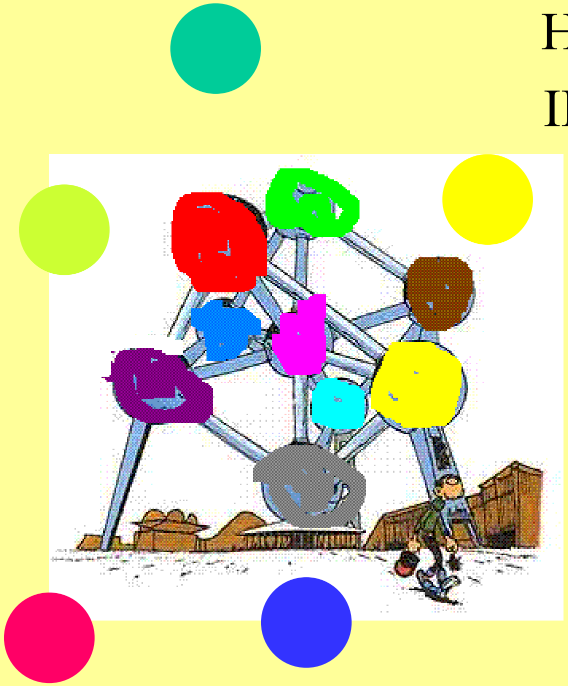
The "new" science of networks

Hugues Bersini
IRIDIA – ULB

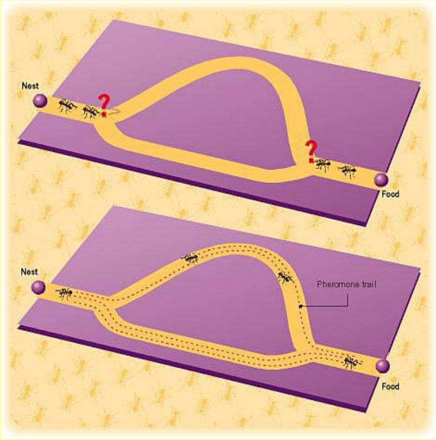


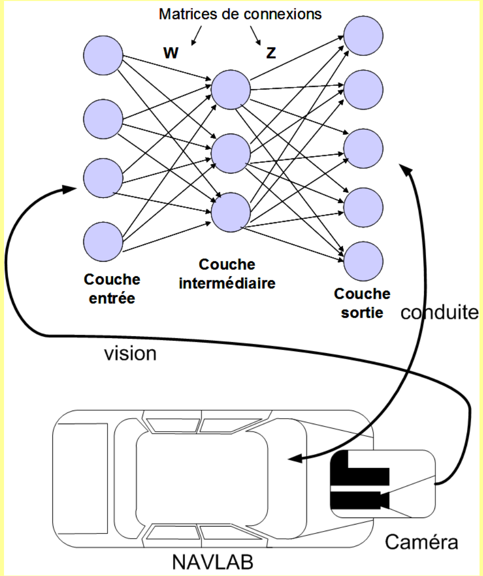
Outline

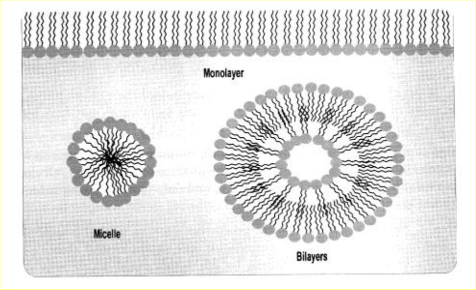
- INTRO: Bio and emergent computation: A broad and shallow overview: 30’
- NETWORKS: 30’
  - Introduction to Networks
  - Networks key properties
- CONCLUSIONS: Networks main applications

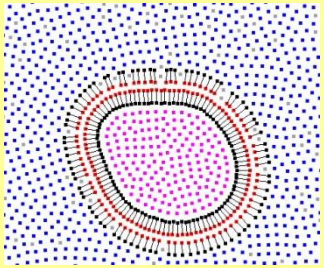
Bio and Emergent Computation

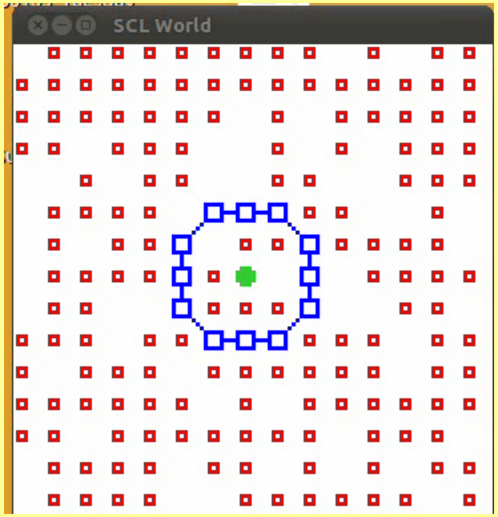
IRIDIA = Bio and Emergent computation

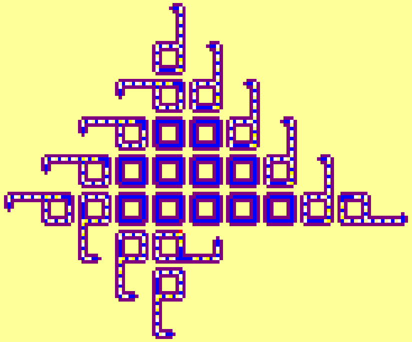








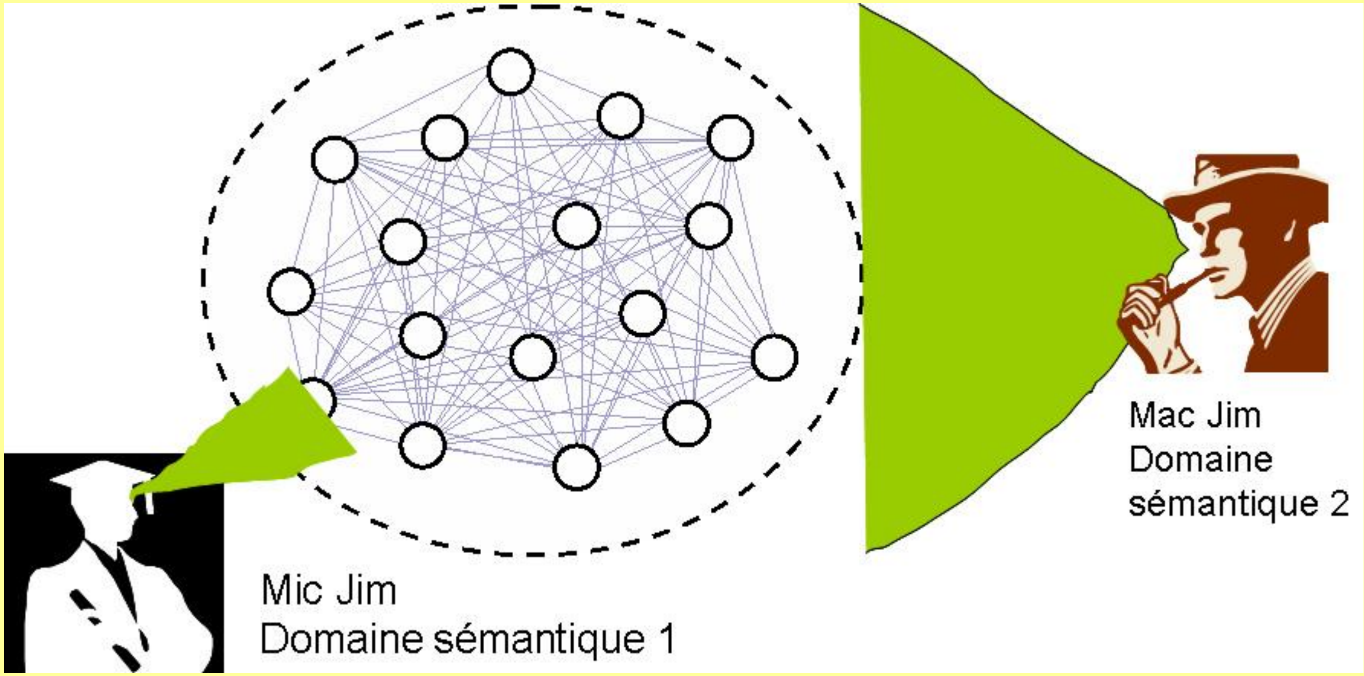




Emergent Computation

The Whole is more than the sum of its Parts

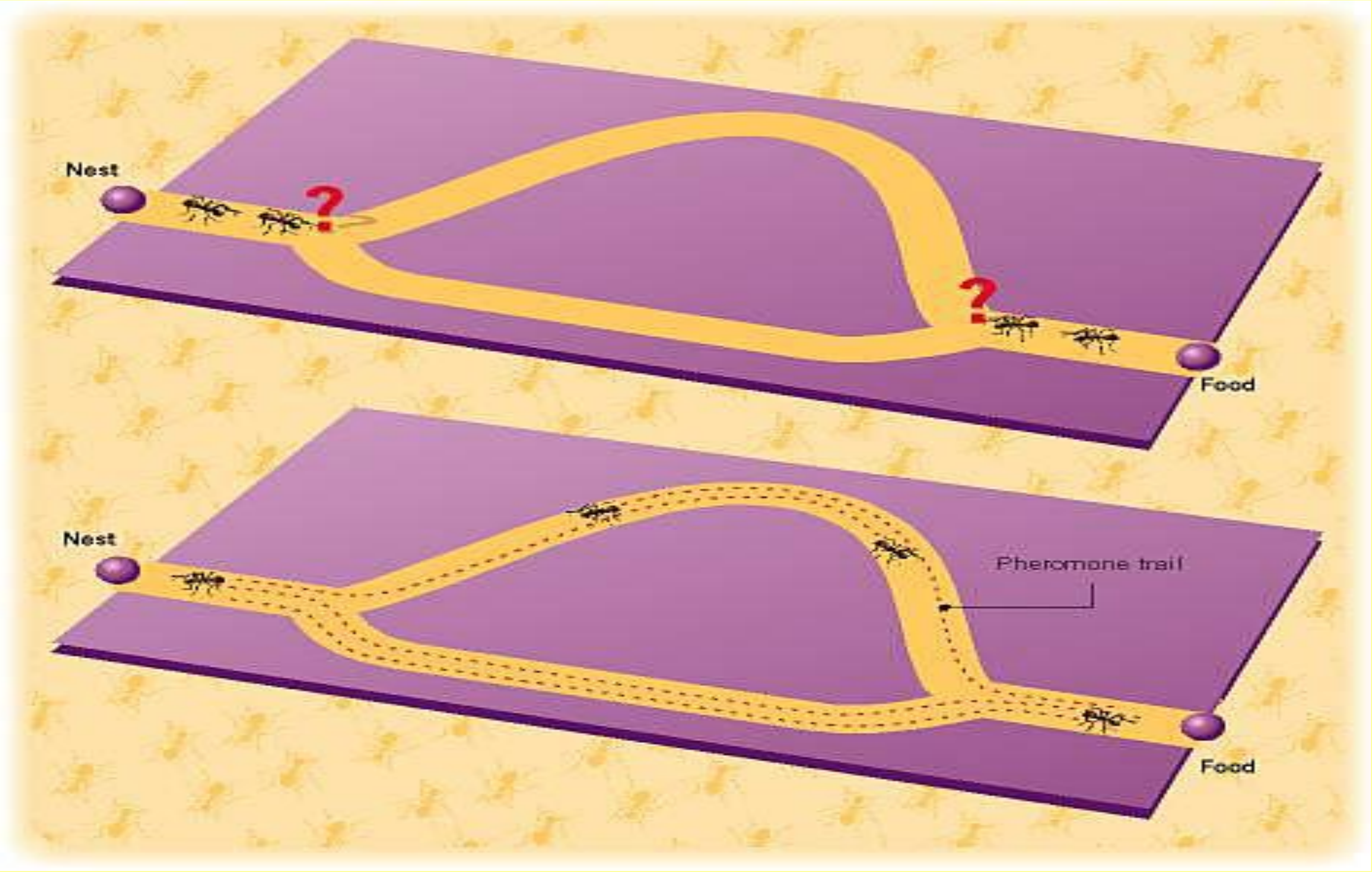
1 + 1 = 3



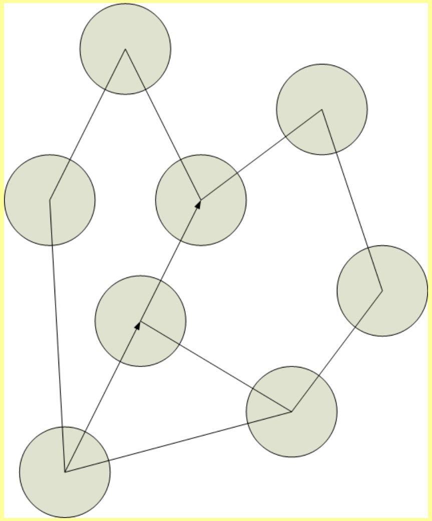
Three emergent phenomena

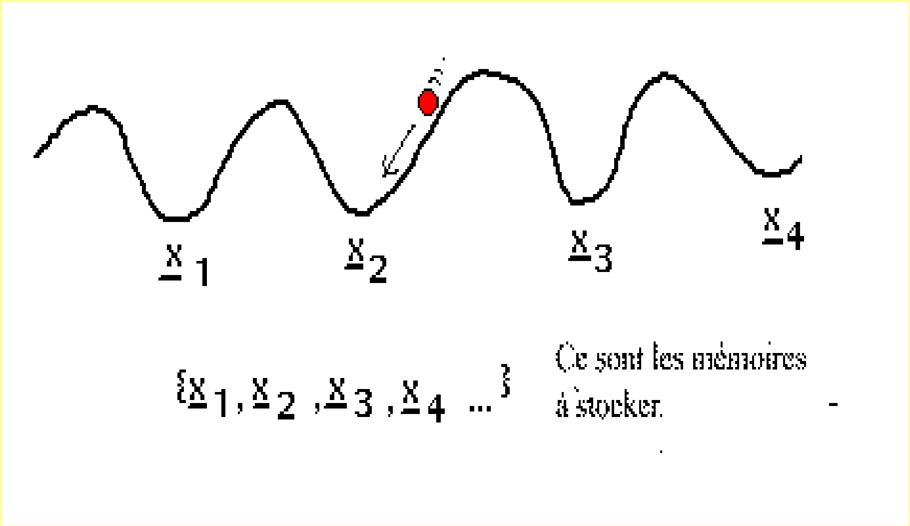
- The traffic jam

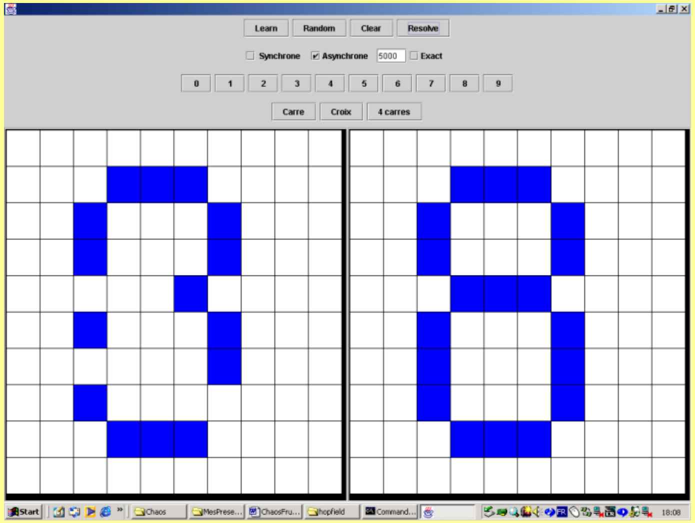
How an ant colony find the shortest path



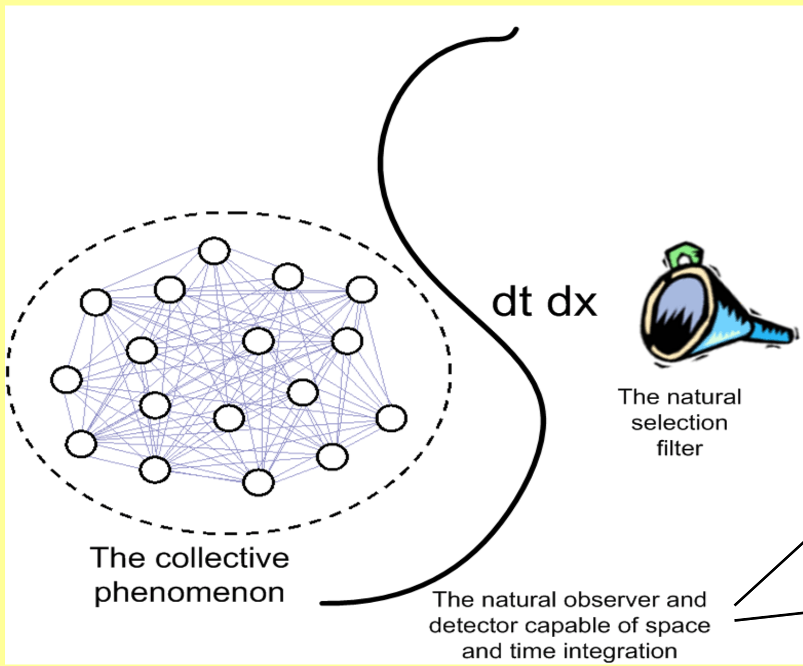
Associative memories







Philosophy: The three natural ingredients of emergence



In biology: Natural selection

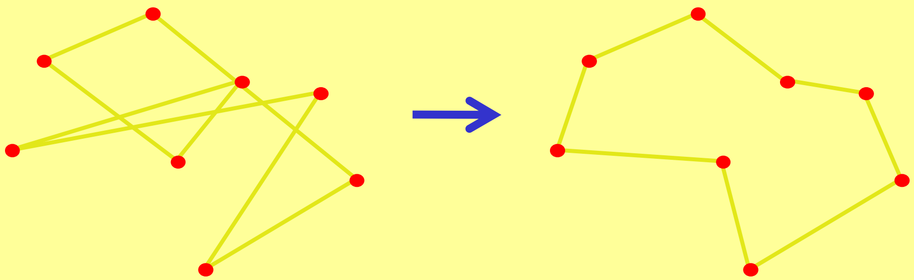
In engineering:
the out-of-control engineer

Fig. 2: The three needed ingredients for a collective phenomenon to be qualified as emergent.

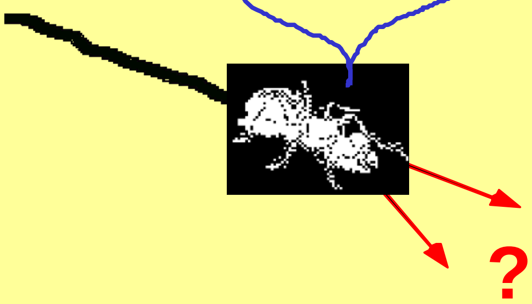
Practical achievements at IRIDIA

1) Ant colony optimisation

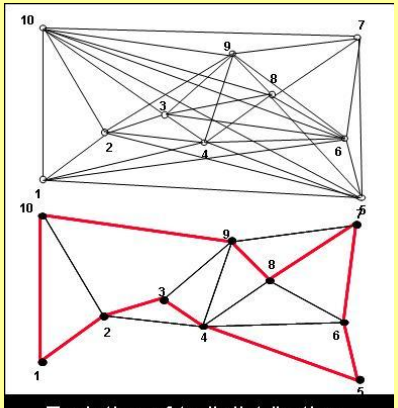
Pheromone trail depositing



Memory

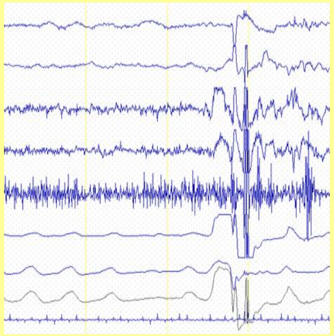


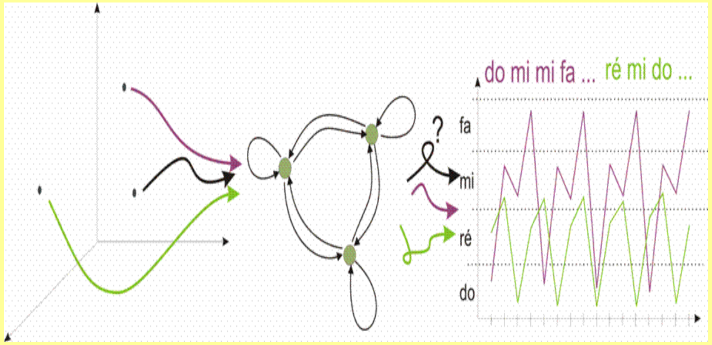
Probabilistic rule to choose the path

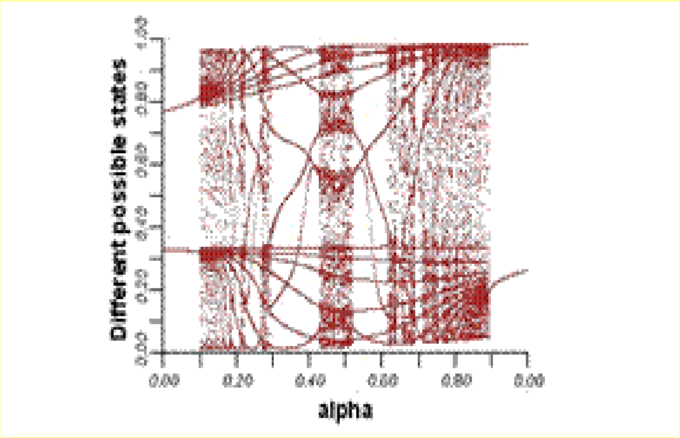


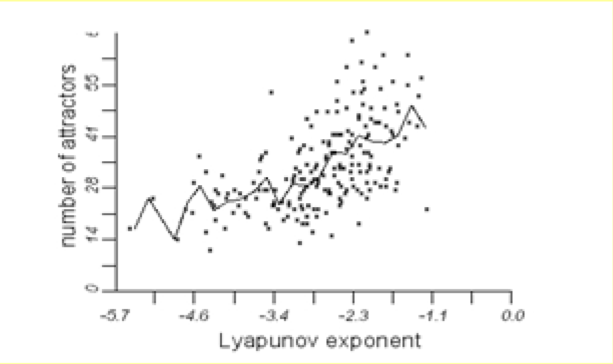
Evolution of trail distribution

2) Chaotic encoding of memories in brain

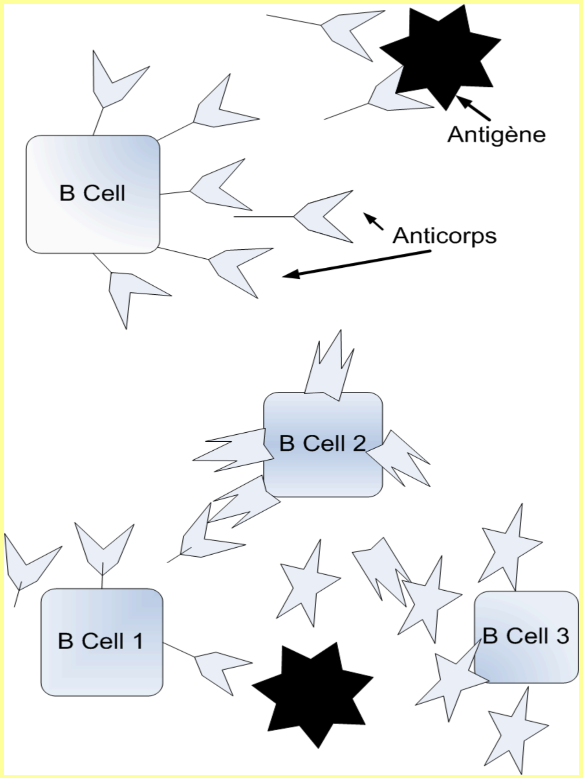


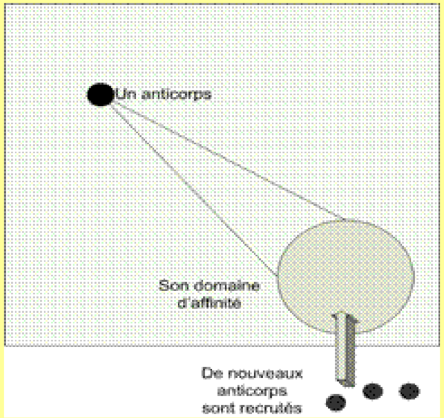


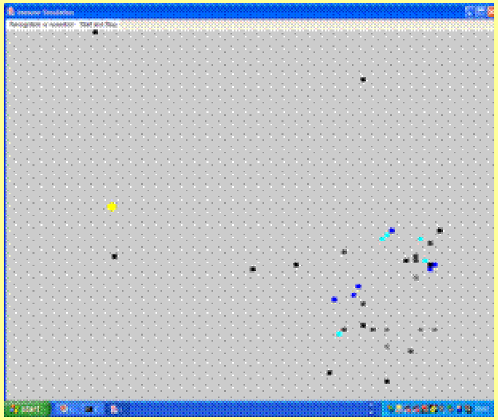


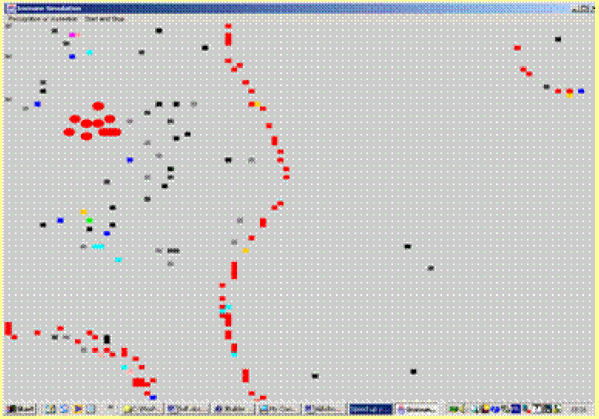


3) What really are immune systems for → Artificial Immune Systems for engineers

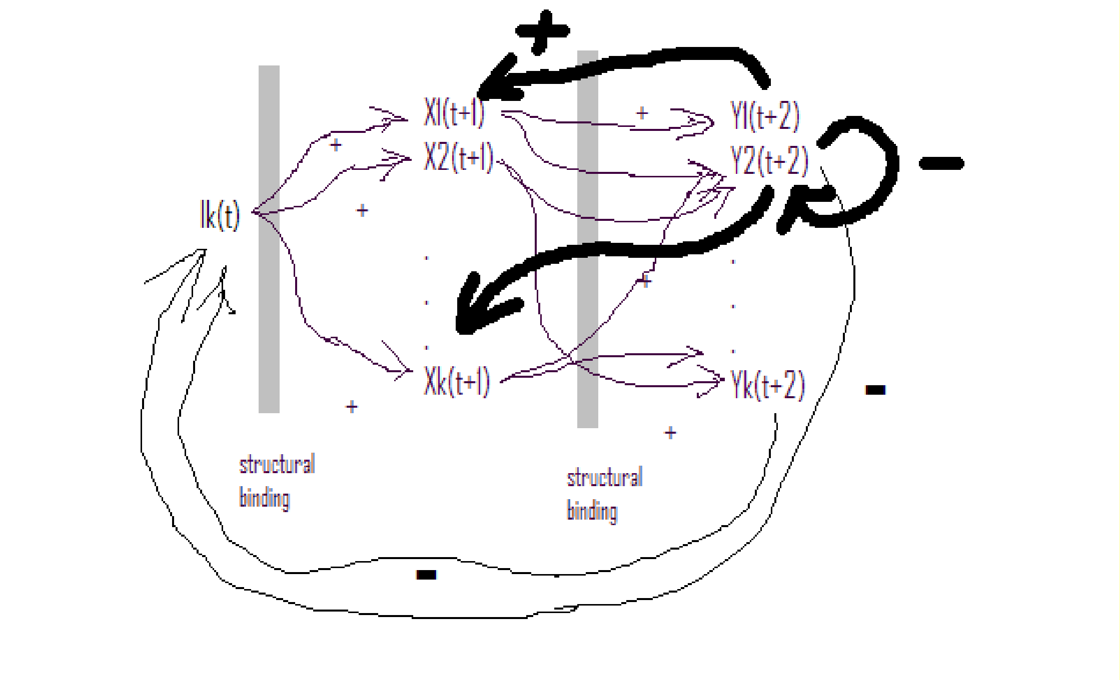




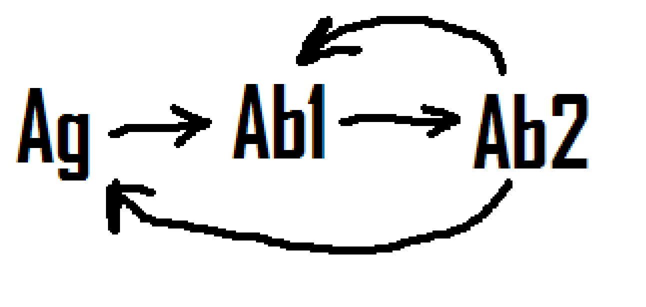




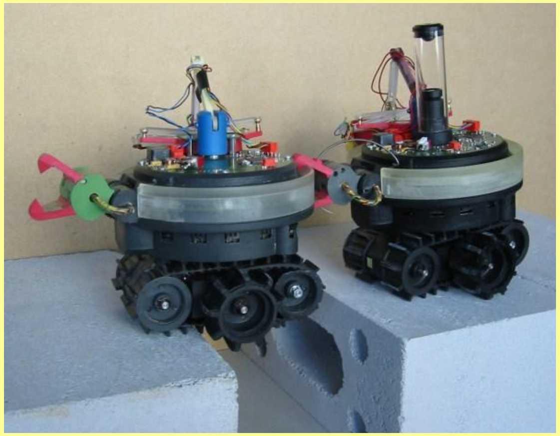
Linear causality vs circular causality



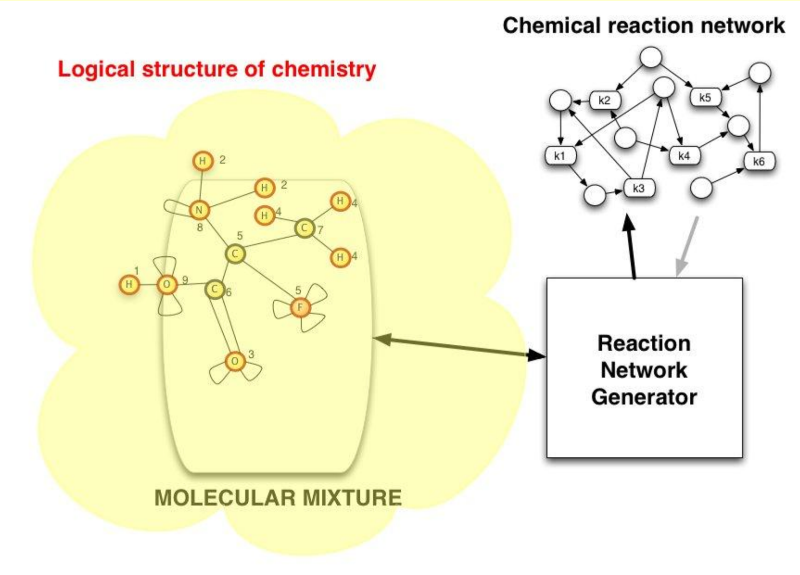
Idiotypic network

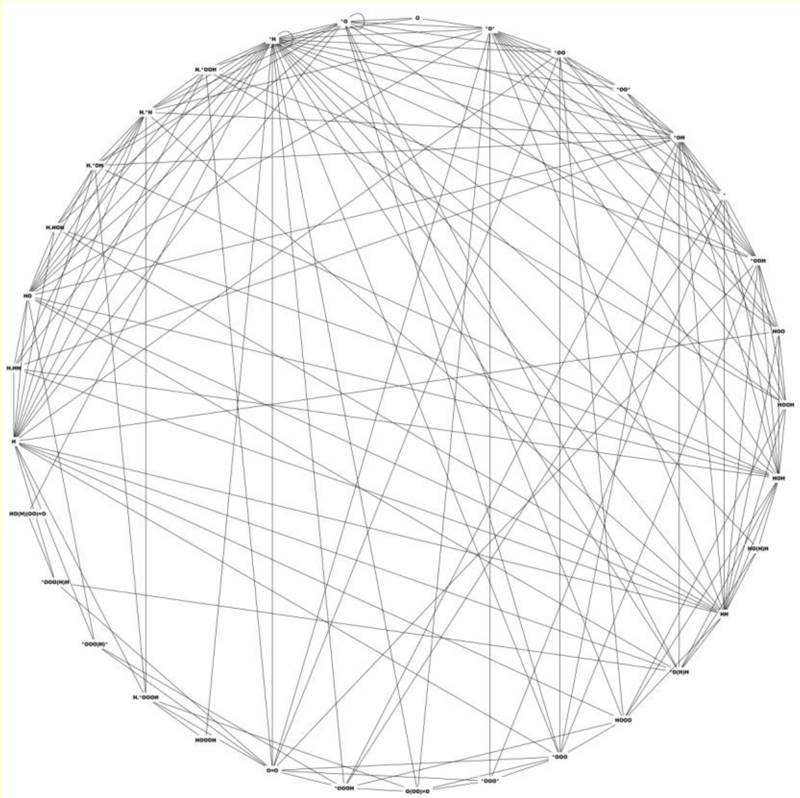


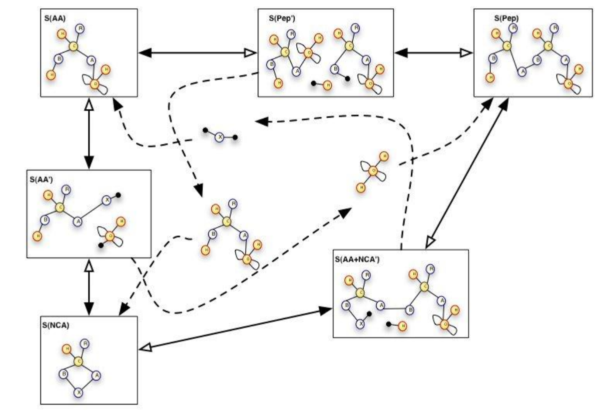
4) Swarm robotics



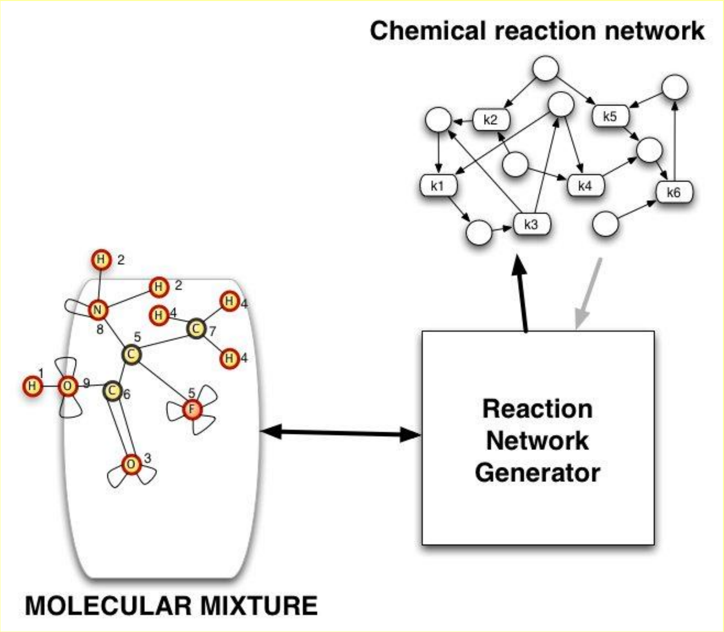
5) Computational Chemical Reactor

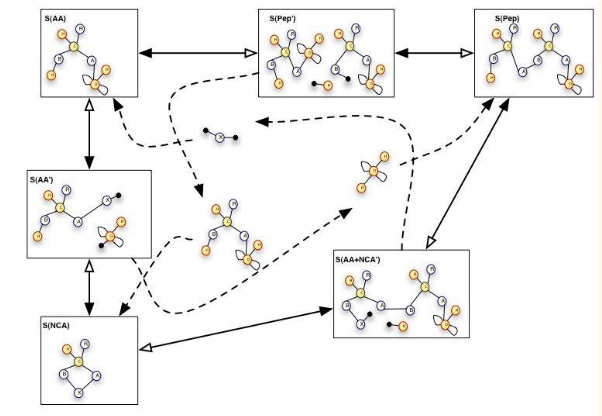




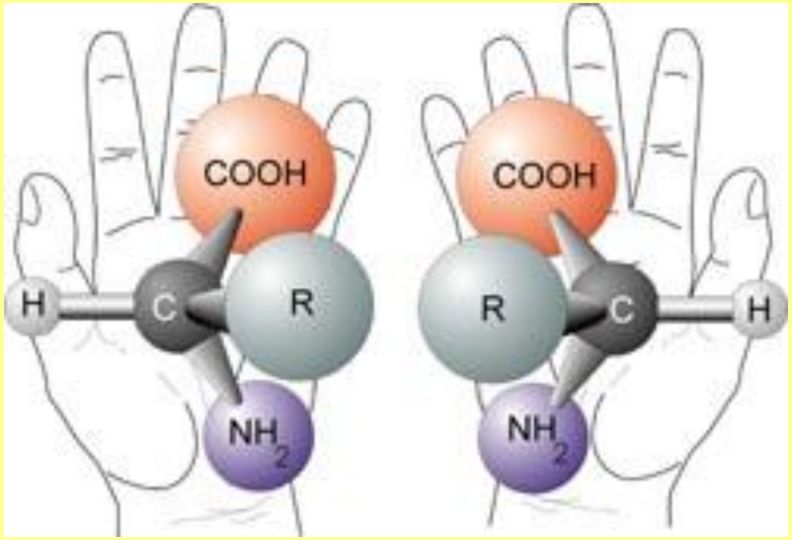


The origin of homochirality

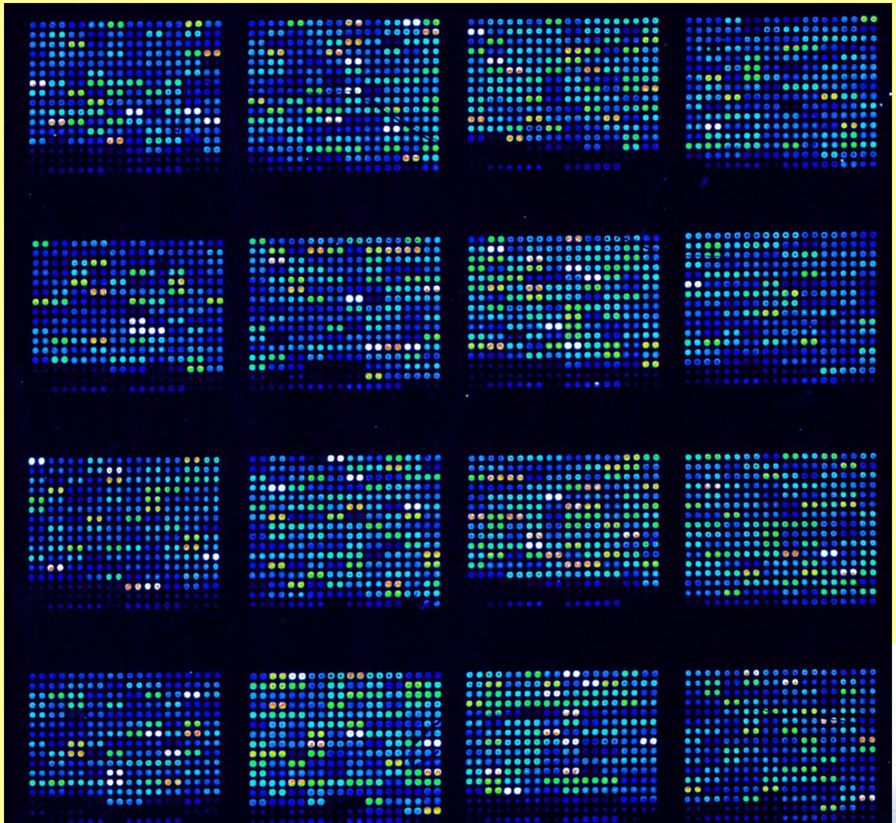




With Raphael Plasson



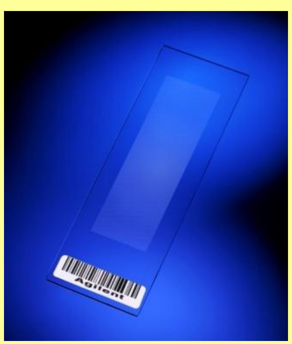
6) Data mining on Microarrays

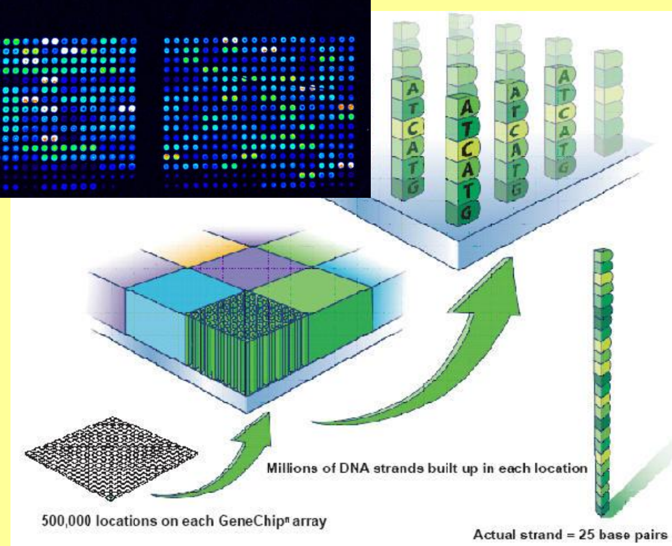


- Microarrays measure the mRNA activity of *all* the genes in a single experiment

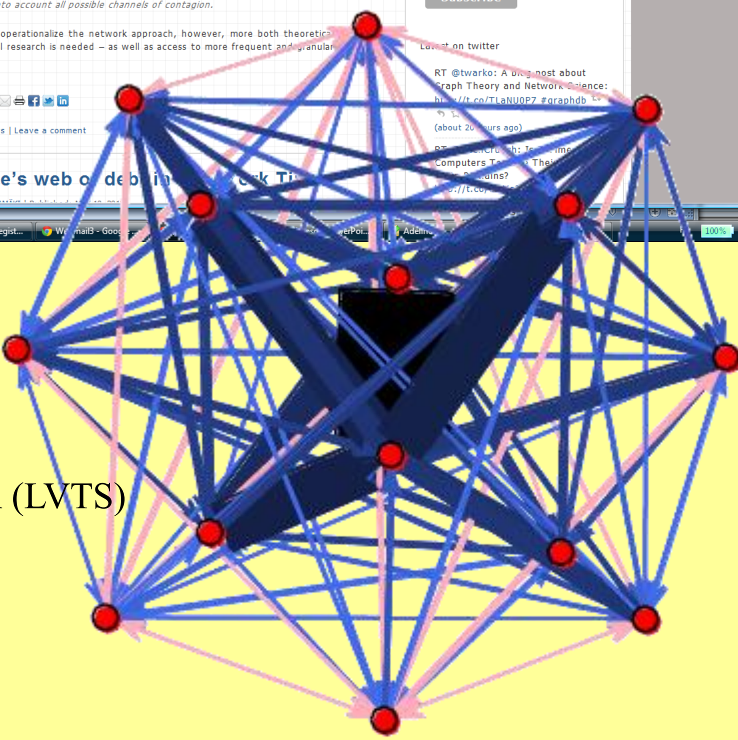
- One can cluster/classify gene or samples

- These may have diagnostic or therapeutic value





7) Financial Network



Intraday network structure
of payment activity in
the Canadian
Large Value Transfer System (LVTS)

Liasons Dangereuses:
Incresing connectivity,
risk sharing and systemic risk
(by Stefano Battiston,
Domenico Delli Gatti,
Mauro Gallegati,
Bruce C. Greenwald and Joseph E. Stiglitz)

The road to an « out of control » engineering

AI

sequential
deliberative
planning
conscious

Min-Max
Expert System
Planning
Knowledge-based

AL

parallel
adaptive
unconscious

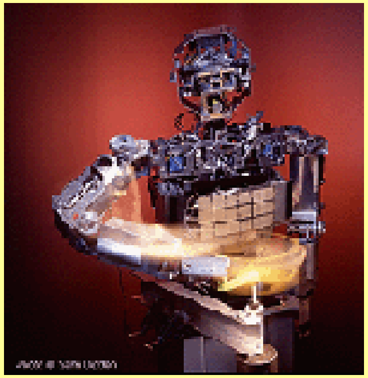
NN
GA
RL
ACO

The two greatest successes of AI

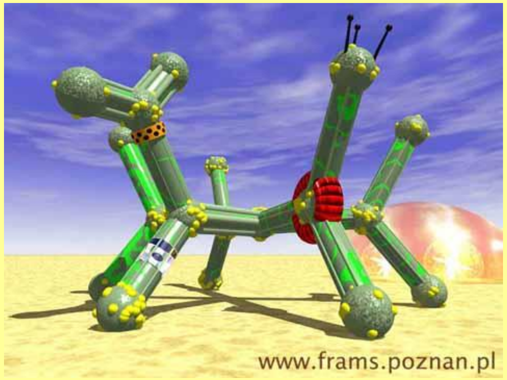
AI

Learning +
Control engineering

Out of control engineering



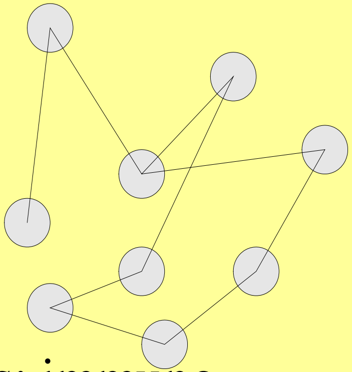
Min-Max



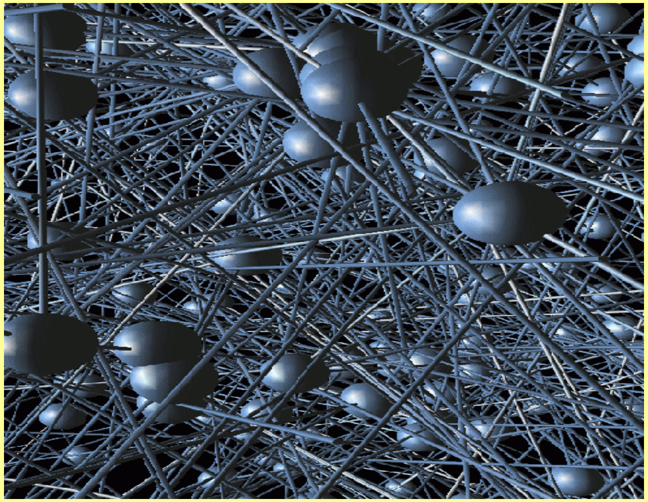
Reinforcement learning

Introduction to Networks

What the « new » science of networks owe to Varela

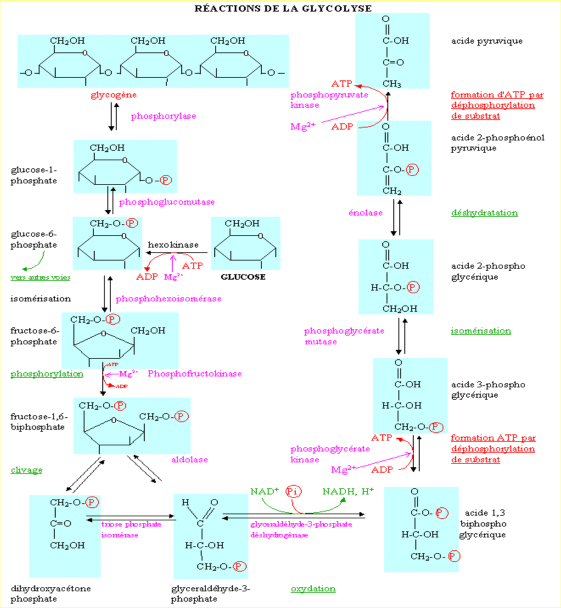


- Network as a scientific object was deep inside his researches: immuno, neuro, socio,cellular automata. He was interested in the plasticity and in the integrating mechanisms of these networks. In immunology (cellular communication), in neurosciences (neuronal synchrony).

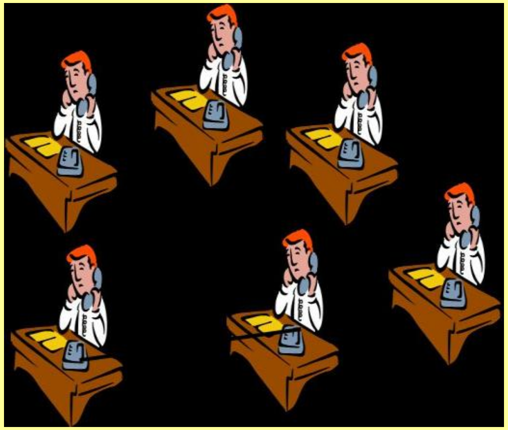


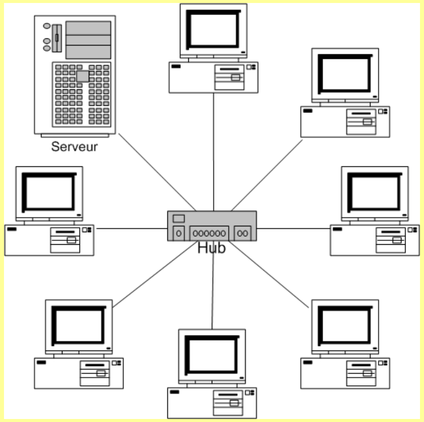
Nodes and connexions from which emerges dynamics, attractors

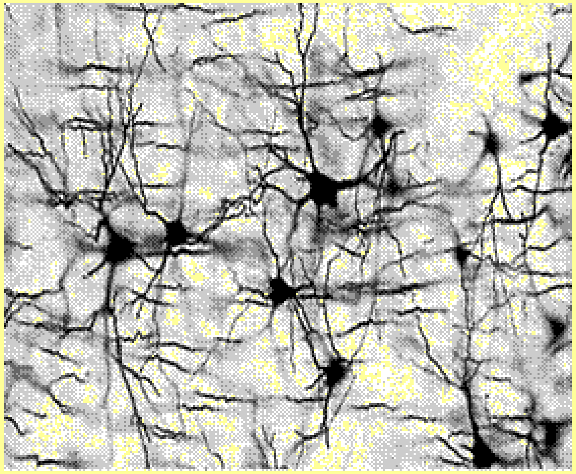
What’s a network ?



Glycolysis

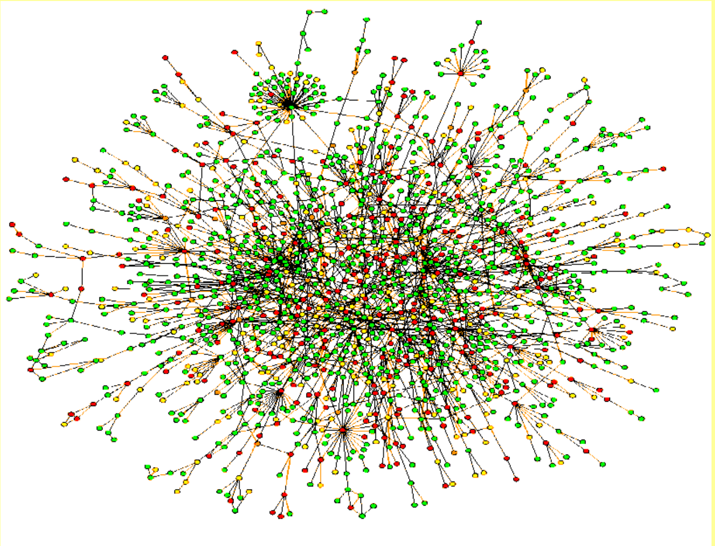




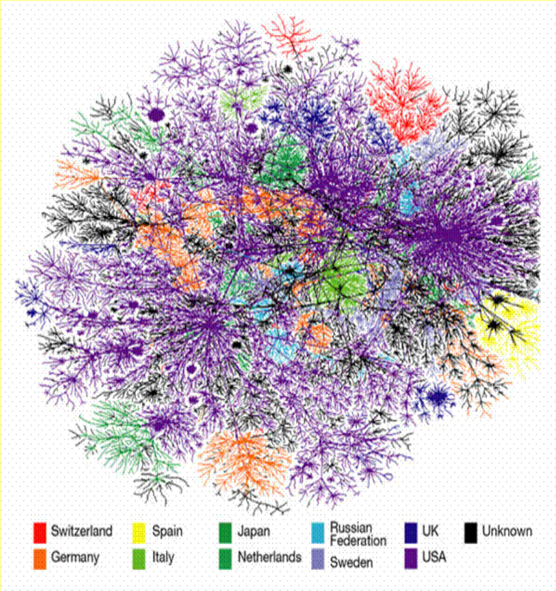


Network = Graph + dynamics

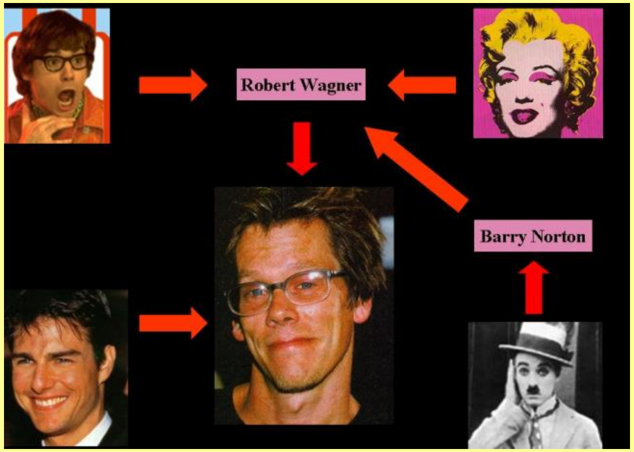
Neural networks



Protein network



The Web



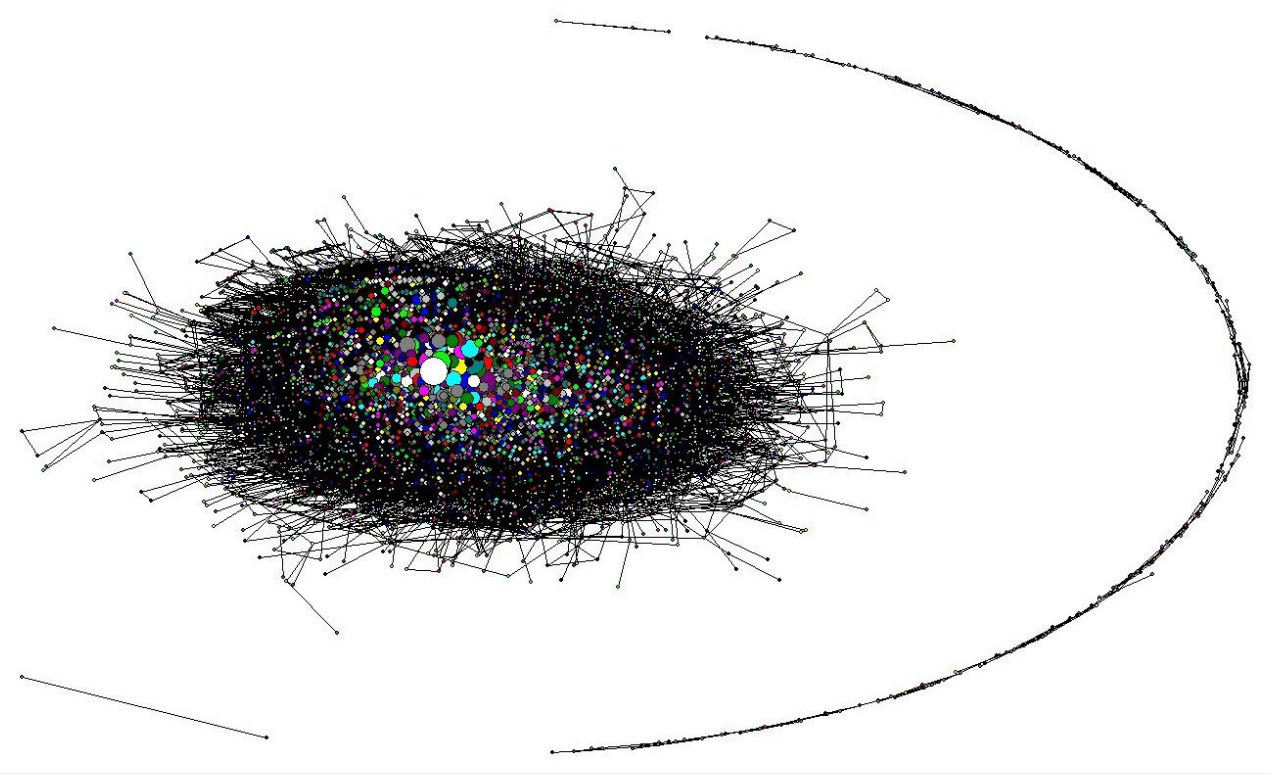
Actors network

Routing network

The three visions of a network

- Take a network of PCs as example
- First: individualistic network, satisfy maximally each node: PC and social networks, etc..
- Second: global network, satisfy globally an outside user: distributed computing, reliable network of PCs, biological networks (natural selection is the user) → Emergence
- Third: afunctional network: network of authors, actors or musicians. No use, neither individual nor global, just interesting for observing collective properties.

My Jazz Musicians Network



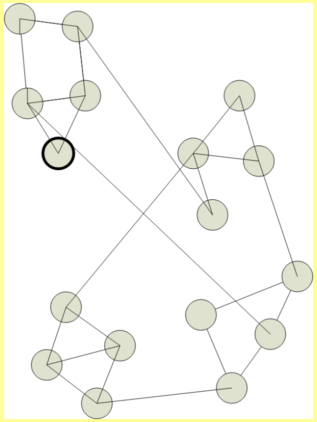
1) Ron Carter
2) Clark Terry
3) Kenny Burrel

- Affinity networks, city networks, PC networks, economical, ecosystem networks are individual
- Biological networks: neural, immune, … are global and emergent
- Authors, actors, chemical networks are afunctional
- What about mafia or terrorist networks: they can be all three.

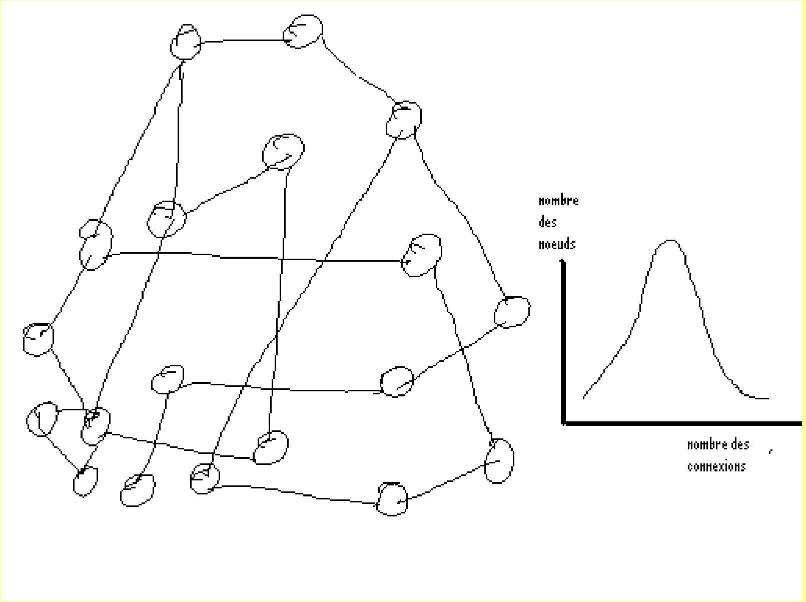
Network Key Properties

1) topology
2) dynamics
3) their interaction

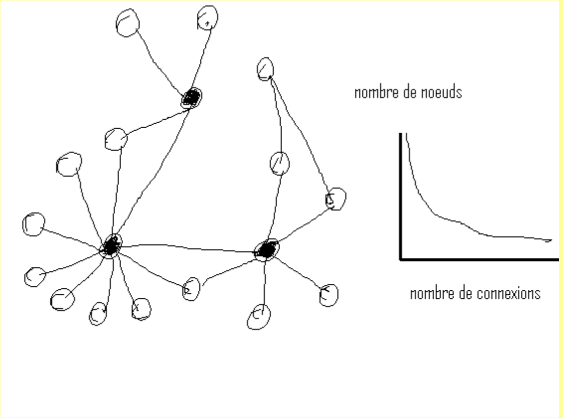
1) Network Topology



Clustered

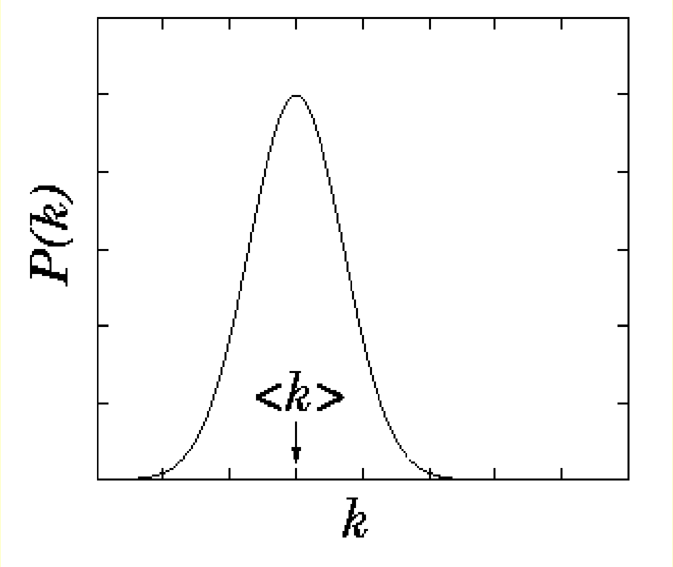


Random

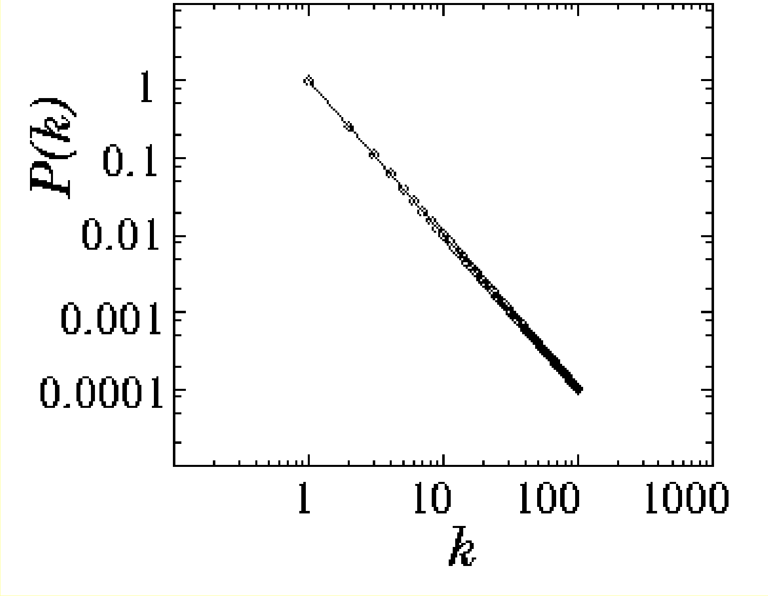


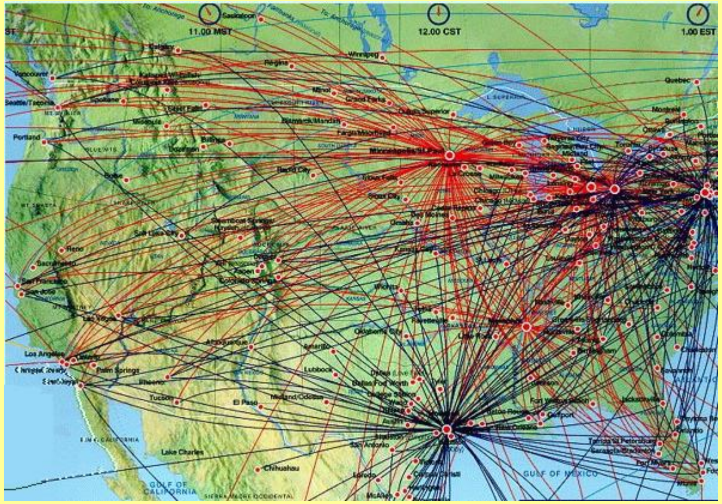
Scale-Free= Hubs

Poisson distribution



Power-law distribution





Exponential Network

Scale-free Network

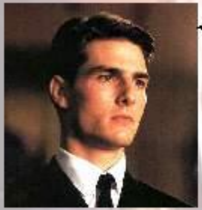
- Actors network, Erdos network, … are all Scale-Free: **P(k) ~k$^{-\gamma}$**

WWW (in)	Internet	Actor	Citation index	Sex Web	Cellular network	Phone call network	linguistics
$\gamma = 2.1$	$\gamma = 2.5$	$\gamma = 2.3$	$\gamma = 3$	$\gamma = 3.5$	$\gamma = 2.1$	$\gamma = 2.1$	$\gamma = 2.8$

ACTOR CONNECTIVITIES

nodes: actors
edges: casted jointly

IMDb Internet Movie Database

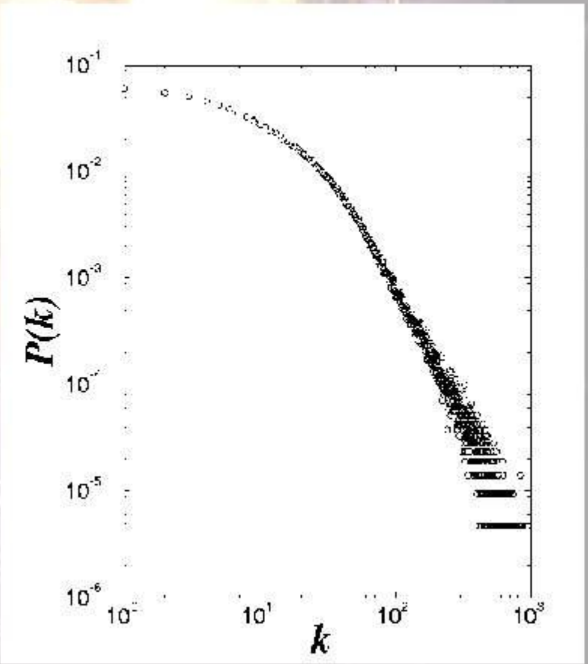


Days of Thunder (1990)
Far and Away (1992)
Eyes Wide Shut (1999)

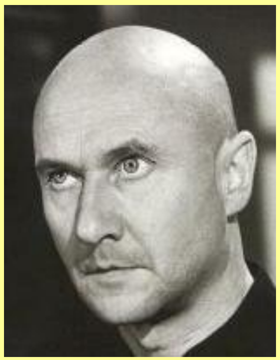
N = 212,250 actors
$\langle k \rangle = 28.78$

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

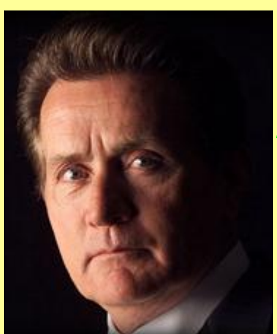
$\gamma = 2.3$



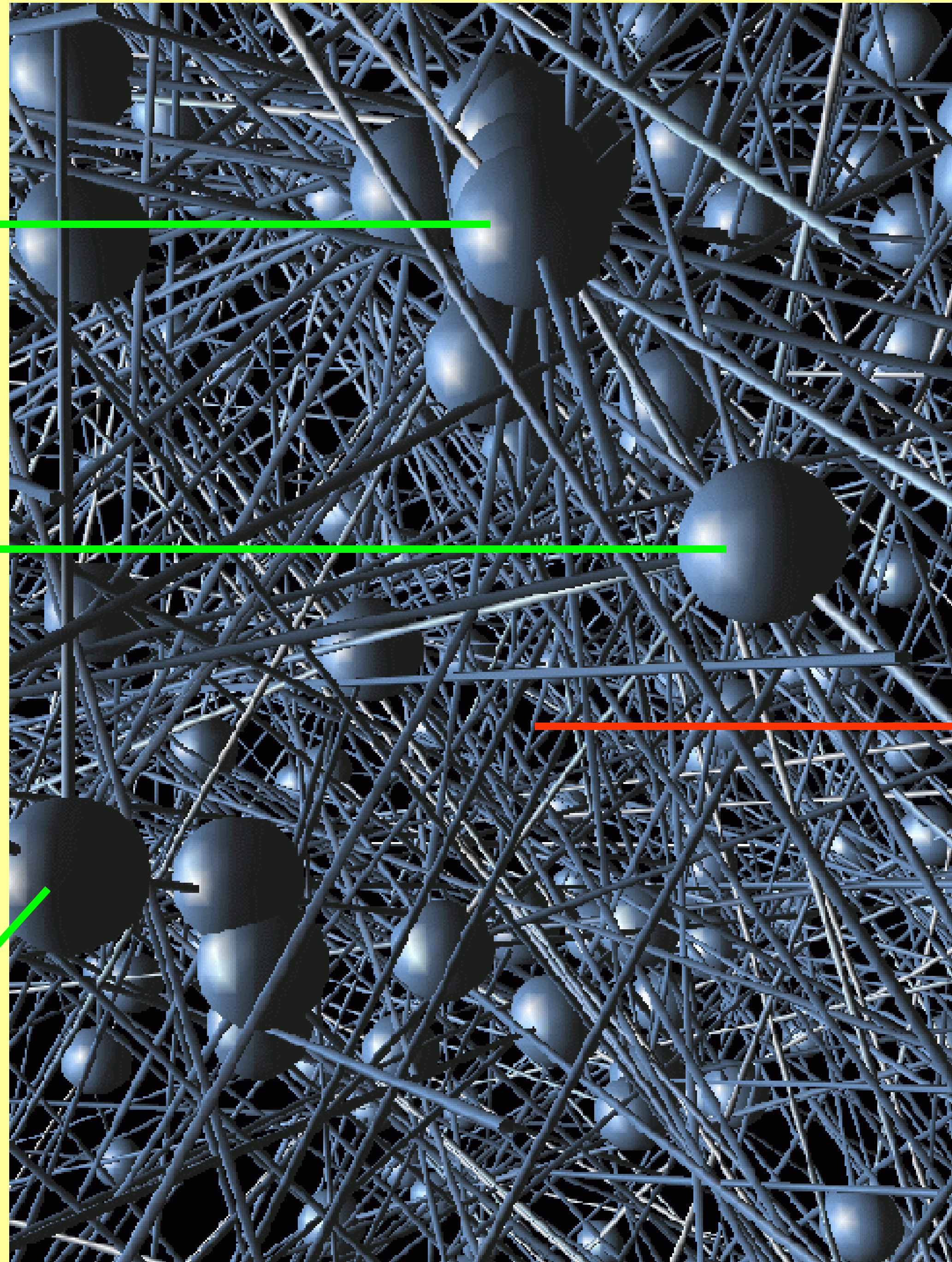
#1 Rod Steiger



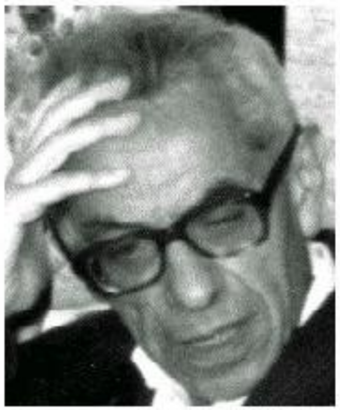
#2 Donald Pleasence



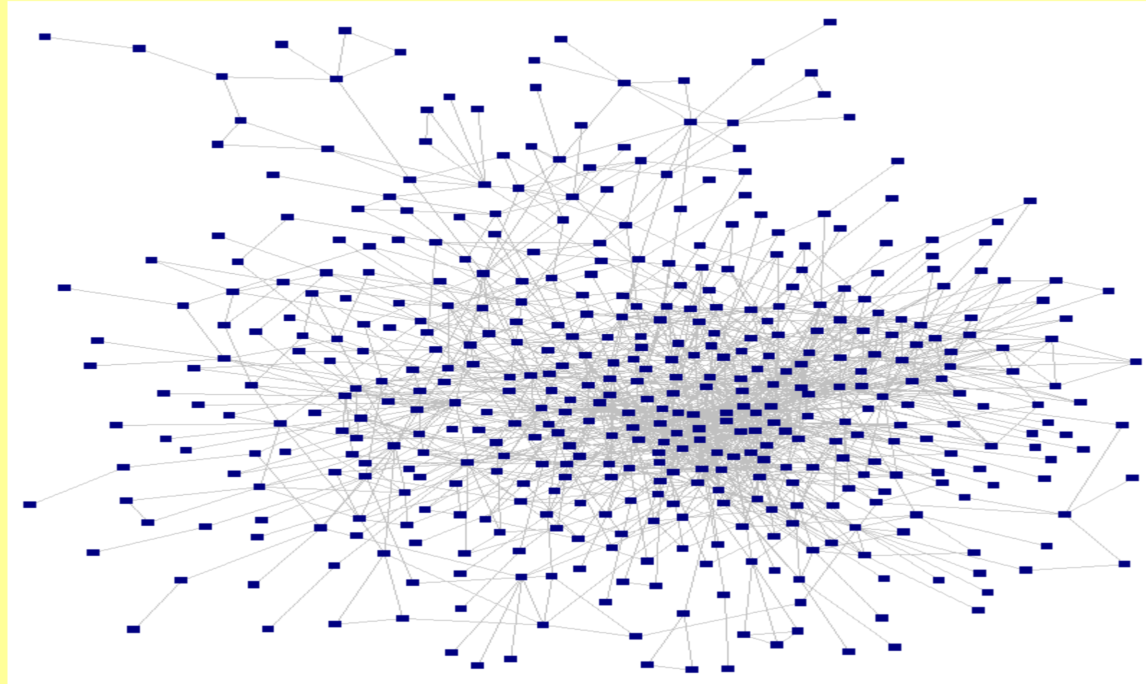
#3 Martin Sheen

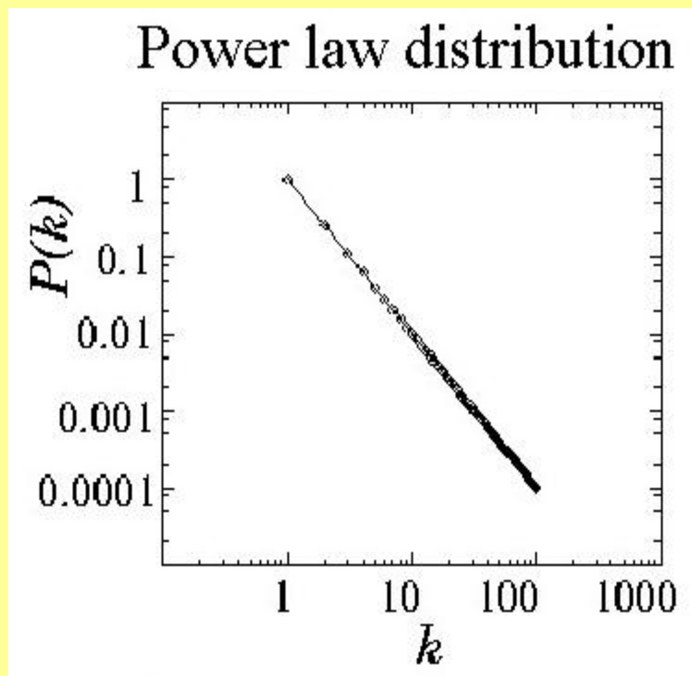


#876 Kevin Bacon



Pál Erdős
(1913-1996)





Erdös number

http://www.acs.oakland.edu/~grossman/erdoshp.html

1- 493
2- 5608

D=11 R=6

Δ = 1- 485

$\Delta_{mitjà}$ = 5.56

......
Collins, P. J.
Colwell, Peter
Comellas, Francesc
Comets, Francis M.
Comfort, W. Wistar
Compton, Kevin J.
Conder, Marston
Conrey, J. Brian
CONWAY, JOHN HORTON
Conze-Berline, Nicole
Cook, Curtis R.
Cook, Janice
.....

Notable Erdös coautors :

Frank Harary (257 coautors)
Noga Alon (143 coautors)
Saharon Shela (136)
Ronald Graham (120)
Charles Colbourn (119)
Daniel Kleitman (115)
A. Odlyzko (104)

Erdös had no common articles with his Ph D supervisor, Leopold Fejér

Some other Erdös coautors

articles together	
András Sárközy	57
András Hajnal	54
Ralph Faudree	45
Richard Schelp	38
Vera Sós	34
Alfréd Rényi	32
Cecil C. Rousseau	32
Pál Turán	30
Endre Szemerédi	29
Ronald Graham	27
Stephan A. Burr	27
Joel Spencer	23
Carl Pomerance	21
Miklos Simonovits	21
Ernst Straus	20
Melvyn Nathanson	19
Richard Rado	18
Jean Louis Nicolas	17
Janos Pach	16
Béla Bollobás	15
Eric Milner	15
John L. Selfridge	13
Harold Davenport	7
Nicolaas G. de Bruijn	6
Ivan Niven	7
Mark Kac	5
Noga Alon	4
Saharon Shela	3
Arthur H. Stone	3
Gabor Szegö	2
Alfred Tarski	2
Frank Harary	2
Irving Kaplansky	2
Lee A. Rubel	2

“famous” scientists

Walter Alvarez	geology	7
Rudolf Carnap	philosophy	4
Jule G. Charney	meteorology	4
Noam Chomsky	linguistics	4
Freeman J. Dyson	quantum physics	2
George Gamow	nuclear physics and cosmology	5
Stephen Hawking	relativity and cosmology	4
Pascual Jordan	quantum physics	4
Theodore von Kármán	aeronautical engineering	4
John Maynard Smith	biology	4
Oskar Morgenstern	economics	4
J. Robert Oppenheimer	nuclear physics	4
Roger Penrose	relativity and cosmology	3
Jean Piaget	psychology	3
Karl Popper	philosophy	4
Claude E. Shannon	electrical engineering	3
Arnold Sommerfeld	atomic physics	5
Edward Teller	nuclear physics	4
George Uhlenbeck	atomic physics	2
John A. Wheeler	nuclear physics	3

Fields medals

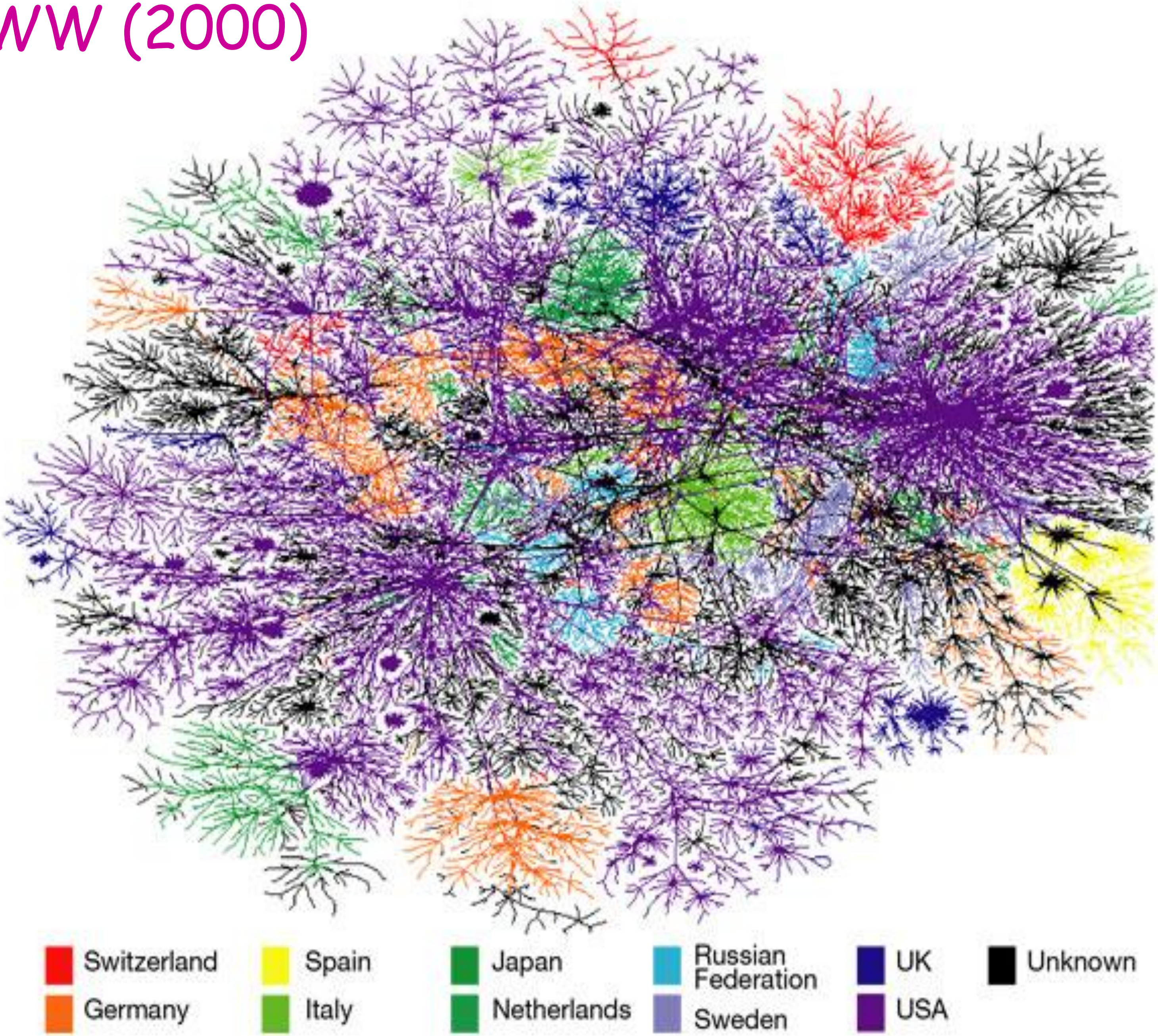
Lars Ahlfors	1936	Finland	4
Jesse Douglas	1936	USA	4
Laurent Schwartz	1950	France	4
Atle Selberg	1950	Norway	2
Kunihiko Kodaira	1954	Japan	2
Jean-Pierre Serre	1954	France	3
Klaus Roth	1958	Germany	2
Rene Thom	1958	France	4
Lars Hormander	1962	Sweden	3
John Milnor	1962	USA	3
Michael Atiyah	1966	Great Britain	4
Paul Cohen	1966	USA	5
Alexander Grothendieck	1966	Germany	5
Stephen Smale	1966	USA	4
Alan Baker	1970	Great Britain	2
Heisuke Hironaka	1970	Japan	4
Serge Novikov	1970	USSR	3
John G. Thompson	1970	USA	3
Enrico Bombieri	1974	Italy	2
David Mumford	1974	Great Britain	2
Pierre Deligne	1978	Belgium	3
Charles Fefferman	1978	USA	2
Gregori Margulis	1978	USSR	4
Daniel Quillen	1978	USA	3
Alain Connes	1982	France	3
William Thurston	1982	USA	3
Shing-Tung Yau	1982	China	2
Simon Donaldson	1986	Great Britain	4
Gerd Faltings	1986	Germany	4
Michael Freedman	1986	USA	3
Valdimir Drinfeld	1990	USSR	4
Vaughan Jones	1990	New Zealand	4
Shigemufi Mori	1990	Japan	3
Edward Witten	1990	USA	3
Pierre-Louis Lions	1994	France	4
Jean Christophe Yoccoz	1994	France	3
Jean Bourgain	1994	Belgium	2
Efim Zelmanov	1994	Russia	3
Richard Borcherds	1998	S Afr/Gt Brtn	2
William T. Gowers	1998	Great Britain	4
Maxim L. Kontsevich	1998	Russia	4
Curtis McMullen	1998	USA	3

Erdös numbers for physics Nobel prizes

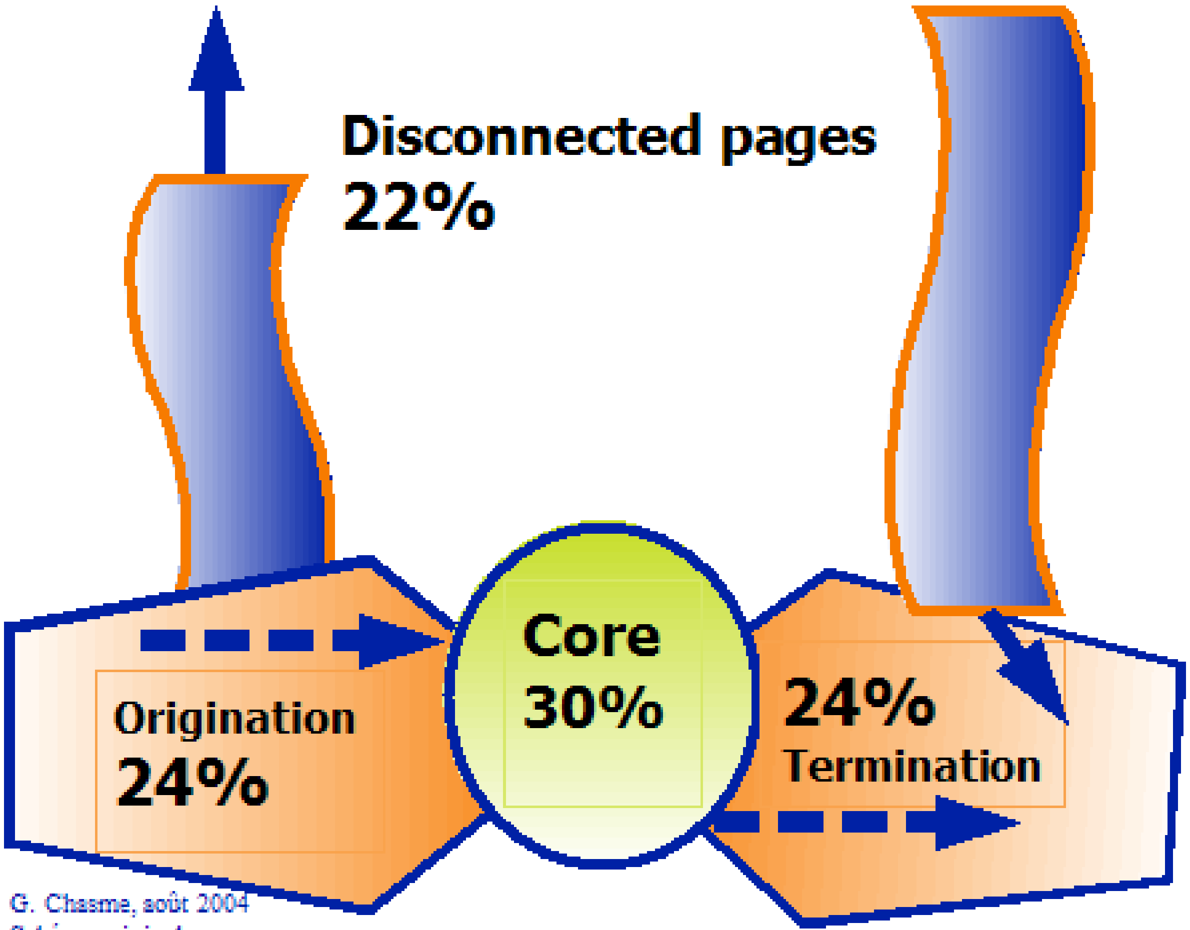
Max von Laue	1914	4
Albert Einstein	1921	2
Niels Bohr	1922	5
Louis de Broglie	1929	5
Werner Heisenberg	1932	4
Paul A. Dirac	1933	4
Erwin Schrödinger	1933	8
Enrico Fermi	1938	3
Ernest O. Lawrence	1939	6
Otto Stern	1943	3
Isidor I. Rabi	1944	4
Wolfgang Pauli	1945	3
Frits Zernike	1953	6
Max Born	1954	3
Willis E. Lamb	1955	3
John Bardeen	1956	5
Walter H. Brattain	1956	6
William B. Shockley	1956	6
Chen Ning Yang	1957	4
Tsung-dao Lee	1957	5
Emilio Segrè	1959	4

Owen Chamberlain	1959	5
Robert Hofstadter	1961	5
Eugene Wigner	1963	4
Richard P. Feynman	1965	4
Julian S. Schwinger	1965	4
Hans A. Bethe	1967	4
Luis W. Alvarez	1968	6
Murray Gell-Mann	1969	3
John Bardeen	1972	5
Leon N. Cooper	1972	6
John R. Schrieffer	1972	5
Aage Bohr	1975	5
Ben Mottelson	1975	5
Leo J. Rainwater	1975	7
Steven Weinberg	1979	4
Sheldon Lee Glashow	1979	2
Abdus Salam	1979	3
S. Chandrasekhar	1983	4
Norman F. Ramsey	1989	3

WWW (2000)


Switzerland
Germany
Spain
Italy
Japan
Netherlands
Russian Federation
Sweden
UK
USA
Unknown

La théorie du nœud papillon

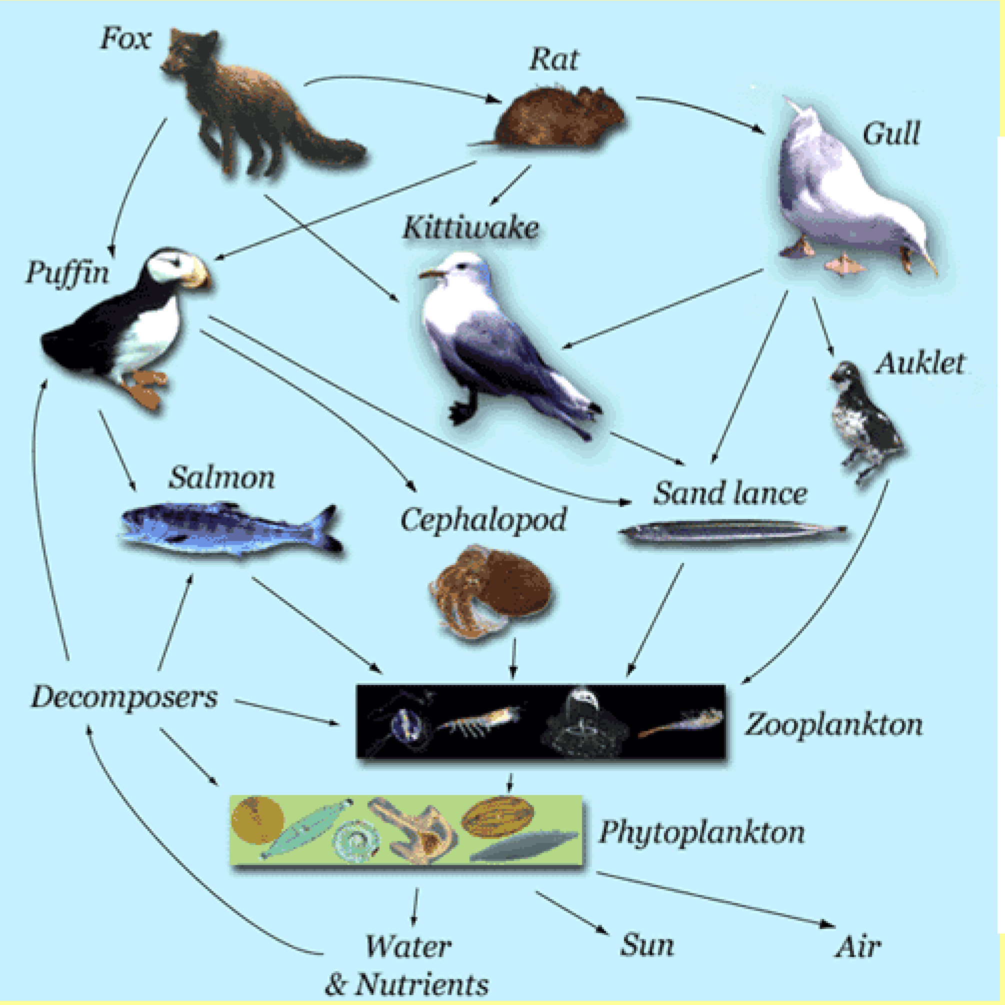


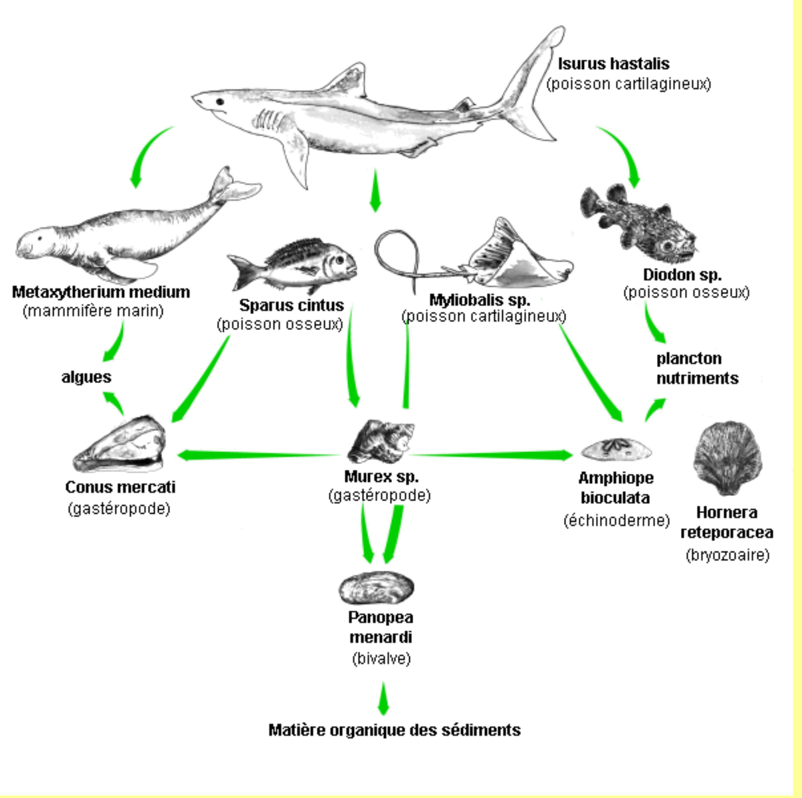
G. Chasme, août 2004
Schéma original :
http://www.research.ibm.com/resources/news/20000511_bowtie.shtml

Topology of immune networks

- "*The rich connectivity of one particular sub-network has been empirically established from newborn mice …. Three independent reports addressing neonatal natural antibody repertoires estimate very similar high levels of antibody connectivity. Close scrutiny of these results reveal that such connectivity matrices are organized into blocks: a high reactivity group of antibodies, two blocks that mirror each other and a low reactivity remnant … It indicates the importance of establishing the entire and detailed structure of neonatal networks… Progress requires that such structural measurements become routine … Further experimental data show that connectivity and the proportion of highly reactive clones are highest in new born mice and considerably lower in adults*". "Immonological Today" in 1991, Varela et al.

Trophic Network

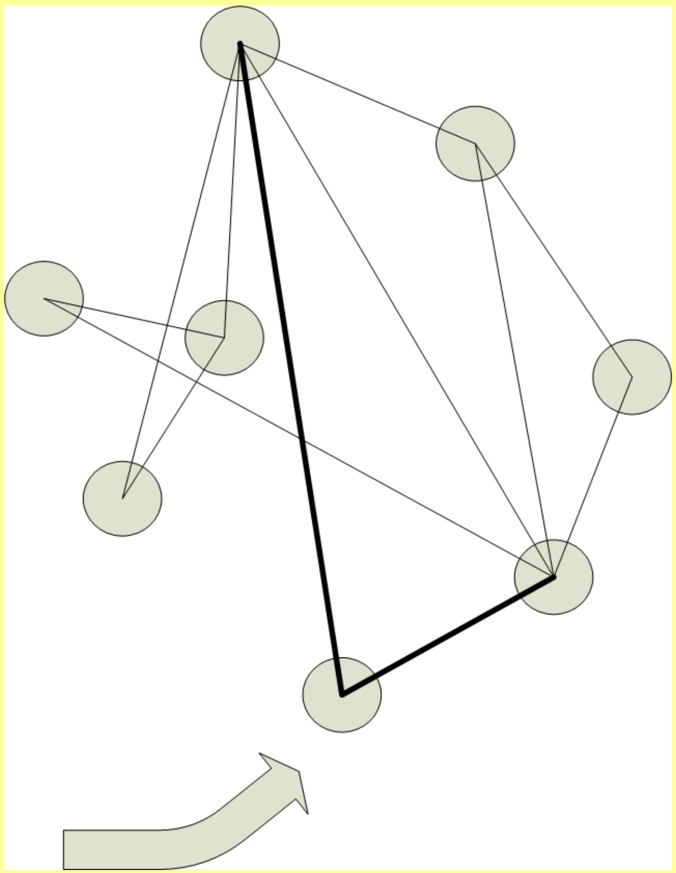


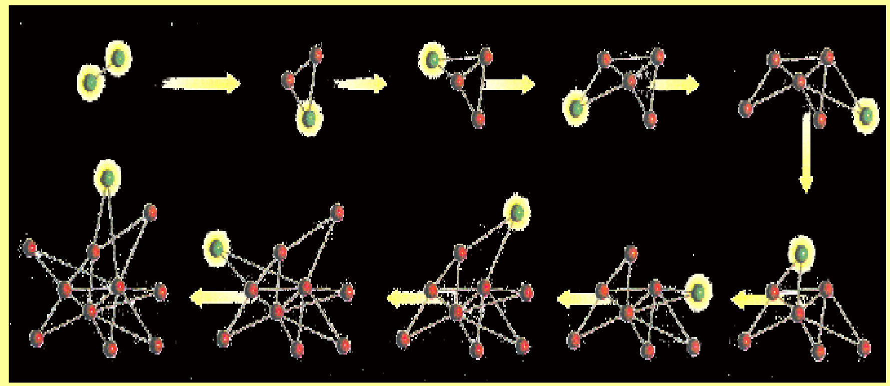


How topology impacts functions ?

- Small-World effect → very short distance between nodes (the 6 degrees of separation)
- Distance scales smoothly with size (like for random networks but even smaller)
- Better robustness (for non targetted attacks) -> Not like random networks
- Hubs are key actors of these networks

Why Scale-Free: Preferential Attachment





More generally: when the new connection depends on the history of the evolution

→ METADYNAMICS

2) Network Dynamics

- Homogeneous units a_i (t) (the same temporal evolution – the same differential equations)

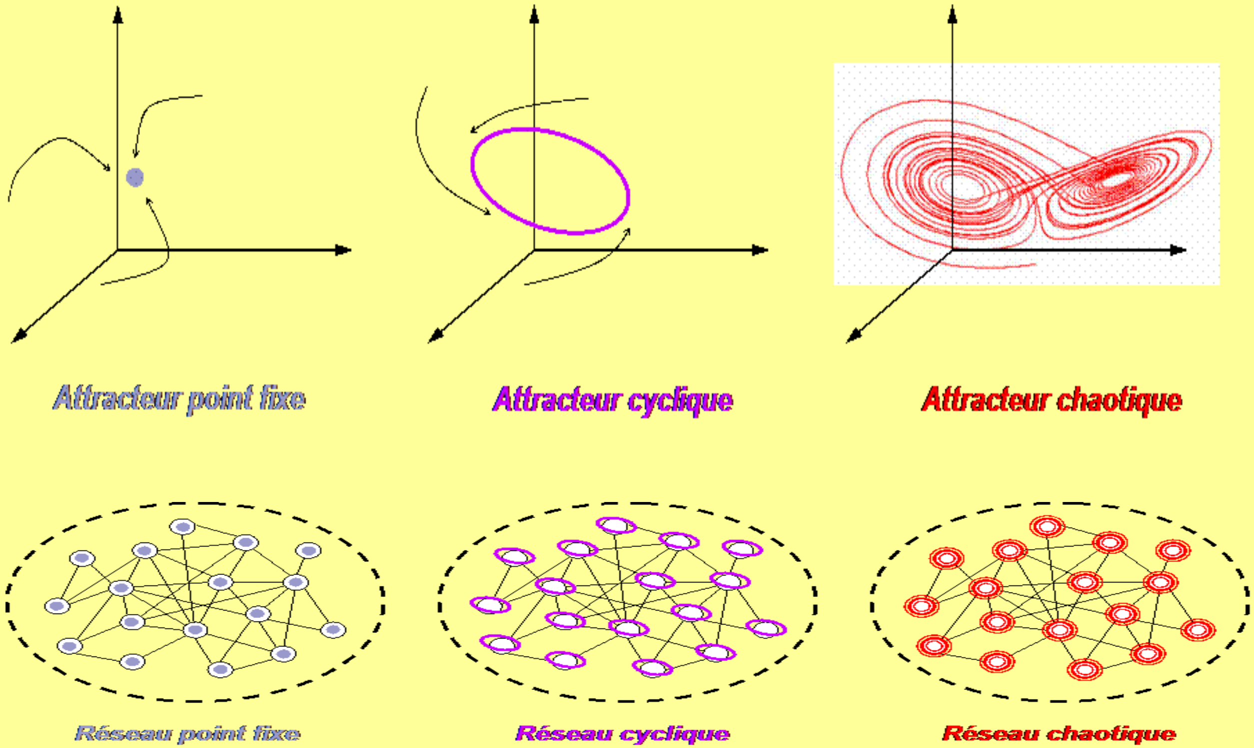
  - $da_i/dt = F(a_j, W_{ij}, I)$

- A given topology in the connectivity matrix: W_{ij}

- Entries I which perturb the dynamics and to which the network gives meaning (→ attractors)

- A very large family of concerned biological networks
  - Idiotypic immune network
  - Hopfield network
  - Coupled Map Lattice
  - Boolean network
  - Ecological network (Lokta-Volterra)
  - Genetic network

Dynamics



Chemistry

Ecosystem: prey/predator

Brain, heart

Topology influences the dynamics of immune network

5076 Immunology: Lundkvist *et al.* *Proc. Natl. Acad. Sci. USA 86 (1989)*

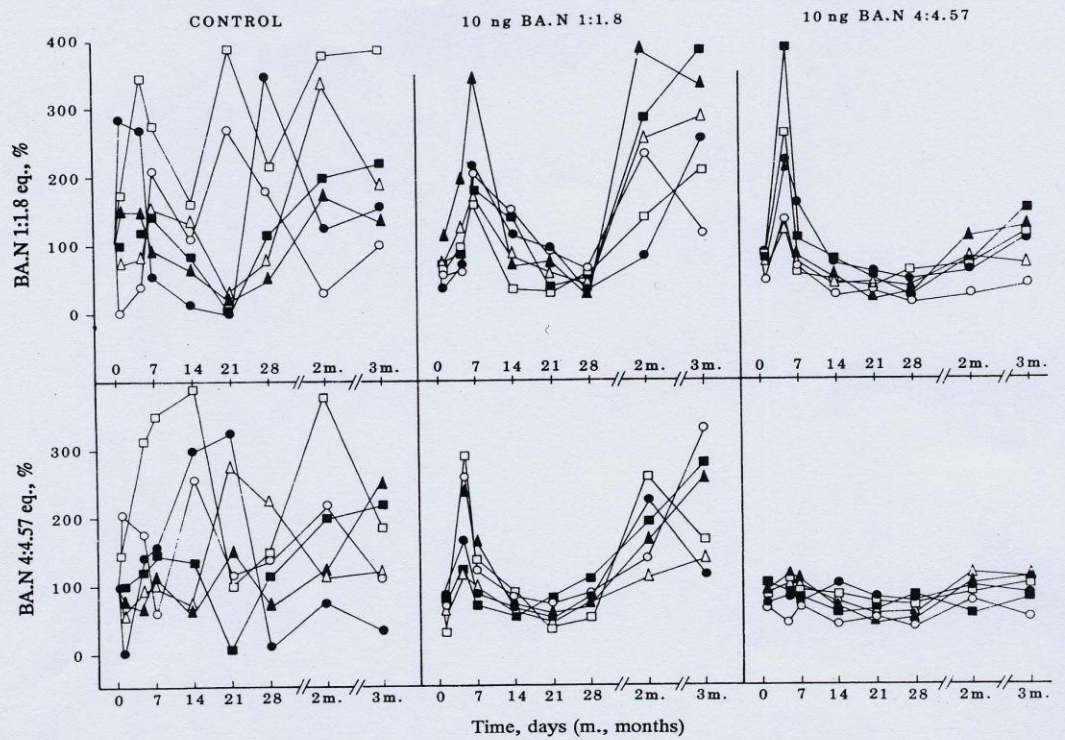
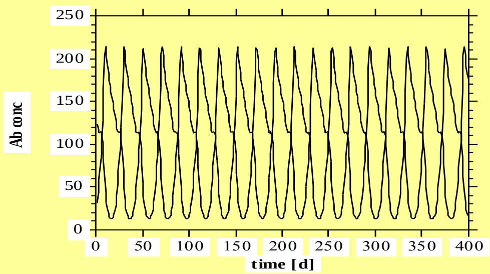
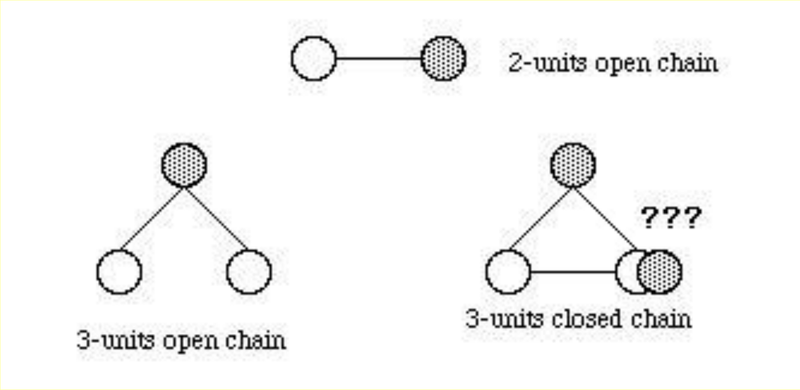


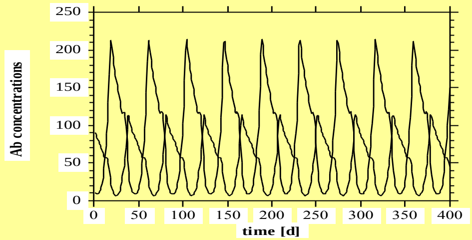
FIG. 2. Time course of expression of two connected idiotypes (BA.N 1:1.8 and BA.N 4:4.57) in adult BALB/c mice that had been injected with 10 ng of either idiotype or had been left untreated. Repeated bleedings from six individual mice, per group, at the indicated times were analyzed for the expression of BA.N 1:1.8 (*Upper*) and BA.N 4:4.57 (*Lower*) equivalents. The concentrations obtained on the day of the first bleeding (day 0) were normalized to 100% for each mouse, and all other titers are expressed as a percentage of this initial value.

Frustrated chaos in biological networks

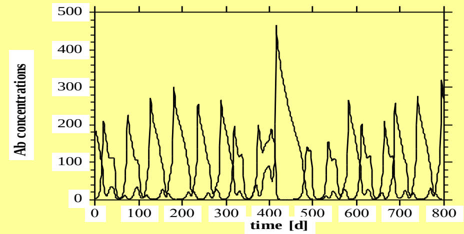


2-clone case $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$





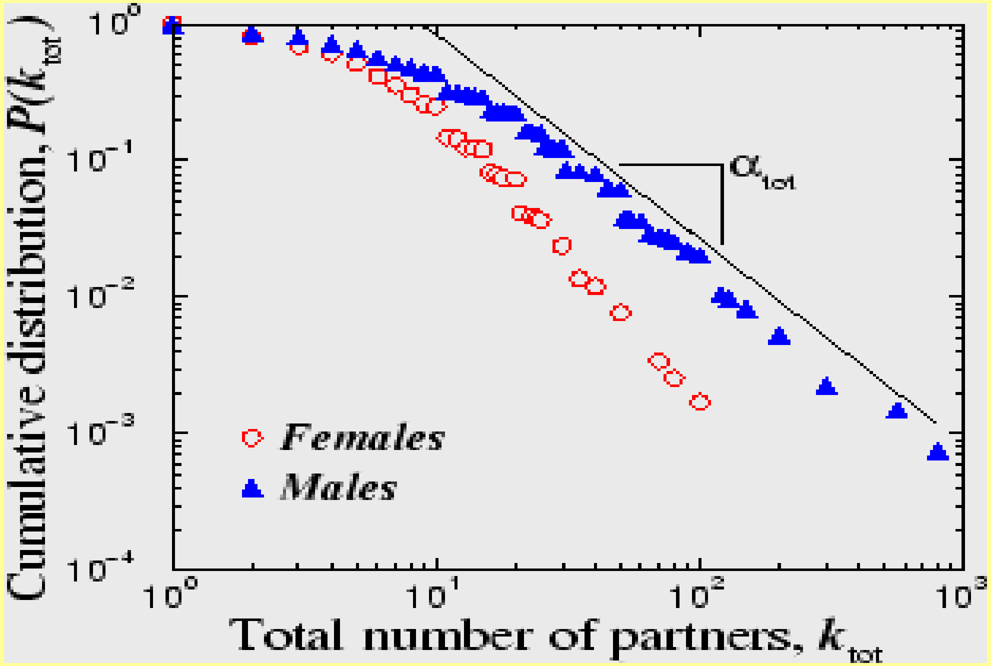
3-clone open chain $\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$

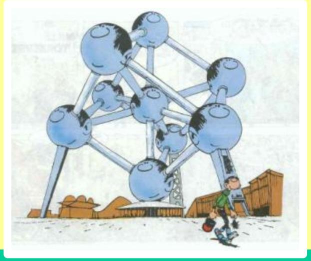


3-clone closed chain $\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$

Elementary dynamics:propagation

Epidemic propagation





A new route to cooperation

With F. Santos - IRIDIA

The prisoner's dilemma

P1/P2	Cooperate	Compete
Cooperate	(1,1)	(-2,3)
Compete	(3,-2)	(-1,-1)

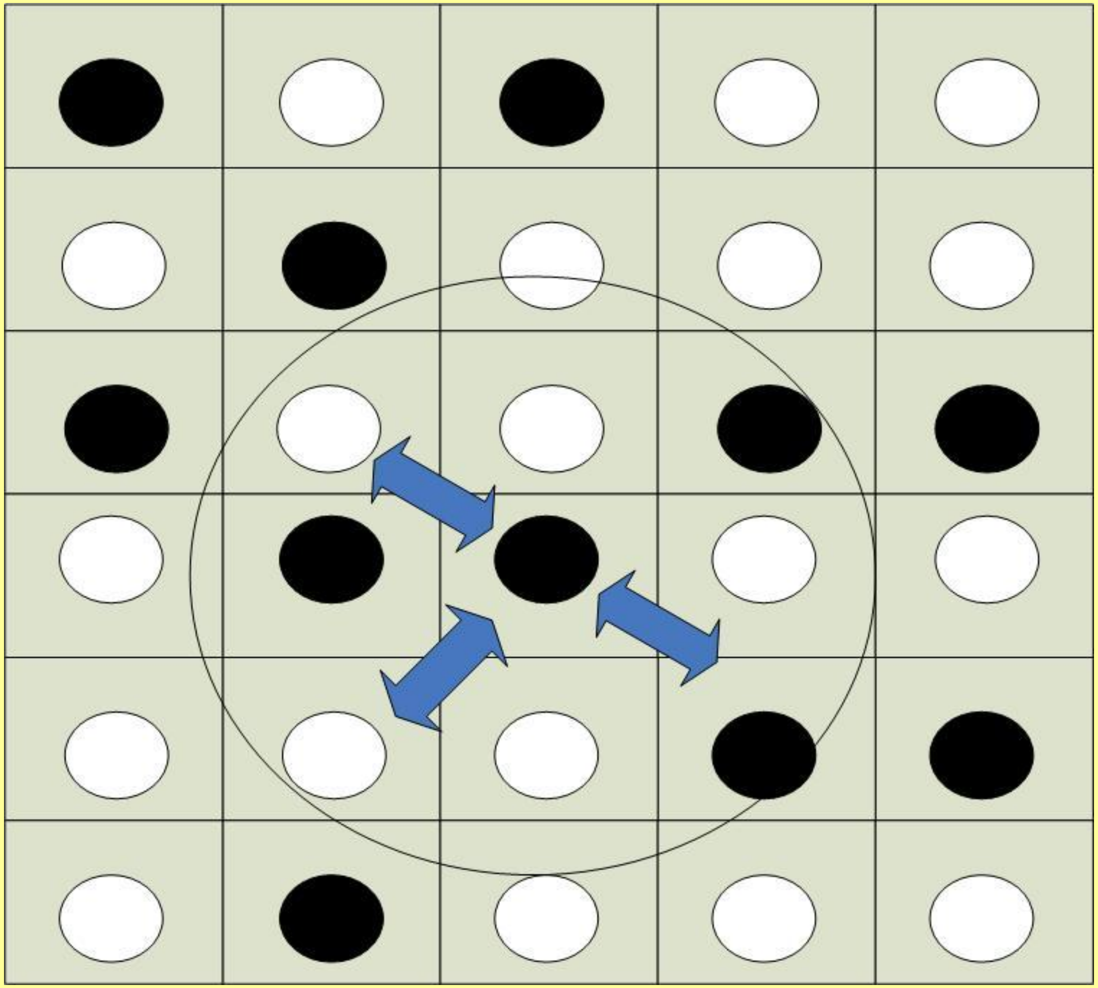
The winning strategy for both players is to compete. But doing so, they miss the cooperating one which is collectively better. The common good is subverted by individual rationality and self-interest.

But is competitive behaviour and collective distress avoidable ?

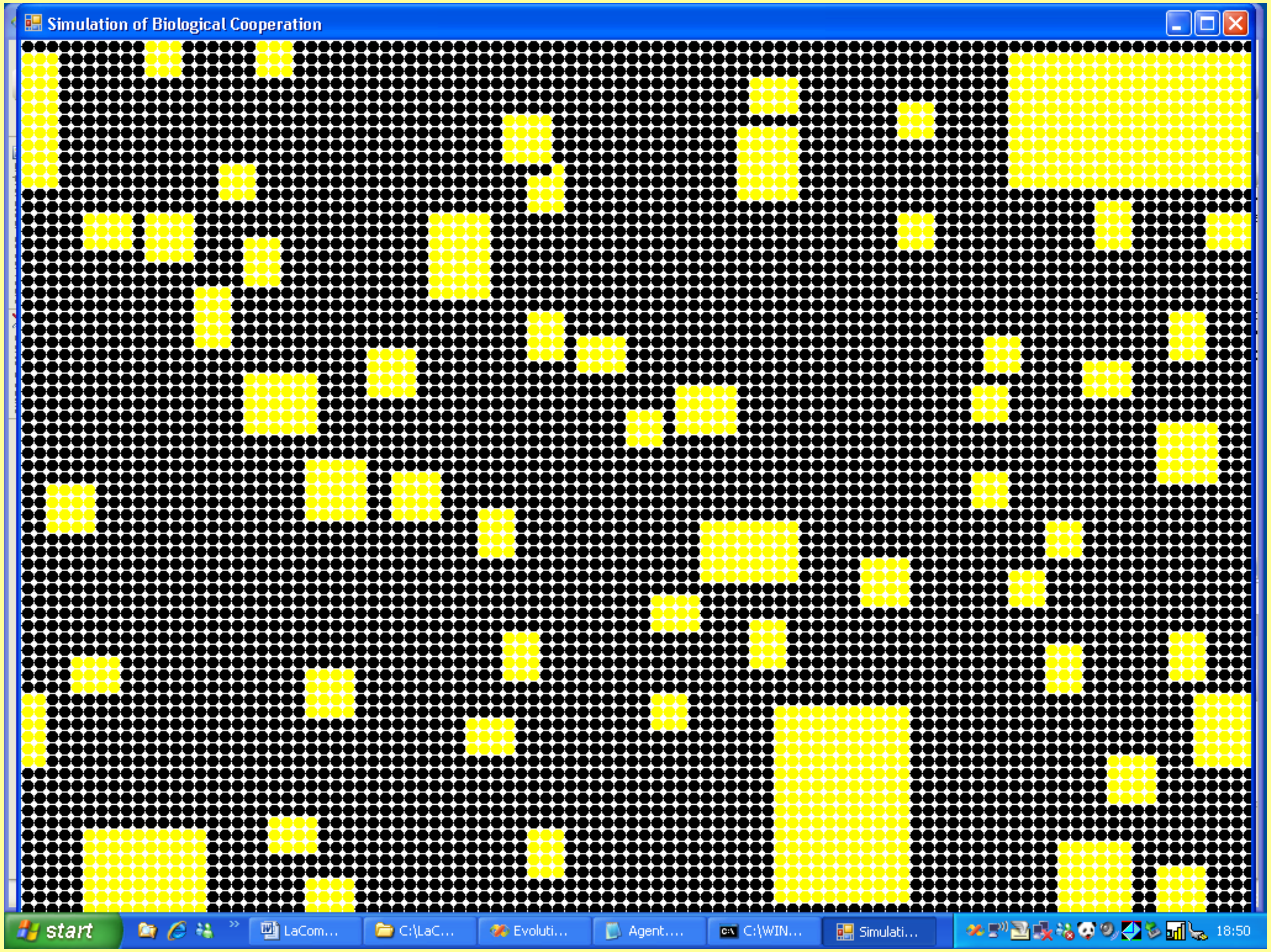
- So far the prisoner's dilemma is lacking some crucial quality that real world situations have.
- 1) Iterated version: play several moves and cumulate your reward over these moves.
- 2) Distribute spatially the players (CA): each cell just cooperates with its immediate neighbours and adapts the local best strategy. Cluster of nice individuals emerge and can prosper in hostile environments -> EVOLUTIONARY GAME THEORY

The spatial cellular automata simulation

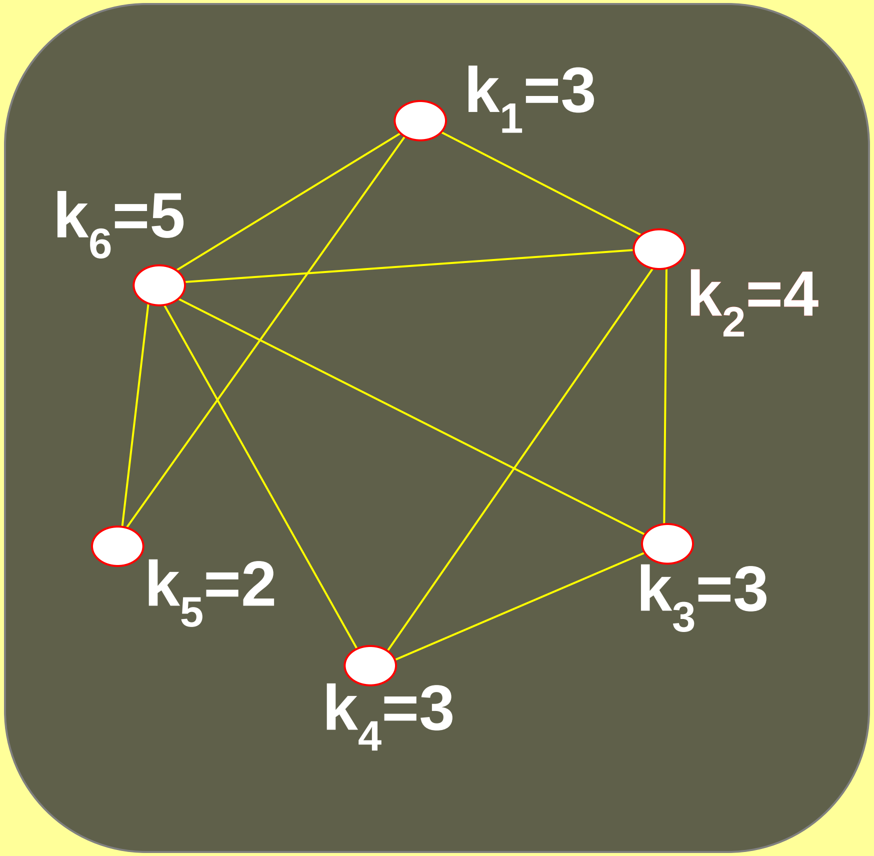
- Largely inspired by Nowak’s work on spatial prisoner dilemma
- A cellular automata in which every cell contains one agent (specialist or generalist)
- In all cells, asynchronously, an agent will subsequently:
  - interact with its neighbors (Moore neighborhood) to “consume” them.
    - Sum the payoff according to the payoff matrix
  - replicate
    - Adopt the identity of the fittest neighbor
- For a given number of iteration steps



Nowak's cooperators vs defectors



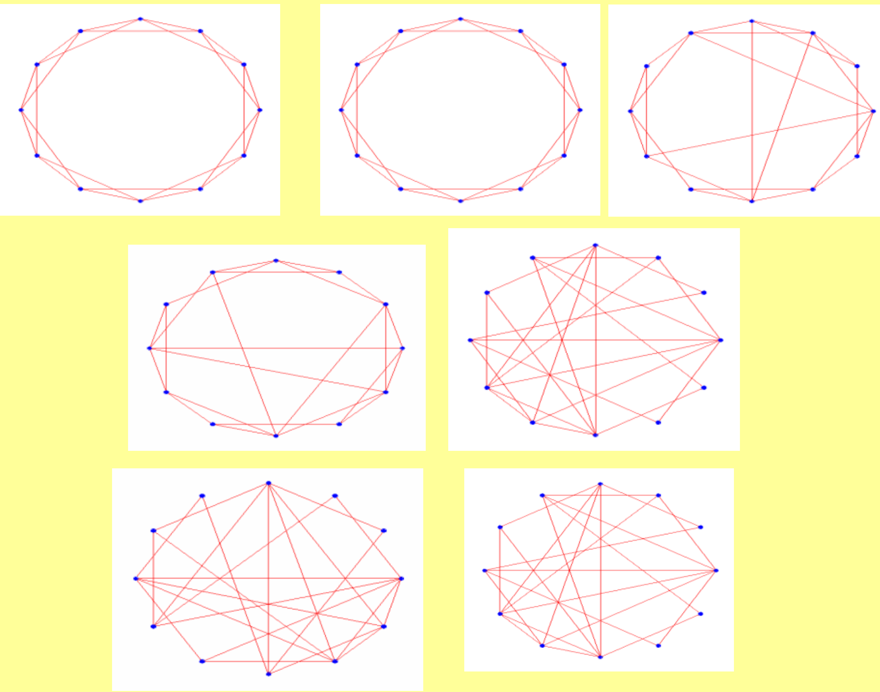
Setting the stage

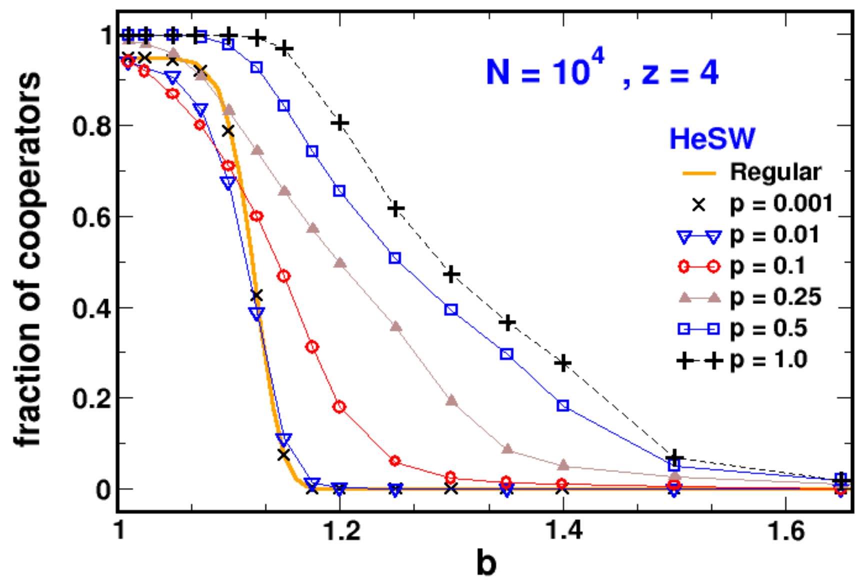


- Stochastic replicator dynamics:
  - Vertex x plays k_x times per generation and accumulates payoff f_x.
  - Choose a random neighbor y with payoff f_y.
  - Replace strategy m_x by m_y with probability:

$$p = \max\left[0, \frac{f_x - f_y}{k_>(T-S)}\right]$$

Games on graphs

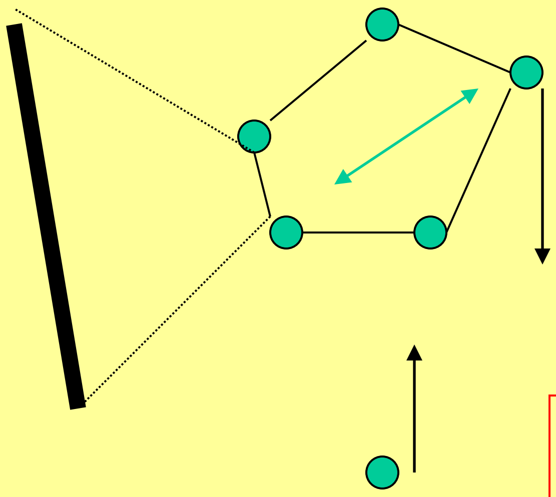




- Conclusions:
  - The more heterogeneous, the more cooperative.
  - Cs benefit most from heterogeneity.

3) Plastic networks: parametrically and structurally: Network Metadynamics

- Various dynamical changes, that Varela called: dynamics and metadynamics

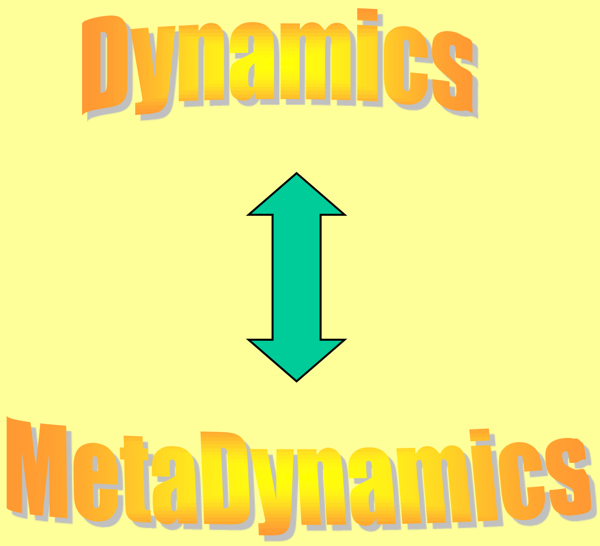


- modification of connexions
- addition of connexions
- addition of new nodes
- suppression of existing nodes

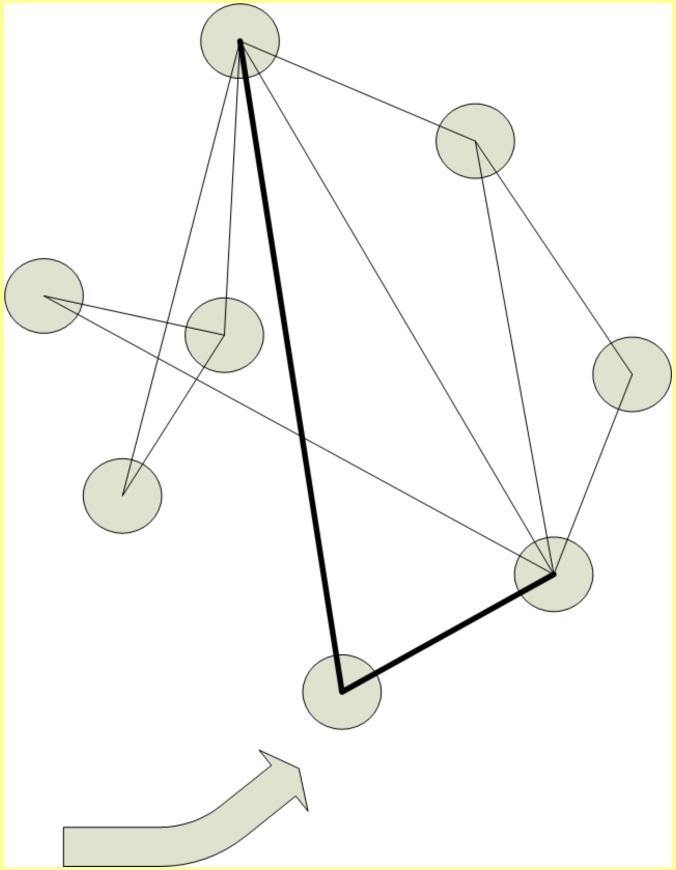
The organisation is maintained independently of the constituants

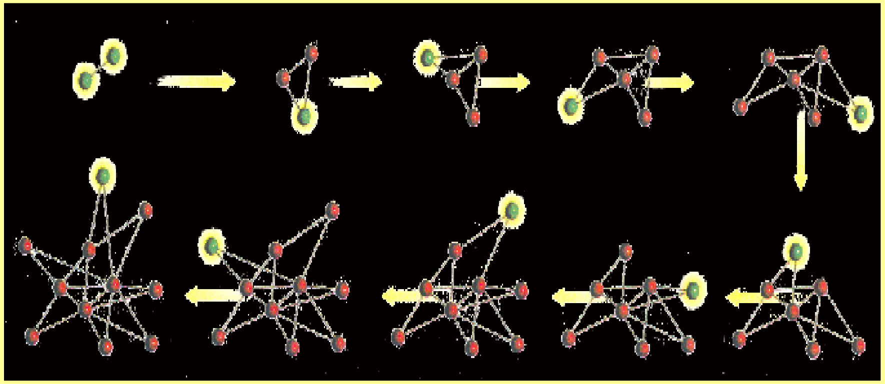
- This is the case for neuro, immuno, chemical, sociological networks, PC networks

A key interdependency



Barabasi's preferential attachment





BUT !!!

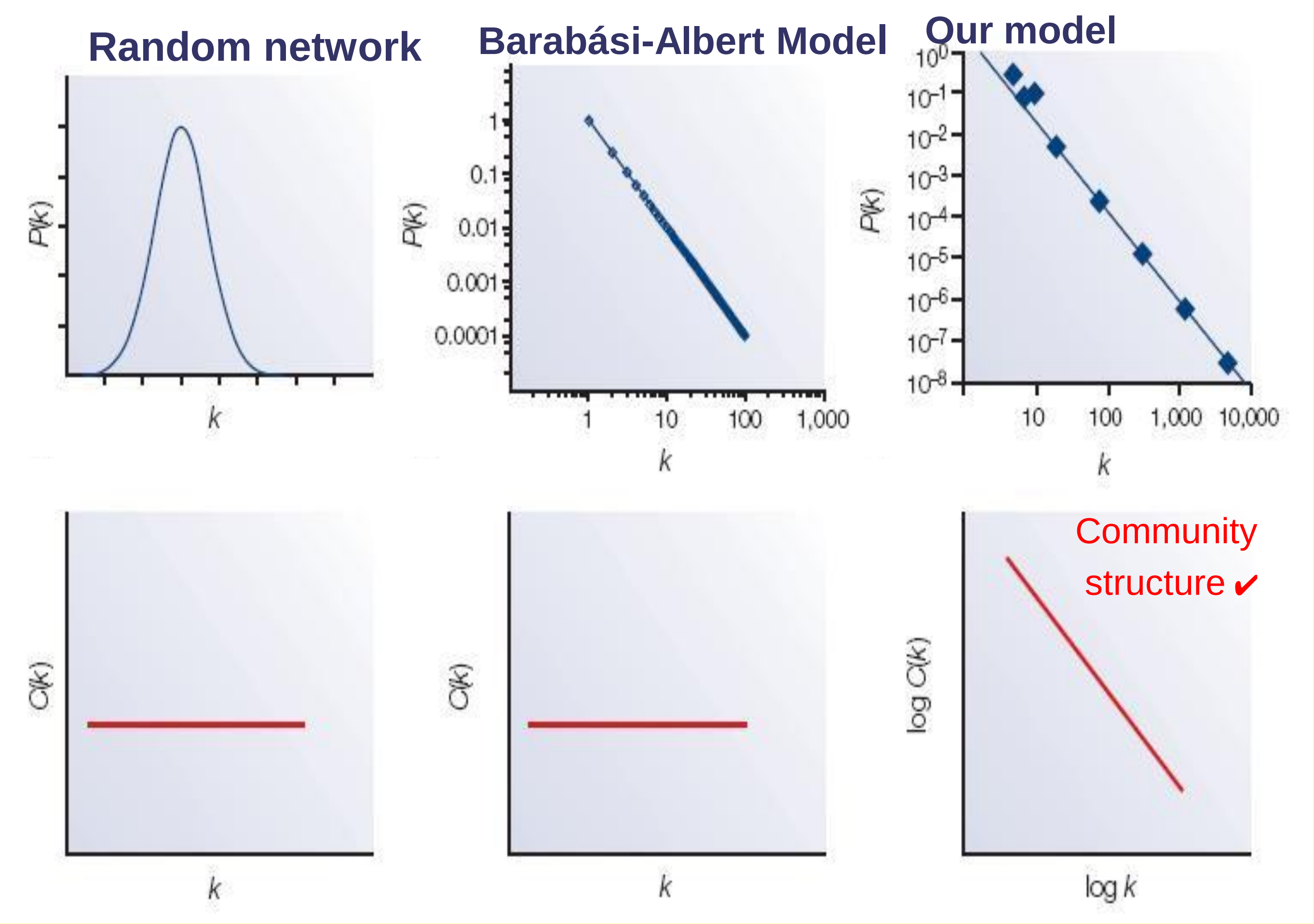
Key differences between biochemical networks and Internet

1. Nodes have different structural identity but the same dynamical behavior.
2. Nodes bind together on the basis of their "mutual affinity".
3. There exist "Natural hubs": nodes which "intrinsically" have more ways to connect than others. Hubs are a priori not a posteriori (natural vs contingent hubs) and are less likely to show up.
4. Networks are "Type-based" and not "Instance-based". Importance of the concentration and the dynamics of it.
5. BA's preferential attachment makes little sense as a biological network growing mechanism
6. Instead, concentration of nodes play a key role in the "preferential attachment" mechanism in introducing randomness.
7. Dynamics <-> MetaDynamics

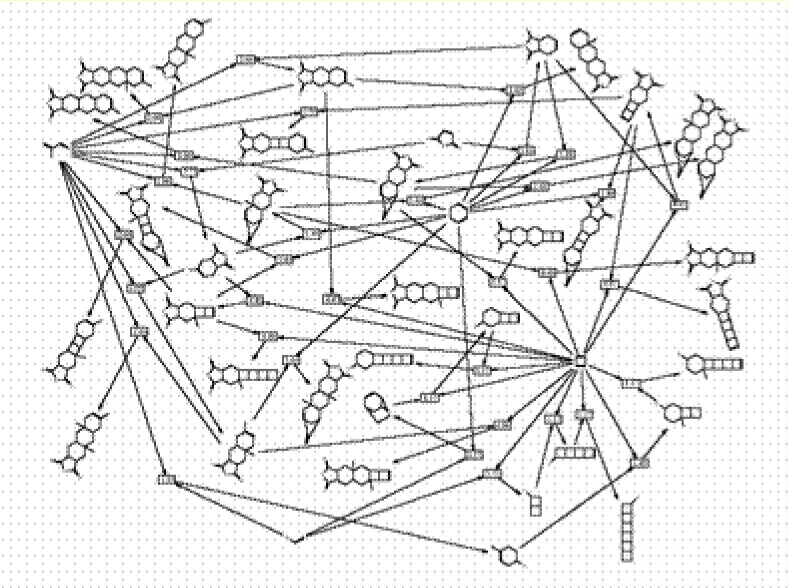
Basic ingredients of our computer models very close to our works on immuno

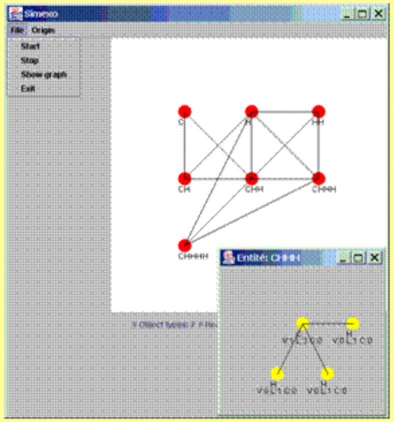
1. In the beginning a small number of nodes with concentration = 1
2. At each time step, a new random node is proposed and enter the network if it connects with an existing node. The affinity test is done with existing node chosen on the basis of their concentration.
3. The test is based on the affinity criterion: DH(ni,nj) > T
4. If the test succeeds → new node with concentration = 1
5. If the incoming node already exists → concentration += 1
    1. → This is the dynamical part of the model, concentration of nodes change with time
6. If the node it connects with did not already connect with it, it adds it as a new partner.

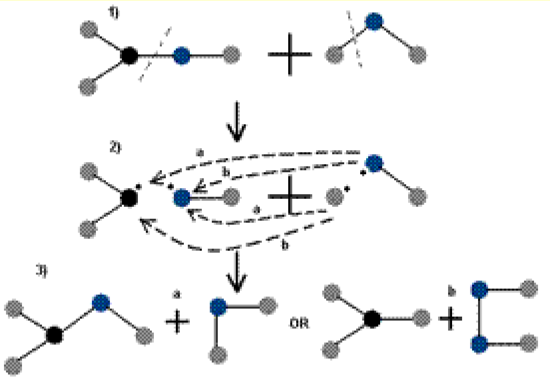
Results of the basic simulation



Exemple 1: Network of chemical reactions

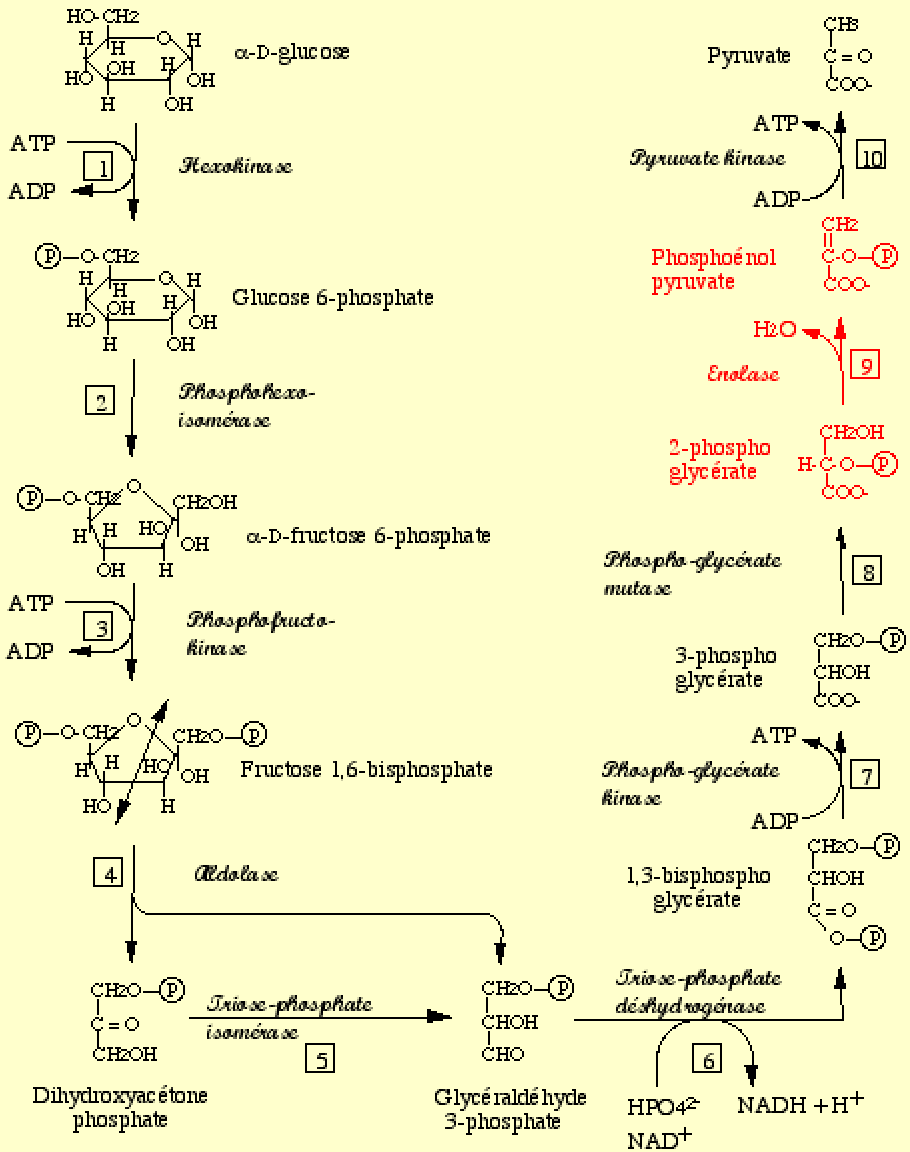


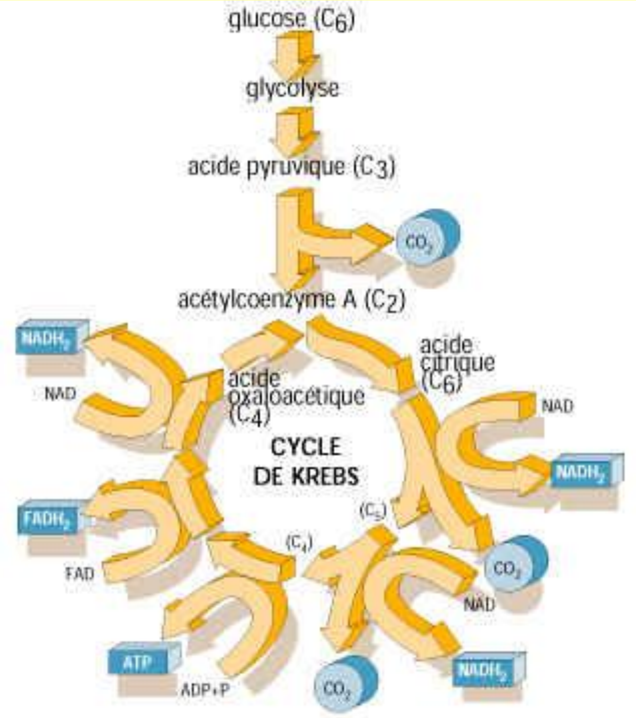




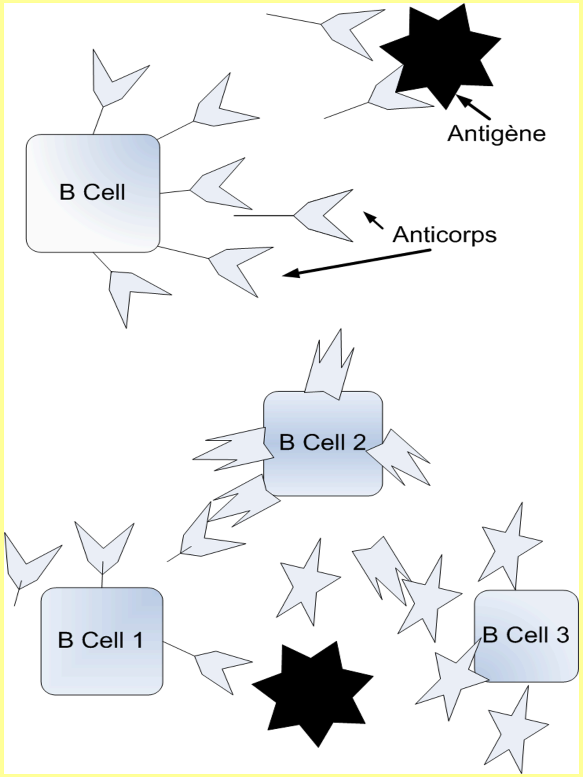
- Dynamics = kinetics
- Metadynamics = appearance and disappearance of molecules

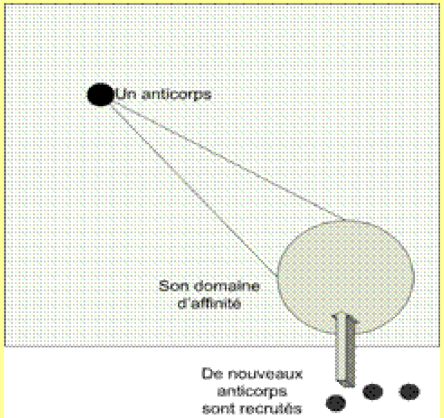
DEGRADATION DU GLUCOSE OU GLYCOLYSE
(voie d' Embden - Meyerhof)

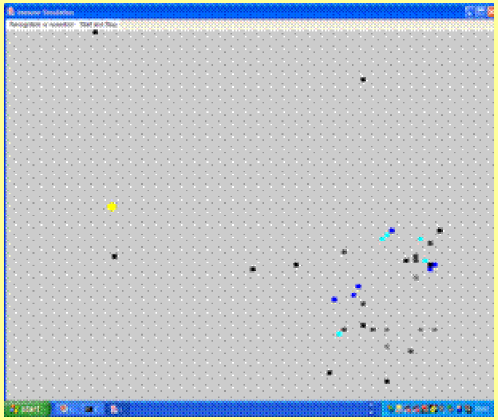


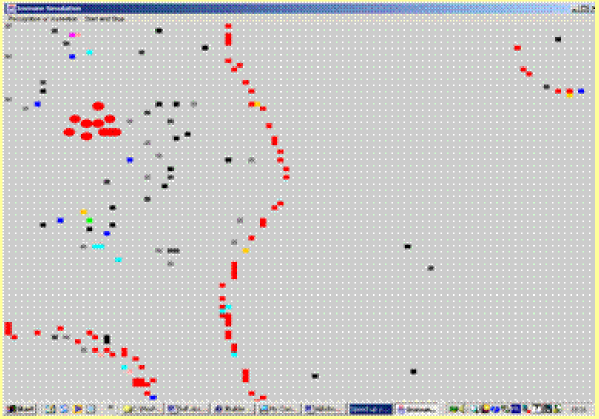


Exemple 2: Immune Networks

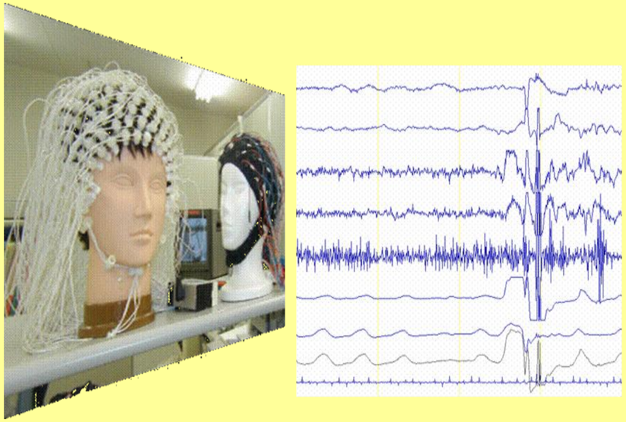


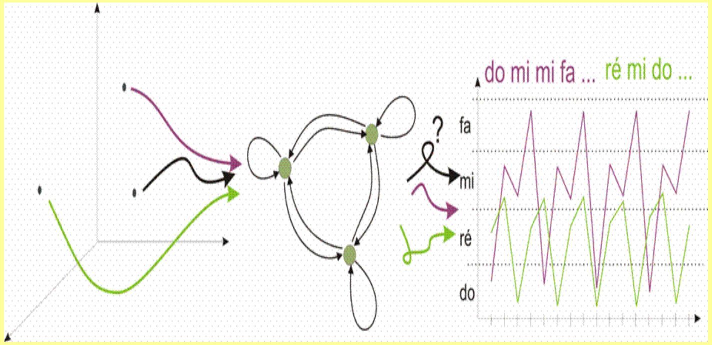


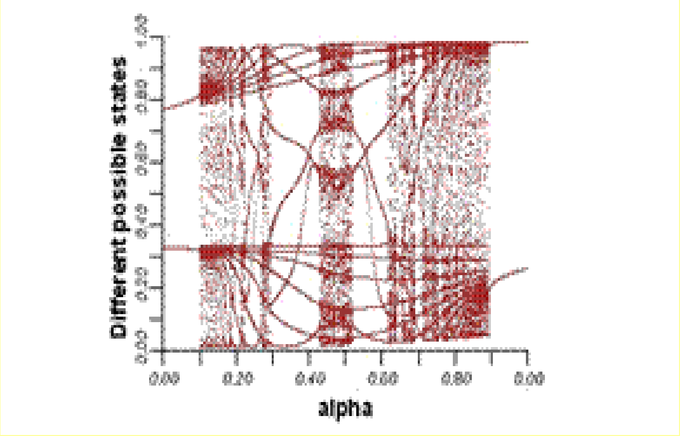


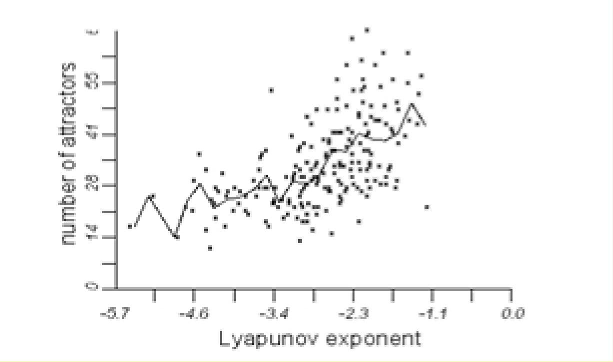


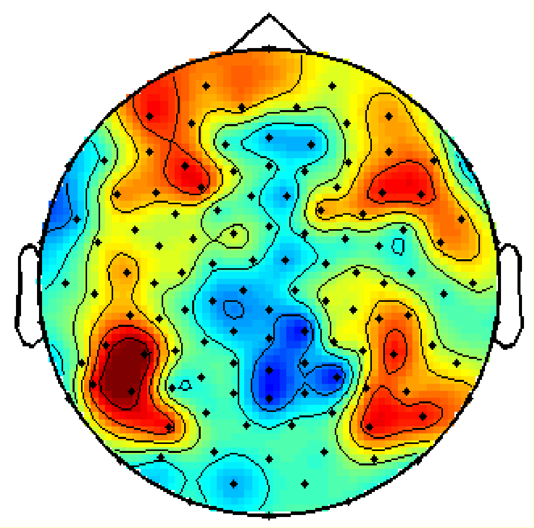
Exemple 3: Neural Networks

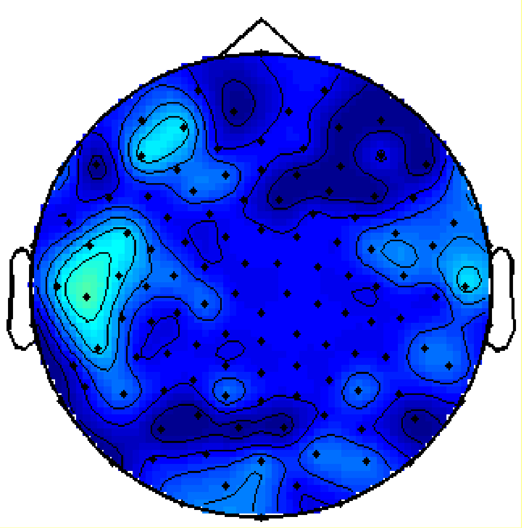












Chaos

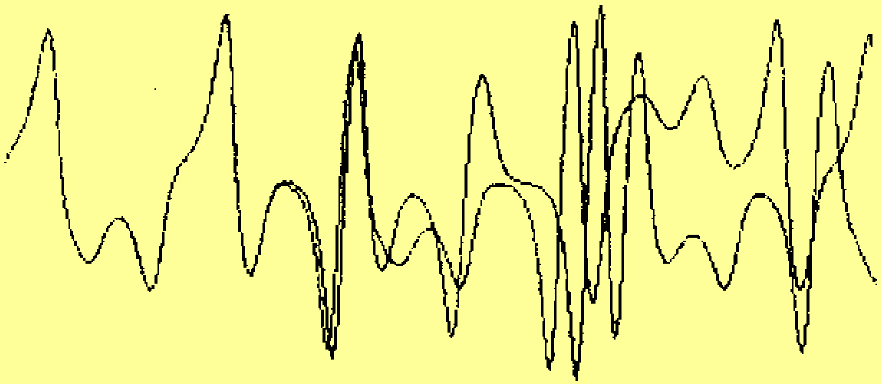
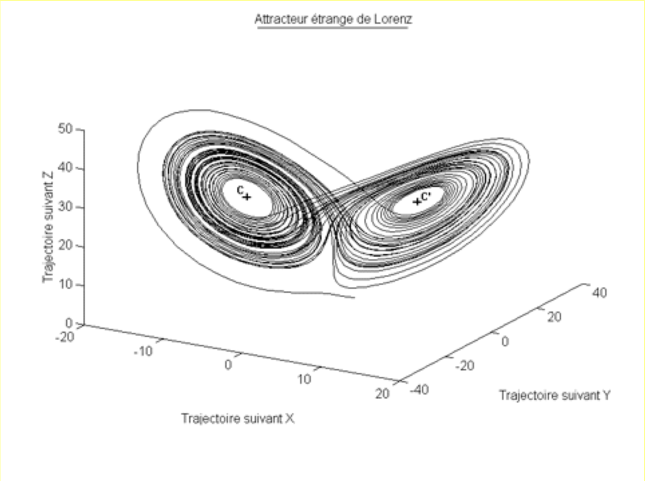
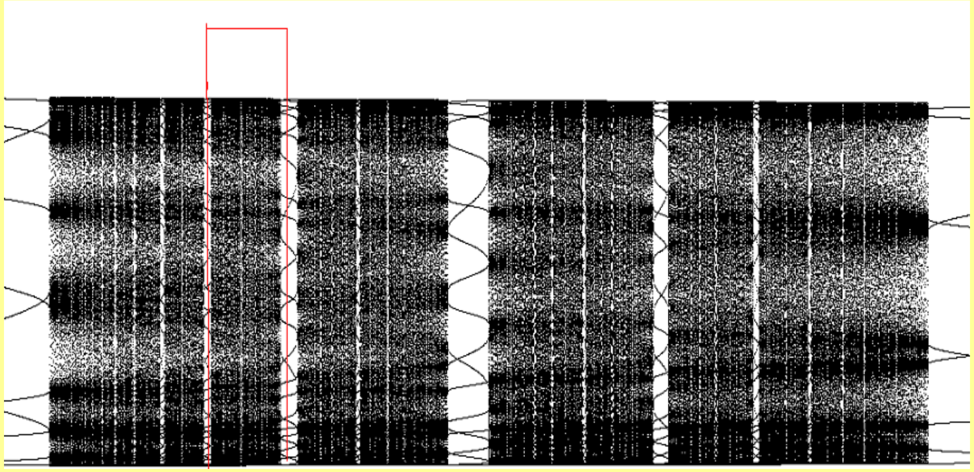
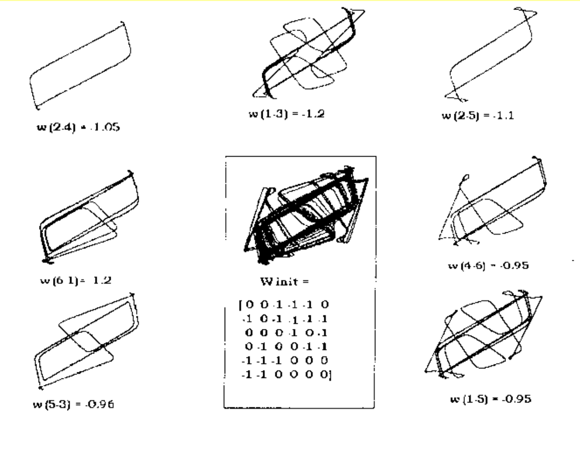


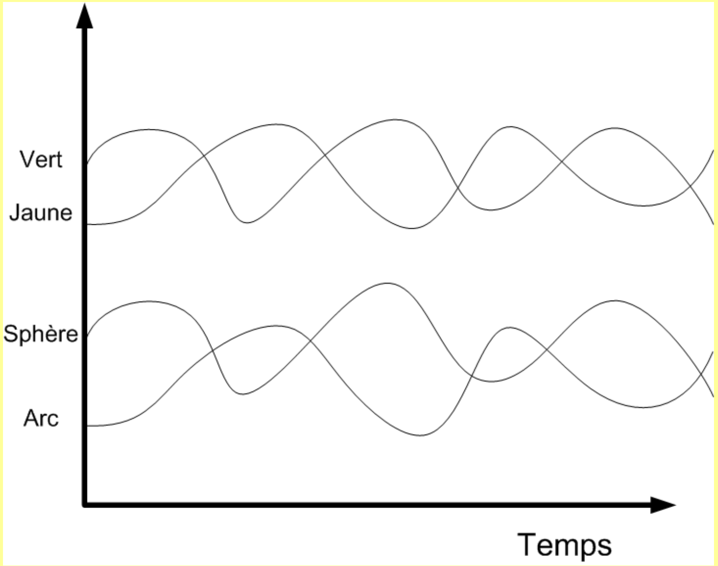
Figure 1: Lorenz's experiment: the difference between the start of these curves is only .000127. (Ian Stewart, Does God Play Dice? The Mathematics of Chaos, pg. 141)

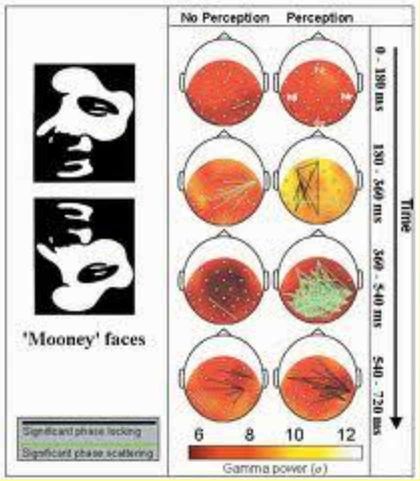






Synchronicité + Varela





Francisco Varela: 1946-2001

Conclusions:
Networks main applications in natural sciences and engineering

Natural sciences

- New lenses for understanding and mastering complex systems (for instance: dynamical diseases)
- Hubs → Viral epidemiology and viral marketing
- Hubs → Robustness: PC networks and Peer-to-Peer networks, medical care, cancer treatment -> gene or protein targetting
- Small-World → new routing strategies
- Small-World → new search engine strategies

Engineering

- Out of control: Bottom-up + learning
- Neural networks
- Swarm intelligence
- Sensor and control networks → immunology
- Distributed traffic control: think global, act local
- Ubiquitous or distributed computing → better optimization algorithms (ant, immune, GA)