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Complexity and social dynamics

Víctor M. Eguíluz

Plan

- Introduction to complex systems
- Social modeling
- Complex Networks: Networks are the skeleton of a complex system
- Conclusions

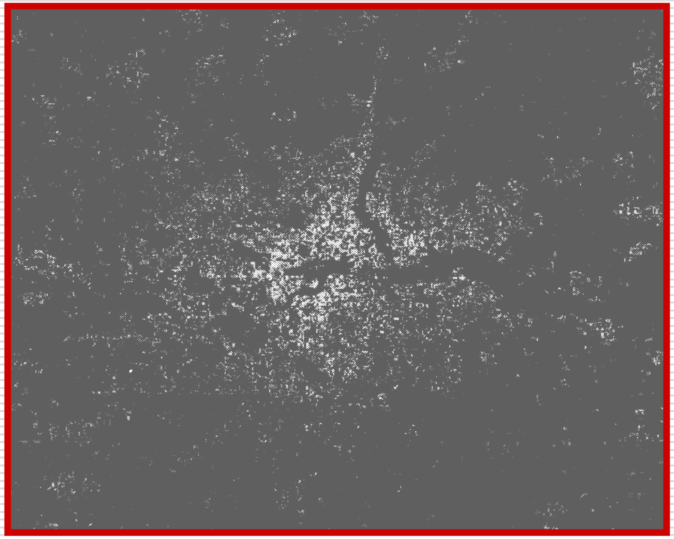
Complex Systems

- What is a complex system?
- A few preliminary *(and incorrect)* remarks:
  - Simple systems display simple dynamics; Complex behavior is a consequence of complicated systems.

    Chaos
  - Different systems behave in a different way.

    Universality
- An intuition: The global behavior cannot be reduced to the addition of the individual components.
  - For instance, the society cannot be reduced to the psychology of the individuals. In many situations the individual features are irrelevant to explain the collective behavior.
- Complex behavior lies between order and disorder.
  - Example: the growth of a city.

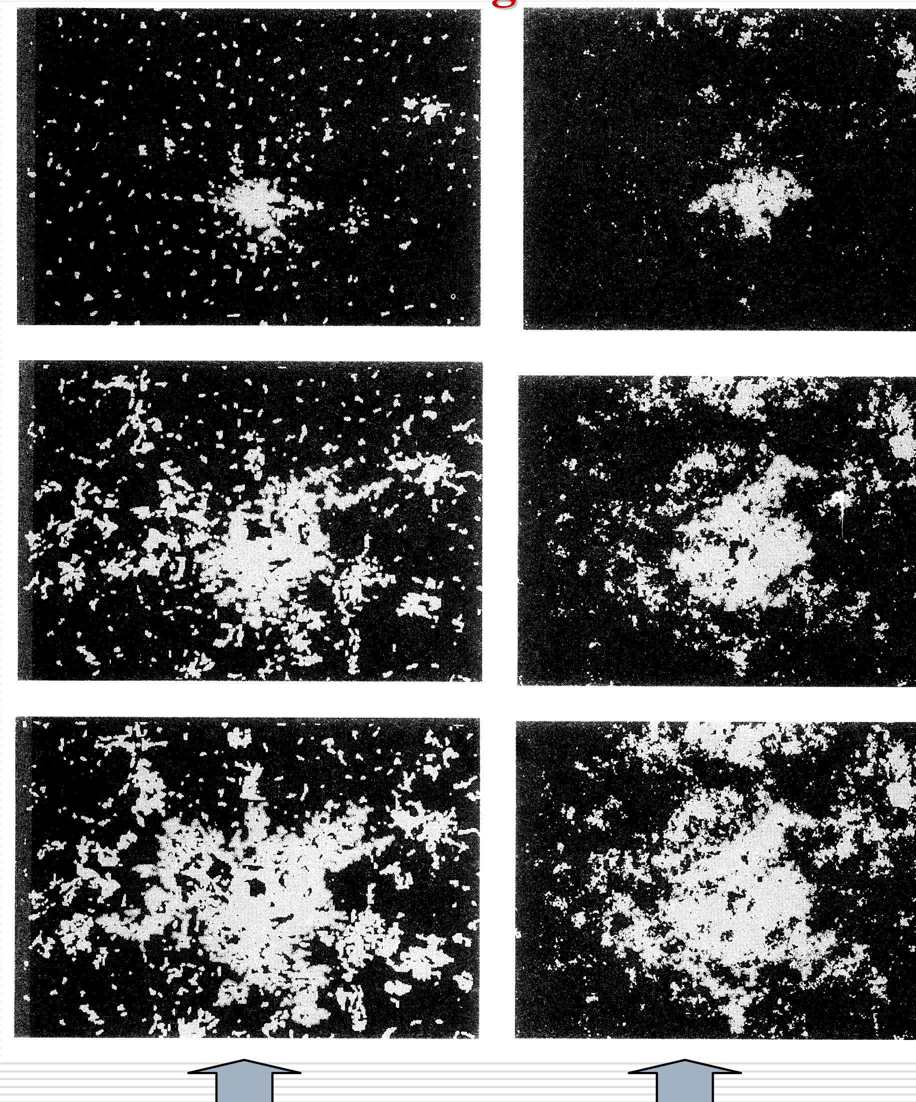
A few examples



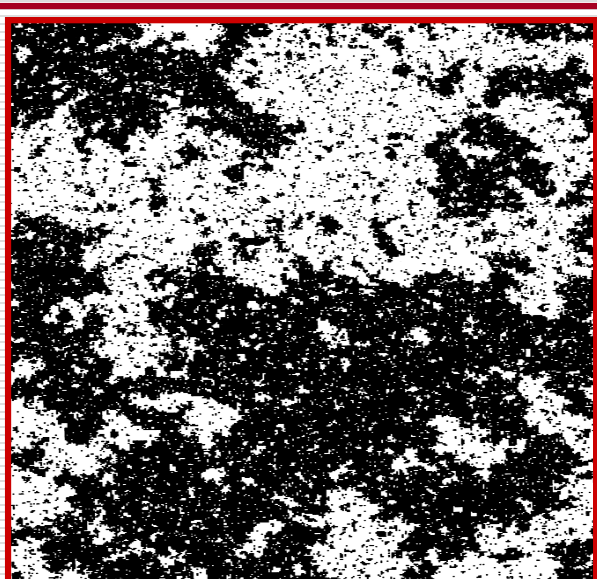
Density of employment in London

(M. Batty, U.C., London)

Urban growth



Berlin 1875-1945 ***Percolation model***



Gas liquid critical point (A. Bruce)

H. Makse (P. Ball, The Self-Made Tapestry, 1999)

Complex systems: collective phenomena

- Individuals, agents, ….:
  - Psychology
  - Preferences
  - What do they do?
- Interaction networks:
  - How do agents interact?
  - Making decision

- Society:

  large number of interacting individuals
- Brain:

  10^9 neurons that interact via chemicals
- Internet:

  computers that exchange information

...bout the idea of complex vs. complicated

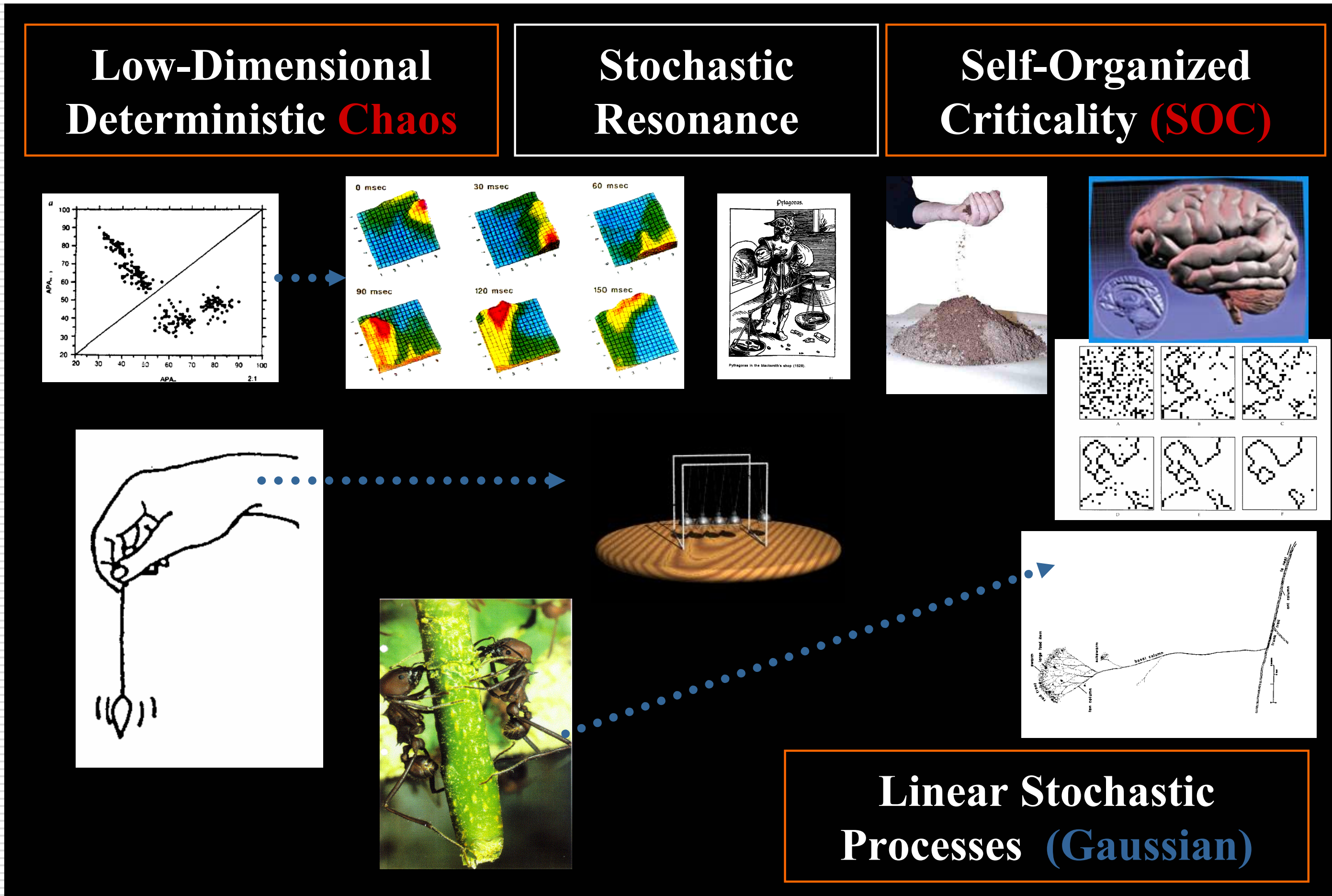
"DynamicsLand"

Emergen...

...nLinear

Non linearity

Linear



Complex... Systems...

Complicat... Systems...

...roof

Few

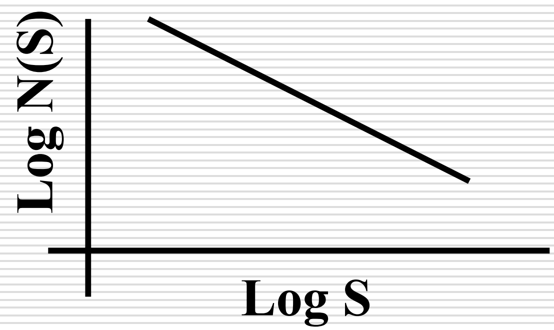
Degrees of Freedom

Many

Critical: sandpile toy model

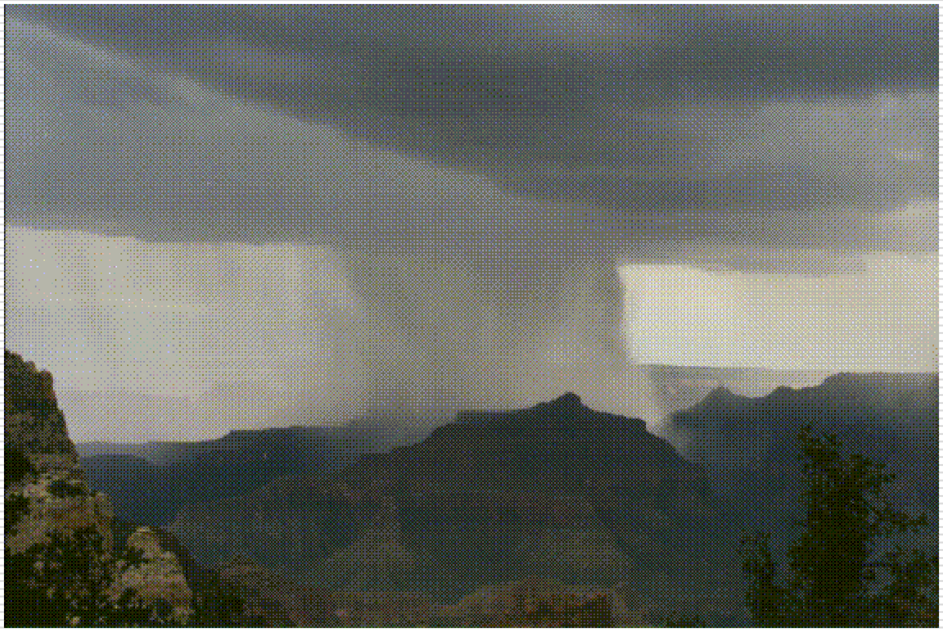
- Drop sand slowly… nothing happen …eventually the pile will reach a state in which the addition of a single grain will produce avalanches of all sizes:

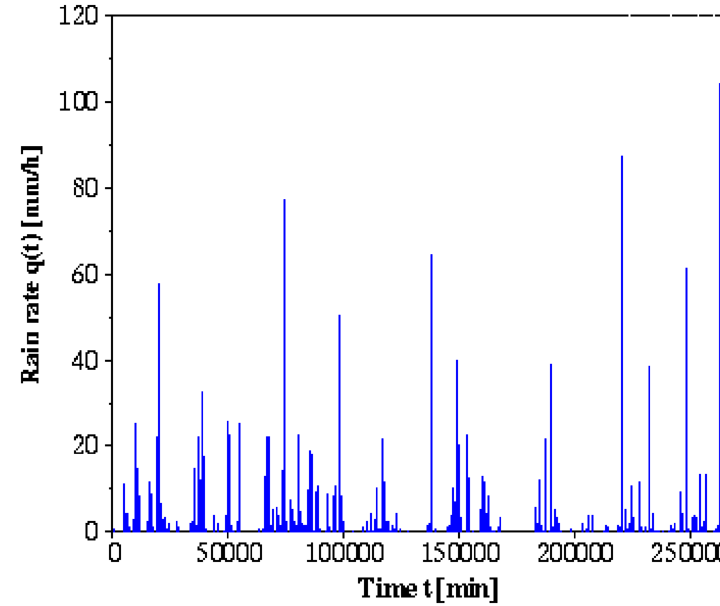
$$N(S) \approx \frac{1}{S^{\alpha}} \longrightarrow$$

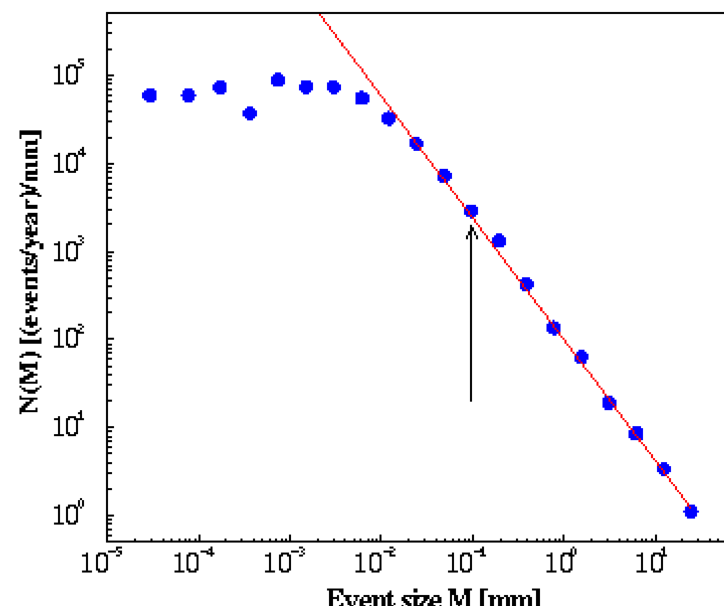


N(S) is the number of avalanches of size ***S*** and α is the critical exponent.

Another example: Rain as ‘Earthquakes in the Sky’*





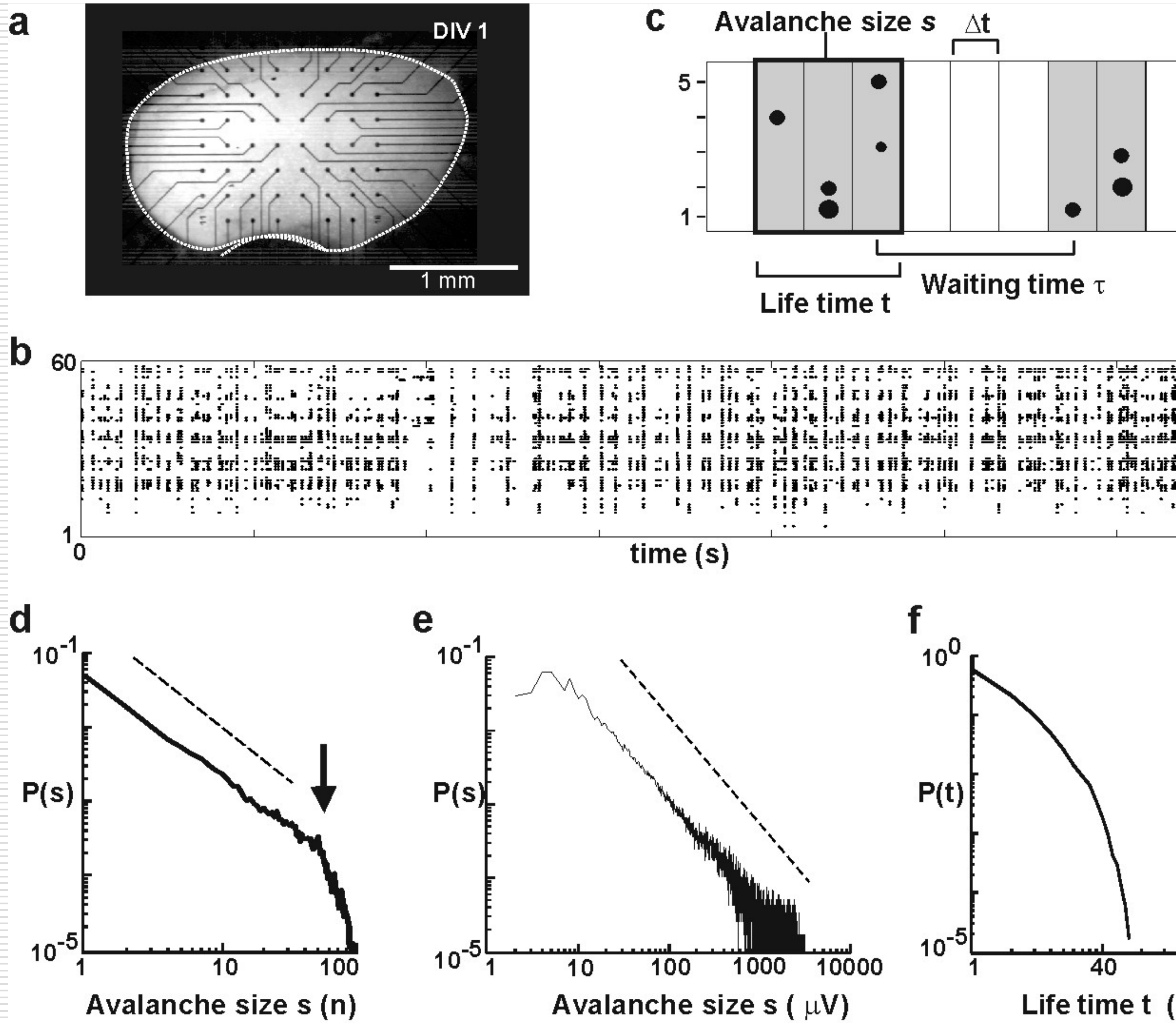


Rain dynamics is equivalent to the Gutenberg-Richter law for earthquakes and the scale-free distribution of avalanche sizes in sandpiles

ures from www.cmth.ph.ic.ac.uk/kim O. Peters, C. Hertlein, K. Christensen, *A complexity view of rainfall*, *Phys. Rev.*

other example: "Earthquakes in the cortex"

"Neuronal avalanches"

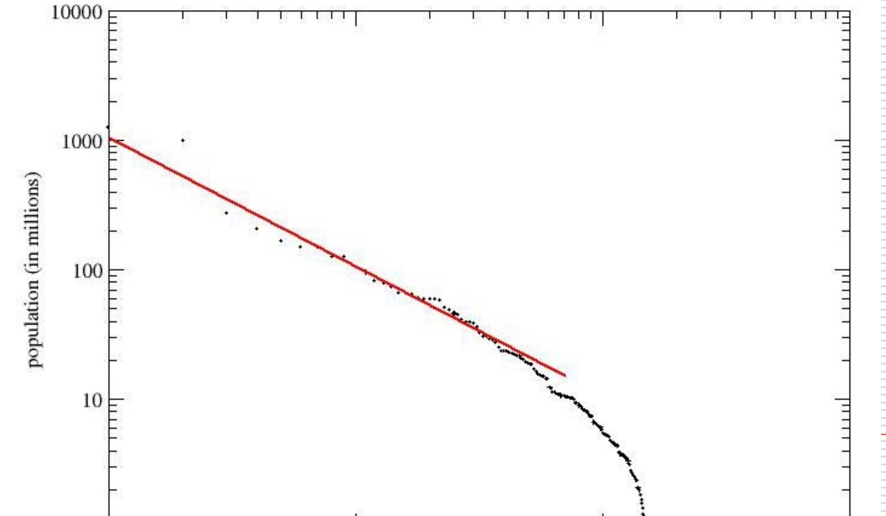


Complexity & Criticality

- The sandpile is a metaphor describing systems with *many nonlinear units interacting locally*.
- It reaches a dynamical attractor characterized by *long-range correlations*.
- There is no way we can study one grain of sand and infer anything relevant about the behavior of the resulting sandpile (*Emergence)*.
- A new behavior *emerges* as a result of interactions between the many simple units. In this sense complexity IS criticality.
- *Power laws* (heterogeneity) are signatures of complexity & criticality.
- Non linear interactions of many degrees of freedom. Lessons:
  - Look for the interaction in the whole and nonlinearity in the individual

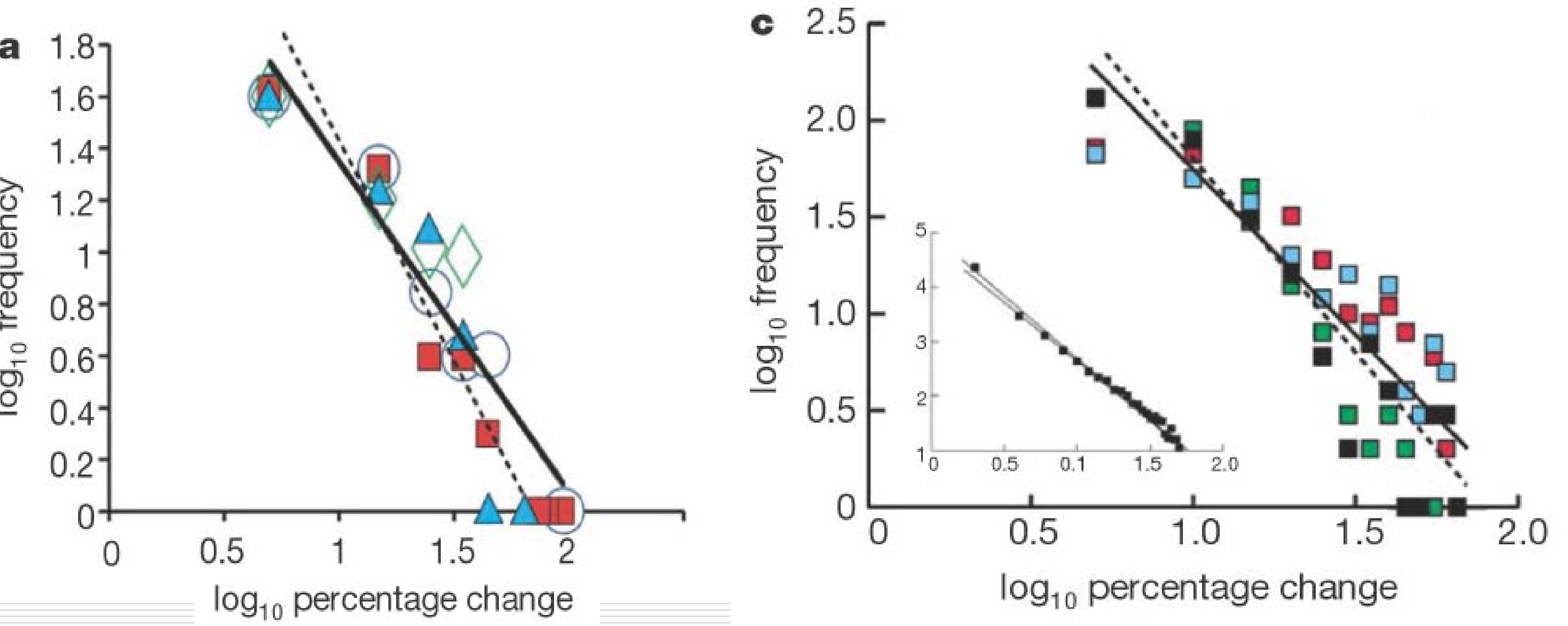
Single scale vs scale-free distributions

- Most of the distributions we learnt describes uniformity (Gaussian, exponential). E.g. heights, weights.
- However complex systems display heterogeneity. E.g. wealth, population.



World population

Hospital waiting-lists



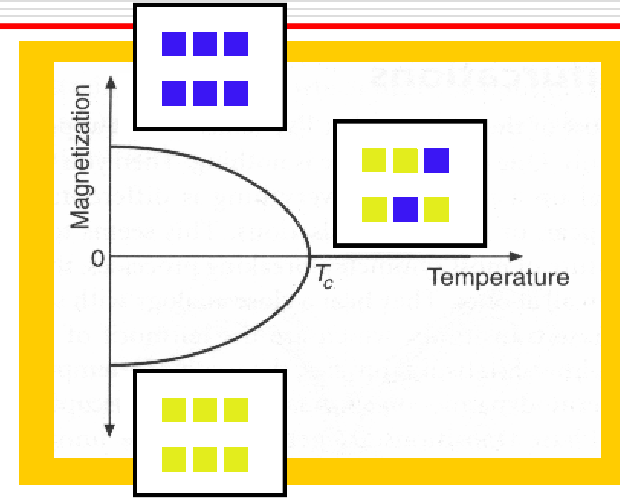
Nature **410**, 652 (20

Part I: Nonlinear dynamics

- Prisoner's Dilemma:
  - rational players?
  - local interaction?
- Voting & opinion formation.
- Imitation leads to herd behavior
  - Stock market
  - Panic

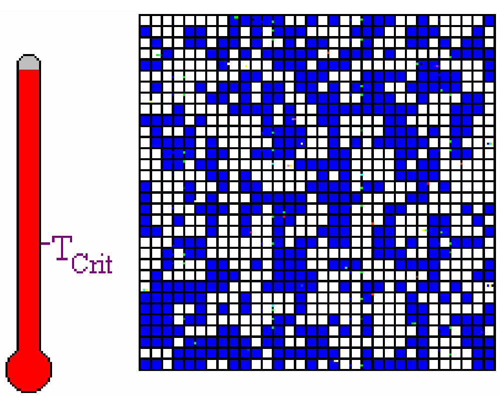
Opinion formation

- **Binary opinion** ((↑,↓),(0,1),(□,■))
- **Competition between**
  - **Order (interaction): neighbors want to be similar**
  - **Disorder (fluctuation): opinion changes randomly**



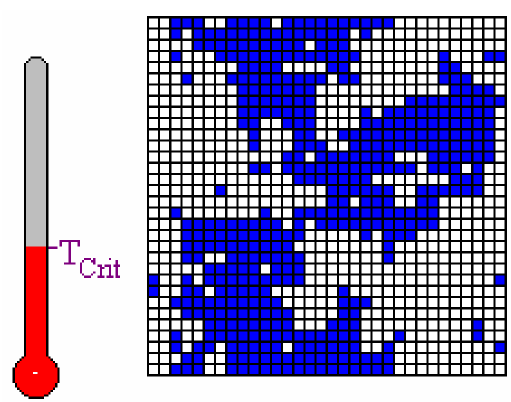
- **Order Parameter.**
- **Symmetry breaking.**

Disorder



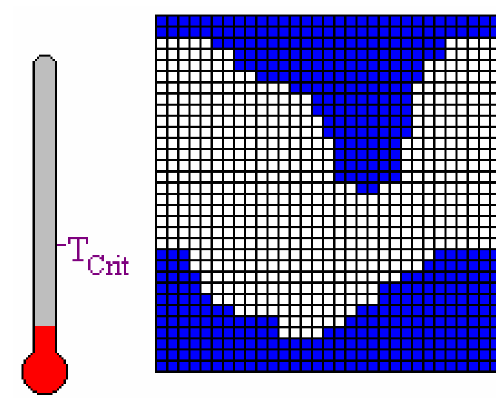
$T > T$

Critical Point



$T = T$

Order



$T < T$

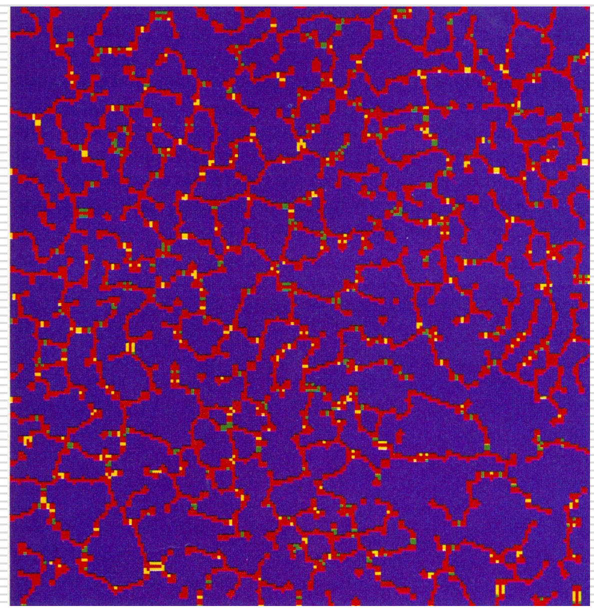
Social Cooperation

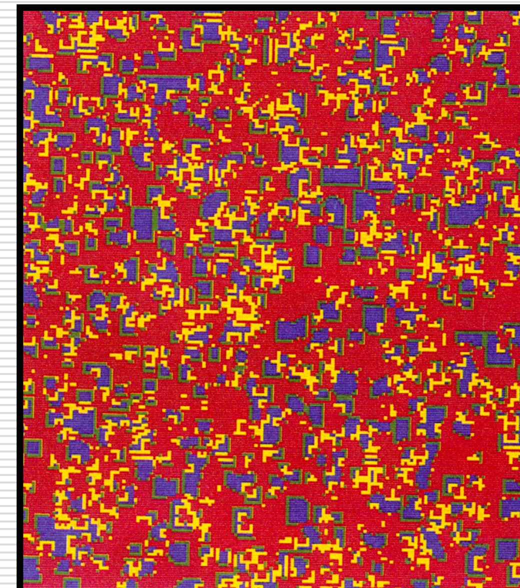
Emergence of cooperation areas:

M.A. Nowak y R. May, *Evolutionary games and Spatial Chaos*, Nature 359, 6398 (1992)

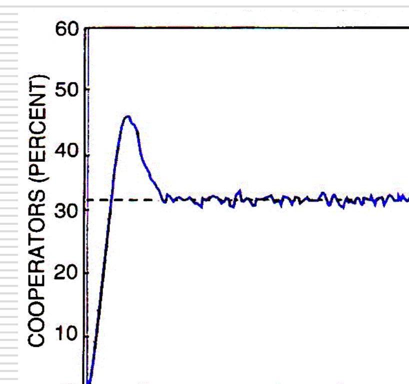
Prisoner's Dilemma:

Prisoner 1 \ Prisoner 2	Cooperation	Defection
Cooperation	1 year / 1 year	Free / 5 years
Defection	5 years / Free	3 years / 3 years





Blue=C (before C);
Red = D (before D)
Yellow=D (before C);
Green = C (before D)



model of social influence *(J. Conflict Res. 41, 203 (1997))*

Question: *"if people tend to become more alike in their beliefs, attitudes and behavior when they interact, why do not all differences eventually disappear?"*

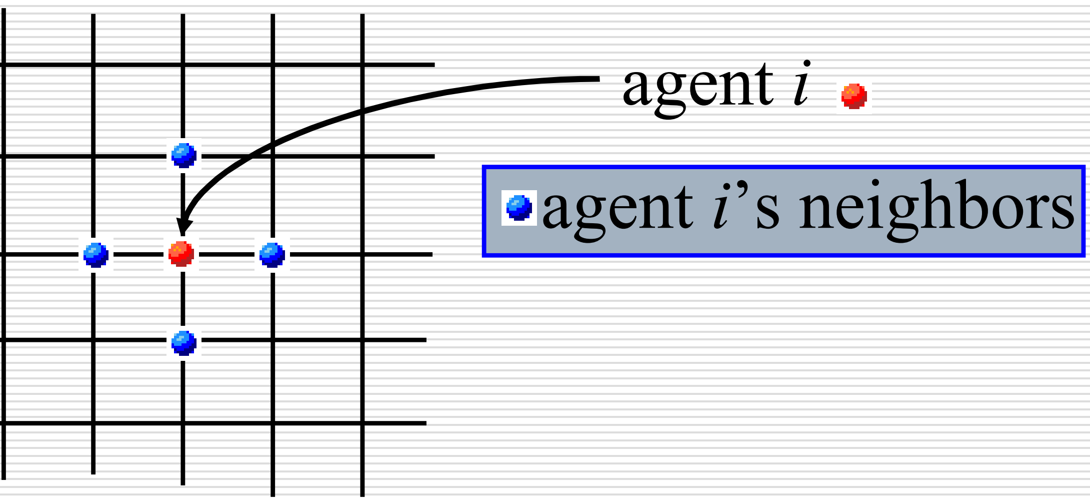
Proposal: Model to explore mechanisms of competition between ***globalization*** and persistence of ***cultural diversity ("polarization")***

- **Definition of culture:** Set of individual attributes subject to social influence
- **Basic premise:** The more similar an actor is to a neighbor, the more likely the actor will adopt one of neighbor's traits (communication mos effective between similar people).
- **Novelty in social modeling:** it takes into account interaction betweer different cultural features.

Physics paradigm: Cooperative behavior and order-disorder transition

"This work is about the mechanisms that translate individual unorganized behavior into collective results" ***(T Schelling, J. Math. Sociology (1971))***

ocial influence: interaction



$$\begin{pmatrix} \sigma_{i1} \\ \sigma_{i2} \\ \vdots \\ \sigma_{iF} \end{pmatrix}$$

F = # **Features**

q = # **Traits** per feature

$\boldsymbol{\sigma_{if}} \in \{0, \ldots, q-$

F=3; q=10 q^F (10^3) *equivalent* cultural options.

$$\begin{pmatrix} 0 \\ 0 \\ 7 \end{pmatrix} \begin{pmatrix} 5 \\ 9 \\ 7 \end{pmatrix}$$

Mechanism of local convergence:

Prob to interact = $\frac{\text{Common features}}{F} = \frac{1}{3}$

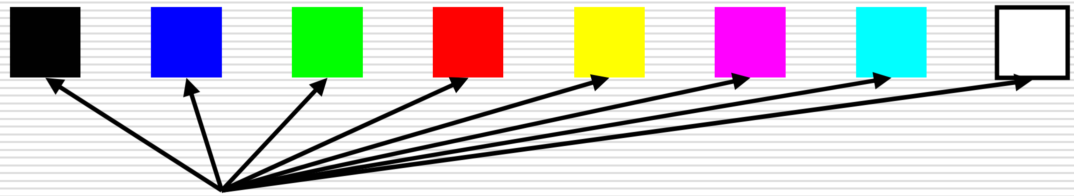
$$\begin{pmatrix} 5 \\ 0 \\ 7 \end{pmatrix} \begin{pmatrix} 5 \\ 9 \\ 7 \end{pmatrix}$$

Visualization of the Dynamics

Color code for F=3, q=2

$$\begin{pmatrix}0\\0\\0\end{pmatrix}\begin{pmatrix}0\\0\\1\end{pmatrix}\begin{pmatrix}0\\1\\0\end{pmatrix}\begin{pmatrix}1\\0\\0\end{pmatrix}\begin{pmatrix}1\\1\\0\end{pmatrix}\begin{pmatrix}1\\0\\1\end{pmatrix}\begin{pmatrix}0\\1\\1\end{pmatrix}\begin{pmatrix}1\\1\\1\end{pmatrix}$$

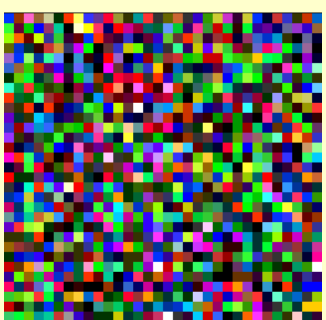
f=0→R
f=1→G
f=2→B



e can identify a cultural domain with a given colour.

general for $q>2$, q weights the basic colours (**R**,**G**,**B**): $0 \le \sigma_{if}/(q-1) \le 1$

$F = 3,\ q = 10$



$t = 0$ ⟶ System freezes in an absorbing multicultural state

- The model illustrates how **loca** **convergence** can generate **globa** **polarization.**
- Number of domains taken as measure of cultural diversity
- Uniform state always prevail without similarity rule *(Kennedy 1998)*

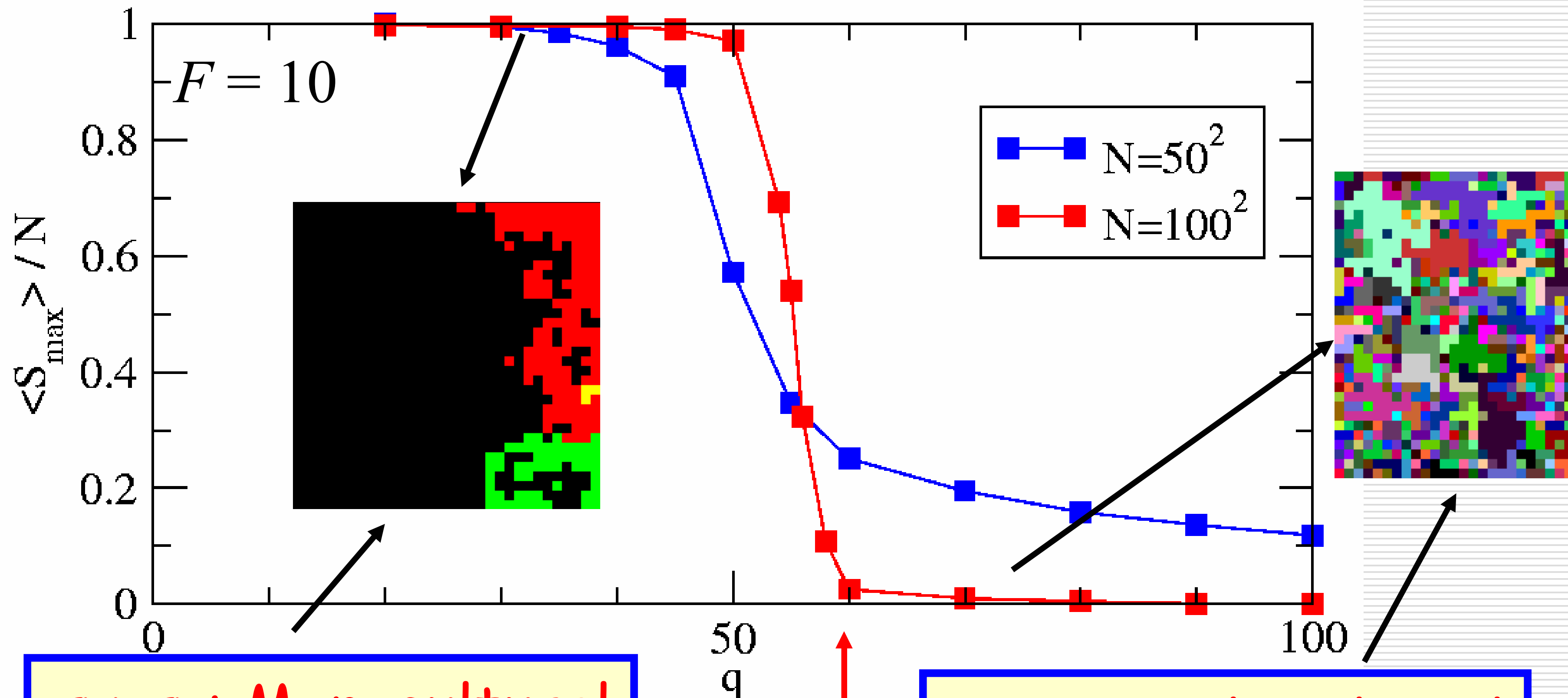
http://www.imedea.uib.es/PhysDept/

atistical Physics: a nonequilibrium phase transitio

Order parameter: S_{max} size of the largest homogeneous domain

Lewenstein et al (199

Control parameter: q measures initial degree of disorder.



q_c

$q < q_c$: Monocultural

Global culture

$q > q_c$: Multicultural

Cultural diversity

Global polarization

order transition well defined as $N \to \infty$

Beyond the original model

Cultural drift: *"Perhaps the most interesting extension and at the same time, the most difficult one to analyze is cultural drift (modeled as spontaneous change in a trait)."* R. Axelrod, J. Conflict Res. (1997)

Questions:
1. Measure of heterogeneity.
2. Time scales of evolution.

Role of noise?

B. Latane et al., Behav. Science (1994)

Social cleavages: *"Electronic communication allow us to develop patterns of interaction which are chosen rather than imposed by geography ... With random long distance interactions, the heterogeneity sustained by local interactions cannot be sustained."*
R. Axelrod, J. Conflict Res. (1997)

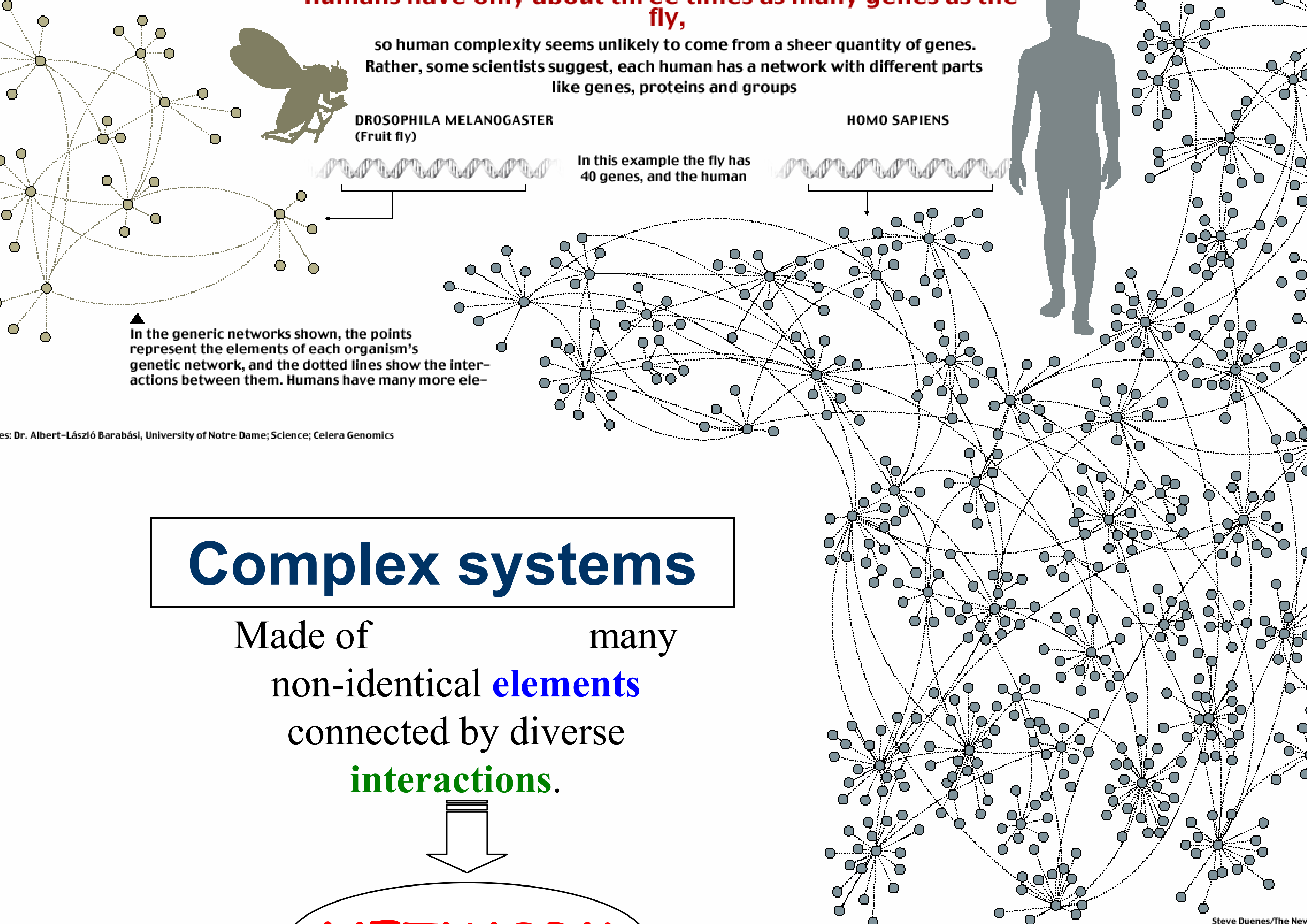
⇒ **Network topology**
1. Small-world networks
2. Scale-free networks

⇨ Structured scale-free

Part II: networks of interaction

… Currently, there are more than 30 different mathematica descriptions of complexity. However, we have yet to understan the mathematical dependency relating the number of genes wit organism complexity. One pragmatic approach to the analysis o biological systems, which are composed of nonidentical element (proteins, protein complexes, interacting cell types, an interacting neuronal populations), is through graph theory. Th elements of the system can be represented by the vertices o complex topographies, with the edges representing th interactions between them. Examination of large networks reveal that they can self-organize… there are no "good" genes or "bac genes, but only networks that exist at various levels and a different connectivities, and at different states of sensitivity t perturbation."

The Sequence of the Hum



Complex systems

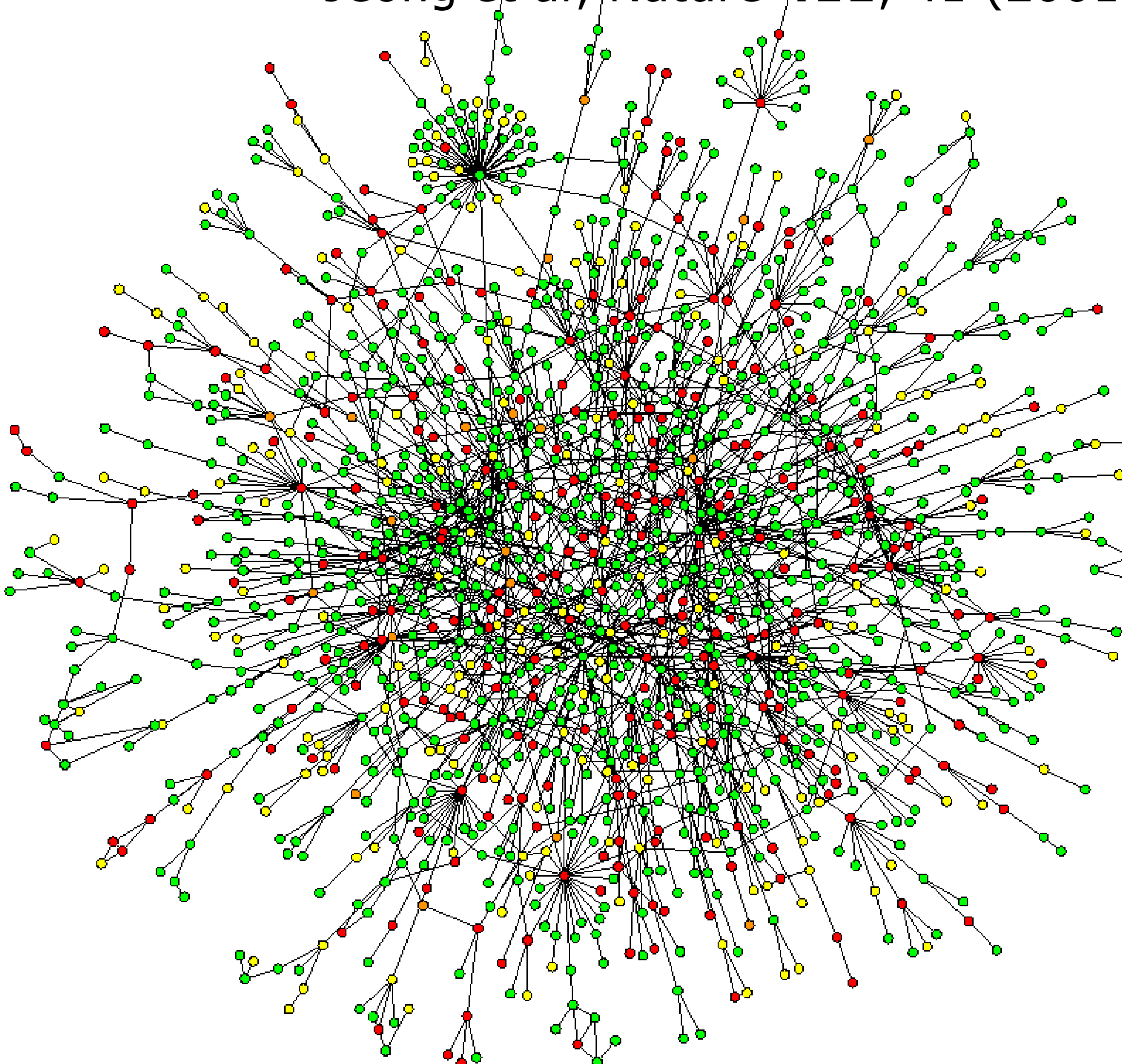
Made of many non-identical **elements** connected by diverse **interactions**.

⇓

NETWORK

Biological networks: Genes, proteins, …

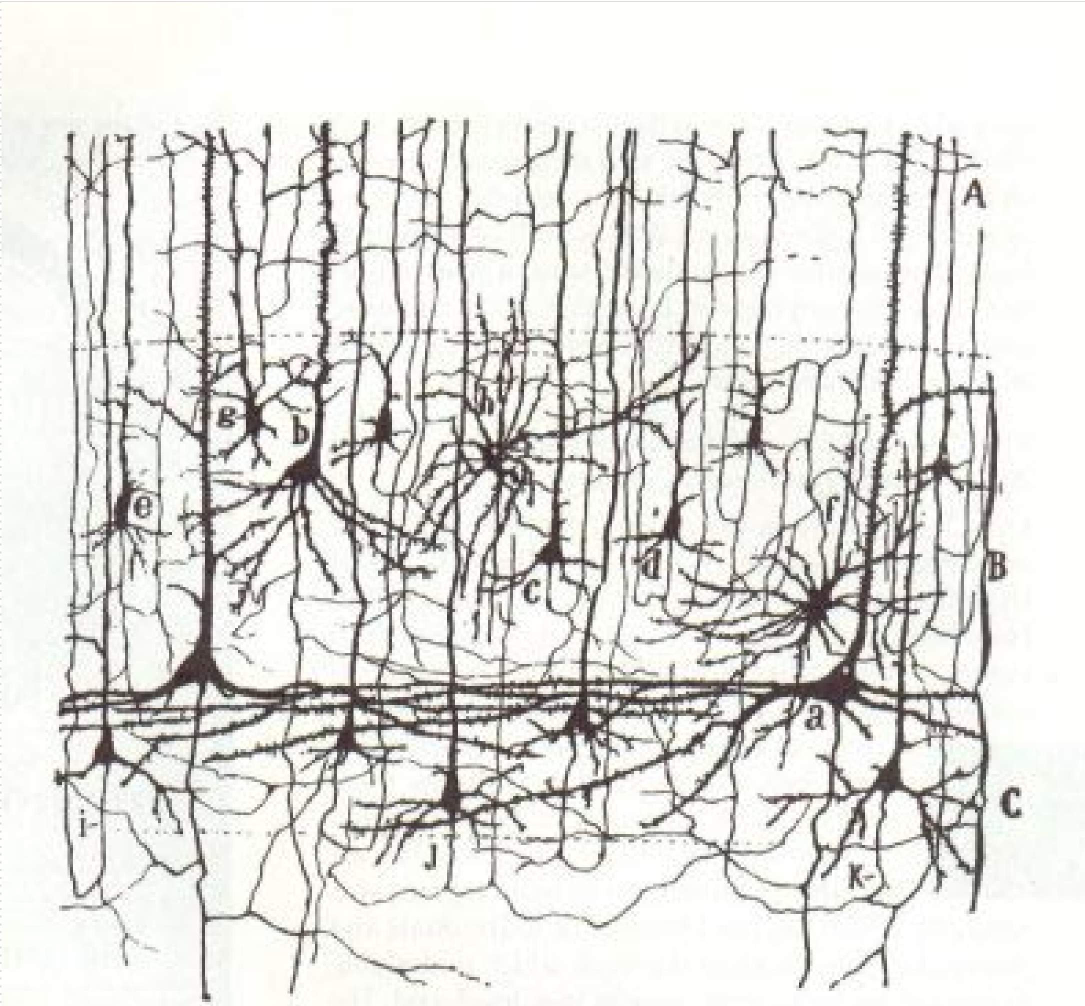
Jeong *et al*, Nature **411**, 41 (2001



Map of protein-protein interactions. The color of a node signifies the phenotypic effect of removing the corresponding protein (red, lethal; green, non-lethal; orange, slow growth; yellow, unknown).

Figure from
http://www.nd.edu/~networks/cell

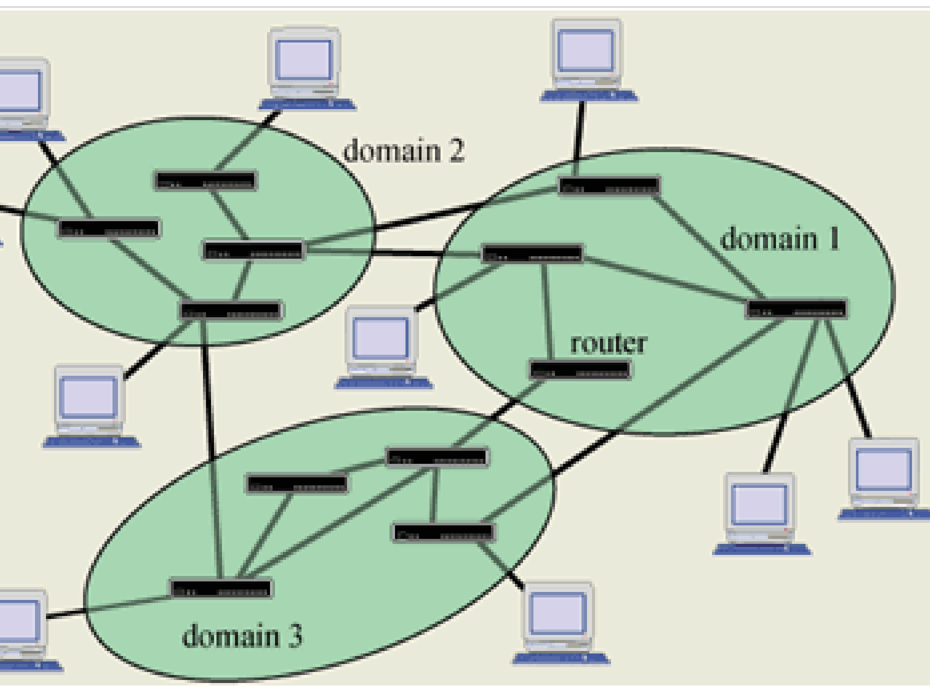
… and the brain



Network:
set of nodes connected by links

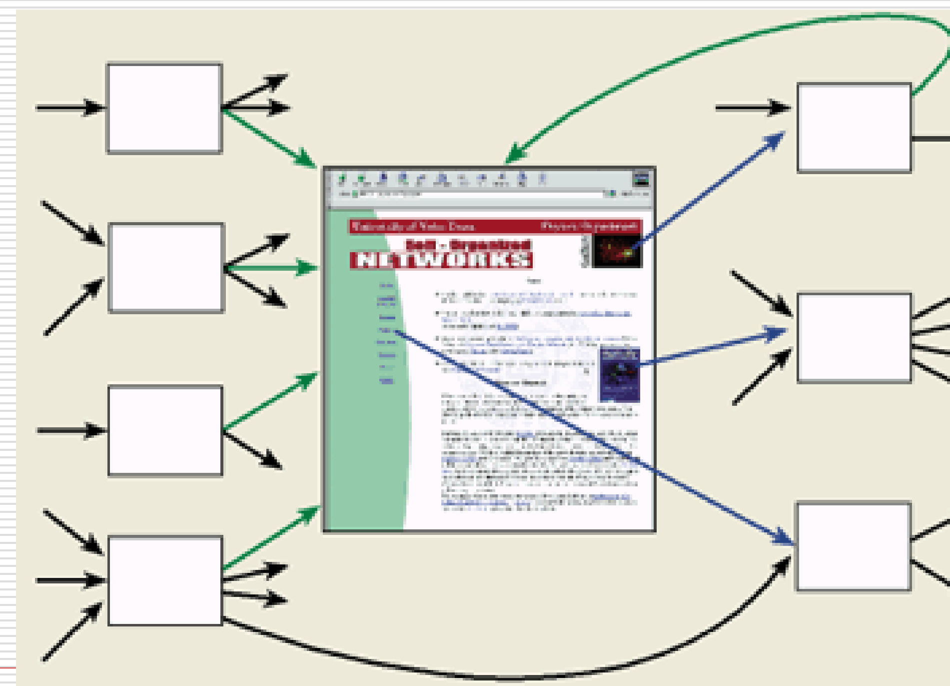
nternet

odes: computers, routers, …
nks: physical connections



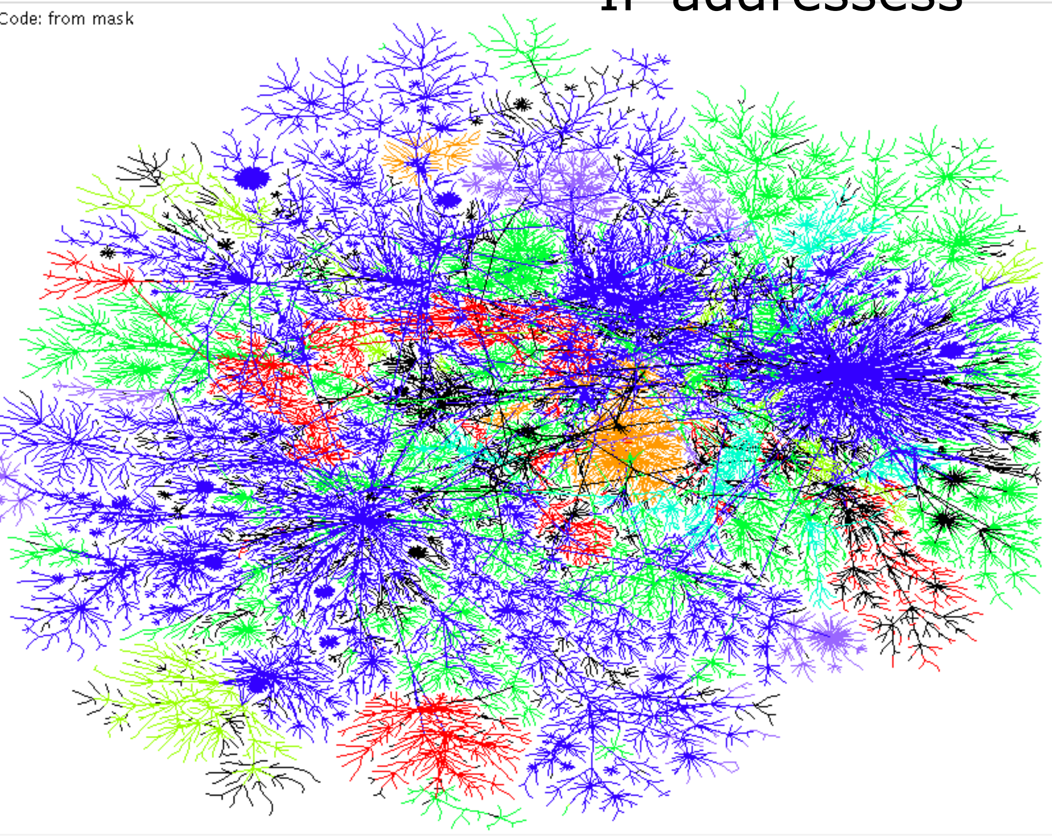
WWW

Nodes: web pages
Links: links

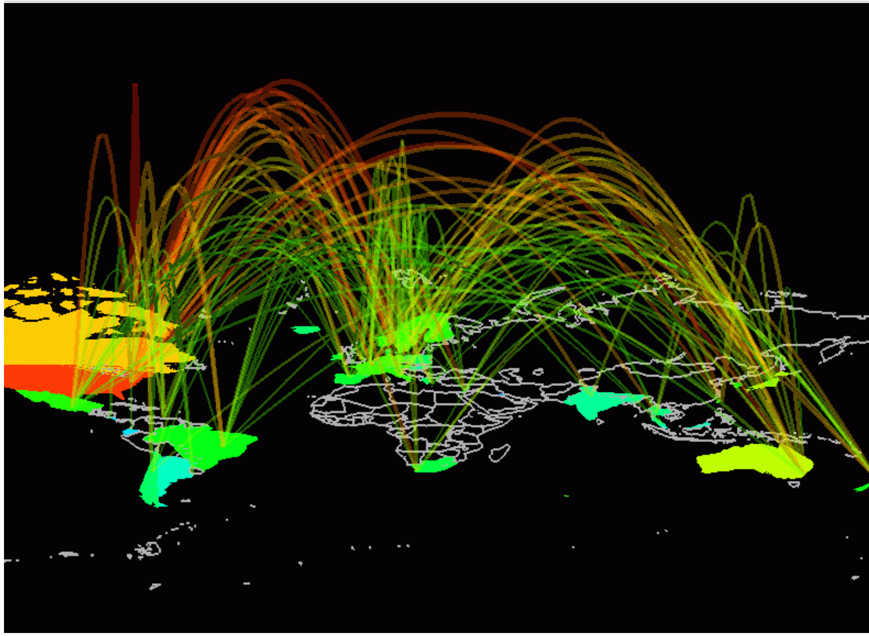


Communication networks

IP addressess



World-wide
Internet traff



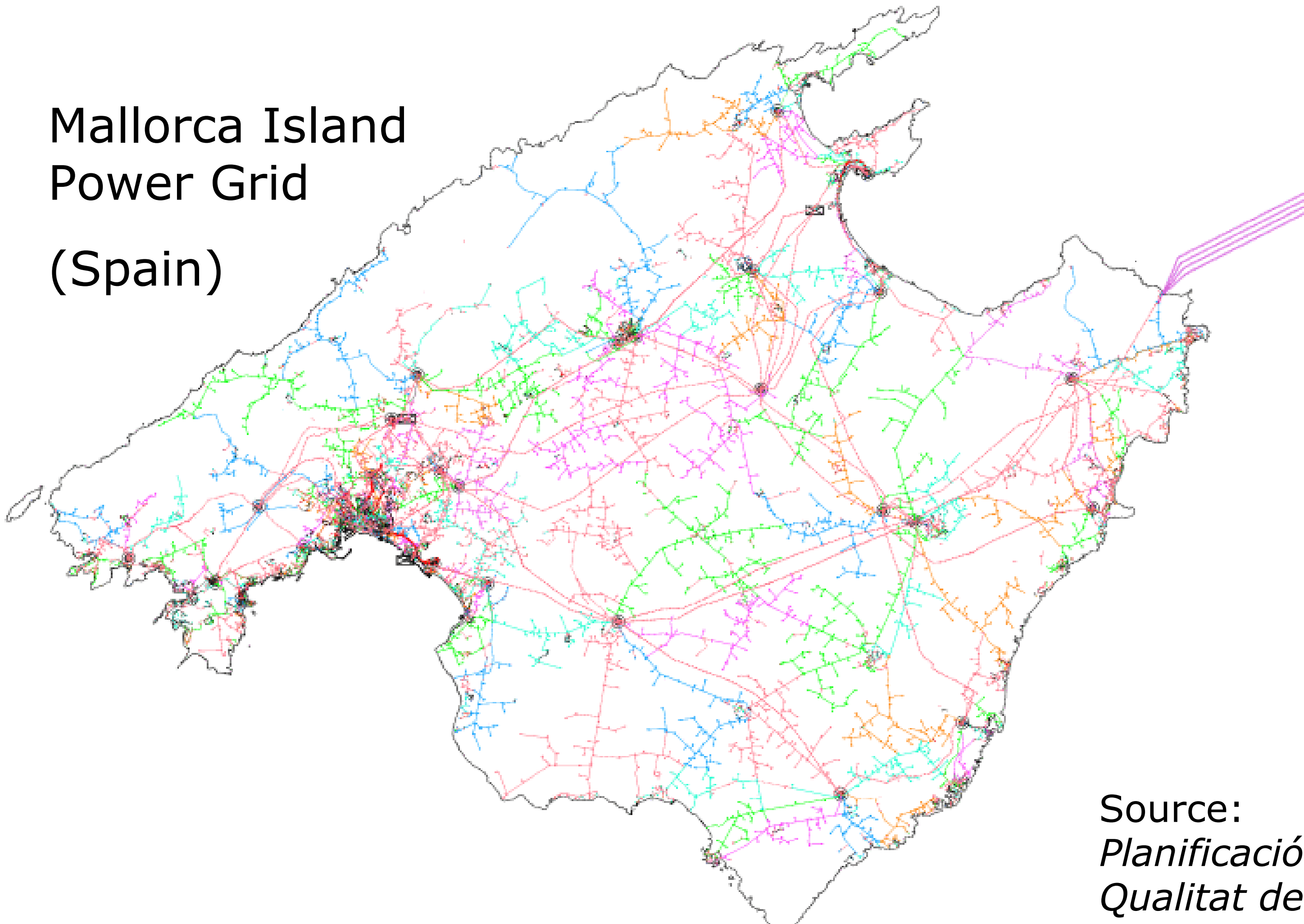
ture from

Picture from

Power grid

Mallorca Island
Power Grid

(Spain)

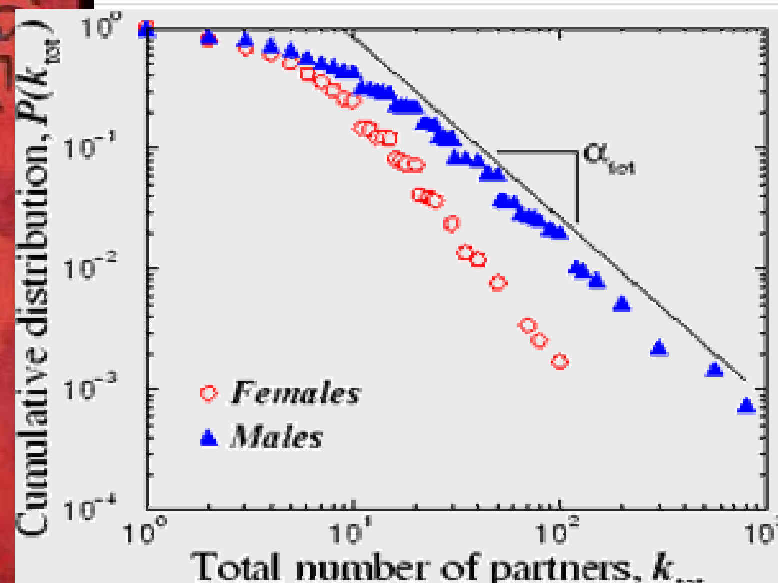


Source:
Planificació i Qualitat de Xarxa,
GESA-ENDESA
Spain

Sex-web

Nodes: people (Females; Males)

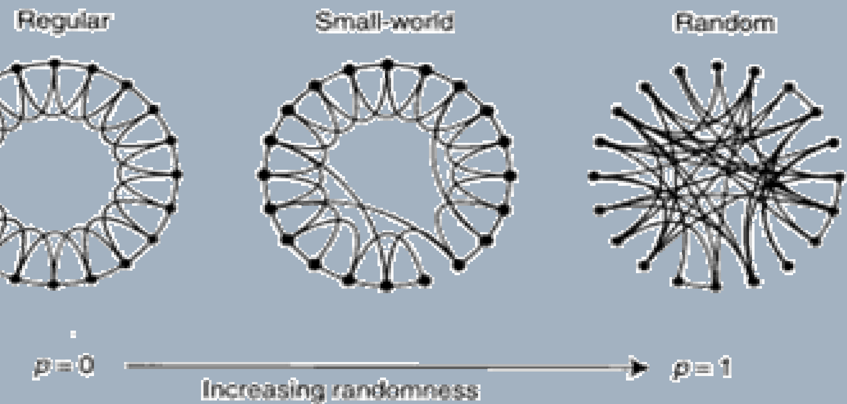
Links: sexual relationships

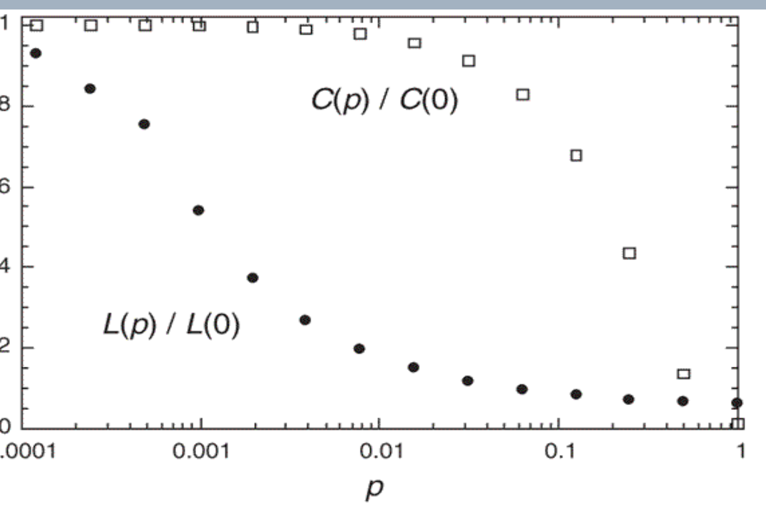


4781 Swedes; 18-74;
59% response rate.

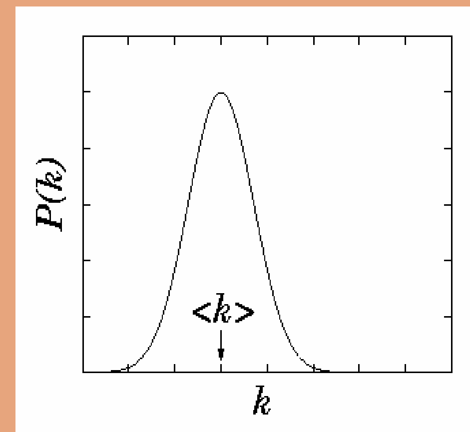
Liljeros et al. Nature 2001

ingle-scale vs. *scale-free* networks

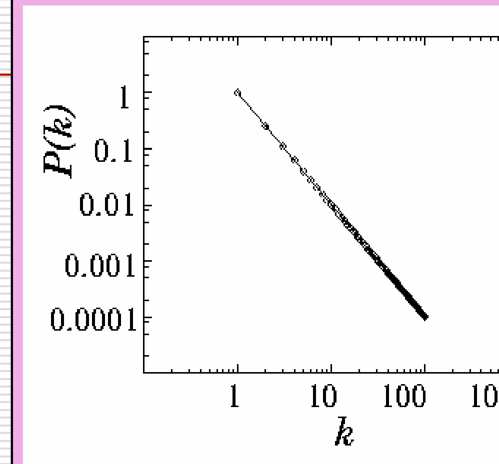


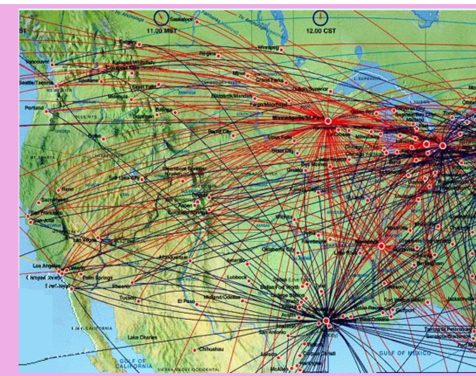


tts, Strogatz, *Nature* **393**, 440 (1998)



Exponential Network





Scale-free Network

Small-world networks

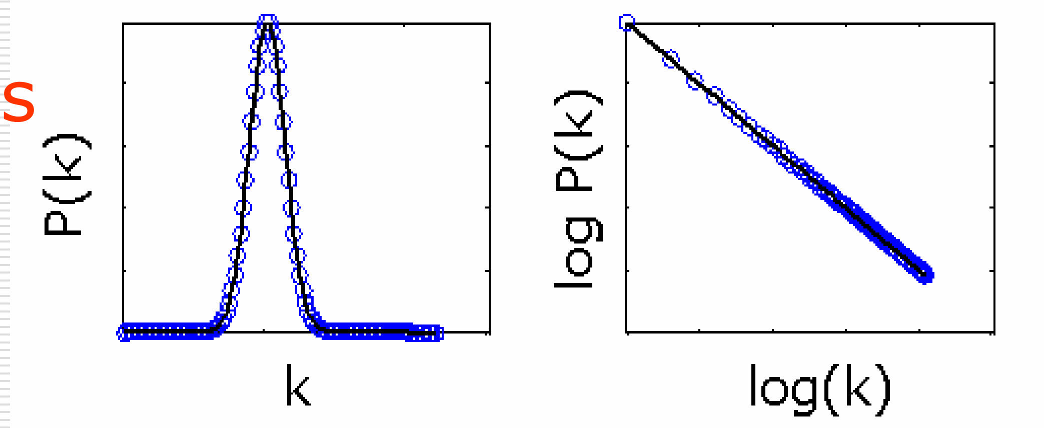
Interaction networks…

Again:

- Many natural and social networks are non-uniform, “many forms”!!!
- Complexity is heterogeneous.

Networks in nature are heterogeneous!

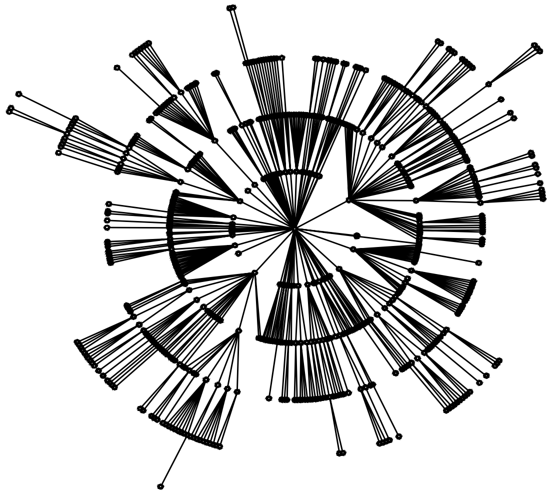
Homogeneous



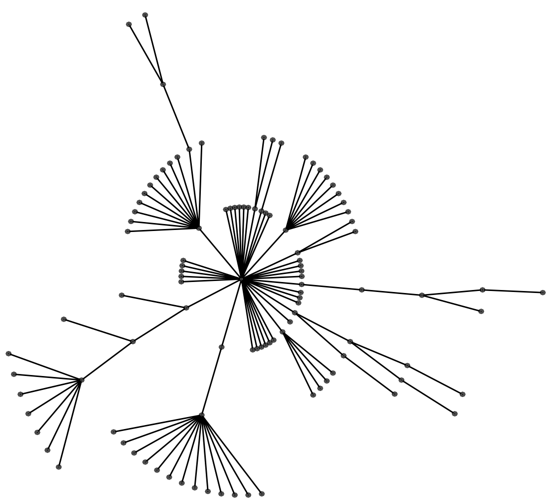
Scale-free

In random nets most nodes are linked by about the same number of links (k), while in

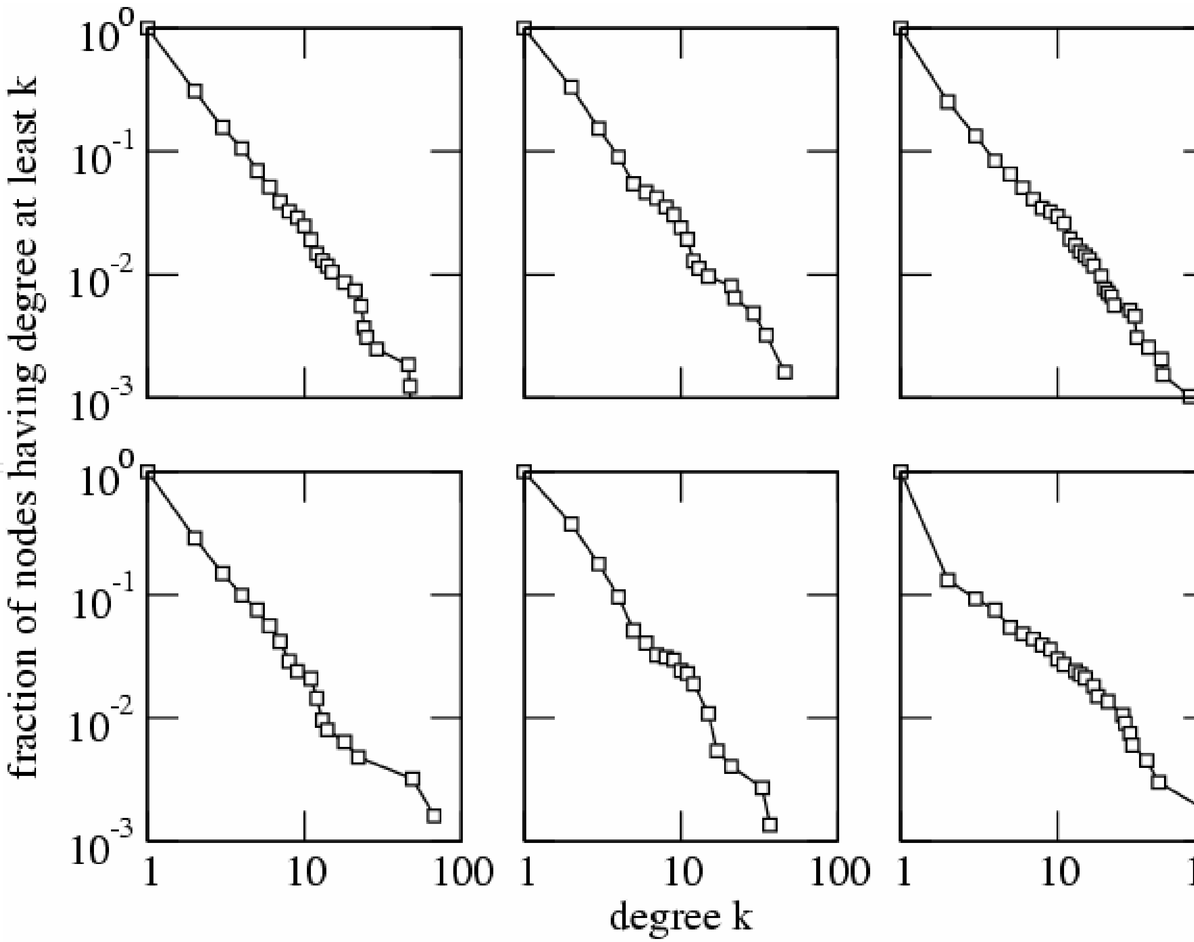
Directory trees



N=604

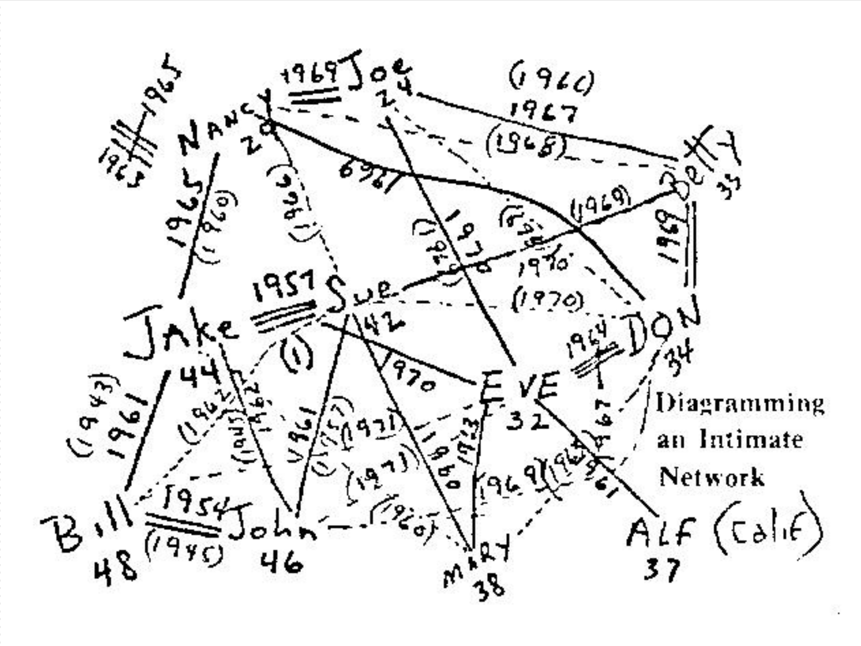


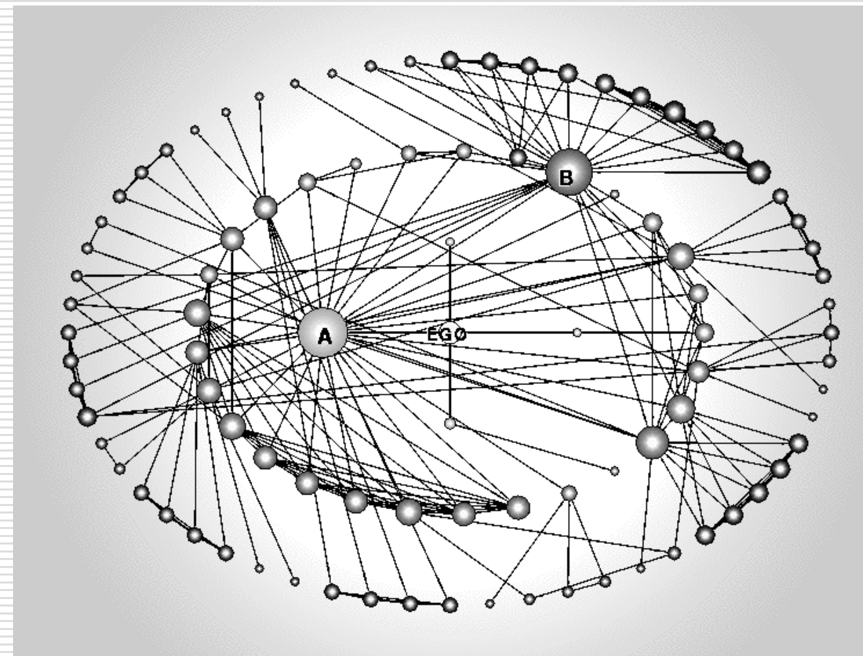
N=107



Klemm et al. cond-mat/040323

Social Networks





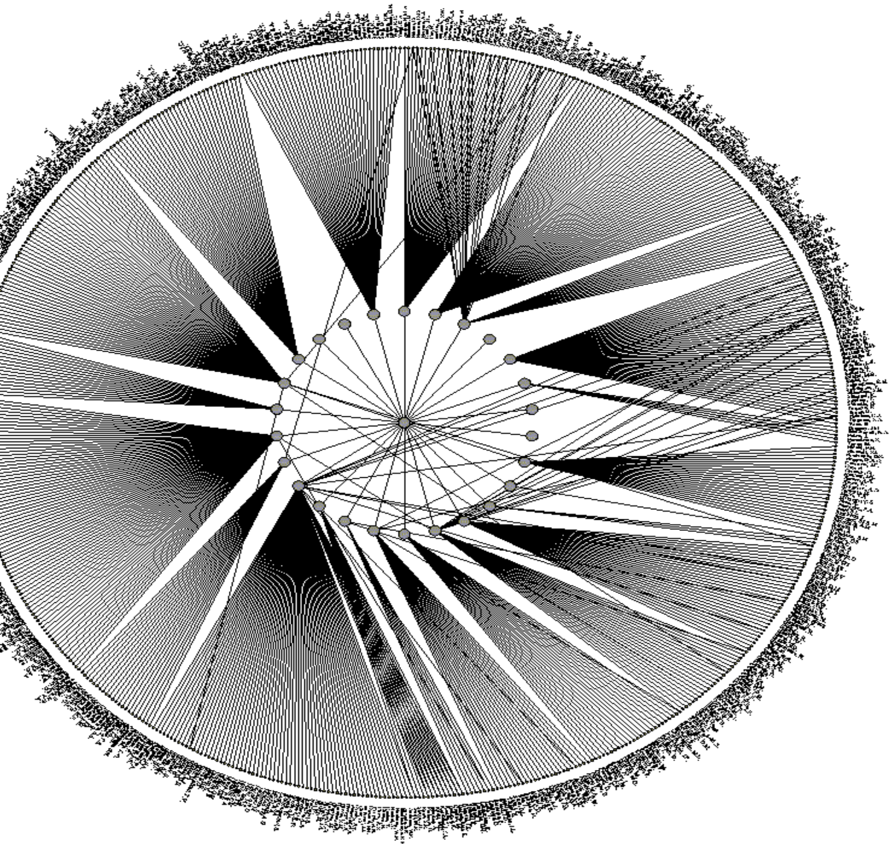
Who do you like?

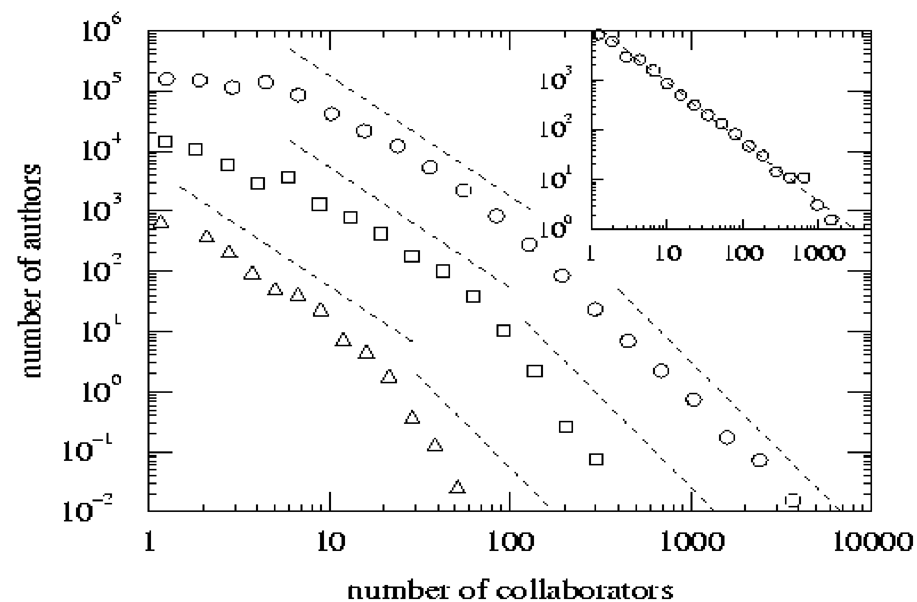
Who do you dislike?

Ego centered view

Co-authorship of scientific papers

Nodes: scientists (authors)
Links: write a paper together





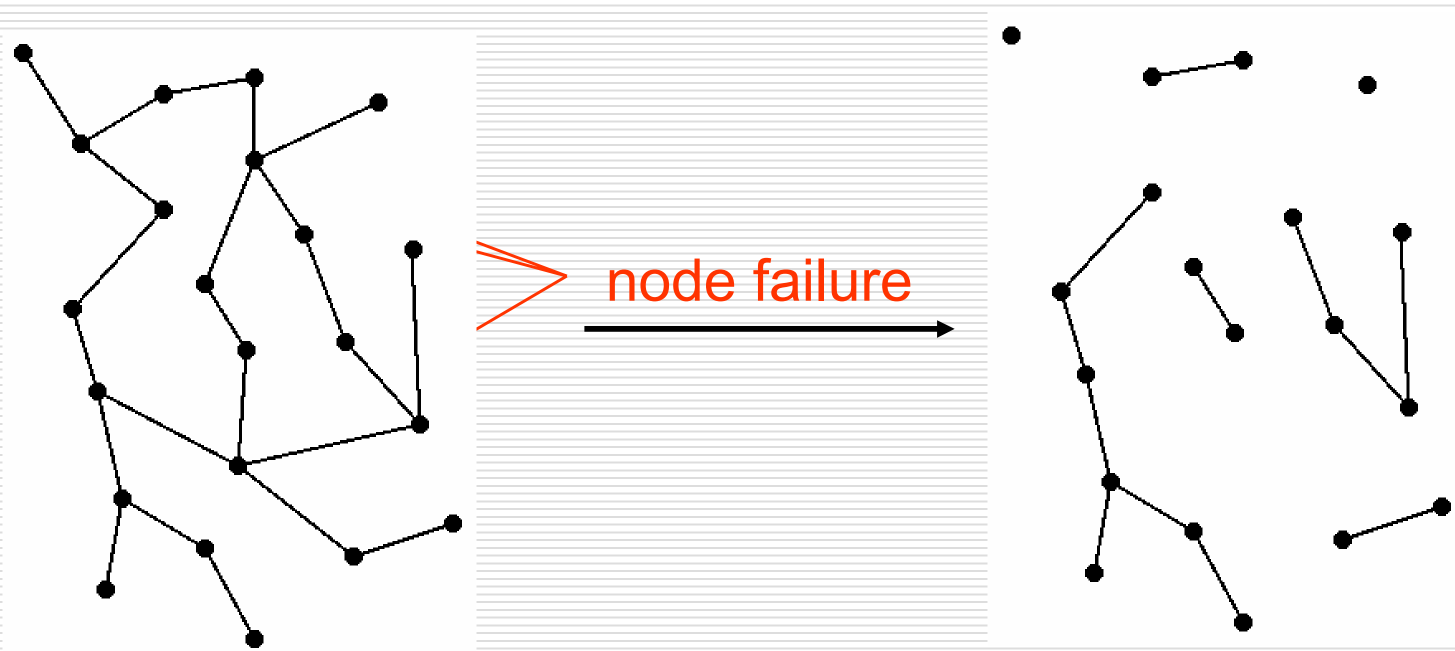
(Newman, 2000, H. Jeong et al 200

What do we learn from the topology

- Resilience against failures, weakness to attacks.
- Spreading of rumors, opinions, infectious diseases.
- Communication in organizations.
- Searching for communities.
- They are highly clustered and at the same time have short path length (sort of well connected at all scales).
- Faster synchronizability.
- In terms of resistance to damage: they are robust (to random) and fragile (to targeted attack).

Robustness

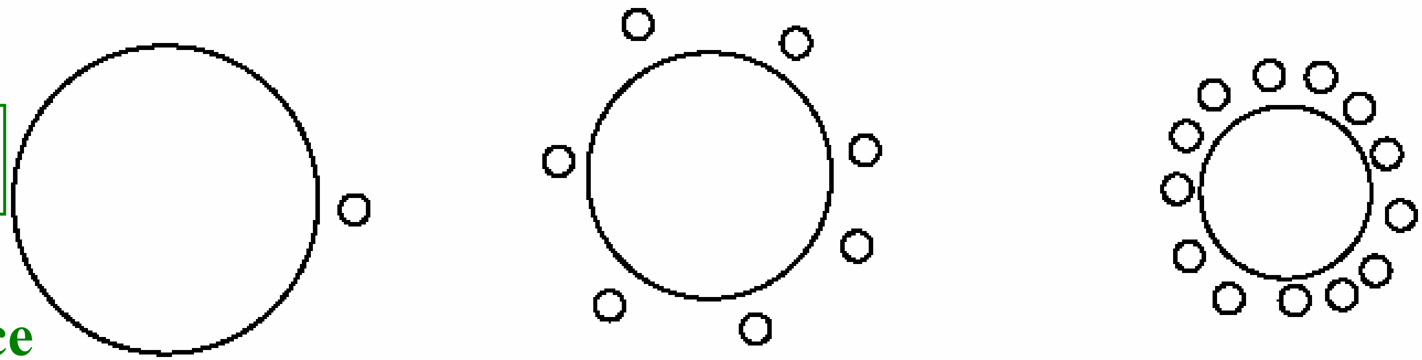
Complex systems maintain their basic functions even under errors and failures (cell $\rightarrow$ mutations; Internet $\rightarrow$ router breakdowns)

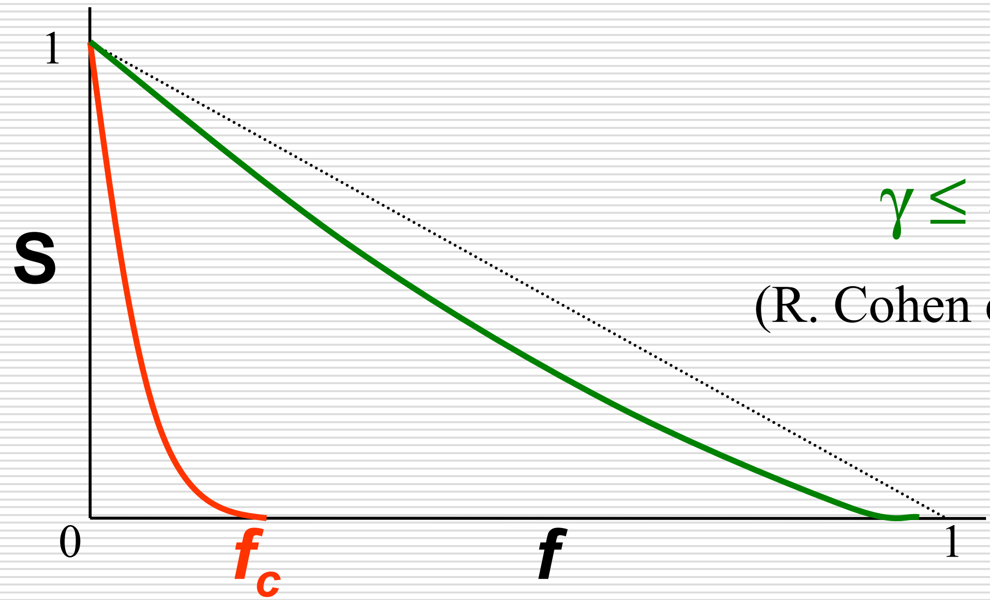


Robustness of scale-free networks

Failures

Topological error tolerance

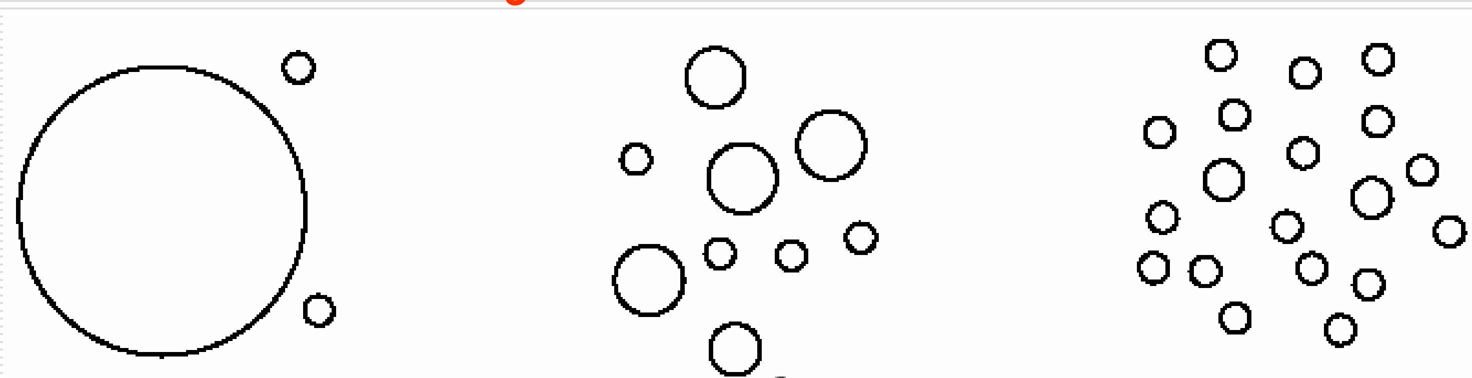




$\gamma \leq 3 : f_c = 1$

(R. Cohen et al PRL, 2000)

Attacks

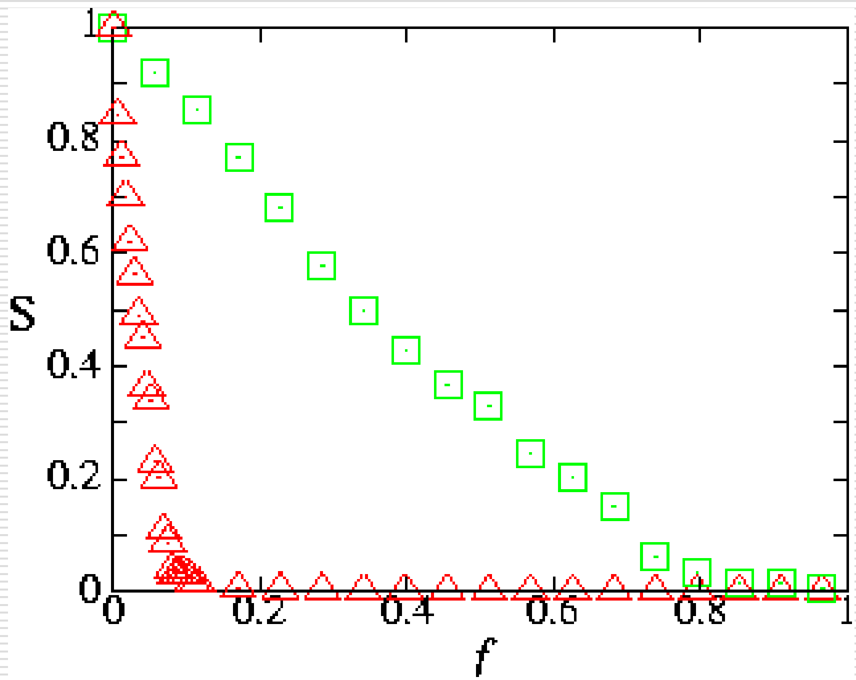


Achilles' Heel of complex networks

Internet

failure

attack



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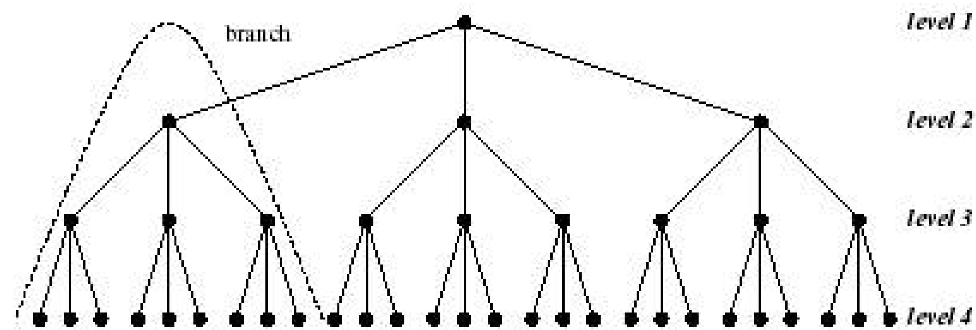
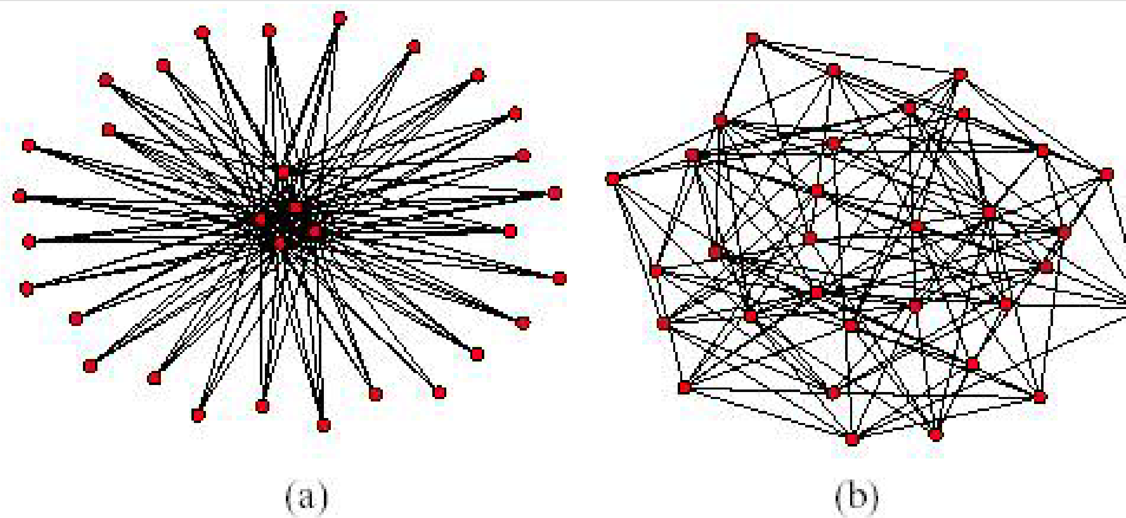
Optimal communication

How good is a hierarchical organization for exchanging information?

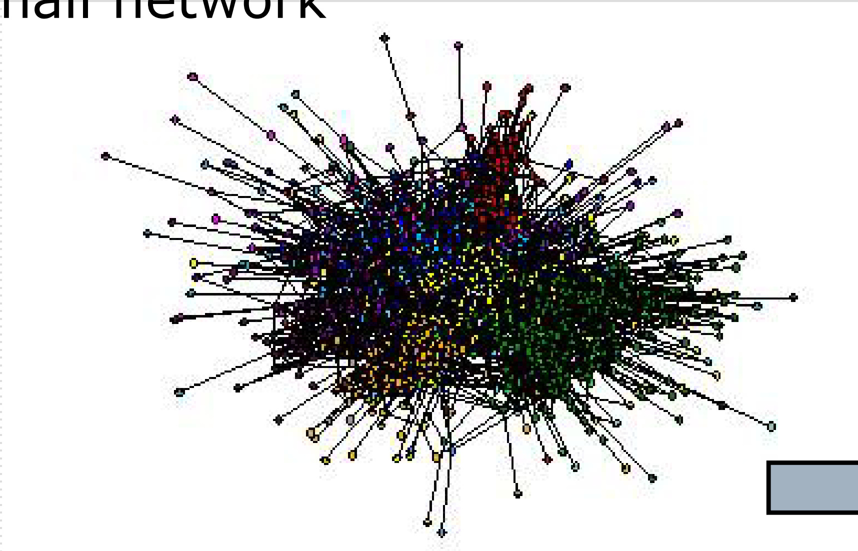


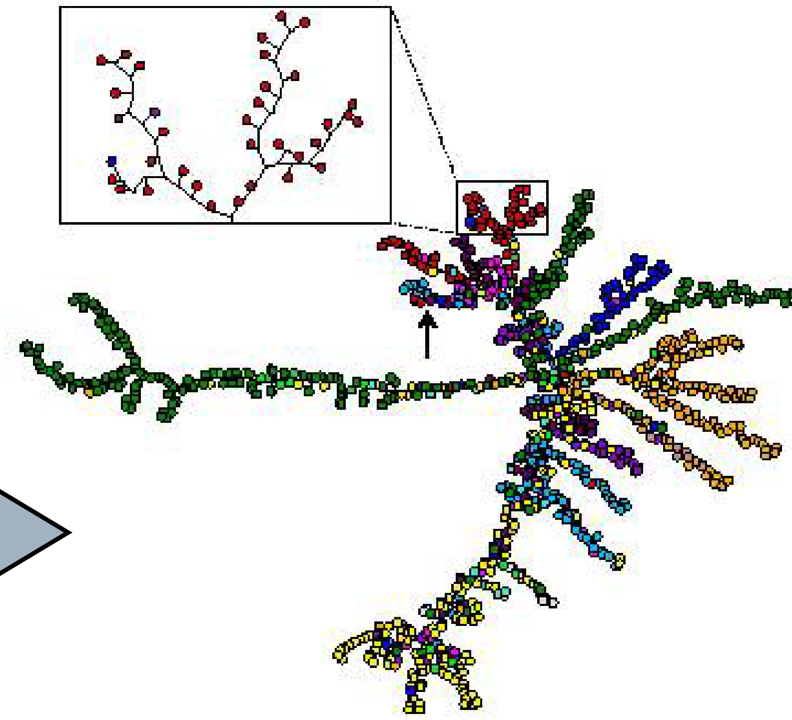
Optimal structures for local search with congestion. (a) Star-like configuration optimal for low load and (b) homogeneous-isotropic configuration optimal for large load.



Communities

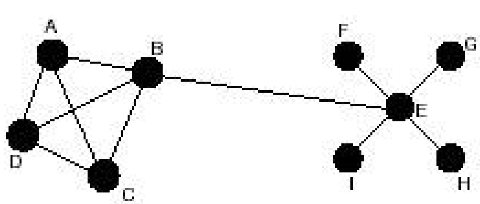
E-mail network

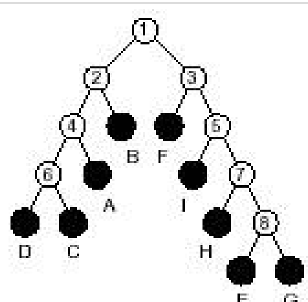




(a)

How to obtain communities
from a network





Conclusions

- Society & organizations are complex systems:
  - Nonlinear individuals + interaction
- Diversity everywhere: power laws.
- Mathematical and computational tools ready to be used:
  - Improve management of information & knowledge in an organization