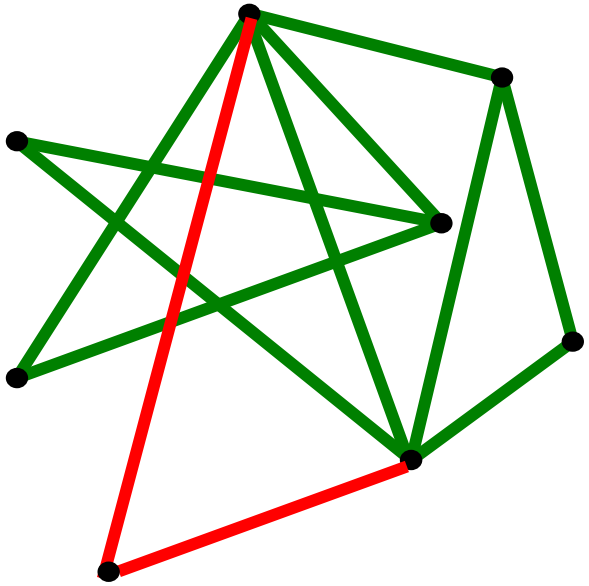
add a new node with m links

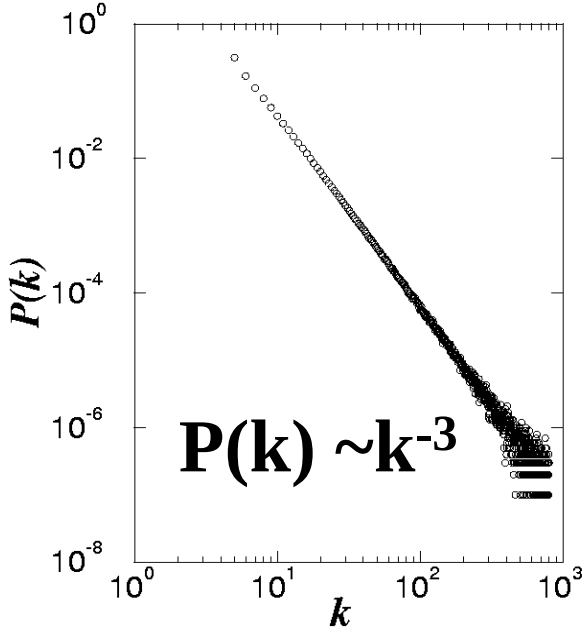
(2) New nodes prefer to link to highly connected nodes.

WWW : linking to well known sites

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

$$\Pi(k_i) = \frac{k_i}{\sum_i k_i}$$





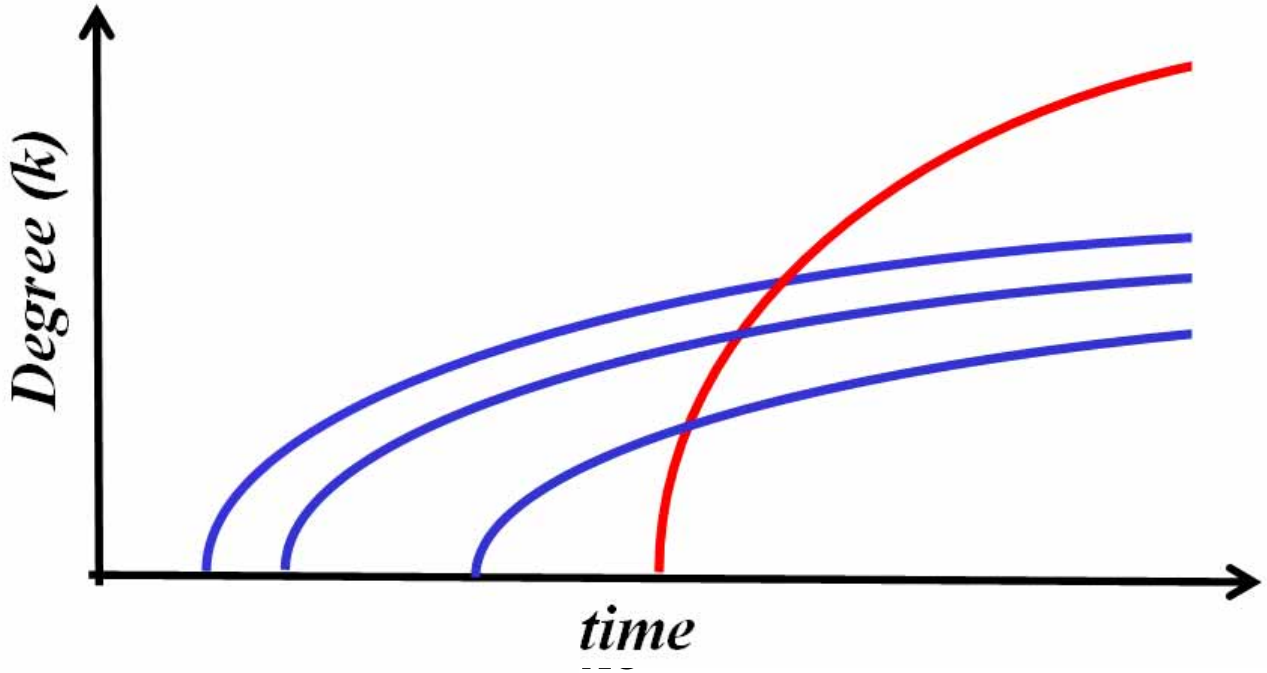
Barabási & Albert, *Science* **286,** 509 (1999)

Fitness Model: Can Latecomers Make It?

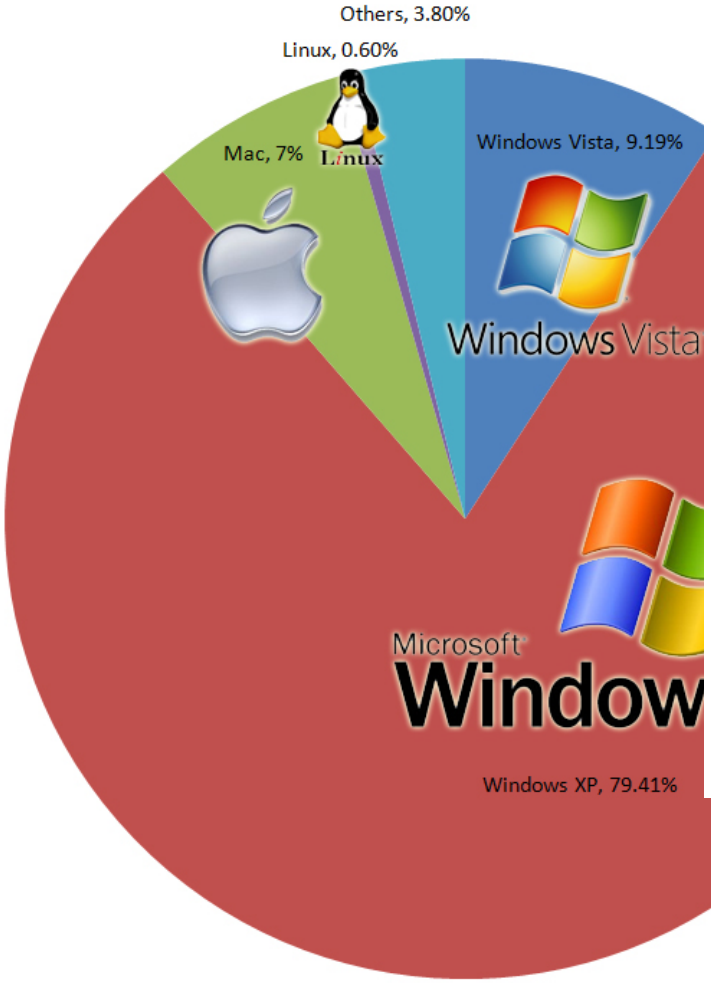
SF model: $k(t) \sim t^{1/2}$ **(first mover advantage)**

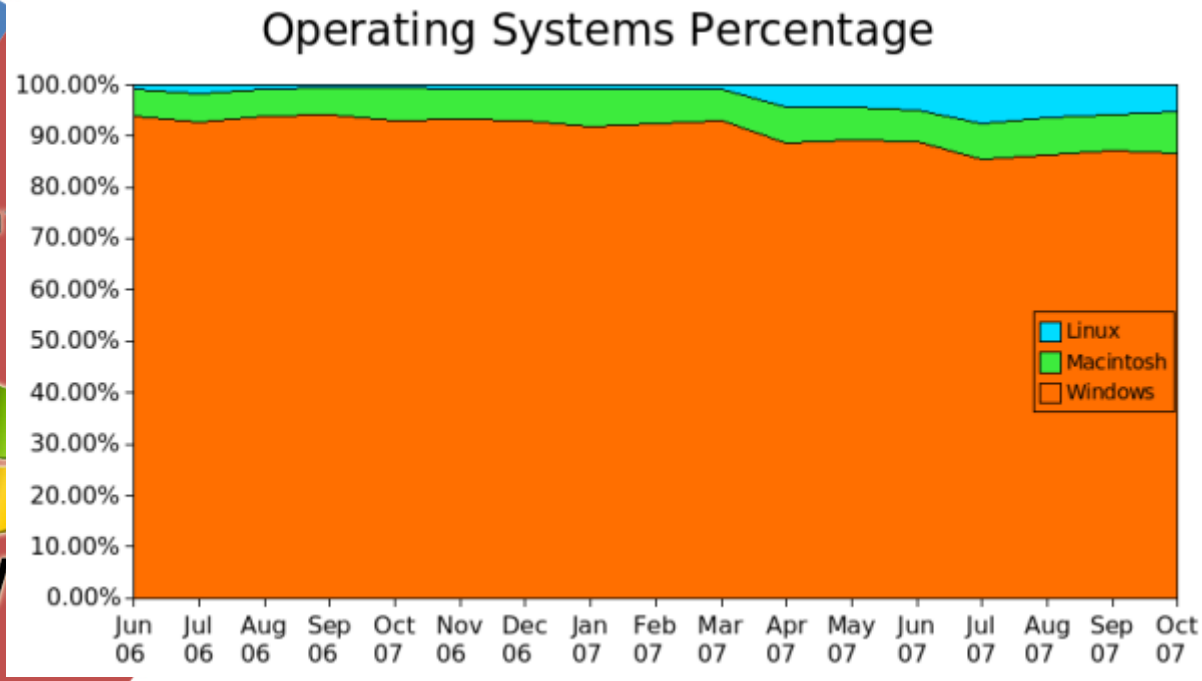
Fitness model: **fitness** (η) $\Pi(k_i) \cong \frac{\eta_i k_i}{\sum_j \eta_j k_j}$ $k(\eta,t) \sim t^{\beta(\eta)}$

$\beta(\eta) = \eta/C$



Bianconi & Barabási, *Physical Review Letters* 2001; *Europhys. Lett.* 2001.


Others, 3.80%
Linux, 0.60%
Mac, 7%
Linux
Windows Vista, 9.19%
Windows Vista
Microsoft
Windows XP, 79.41%


Operating Systems Percentage
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Jun 06
Jul 06
Aug 06
Sep 06
Oct 07
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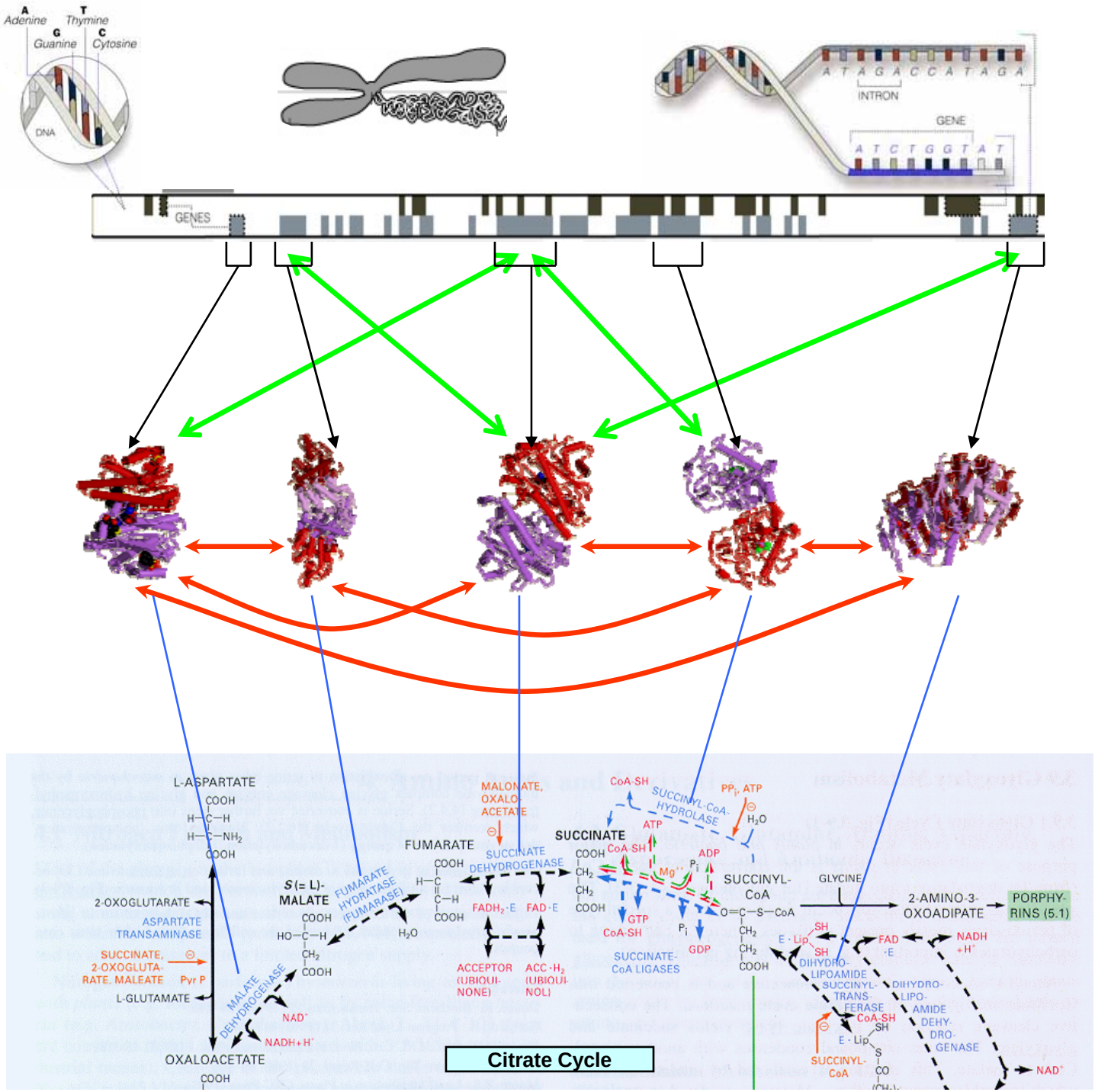
Aug 07
Sep 07
Oct 07
Linux
Macintosh
Windows



GENOME

protein-gene interactions

PROTEOME

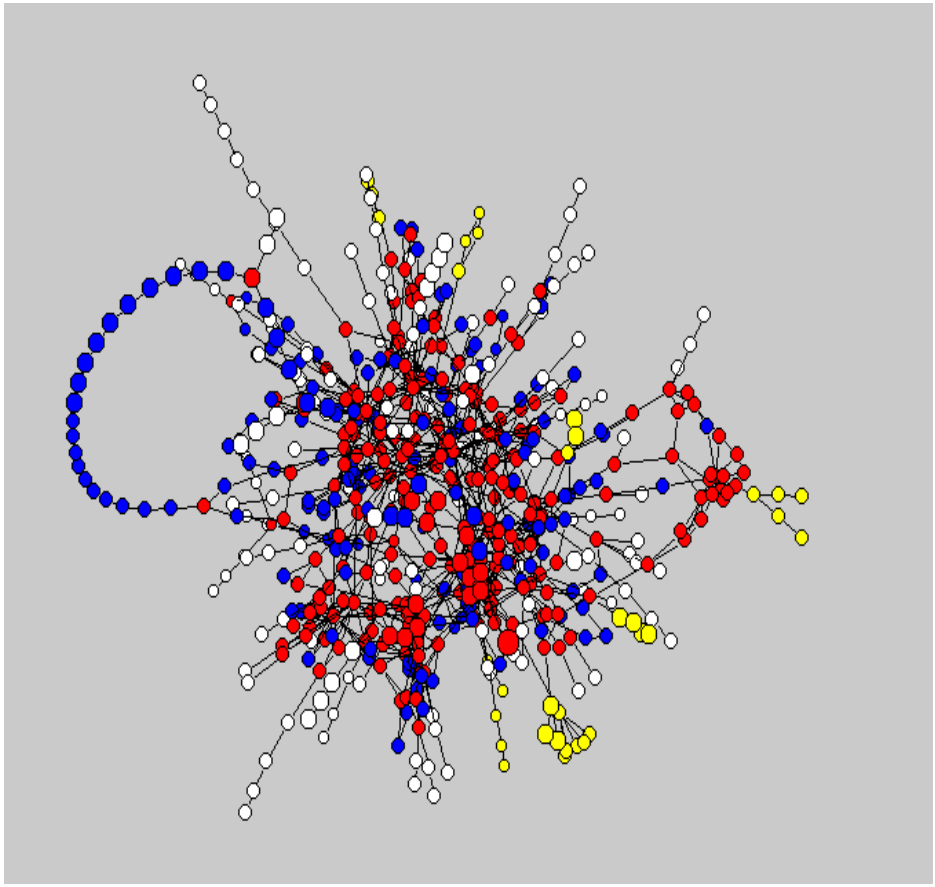
protein-protein interactions

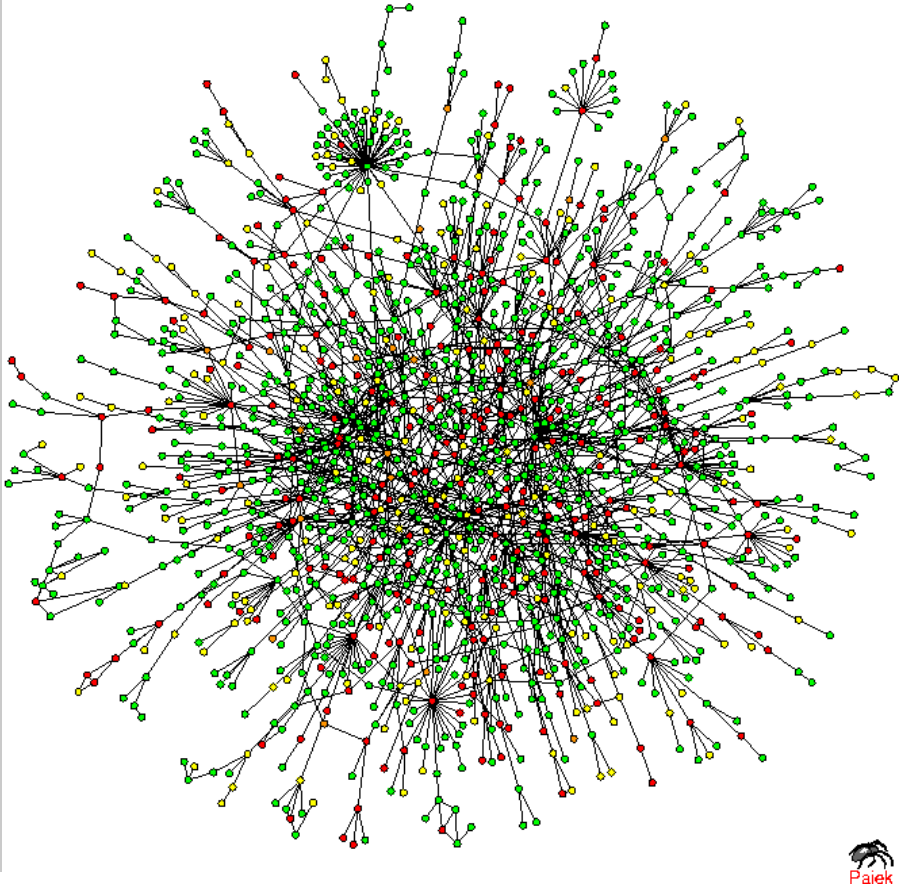
METABOLISM

Bio-chemical reactions

Metabolic Network

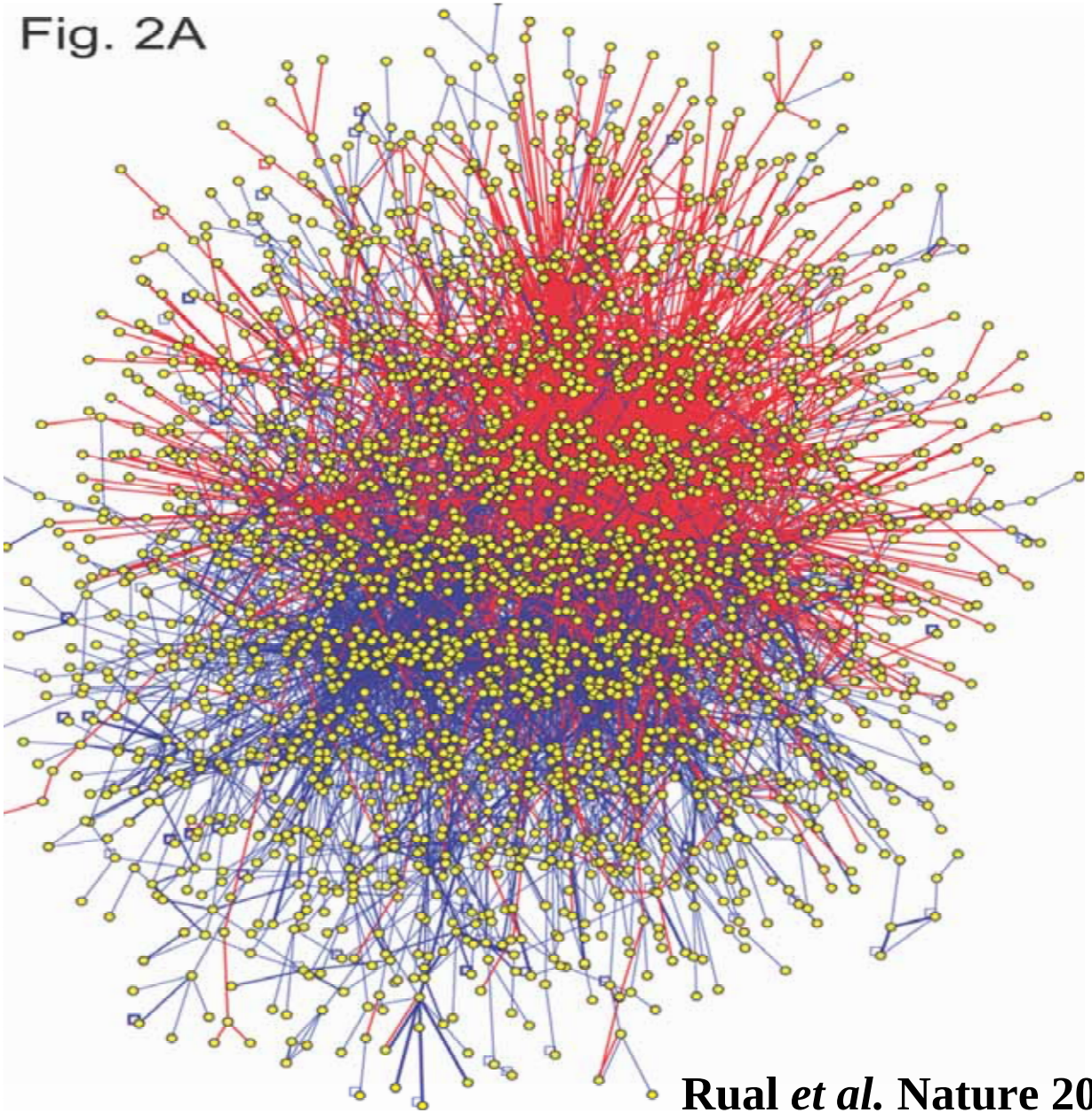
Protein Interactions

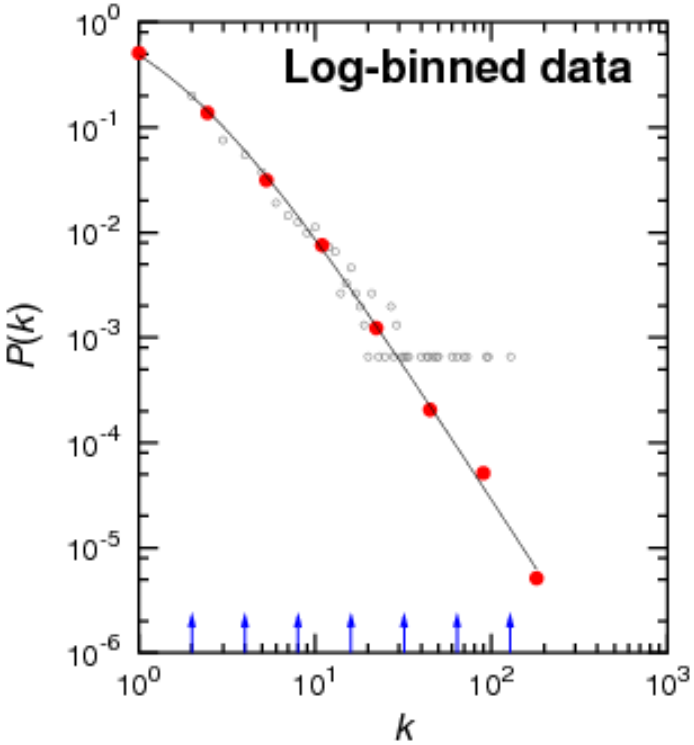




Jeong, Tombor, Albert, Oltvai, & Barabási, *Nature* (2000); Jeong, Mason, Barabási &. Oltvai, *Nature* (2001); Wagner & Fell, *Proc. R. Soc. B* (2001)

Human Interaction Network

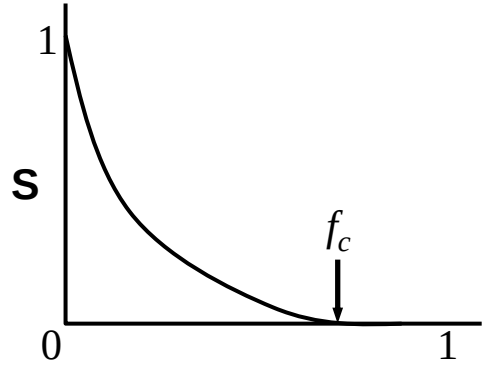


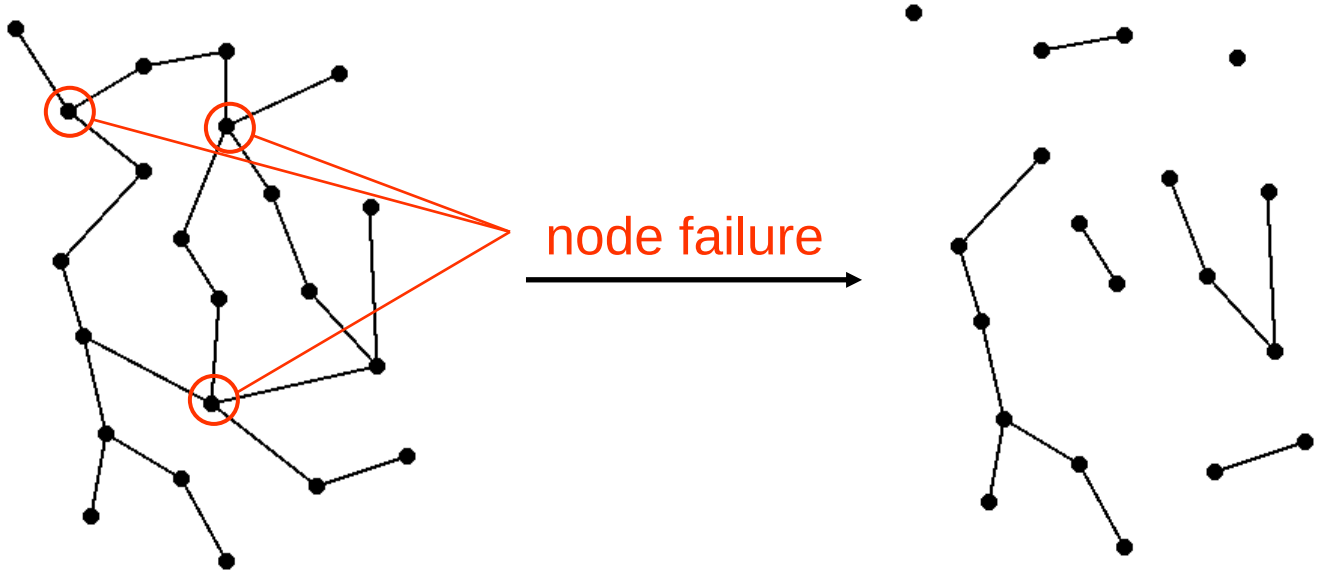


Rual *et al.* Nature 2005; Stelze *et al.* Cell 2005

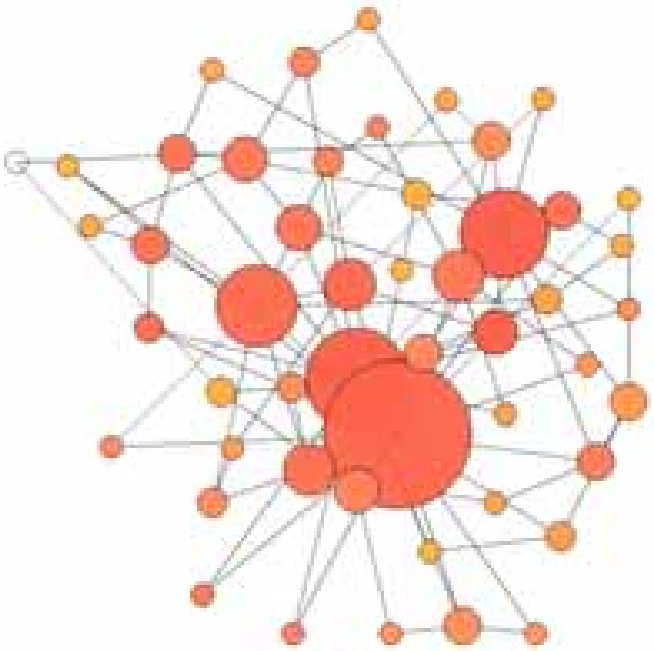
Robustness

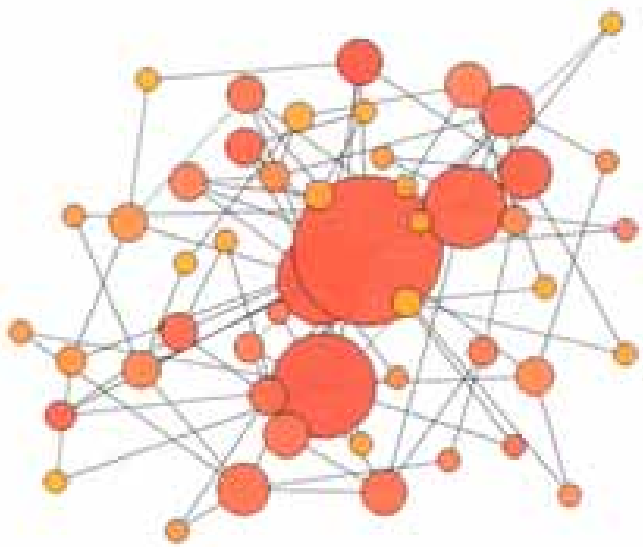
Complex systems maintain their basic functions even under errors and failures
(cell → mutations; Internet → router breakdowns)



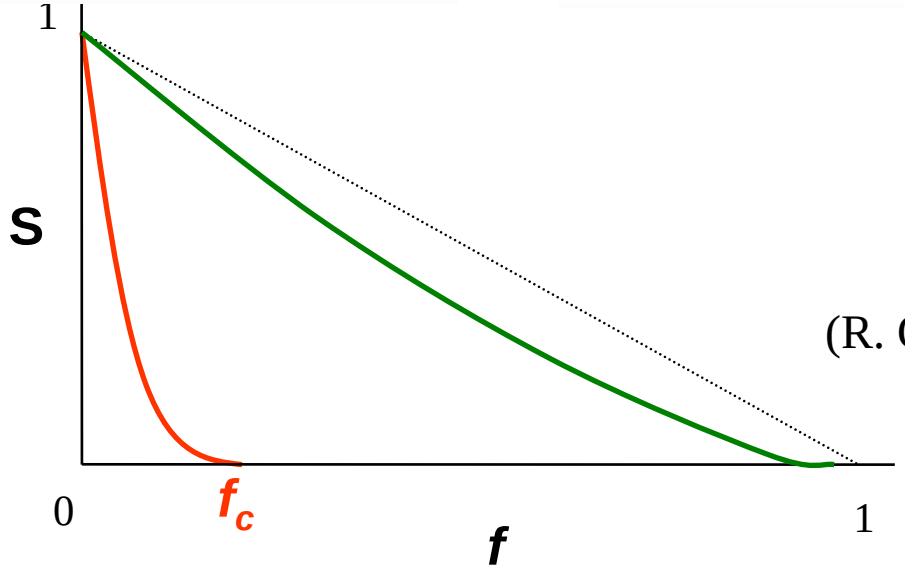


Robustness of scale-free networks





Attacks



Failures

$\gamma \leq 3 : f_c=1$

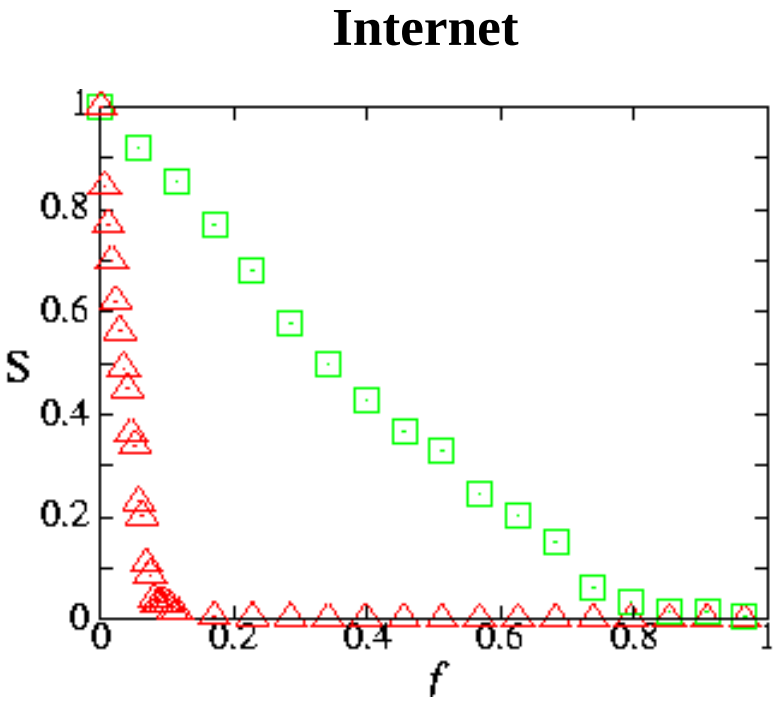
(R. Cohen et al PRL, 2000)

Albert, Jeong, Barabási, *Nature* **406** 378 (2000)

Achilles' Heel of complex networks

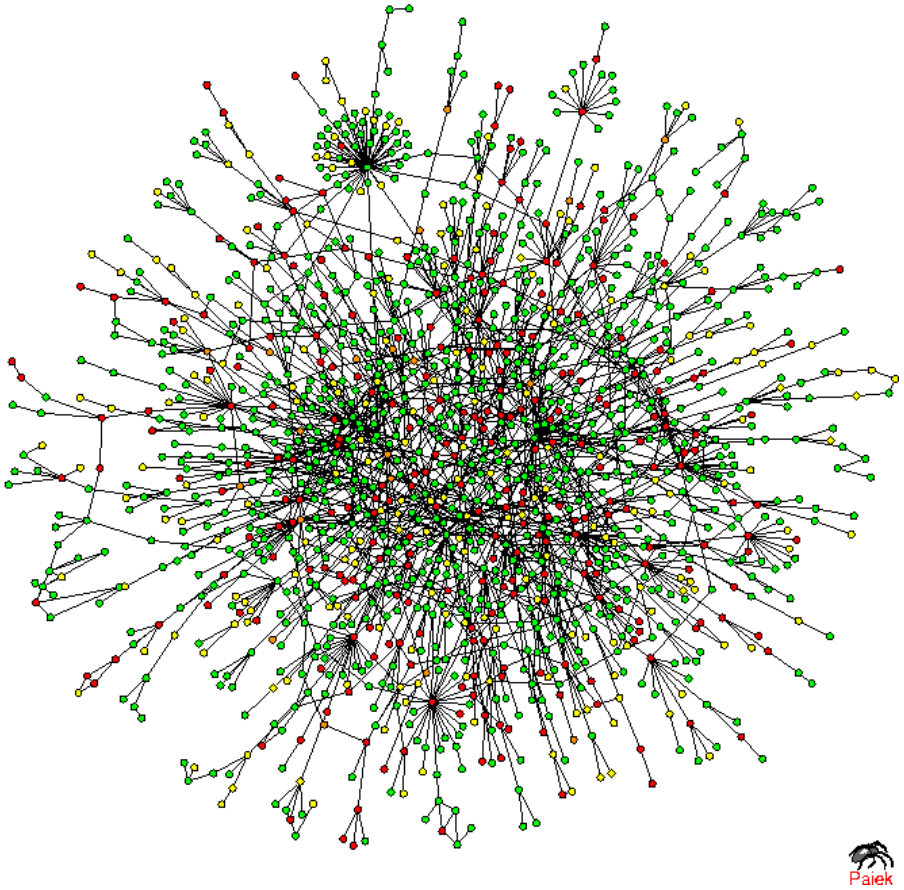
failure

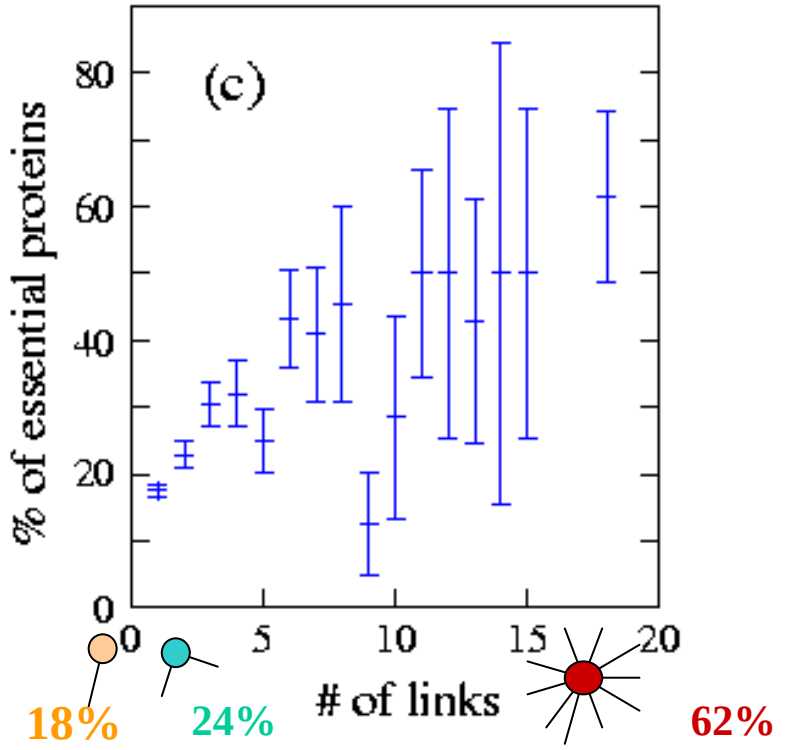
attack



R. Albert, H. Jeong, A.L. Barabási, *Nature* **406** 378 (2000)

Hubs and Essentiality





Hubs evolve slower: they are more alike in different organisms

[H Fraser et al., *Science* (2002). Krylov, *et al. Genome Res.*(2003)]

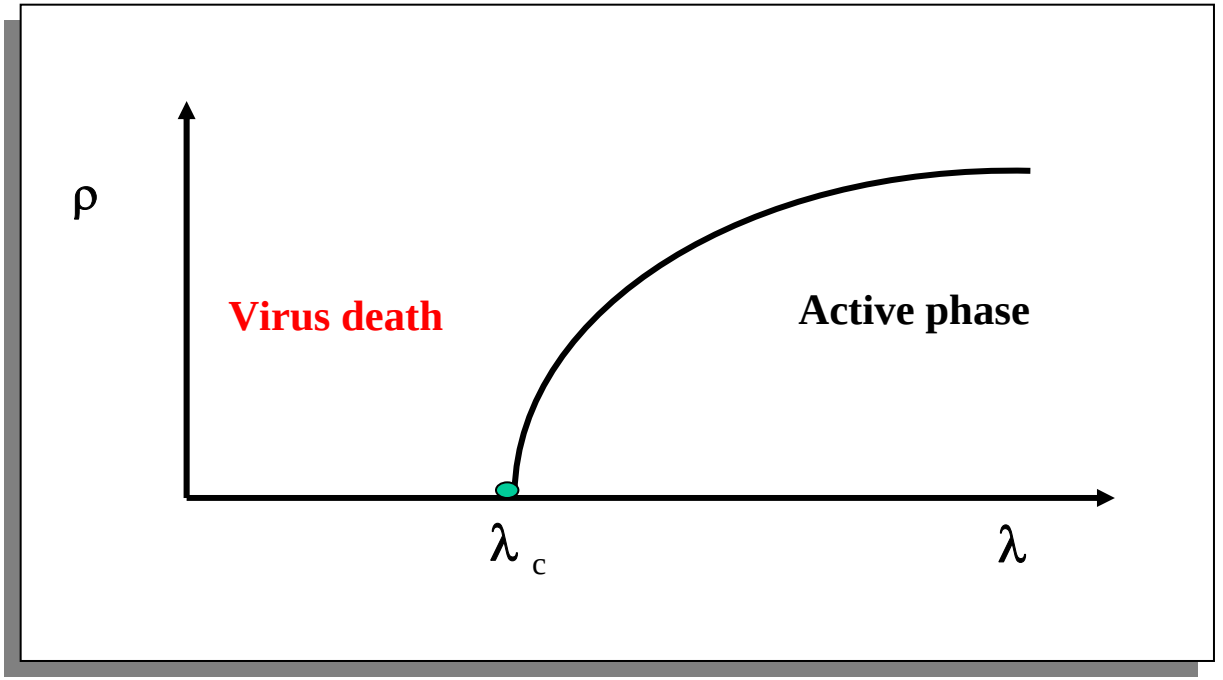
Hub removal has more phenotypic consequences [Yu *et al. Science* (2008)]

Jeong, Mason, Barabási, and Oltvai, *Nature* 411, 41-42 (2001

Epidemic threshold in scale-free networks

λ: spreading rate of a virus

ρ: density of infected users



Biology:

If a virus is not too infectious, it will die out

Economics and social sciences:

If a product or an idea is not too 'sticky,' it will not succeed.

$$\lambda_c = \frac{\langle k \rangle}{\langle k^2 \rangle}$$

$$\langle k^2 \rangle \rightarrow \infty$$

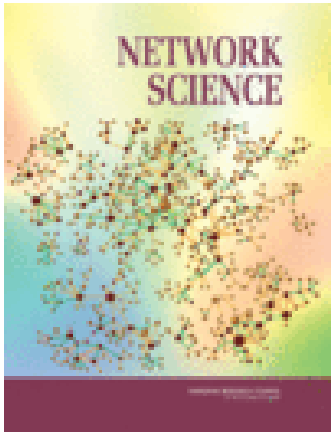
$$\lambda_c \rightarrow 0$$

Pastor Satorras & Vespignani, *Physical Review Letters* (2001)

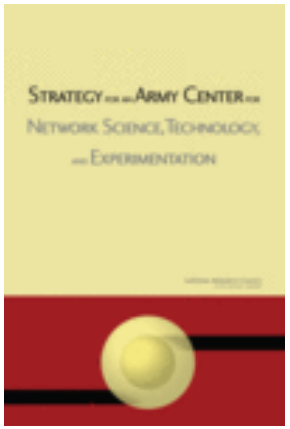
THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

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?

Despite the apparent differences, many networks emerge and evolve driven by a *fundamental set of laws and mechanism.*

Réka Albert,	Penn State
Hawoong Jeong,	KAIST, Korea
Ginestra Bianconi,	ICTP, Trieste
Kwang-Il Goh,	Korea University
Cesar Hidalgo,	Notre Dame
Mark Vidal,	Dana-Farber, Harvard
Michael E. Cusick,	Dana Farber, Harvard
David Valle,	Johns Hopkins
Barton Childs,	Johns Hopkins
Nicholas Christakis,	Harvard
Deok-Sun Lee,	Northeastern University & DF
Juyong Park,	Northeastern University & DF
Zoltan N. Oltvai,	Pitssburgh Medical School
Dashun Wang,	Northeastern University

www.BarabasiLab.com