Network Science

Class 4: Scale-free property

Albert-László Barabási

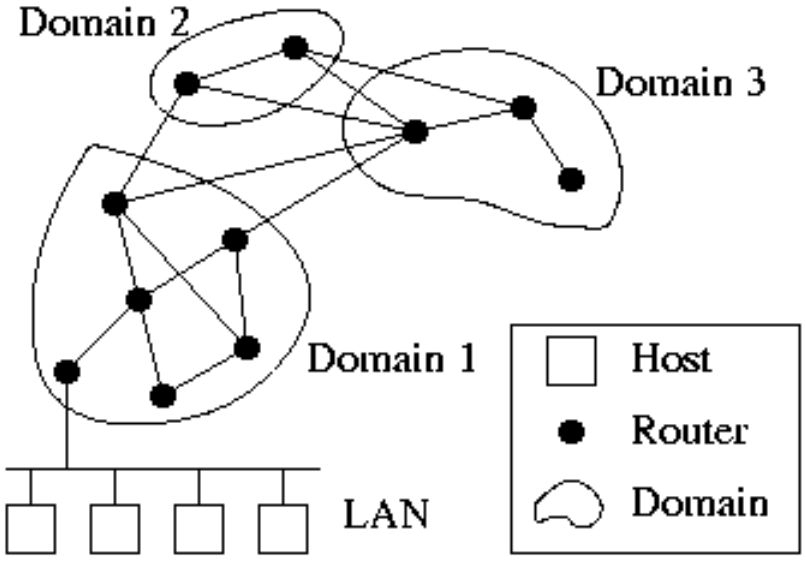
with Emma K. Towlson, Michael M. Danziger,
Sebastian Ruf and Louis Shekhtman

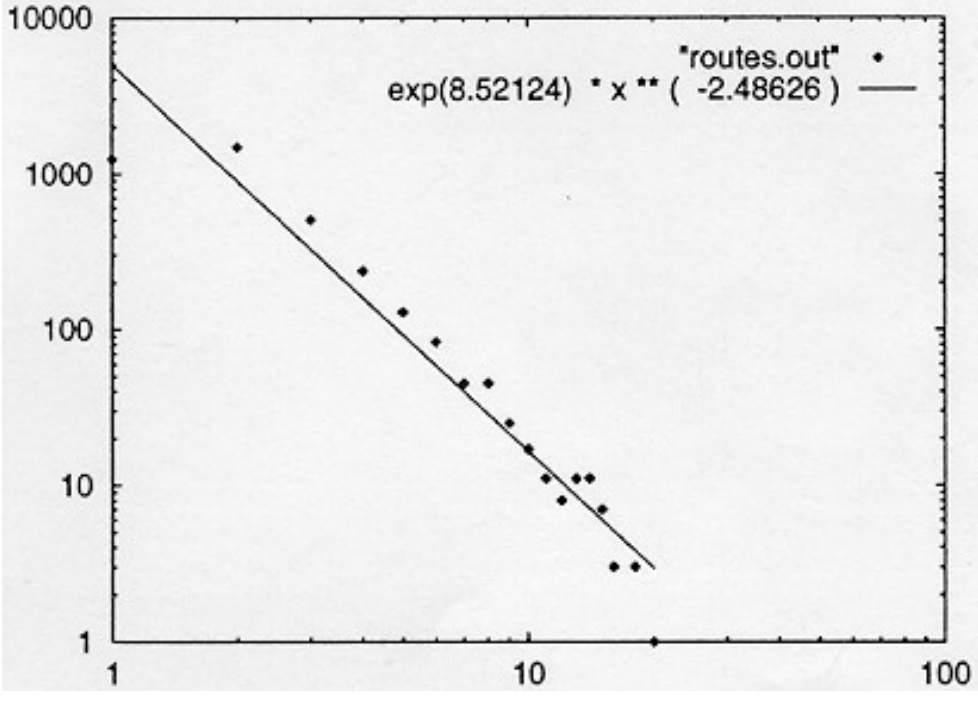
www.BarabasiLab.com

universality

INTERNET BACKBONE

Nodes: computers, routers
Links: physical lines





(Faloutsos, Faloutsos and Faloutsos, 1999)


Network Science: Scale-Free Property

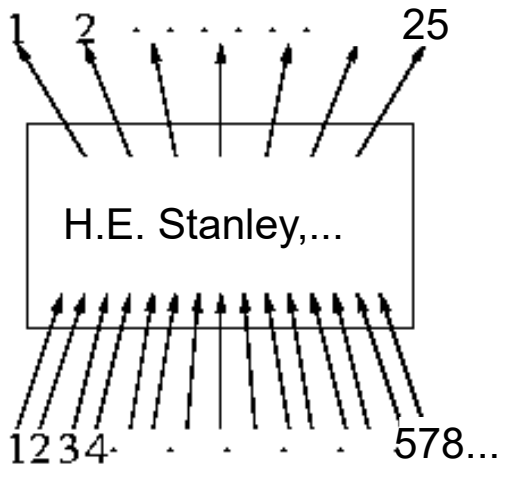
SCIENCE CITATION INDEX

Nodes: papers
Links: citations

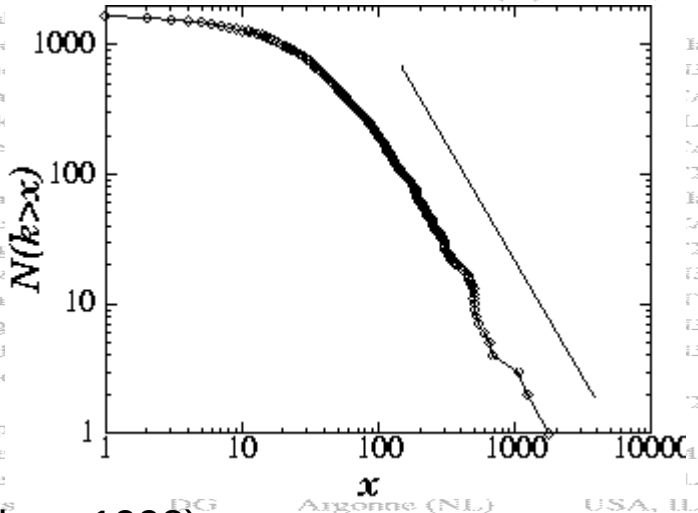
Out of over 500,000 Examined
(see http://www.sst.nrel.gov)

		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
[illegible]	AC	UCSB (U)	USA, CA	Semic				2
Cava	RJ	Bell Labs (I)	USA, NJ	Super				3
Batlogg	B	Bell Labs (I)	USA, NJ	Super				4
Ploog	K	Max-Planck (NL)	Germany	Semic				5
Ellis	J	Euro Nuclear Cent.	Switzerland	Astrop				6
Fisk	Z	Florida State (U)	USA, FL	Solid S				7
Cardona	M	Max Planck (NL)	Germany	Semic				8
Nanopoulos	DV	Texas A&M (U)	USA, TX	High-				9
Heeger	AJ	UCSB (U)	USA, CA	Polym				10
Lee*	PA							11
Suzuki*	T							12
Anderson			NJ	Solid S				13
Suzuki*								14
Freeman			IL	Solid S				15
Tana								16
Mull			land	Super				17
Schu				Super				18
Chen			A	Optics				19
Mork				Semic				19
Mille			A	Semic				21
Chu			X	Superconductivity (E)	44	213	9453	22
Bedn			land	Supercond [illegible] (E)	[illegible]	85	9311	23
Cohe			A	Solid State [illegible]	[illegible]	284	9311	23
Meng			X	Superconductivity (E)	86	108	9300	25
Wasz				Superconductivity (E)	57	162	9170	26
Shira			Y	Superconductivity (E)	33	269	8841	27
Wieg				Semiconductors (E)	85	104	8822	28
Vand				Magnetism (E)	67	129	8686	29
Uchi					28	301	8520	30
Hor			X	Superconductivity (E)	72	119	8512	31
Murp				Astronomy (E)	111	76	8439	32
Birge			A	Superconductivity (E)	41	286	8375	33
Jorge				Superconductivity (E)	50	167	8298	34
Hinks	DG	Argonne (NL)	USA, IL	Superconductivity (E)	37	223	8263	35

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



1736 PRL papers (1988)



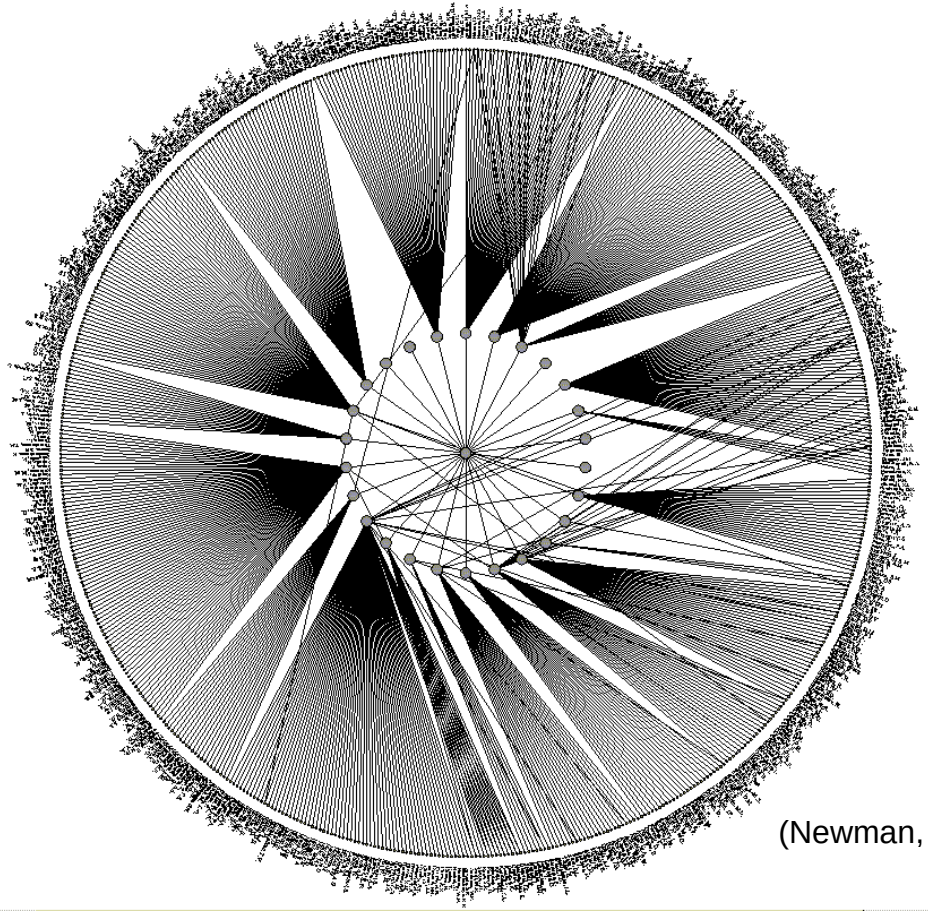
$P(k) \sim k^{-\gamma}$

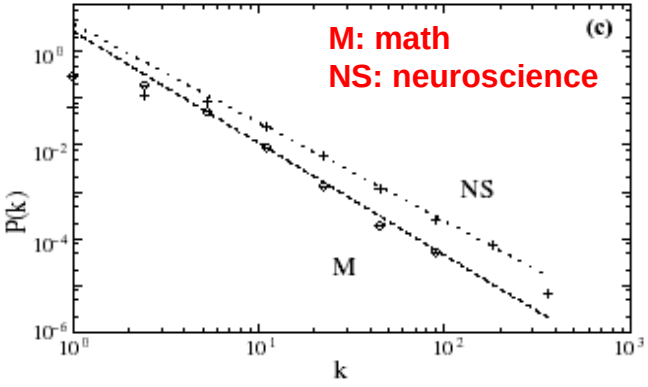
$(\gamma = 3)$

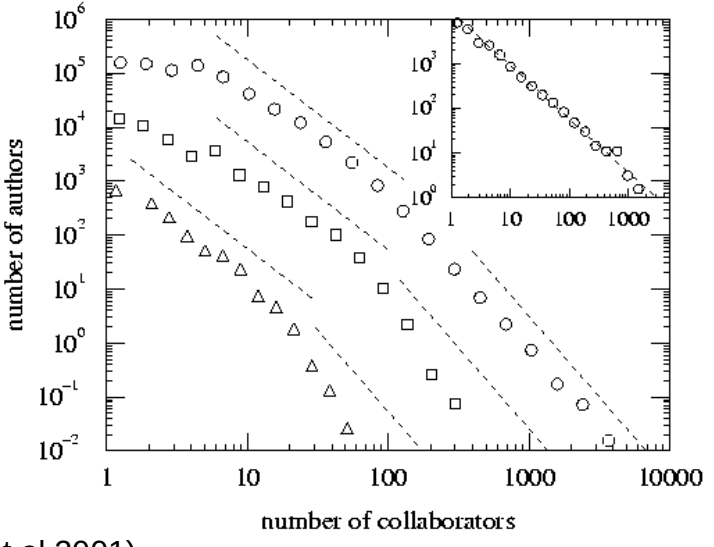
(S. Redner, 1998)

SCIENCE COAUTHORSHIP

Nodes: scientist (authors)
Links: joint publication





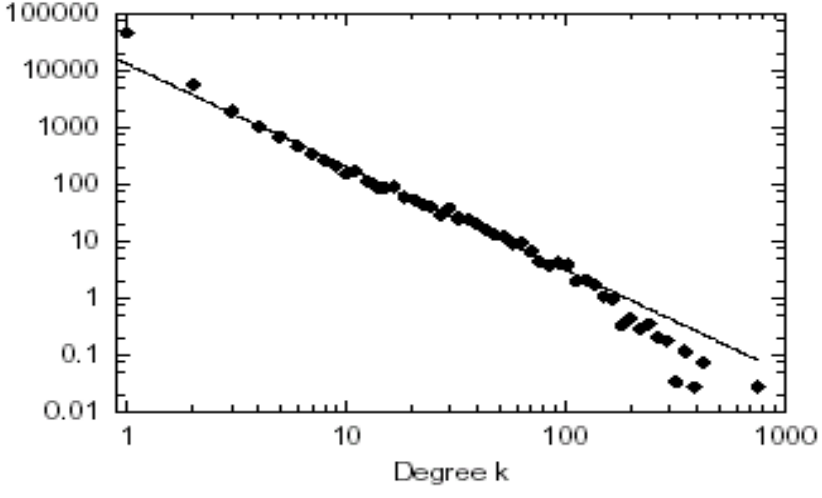


(Newman, 2000, Barabasi et al 2001)

ONLINE COMMUNITIES

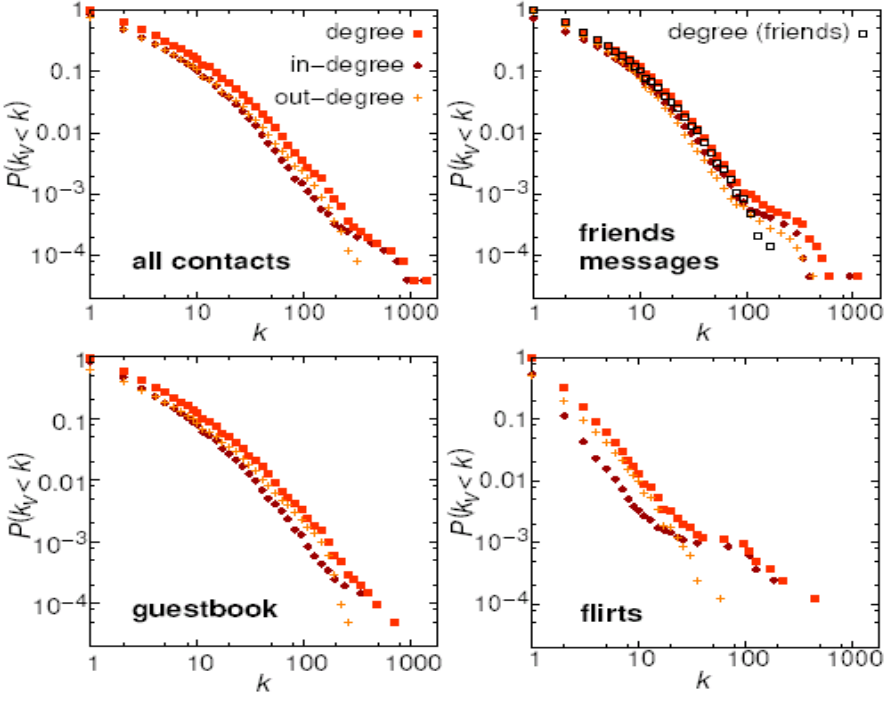
Nodes: online user
Links: email contact

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



Ebel, Mielsch, Bornholdtz, PRE 2002.

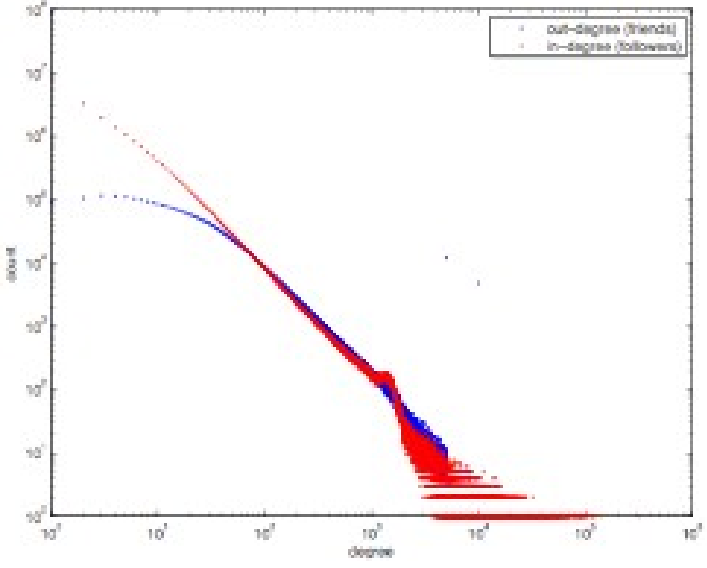
Pussokram.com online community;
512 days, 25,000 users.



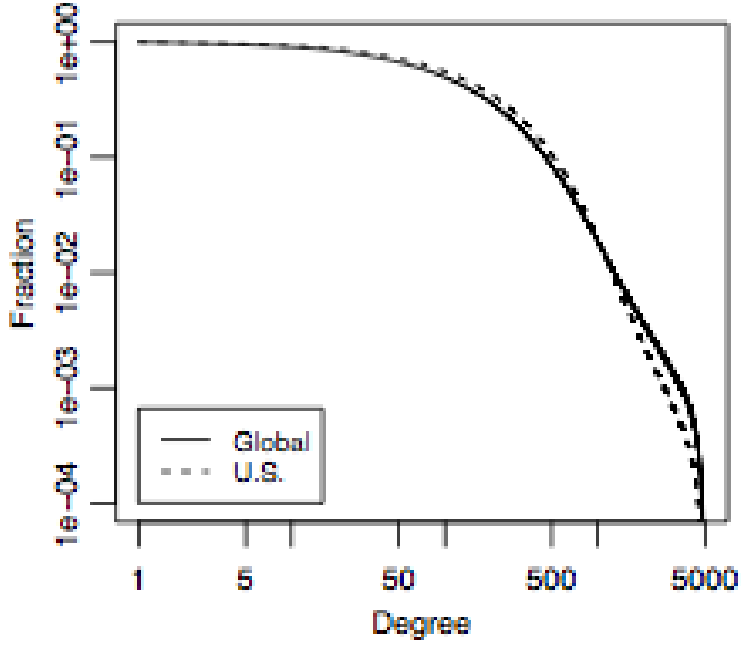
Holme, Edling, Liljeros, 2002.

ONLINE COMMUNITIES

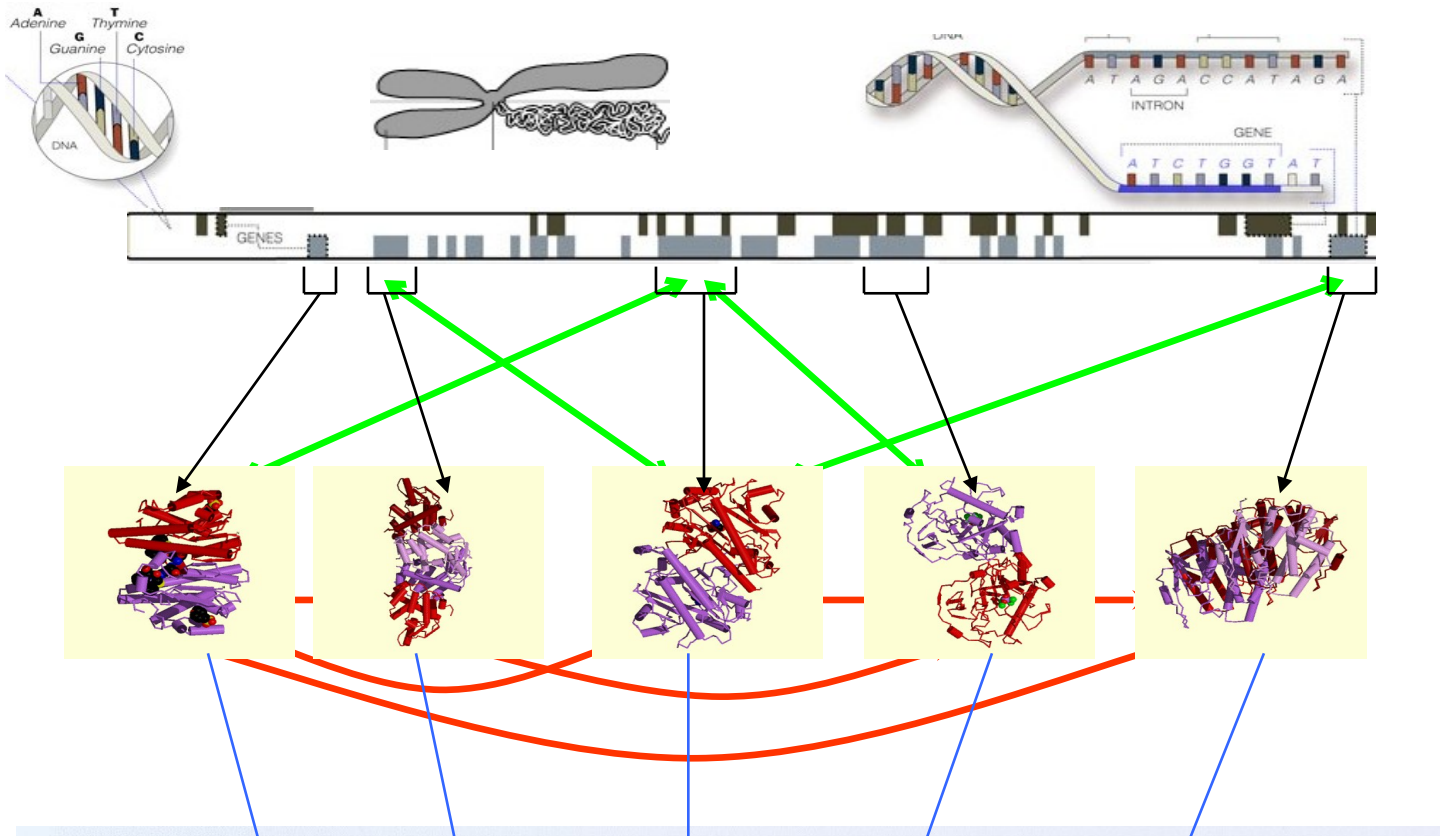
Twitter:



Facebook



Brian Karrer, Lars Backstrom, Cameron Marlowm 2011

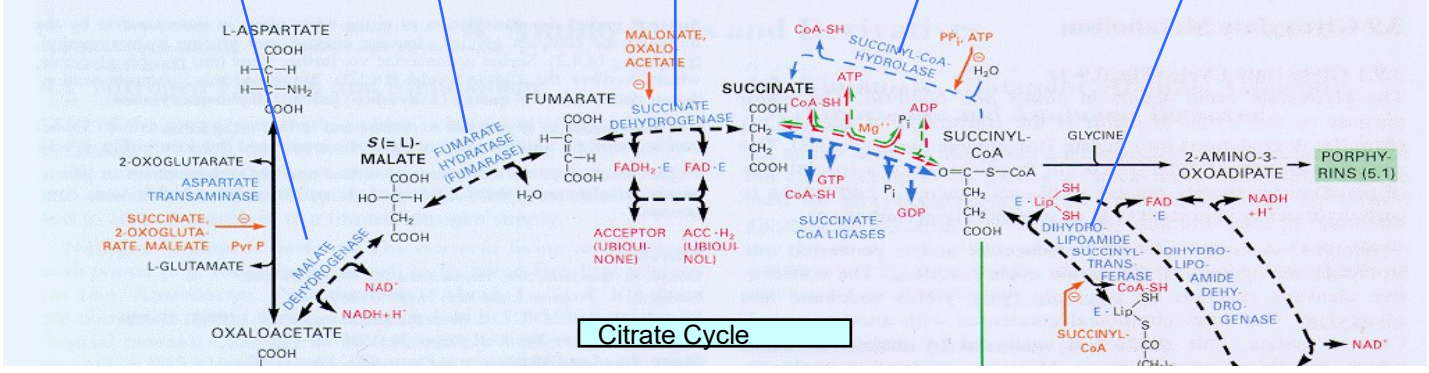


GENOME

protein-gene interactions

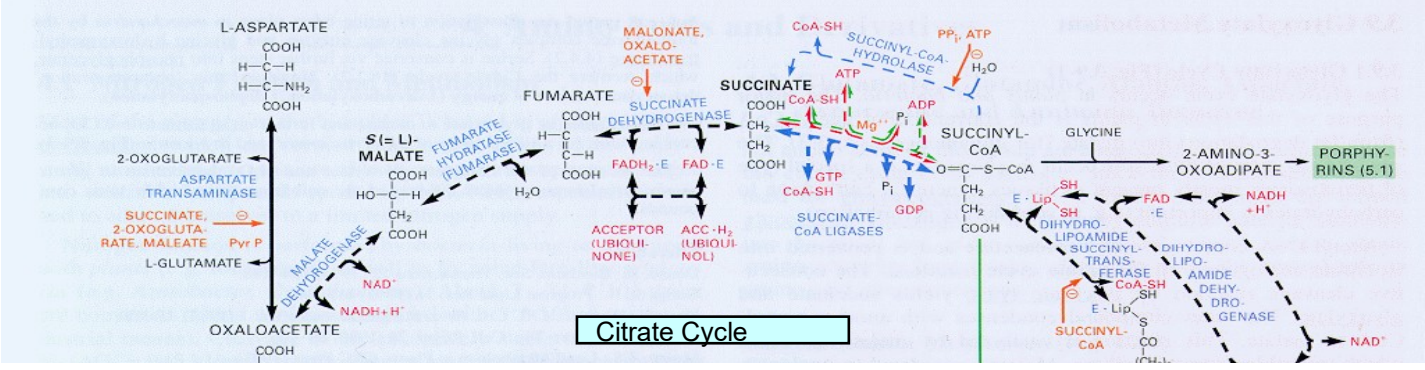
PROTEOME

protein-protein interactions



METABOLISM

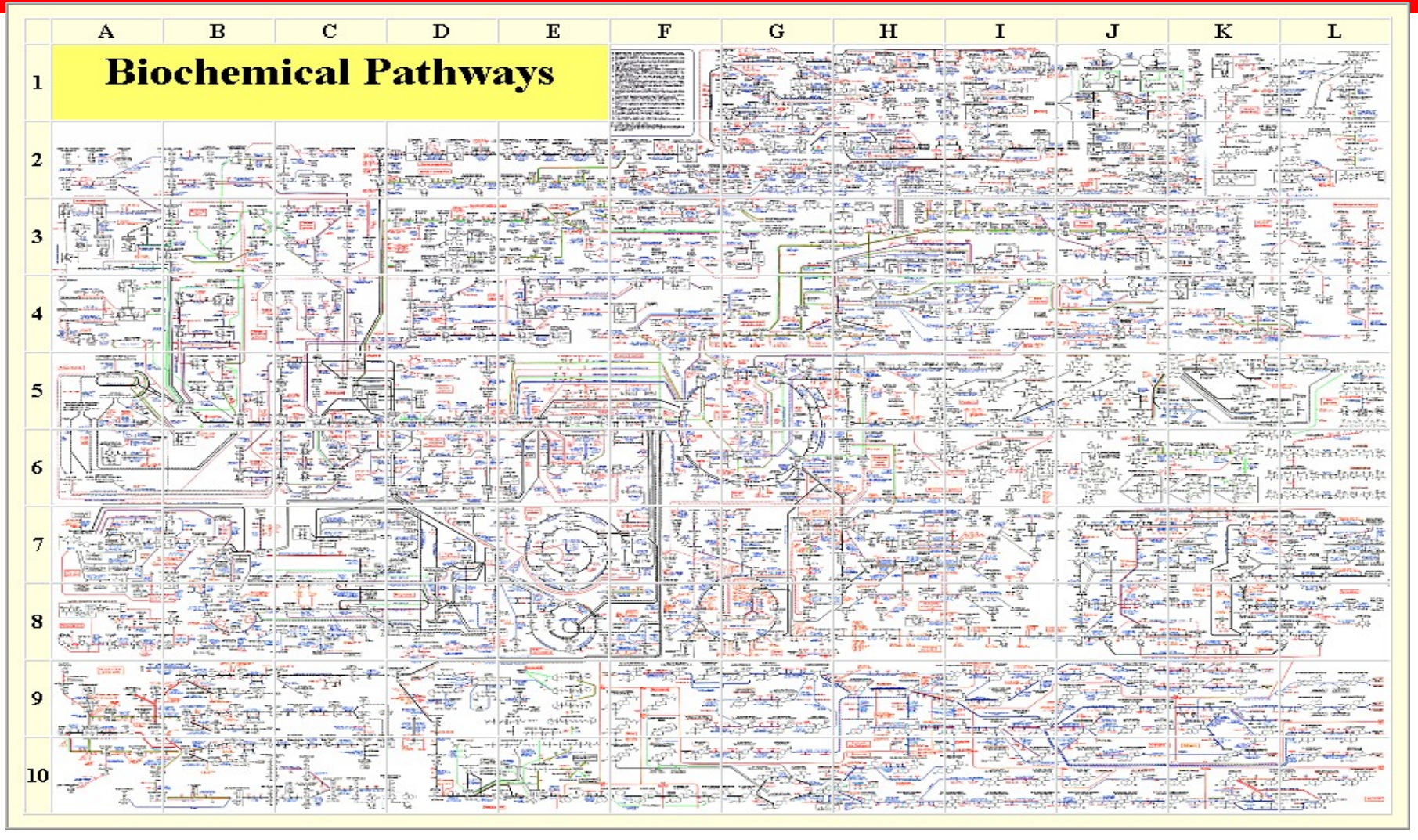
Bio-chemical reactions



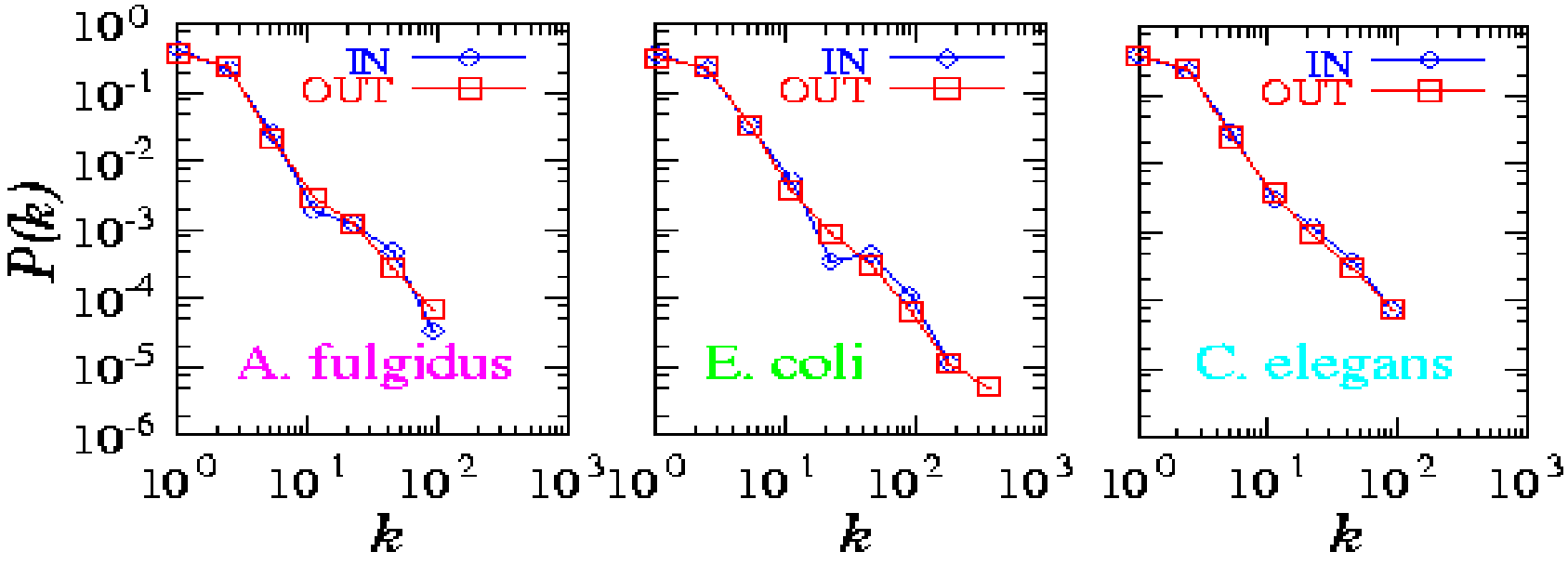
METABOLISM

Bio-chemical reactions

BOEHRING-MENNHEIN



METABOLIC NETWORK



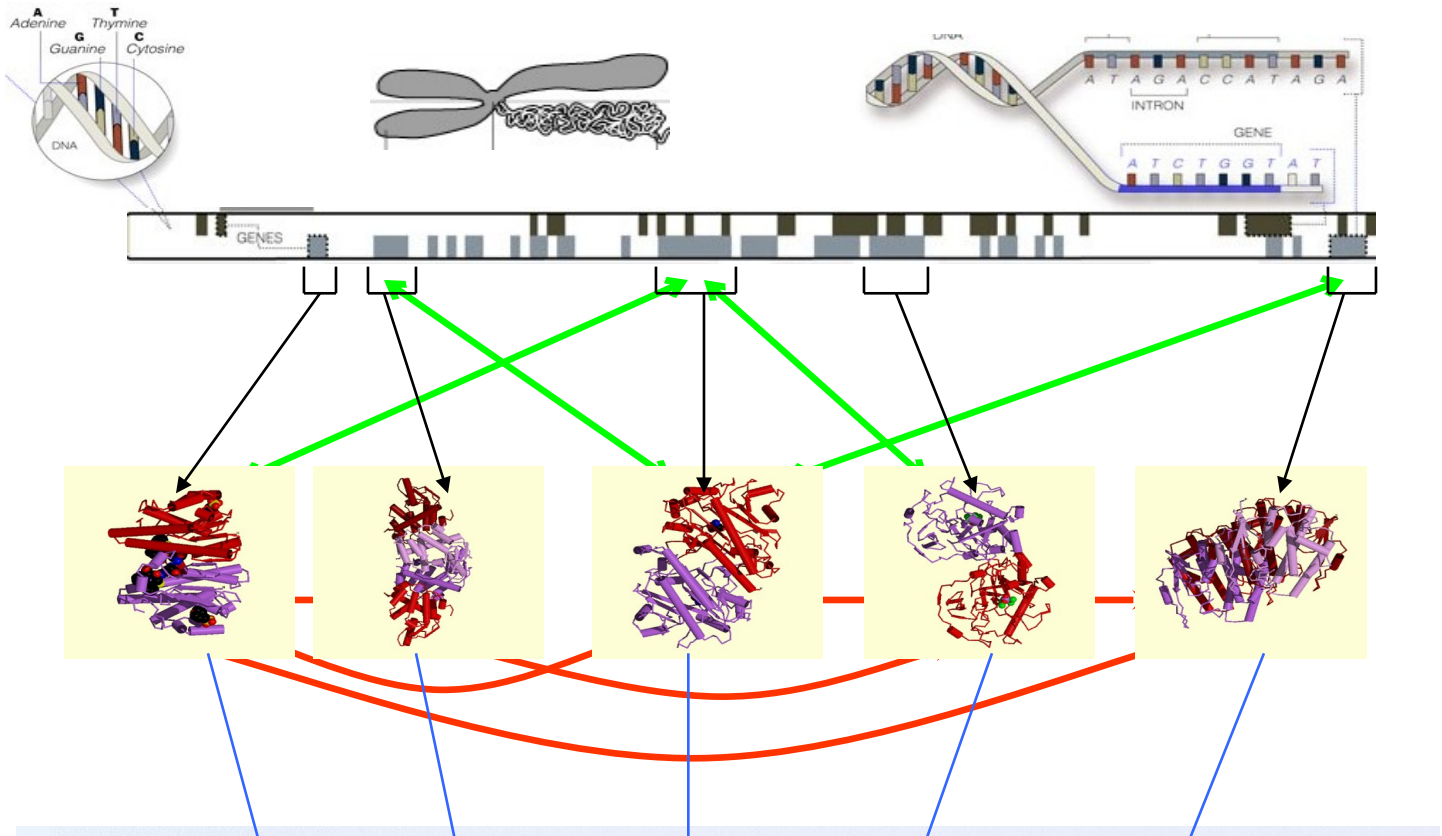
Archaea Bacteria Eukaryotes

Organisms from all three domains of life are scale-free!

$$P_{in}(k) \approx k^{-2.2}$$

$$P_{out}(k) \approx k^{-2.2}$$

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

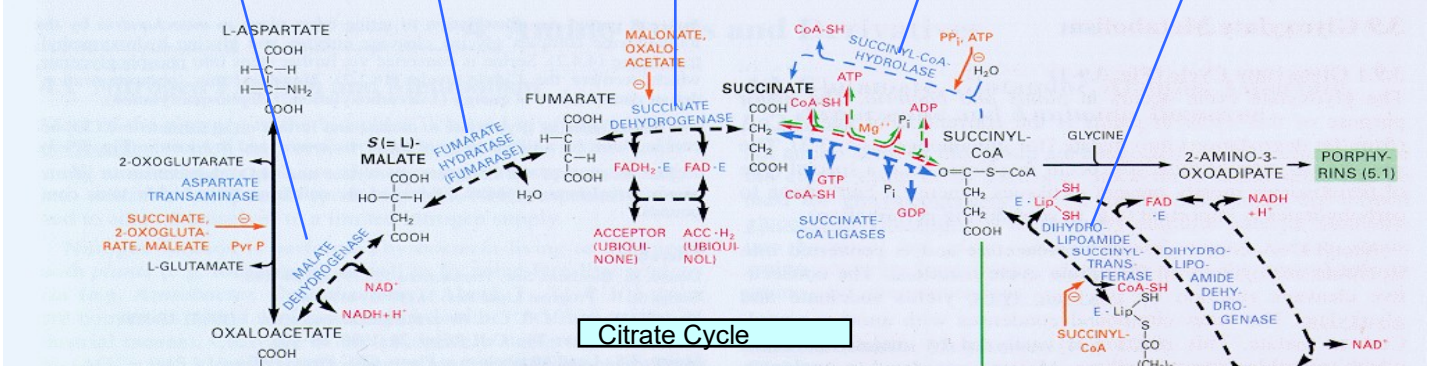


GENOME

protein-gene interactions

PROTEOME

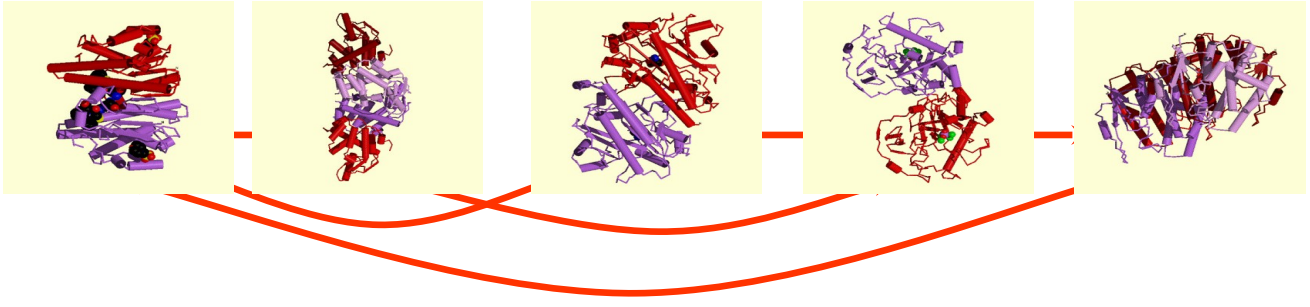
protein-protein interactions



METABOLISM

Bio-chemical reactions

METABOLIC NETWORK

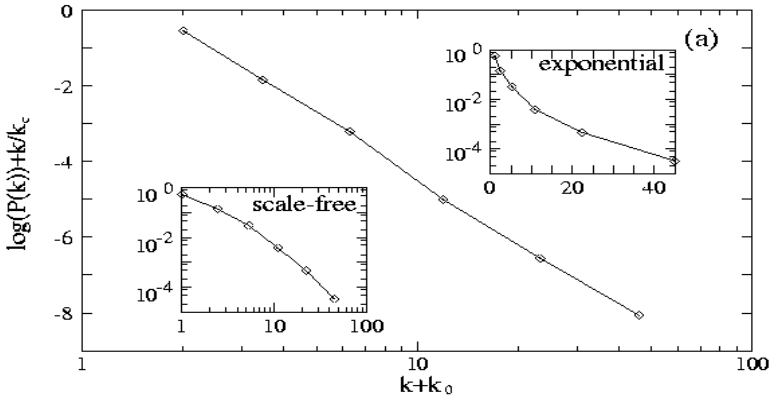


PROTEOME

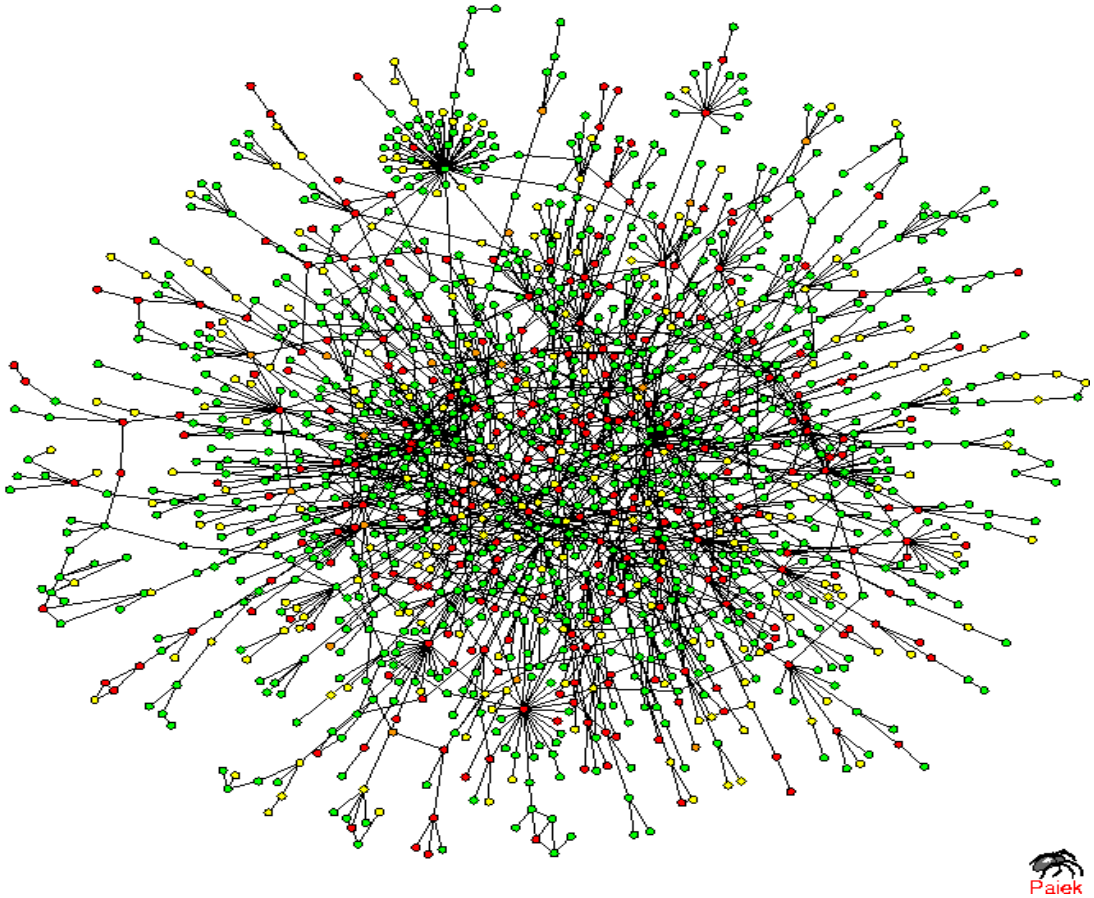
protein-protein interactions

TOPOLOGY OF THE PROTEIN NETWORK

Nodes: proteins
Links: physical interactions-binding

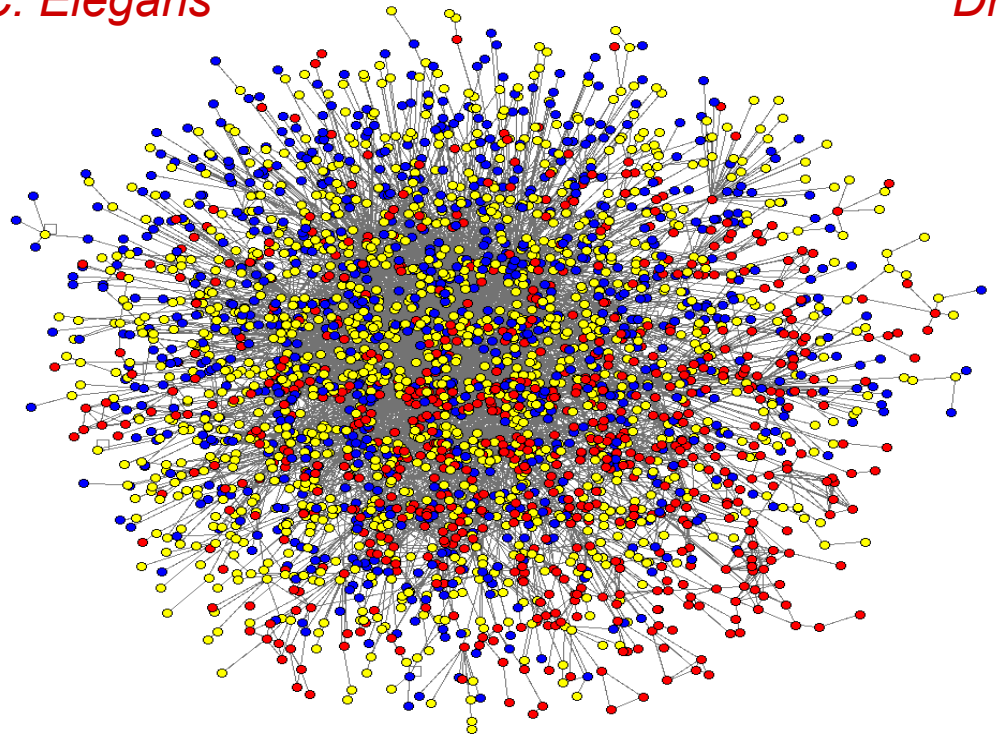


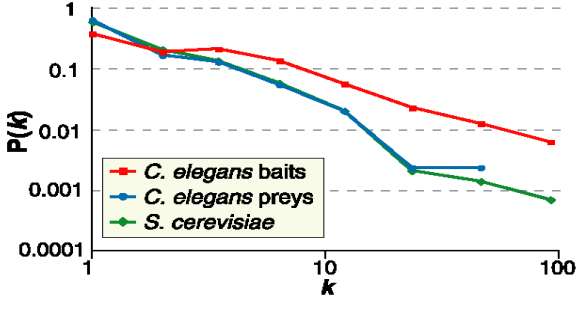
$$P(k) \sim (k + k_0)^{-\gamma} \exp(-\frac{k + k_0}{k_\tau})$$



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

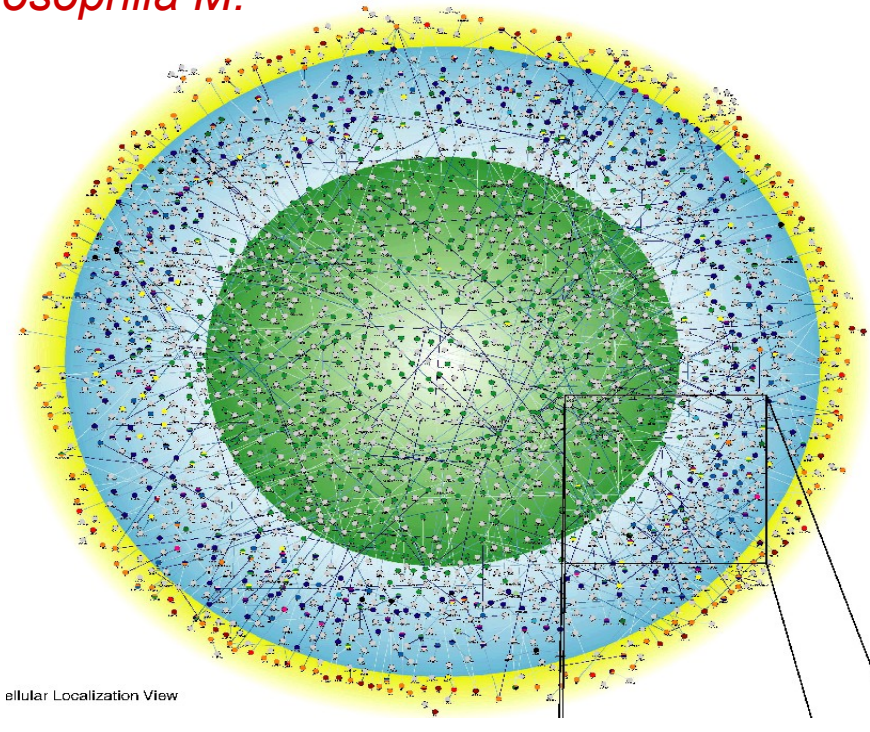
C. Elegans

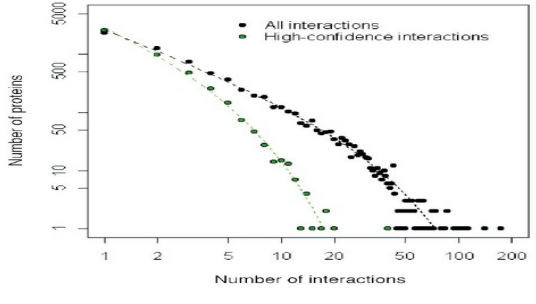




Li *et al.* Science 2004

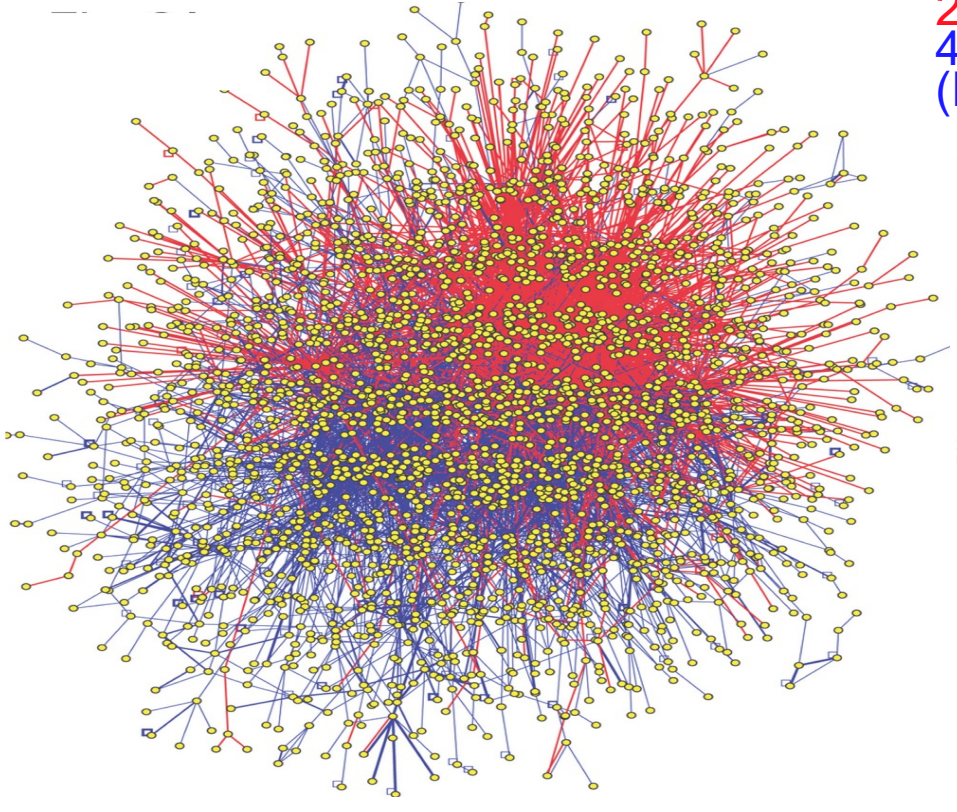
Drosophila M.



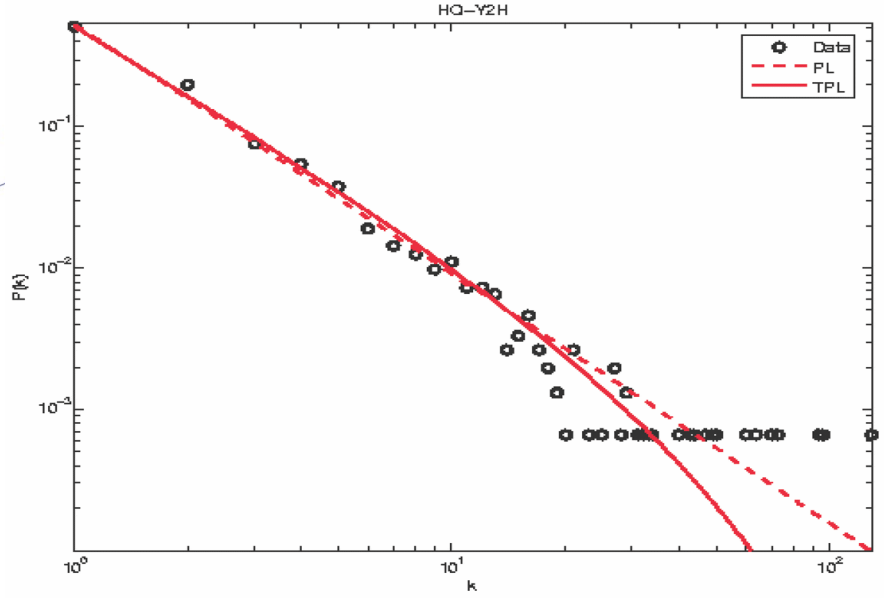


Giot *et al.* Science 2003

HUMAN INTERACTION NETWORK



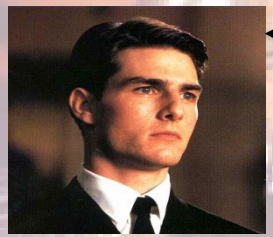
2,800 Y2H interactions
4,100 binary LC interactions
(HPRD, MINT, BIND, DIP, MIPS)



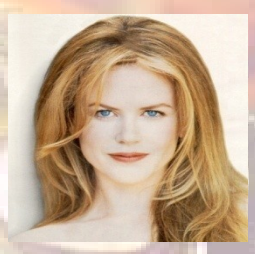
Rual *et al.* Nature 2005; Stelzl *et al.* Cell 2005

ACTOR NETWORK

Nodes: actors
Links: cast jointly

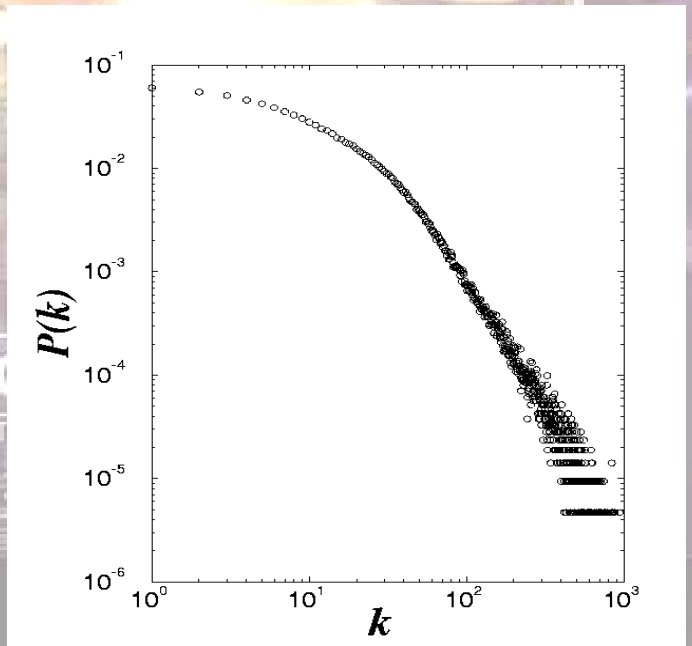


Days of Thunder *(1990)*
Far and Away *(1992)*
Eyes Wide Shut *(1999)*



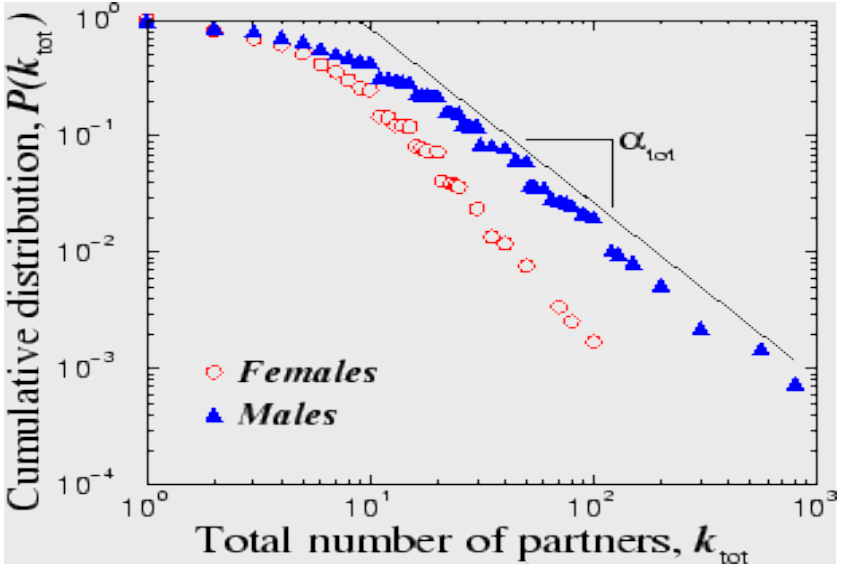
N = 212,250 actors

$\langle k \rangle = 28.78$
$P(k) \sim k^{-\gamma}$
$\gamma = 2.3$



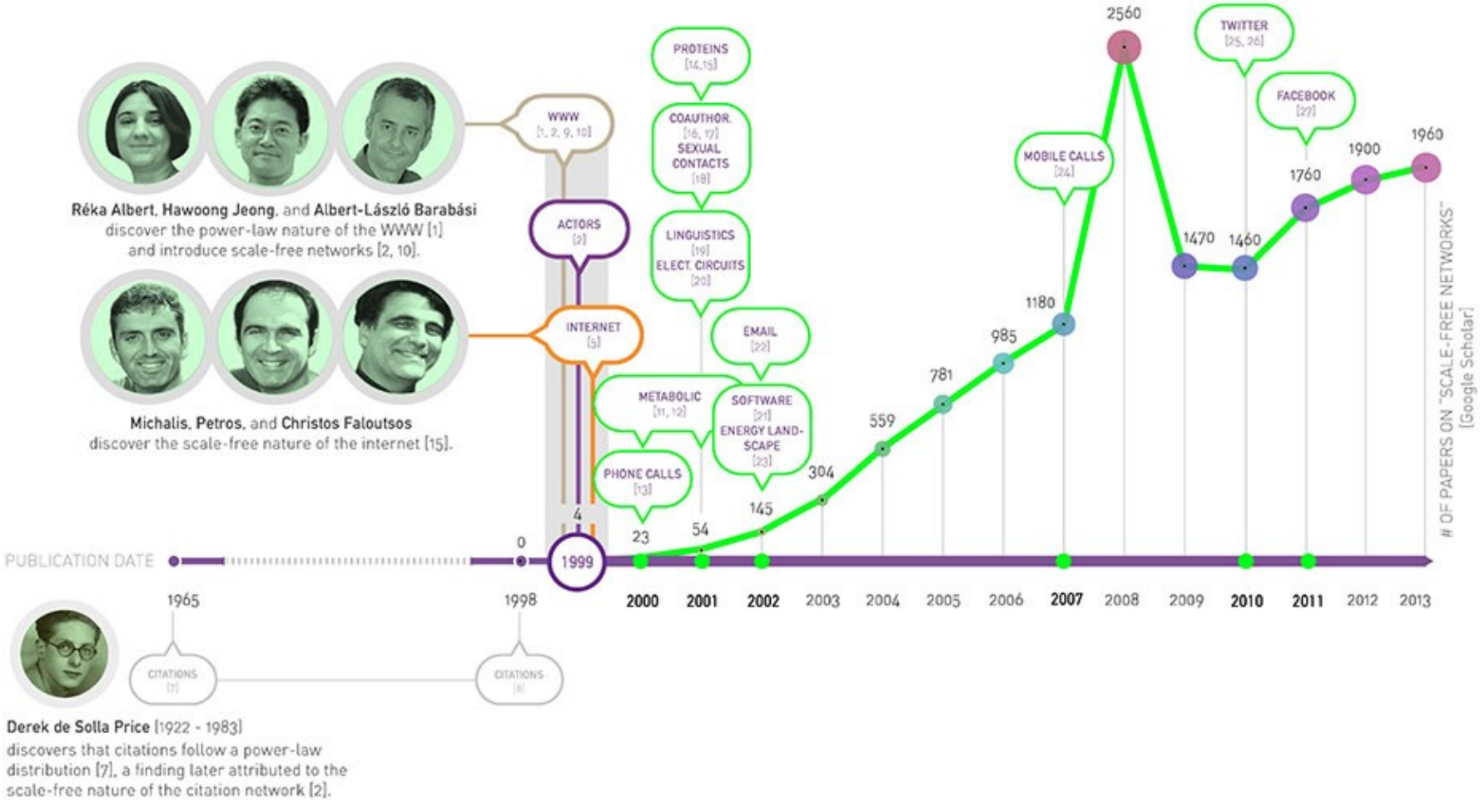
SWEDISH SE-WEB

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



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

Liljeros et al. Nature 2001


Réka Albert, Hawoong Jeong, and Albert-László Barabási
discover the power-law nature of the WWW [1]
and introduce scale-free networks [2, 10].
Michalis, Petros, and Christos Faloutsos
discover the scale-free nature of the internet [15].
Derek de Solla Price (1922 - 1983)
discovers that citations follow a power-law
distribution [7], a finding later attributed to the
scale-free nature of the citation network [2].
WWW [1, 2, 9, 10]
ACTORS [2]
INTERNET [5]
PROTEINS [14,15]
COAUTHOR. [16, 17]
SEXUAL CONTACTS [18]
LINGUISTICS [19]
ELECT. CIRCUITS [20]
EMAIL [22]
METABOLIC [11, 12]
SOFTWARE [21]
ENERGY LAND-SCAPE [23]
PHONE CALLS [13]
MOBILE CALLS [24]
TWITTER [25, 26]
FACEBOOK [27]
CITATIONS [7]
CITATIONS [8]
PUBLICATION DATE
1965
1998
1999
0
4
23
54
145
304
559
781
985
1180
2560
1470
1460
1760
1900
1960
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
OF PAPERS ON "SCALE-FREE NETWORKS" [Google Scholar]

Not all networks are scale-free

- *Networks appearing in material science, like the network describing the bonds between the atoms in crystalline or amorphous materials, where each node has exactly the same degree.*
- *The neural network of the C.elegans worm.*
- *The power grid, consisting of generators and switches connected by transmission lines*