A Tour of complex systems 2015

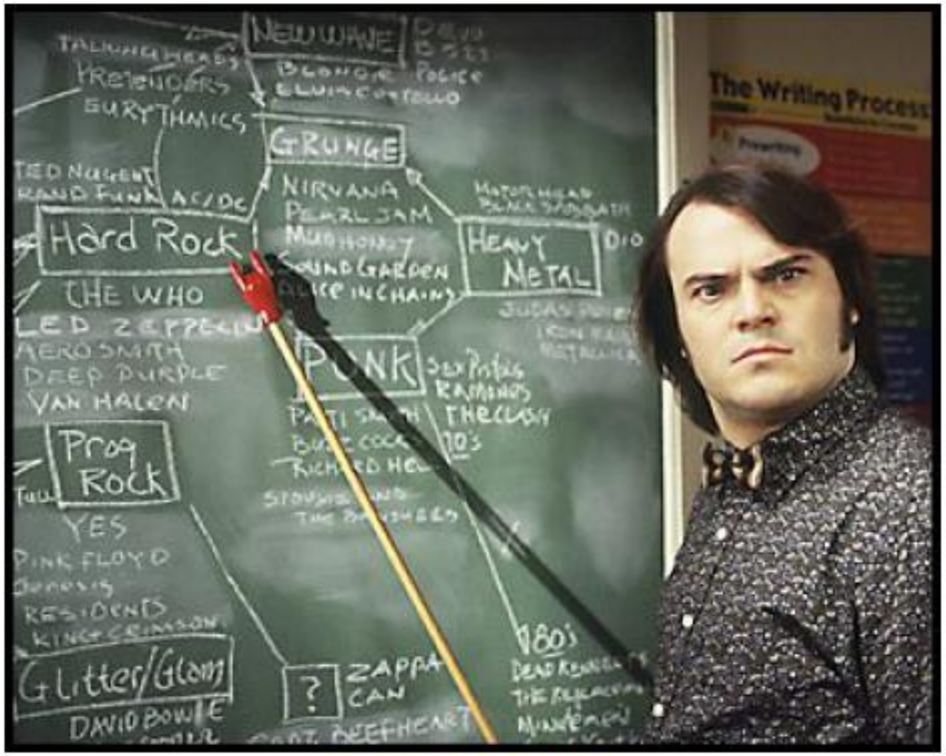
Nathalie Perrot

Dr INRA

Inspired by René Doursat ISCPIF

1. Introduction — a. What are complex systems?

- ➢ **Any ideas?**



The School of Rock (2003)
Jack Black, Paramount Pictures

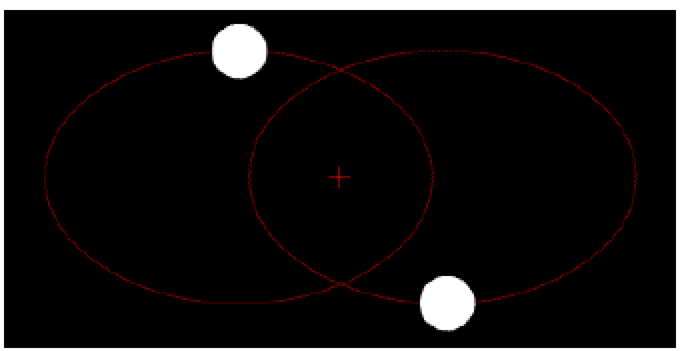
1. Introduction — a. What are complex systems?

➢ Few agents, "simple" emergent behavior

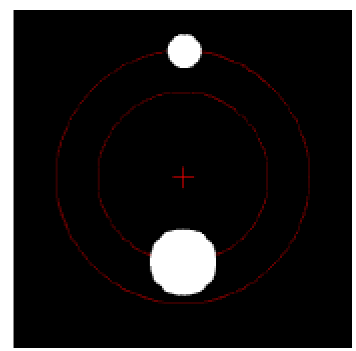
→ *ex: two-body problem*

✓ fully solvable and ***regular*** trajectories for inverse-square force laws (e.g., gravitational or electrostatic)

$$\begin{cases} \mathbf{F}_{12}(\mathbf{x}_1, \mathbf{x}_2) = m_1 \ddot{\mathbf{x}}_1 & (Equation\ 1) \\ \mathbf{F}_{21}(\mathbf{x}_1, \mathbf{x}_2) = m_2 \ddot{\mathbf{x}}_2 & (Equation\ 2) \end{cases}$$



Two bodies with similar mass
Wikimedia Commons

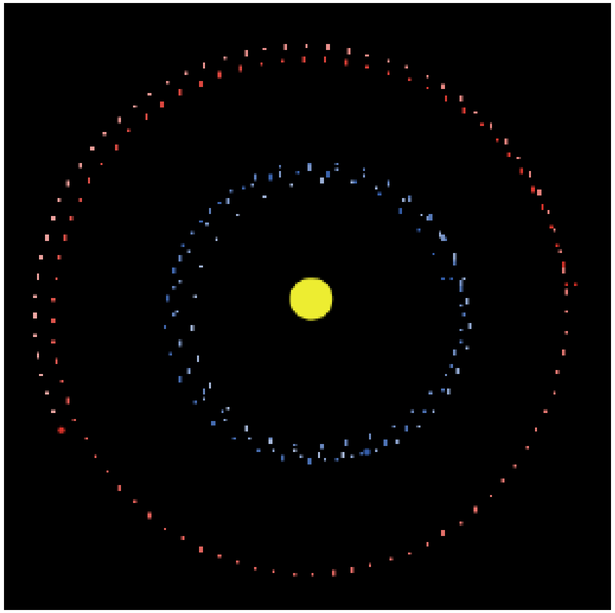


Two bodies with different mass
Wikimedia Commons

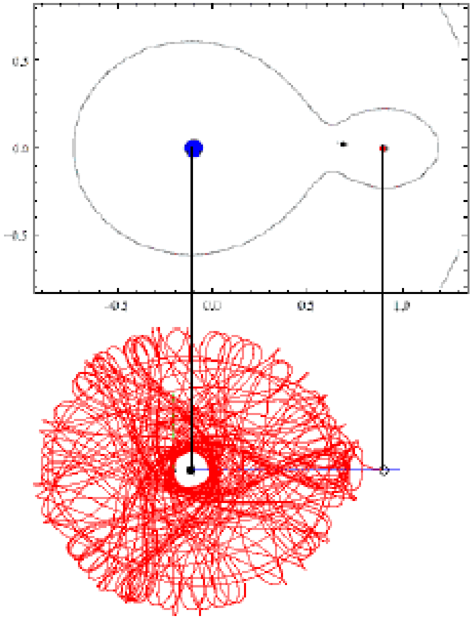
1. Introduction — a. What are complex systems?

- **Few agents, complex emergent behavior**
  - → *ex: three-body problem*
  - ✓ generally no exact mathematical solution (even in “restricted” case $m_1 \langle\langle\, m_2 \approx m_3$): must be solved numerically → ***chaotic*** trajectories

NetLogo model: /Chemistry & Physics/Mechanics/Unverified

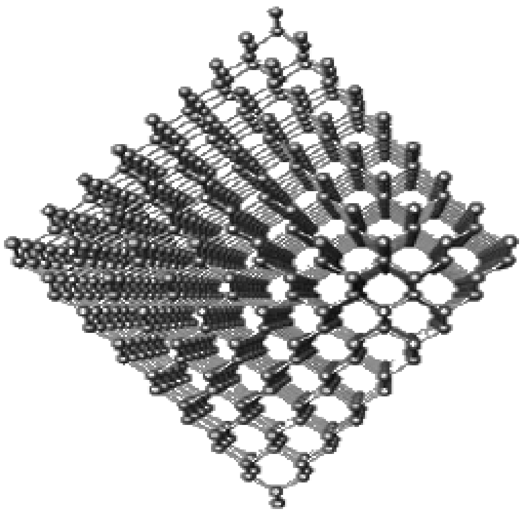


Transit orbit of the planar circular restricted problem
Scholarpedia: Three Body Problem & Joachim Köppen Kiel's applet



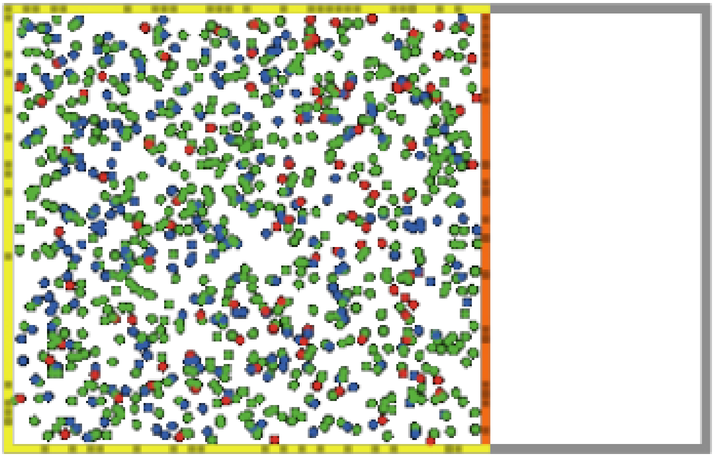
1. Introduction — a. What are complex systems?

- **Many agents, simple rules, "simple" emergent behavior**
  - → *ex: crystal and gas (covalent bonds or electrostatic forces)*
  - ✓ either highly ordered, ***regular*** states (crystal)
  - ✓ or disordered, random, statistically ***homogeneous*** states (gas): a few global variables (P, V, T) suffice to describe the system

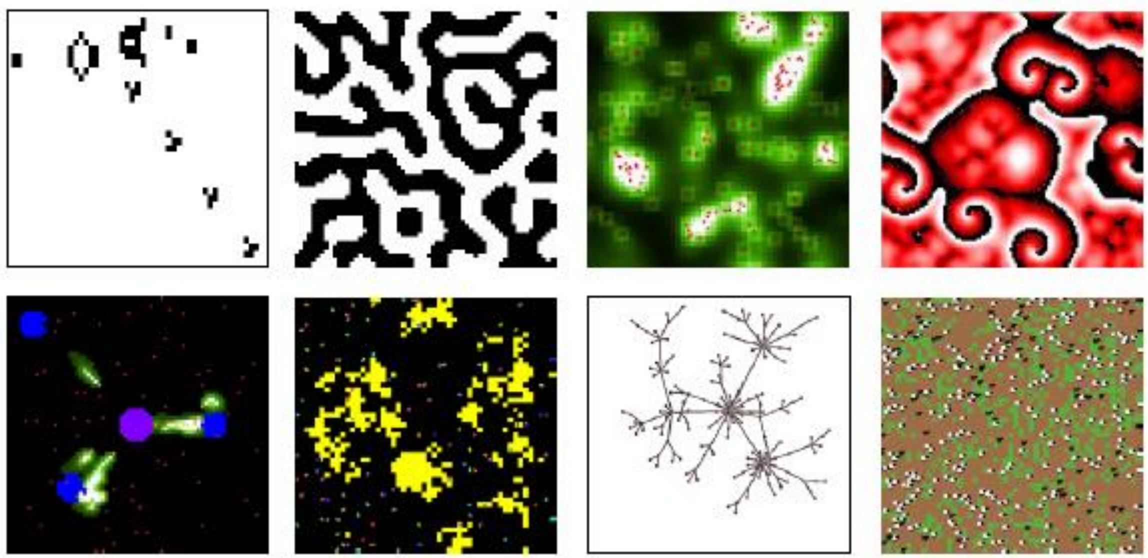


Diamond crystal structure
Tonci Balic-Zunic, University of Copenhagen

NetLogo model: /Chemistry & Physics/GasLab Isothermal Piston

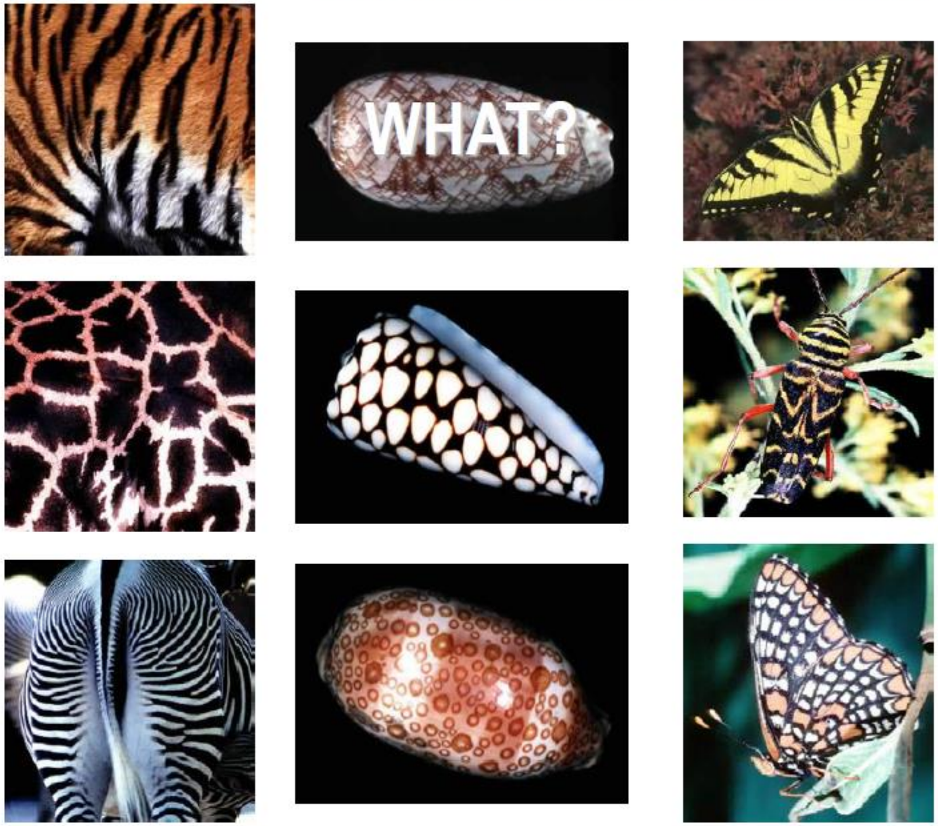


- **Many agents, simple rules, complex emergent behavior**
  - → *ex: cellular automata, pattern formation, swarm intelligence (insect colonies, neural networks), complex networks, spatial communities*
  - ✓ the "clichés" of complex systems: a major part of this course and NetLogo models

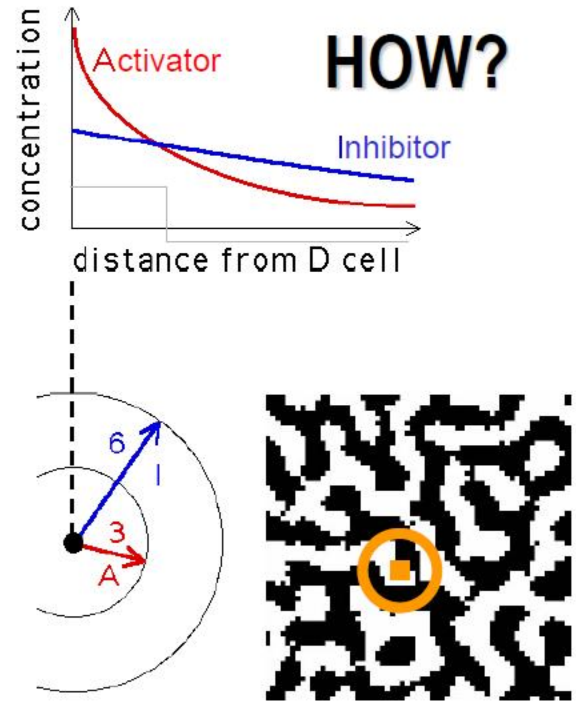


1. Introduction — a. What are complex systems?

Biological pattern formation: Animal colors



Mammal fur, seashells, and insect wings
(Scott Camazine, http://www.scottcamazine.com)

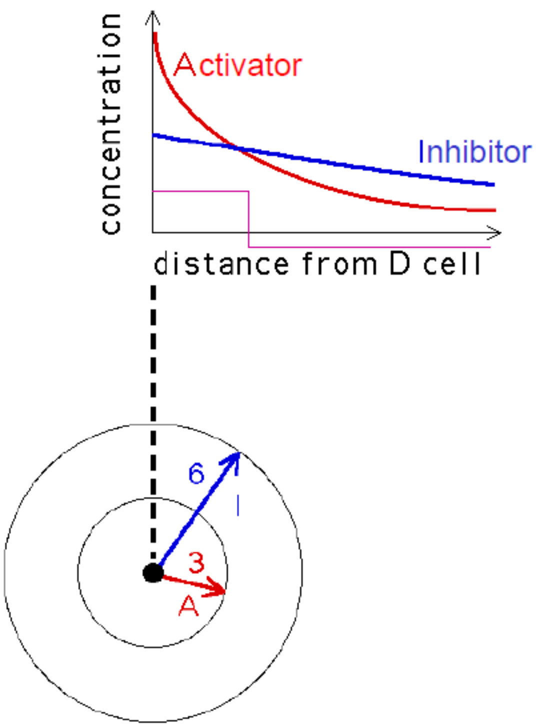


NetLogo fur coat simulation, after
David Young's model of fur spots and stripes
(Michael Frame & Benoit Mandelbrot, Yale University)

- animal patterns (for warning, mimicry, attraction) can be caused by pigment cells trying to copy their nearest neighbors but differentiating from farther cells

2. A Complex Systems Sampler

b. Pattern formation – *Biological: animal colors*



David Young's model of fur spots and stripes
(Michael Frame & Benoit Mandelbrot, Yale University)

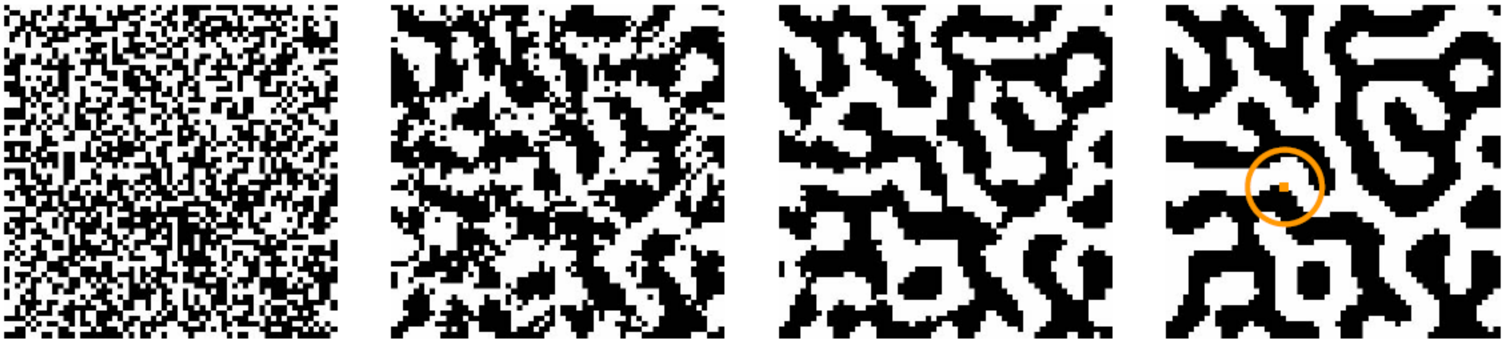
Possible mechanism (schematic)

- development of spots and stripes on mammal fur
- melanocytes (pigment cells) can be undifferentiated "U", or differentiated "D"
- only D cells produce color → they diffuse two morphogens, activator "A" and inhibitor "I"
- neighboring cells differentiate or not according to:
  - short-range activation
  - long-range inhibition
- a classical case of *reaction-diffusion*

2. A Complex Systems Sampler

b. Pattern formation – *Biological: animal colors*

NetLogo model: /Biology/Fur



NetLogo fur coat simulation, after David Young's model
(Uri Wilensky, Northwestern University, IL)

Modeling & simulation

- example of *cellular automaton*
- each cell has 2 states:
  - "pigmented" (black)
  - "undifferentiated" (white)

- each cell's state is updated by:
  - counting pigmented neighbors within radius 3 (they contribute to activation)
  - counting pigmented neighbors between radius 3 and 6 (they contribute to inhibition)
  - calculating weighted vote

Cf. netlogo

2. A Complex Systems Sampler

b. Pattern formation – *Biological: animal colors*

Concepts collected from this example

- simple microscopic rules
- emergence of macroscopic structures (spots >> cells)
- self-arranged patterns (random, unique)
- amplification of small fluctuations (positive feedback, symmetry breaking)
- local cooperation, distant competition (cell $\leftrightarrow$ cell)

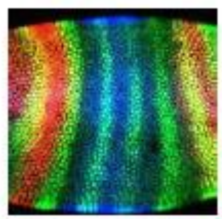
1. Introduction — a. What are complex systems?

➢ Complex systems in this course

- **large** number of elementary **agents** interacting **locally**
- (more or less) simple individual agent behaviors creating a complex **emergent**, **self-organized** behavior
- ***decentralized*** *dynamics: no master blueprint or grand architect*

✓ **physical**, **biological**, **technical**, **social** systems (natural or artificial)

pattern formation
○ = matter

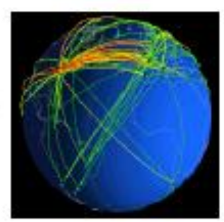


biological development
○ = cell

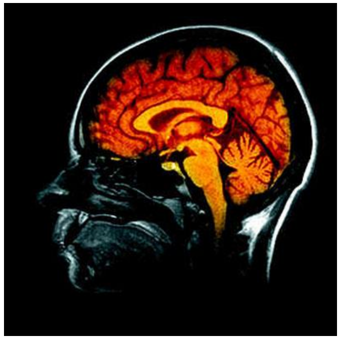
the brain & cognition
○ = neuron

insect colonies
○ = ant

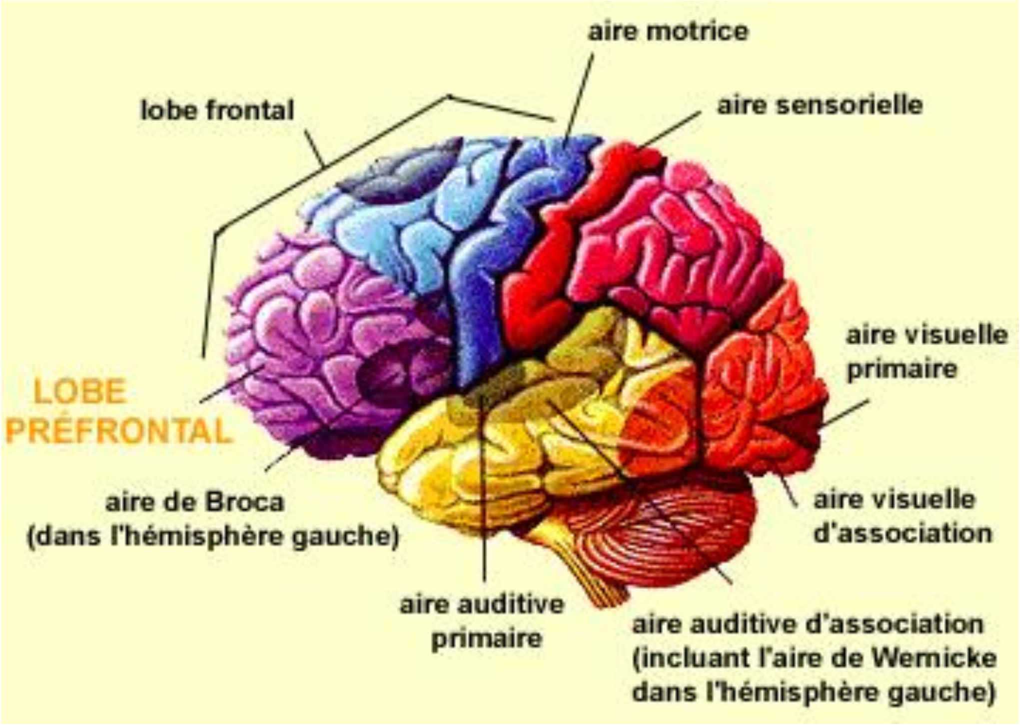
Internet & Web
○ = host/page

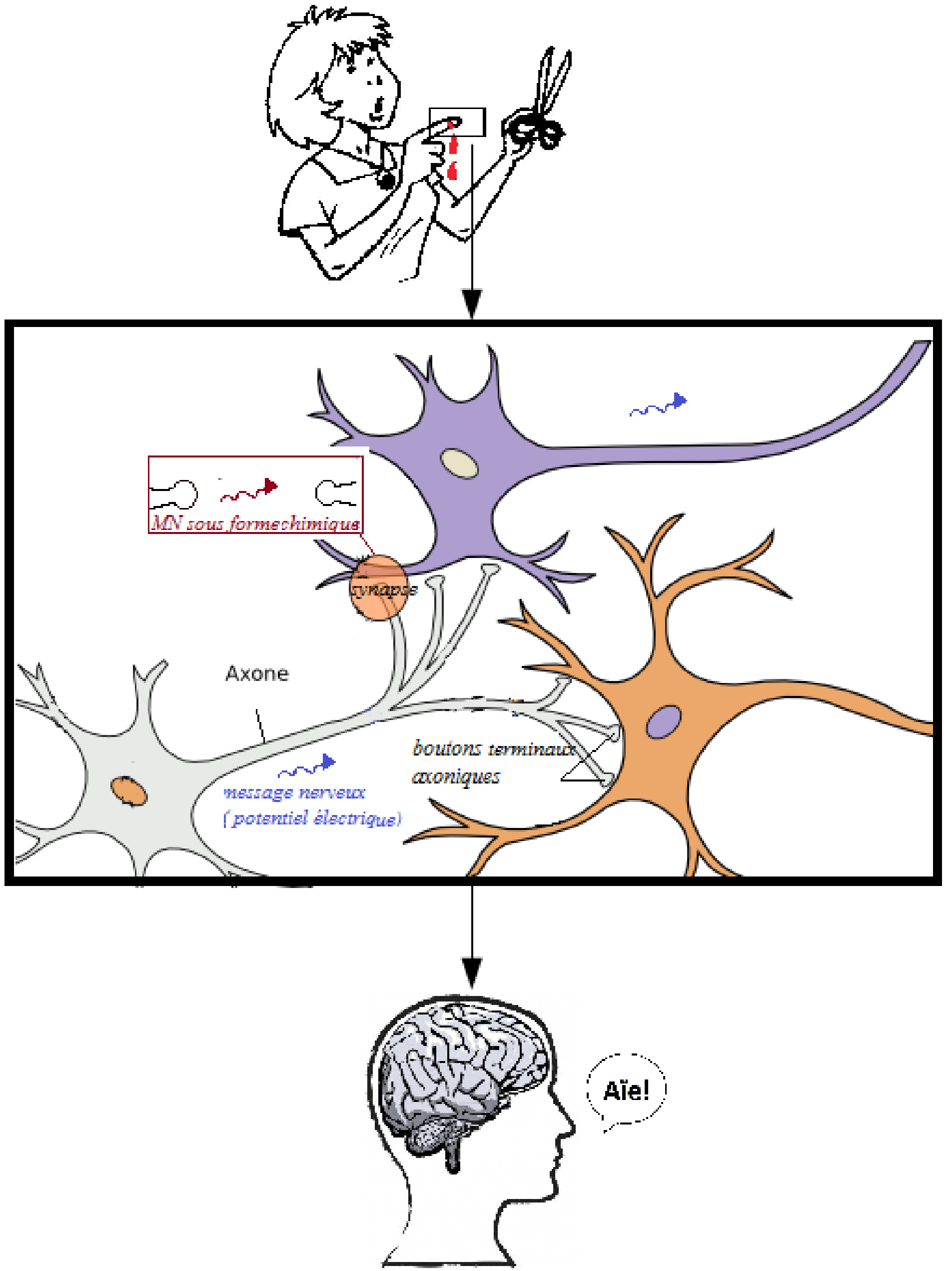


social networks
○ = person

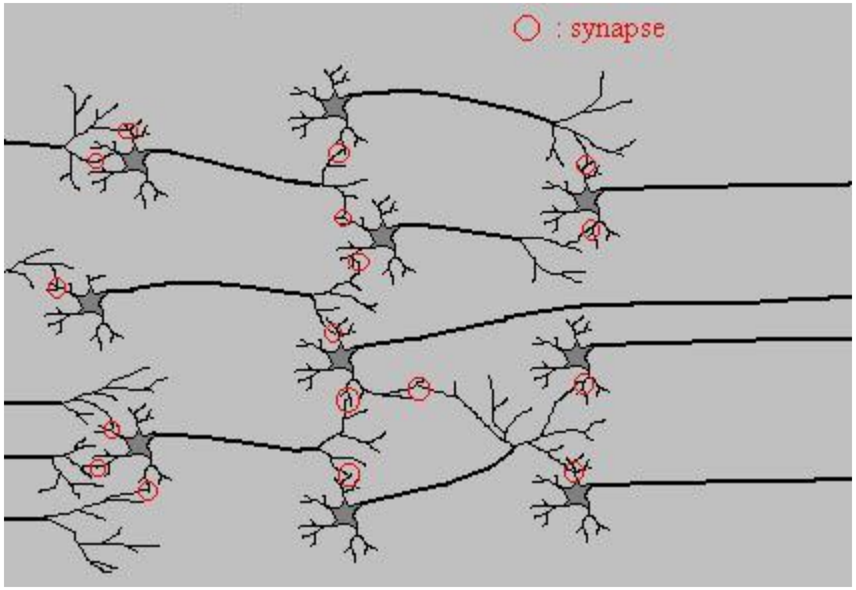


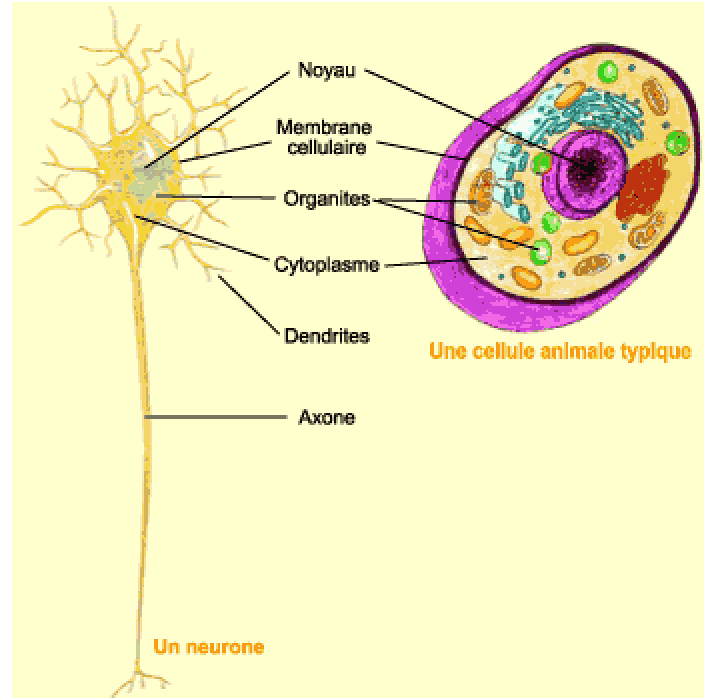

Humain
Éléphant
Dauphin
Gorille
Chien
Chat
Macaque
Souris
5cm

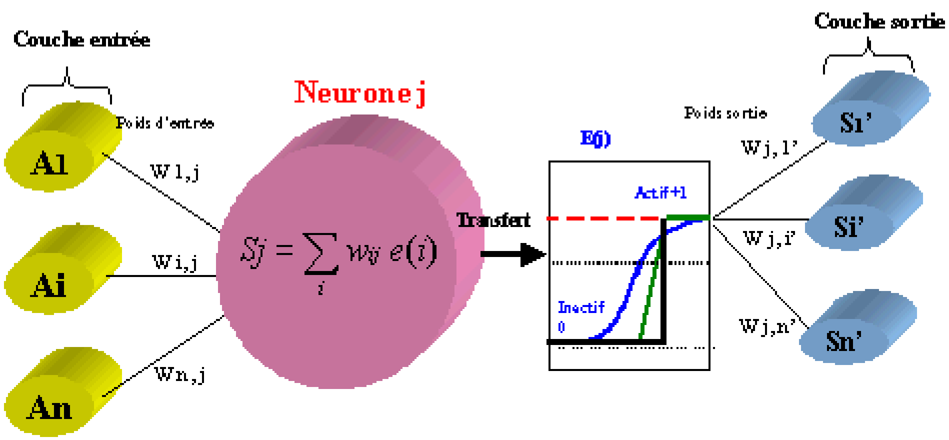

aire motrice
lobe frontal
aire sensorielle
aire visuelle
primaire
LOBE
PRÉFRONTAL
aire de Broca
(dans l'hémisphère gauche)
aire visuelle
d'association
aire auditive
primaire
aire auditive d'association
(incluant l'aire de Wernicke
dans l'hémisphère gauche)

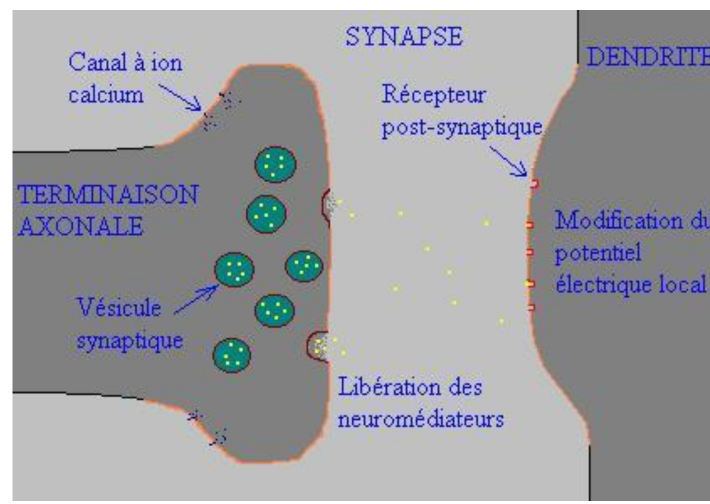


MN sous formechimique
synapse
Axone
boutons terminaux
axoniques
message nerveux
(potentiel électrique)
Aïe!







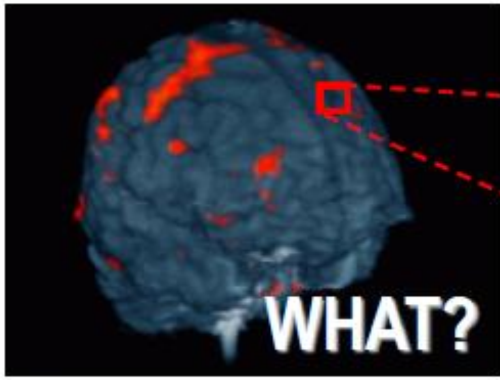


Mechanism

- each neuron receives signals from many other neurons through its *dendrites*
- the signals converge to the *soma* (cell body) and are integrated
- if the integration exceeds a threshold, the neuron fires a signal on its *axon*

1. Introduction — a. What are complex systems?

Spatiotemporal synchronization: Neural networks

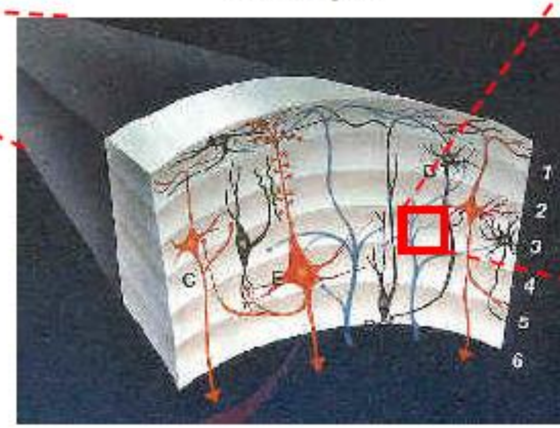


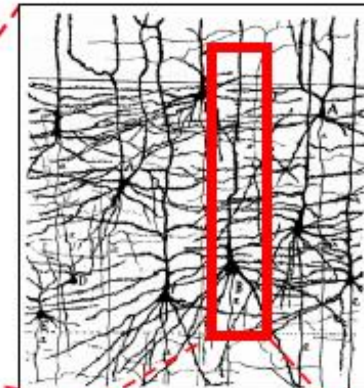
Animation of a functional MRI study
(J. Ellermann, J. Strupp, K. Ugurbil, U Minnesota)

- the brain constantly generates patterns of activity ("the mind")
- they emerge from 100 billion neurons that exchange electrical signals via a dense network of contacts

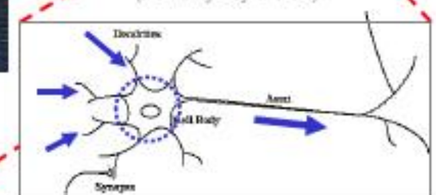
HOW?

Cortical layers

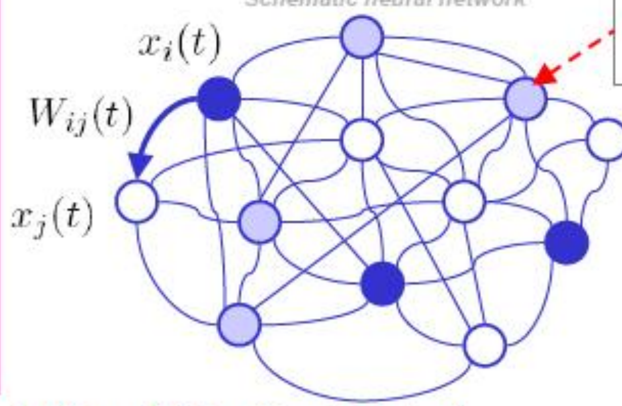


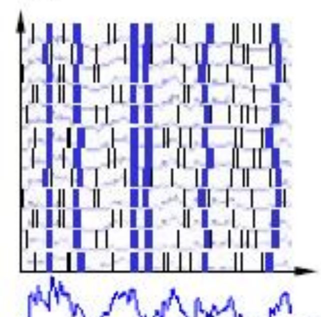


Pyramidal neurons & interneurons
(Ramón y Cajal 1900)

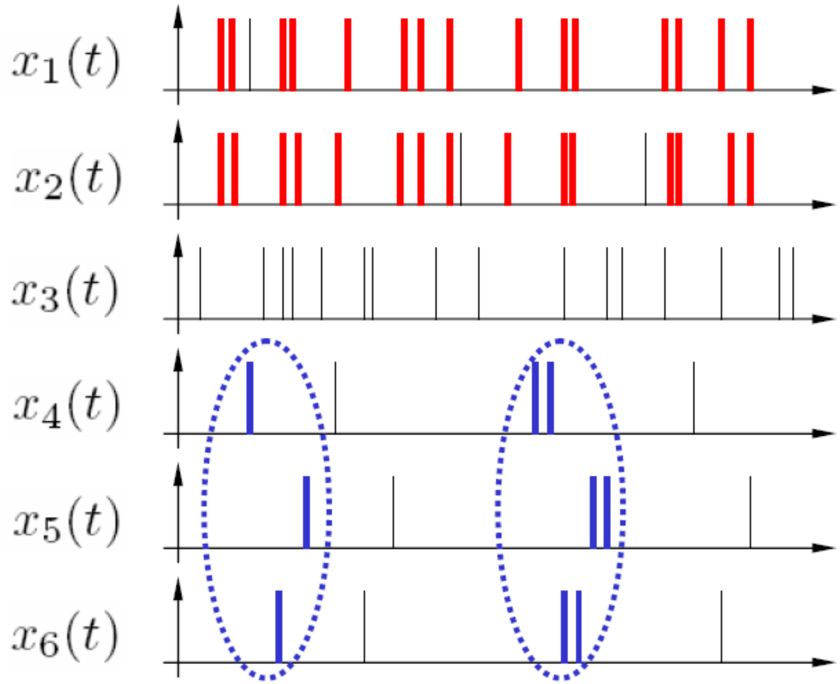


Schematic neural network





c. Swarm intelligence – *Synchronization: neurons*



$\langle\, x_1(t)\,\rangle = \bullet$ high activity rate

$\langle\, x_2(t)\,\rangle = \bullet$ high activity rate

$\langle\, x_3(t)\,\rangle = \bullet$ high activity rate

$\langle\, x_4(t)\,\rangle = \circ$ low activity rate

$\langle\, x_5(t)\,\rangle = \circ$ low activity rate

$\langle\, x_6(t)\,\rangle = \circ$ low activity rate

$\boxed{\langle\, x_1(t)\, x_2(t)\,\rangle \gg \langle\, x_1(t)\, x_3(t)\,\rangle}$

- 1 and 2 more in sync than 1 and 3

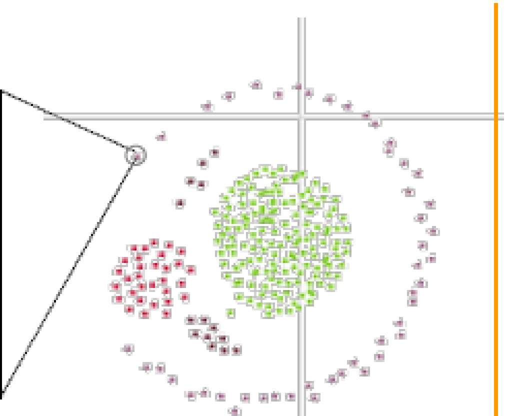
$\boxed{\langle\, x_4(t)\, x_5(t-\tau_{4,5})\, x_6(t-\tau_{4,6})\,\rangle}$

- 4, 5 and 6 correlated through delays

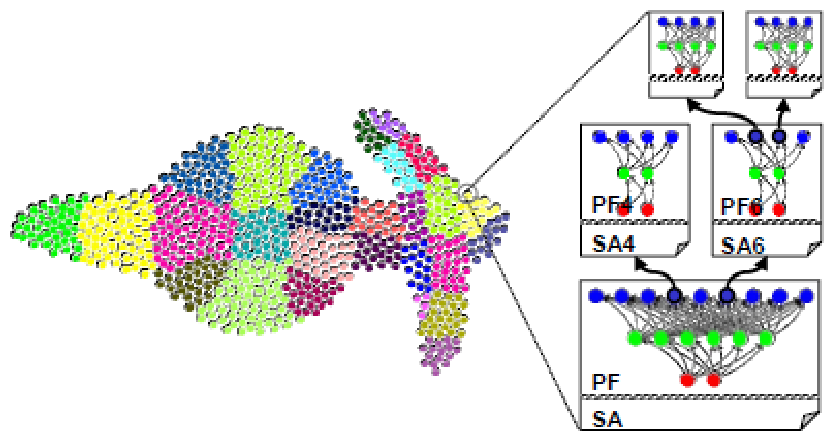
1. Introduction — a. What are complex systems?

- **Many agents, complicated rules, complex emergent behavior**
  - → *ex: self-organized "artificial life": swarm chemistry, morphogenesis*
  - ✓ in *swarm chemistry* (Sayama 2007), mixed self-propelled particles with different flocking parameters create nontrivial formations
  - ✓ in *embryomorphic engineering* (Doursat 2006), cells contain the same genetic program, but differentiate and self-assemble into specific shapes

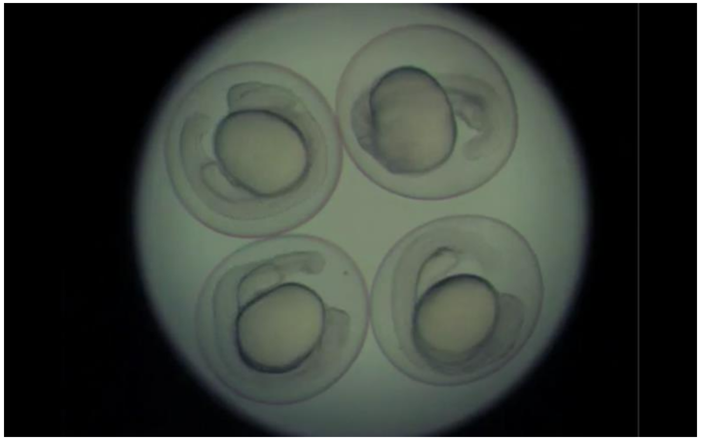
Name	Min	Max
R^i	0	300
V_n^i	0	20
V_m^i	0	40
c_1^i	0	1
c_2^i	0	1
c_3^i	0	100
c_4^i	0	0.5
c_5^i	0	1

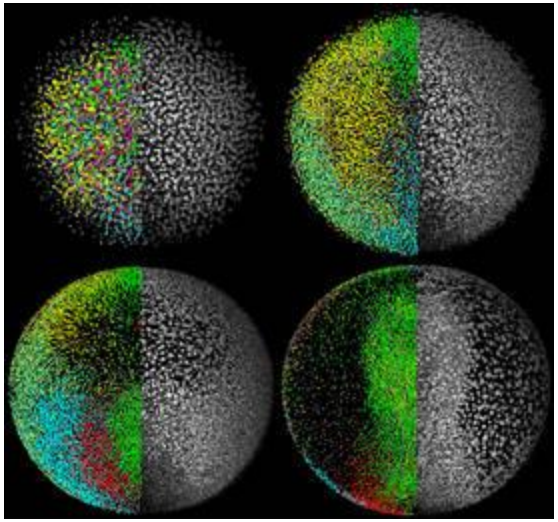


Swarm chemistry
Hiroki Sayama, Binghamton University SUNY



Embryomorphic engineering
René Doursat, Insitut des Systèmes Complexes, Paris





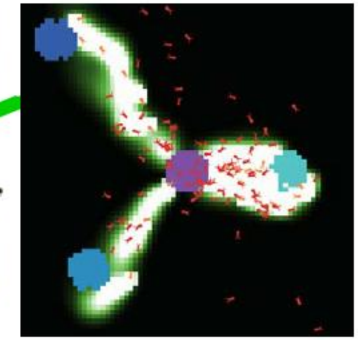
1. Introduction — a. What are complex systems?

Swarm intelligence: Insect colonies (ant trails, termite mounds)

http://taos-telecommunity.org/epow/epow-archive/archive_2003/EPOW-030811_files/matabele_ants.jpg

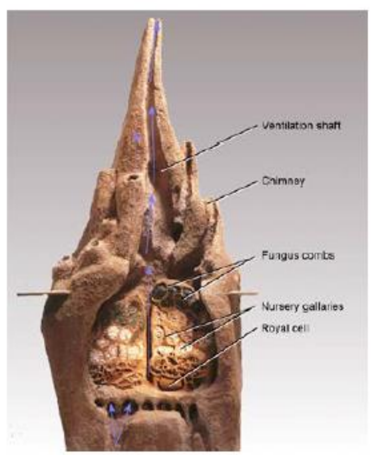
http://picasaweb.google.com/tridentoriginal/Ghana

Harvester ant
(Deborah Gordon, Stanford University)

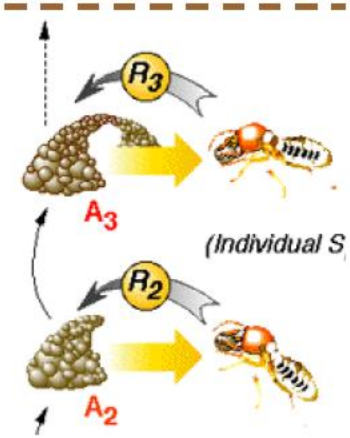


HOW?

Termite mound
(J. McLaughlin, Penn State University)



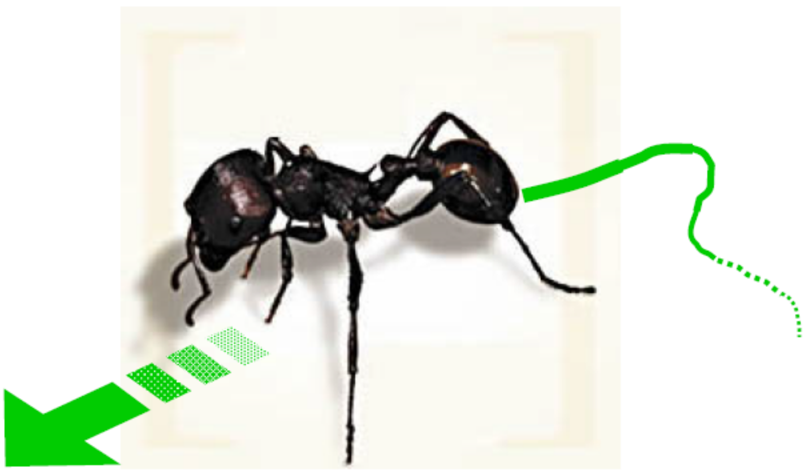
http://cas.bellarmine.edu/tietjen/TermiteMound%20CS.gif



Termite stigmergy
(after Paul Grassé; from Solé and Good "Signs of Life", Perseus Books)

- ants form trails by following and reinforcing each other's pheromone path
- termite colonies build complex mounds by "stigmergy"

c. Swarm intelligence – *Insect colonies: ant trails*



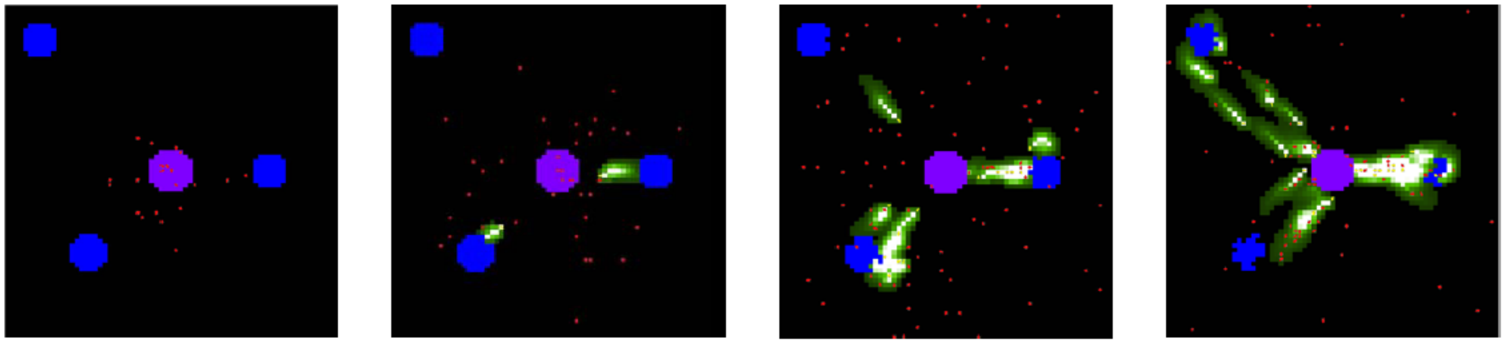
Harvester ant
(Deborah Gordon, Stanford University)

Basic mechanism

- while moving, each ant deposits a chemical (“pheromone”) to signal the path to other ants
- each ant also “smells” and follows the pheromone gradient laid down by others

c. Swarm intelligence – *Insect colonies: ant trails*

NetLogo model: /Biology/Ants



StarLogo ant foraging simulation, after Mitchel Resnick
(StarLogo Project, MIT Media Laboratory, MA)

Modeling & simulation

- setup:
  - 1 nest (purple)
  - 3 food sources (blue spots)
  - 100 to 200 ants (moving red dots)

- ant's behavioral repertoire:
  - walk around randomly
  - if bump into food, pick it and return to nest
  - if carrying food, deposit pheromone (green)
  - if not carrying food, follow pheromone gradient

- typical result: food sources are exploited in order of increasing distance and decreasing richness
- emergence of a collective “intelligent” decision

c. Swarm intelligence – *Collective motion: traffic jams*

Traffic jam
(Department of Physics, University of Illinois at Urbana-Champaign)

Phenomenon

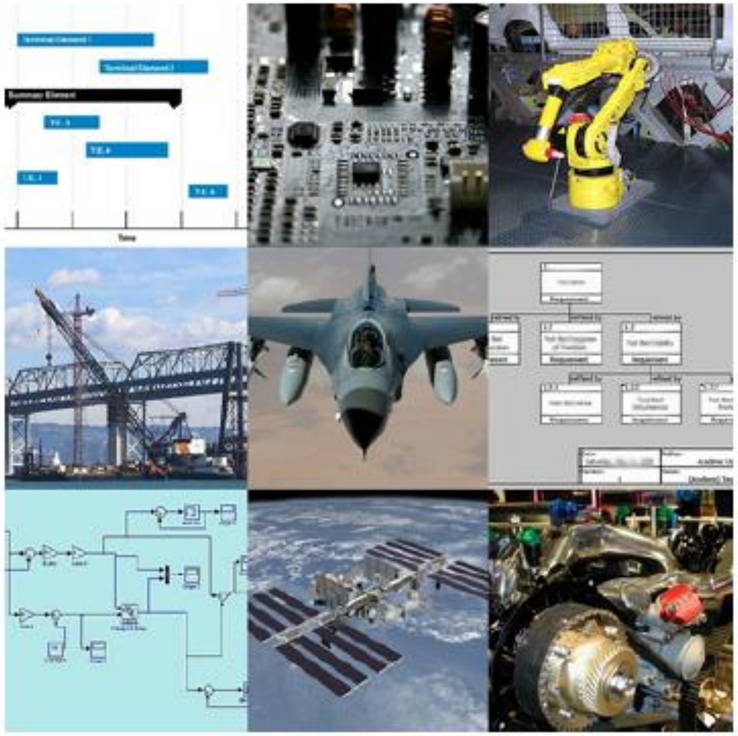
- stream of cars breaks down into dense clumps and empty stretches
- spontaneous symmetry-breaking of initially uniform density and speed
- no need for a central cause (such as slow vehicle, stop light or accident)

1. Introduction — a. What are complex systems?

➢ Many agents, complicated rules, “deterministic” behavior

→ *classical engineering: electronics, machinery, aviation, civil construction*

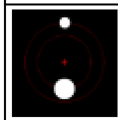
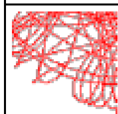
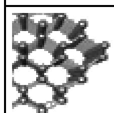
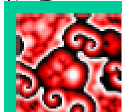
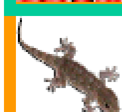
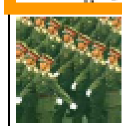
- ✓ artifacts composed of a immense number of parts
- ✓ yet still designed globally to behave in a limited and ***predictable*** (reliable, controllable) number of ways — "I don’t want my aircraft to be creatively emergent in mid-air"
- ✓ **not "complex" systems** in the sense of:
  - little decentralization
  - no emergence
  - no self-organization



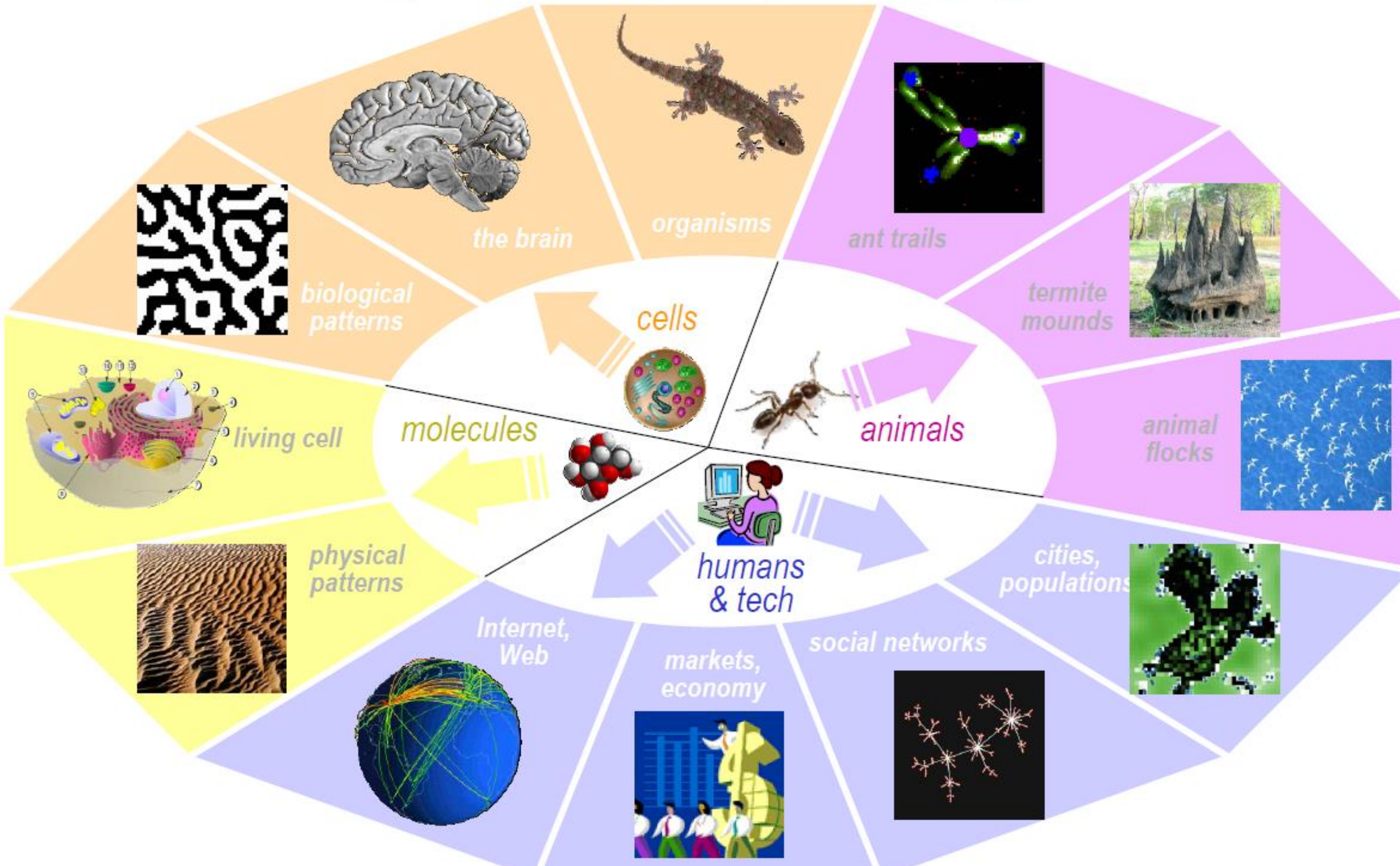
Systems engineering
Wikimedia Commons, http://en.wikipedia.org/wiki/Systems_engineering

1. Introduction — a. What are complex systems?

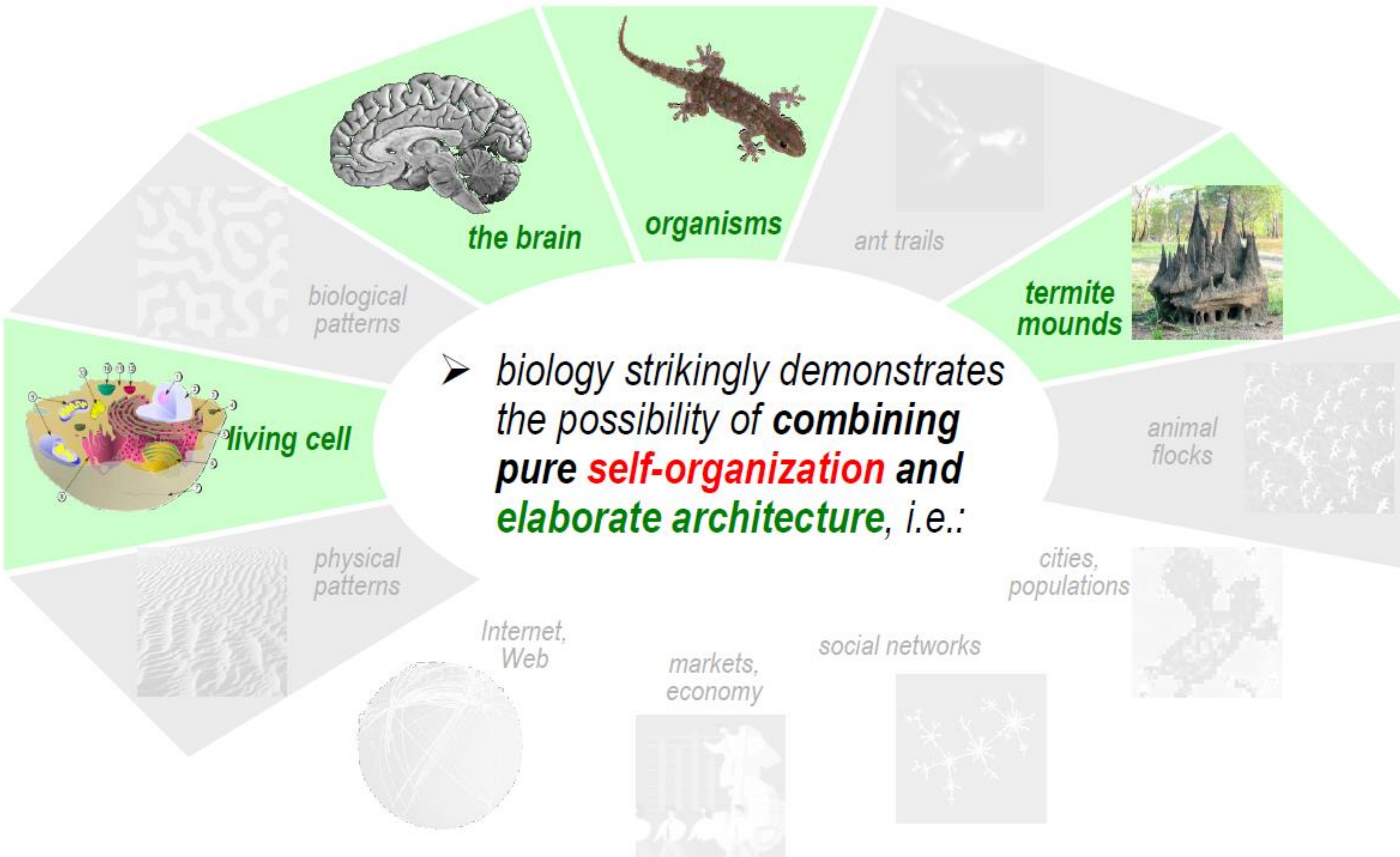
➢ Recap: complex systems in this course

Category	*Agents / Parts*	*Local Rules*	*Emergent Behavior*	*A "Complex System"?*
 2-body problem	*few*	*simple*	*"simple"*	*NO*
 3-body problem, low-D chaos	*few*	*simple*	*complex*	*NO – too small*
 crystal, gas	*many*	*simple*	*"simple"*	*NO – few params suffice to describe it*
 patterns, swarms, complex networks	*many*	*simple*	*"complex"*	*YES – but mostly random and uniform*
 structured morphogenesis	*many*	*complicated*	*complex*	*YES – reproducible and heterogeneous*
 machines, crowds with leaders	*many*	*complicated*	*deterministic/ centralized*	*COMPLICATED – not self-organized*

Categories of complex systems by agents



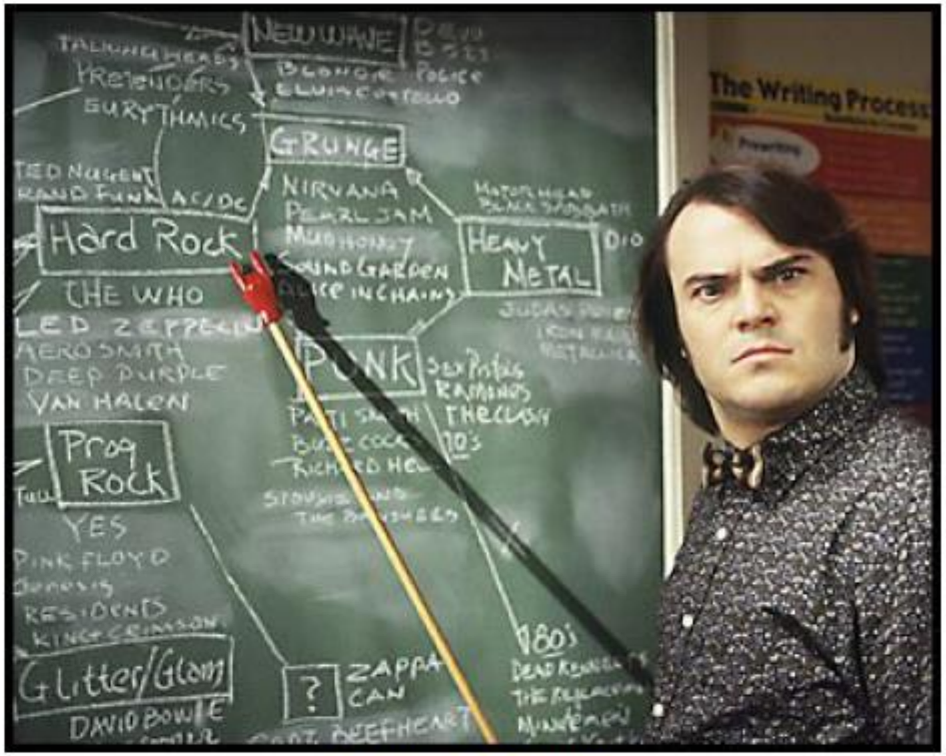
“Simple/random” vs. **architectured** natural complex systems



And food…

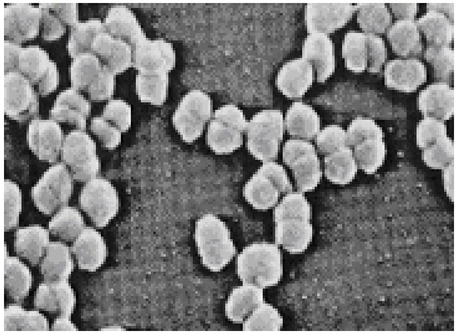
AND THEN … FOR FOOD SYSTEMS…??

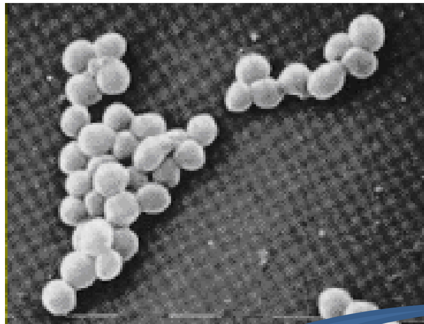
- **Any ideas?**



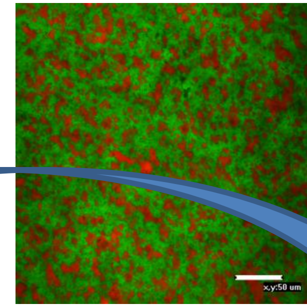
The School of Rock (2003)
Jack Black, Paramount Pictures

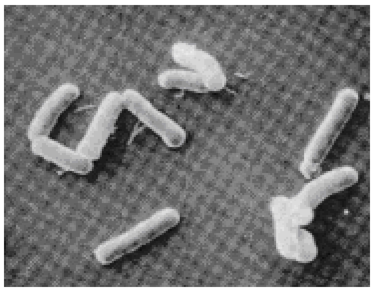
Fromage: un système complexe





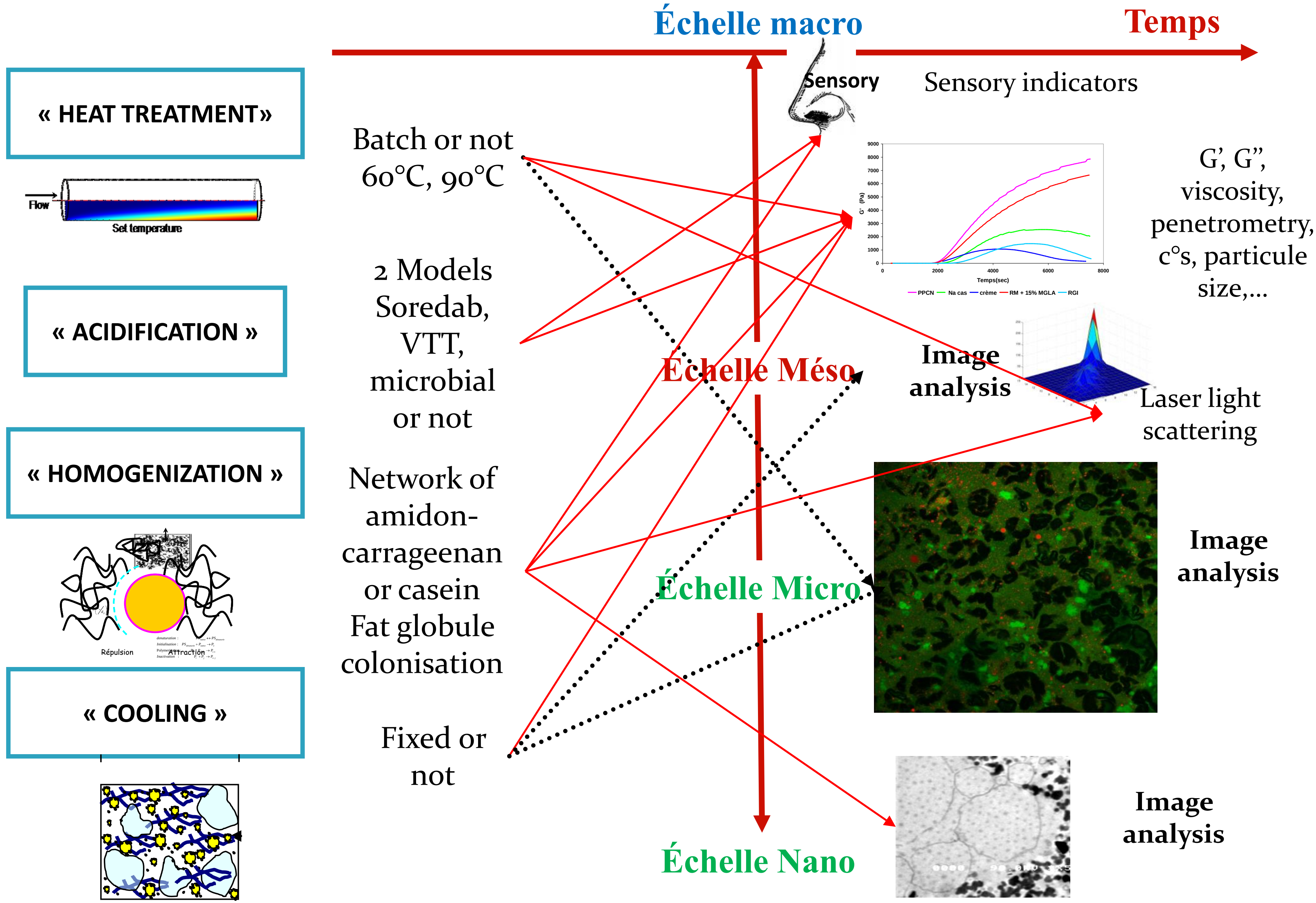
Multi-scale



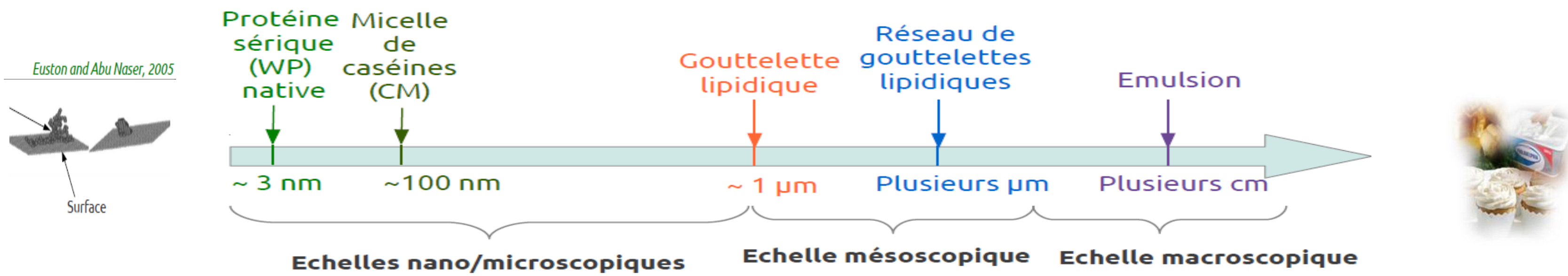


Processus off-balance in time

WP4 food models example: Four key global functions in a **multiscale approach**



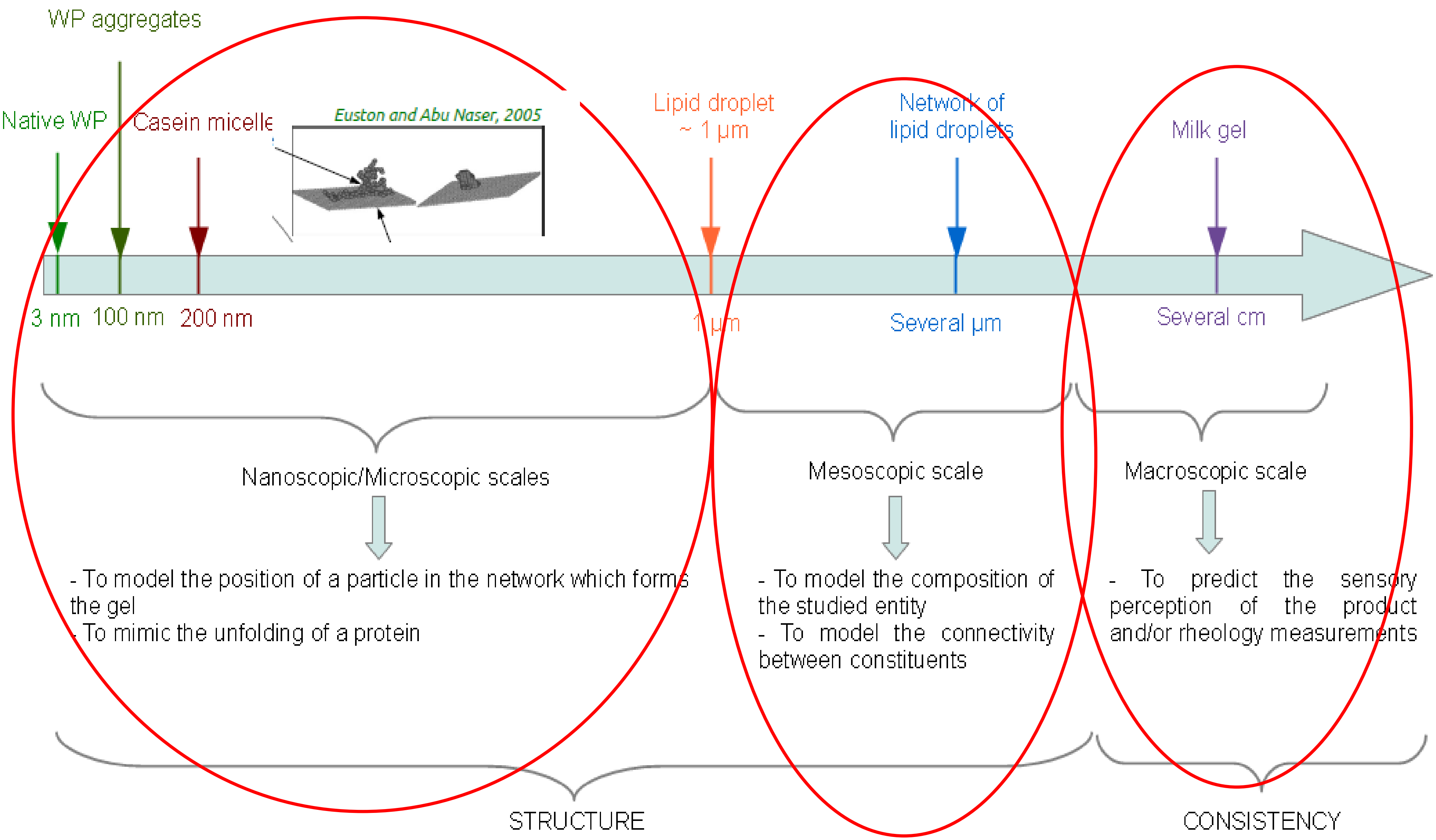
Modélisation multi-échelle d'une émulsion laitière

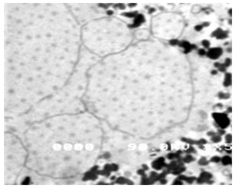


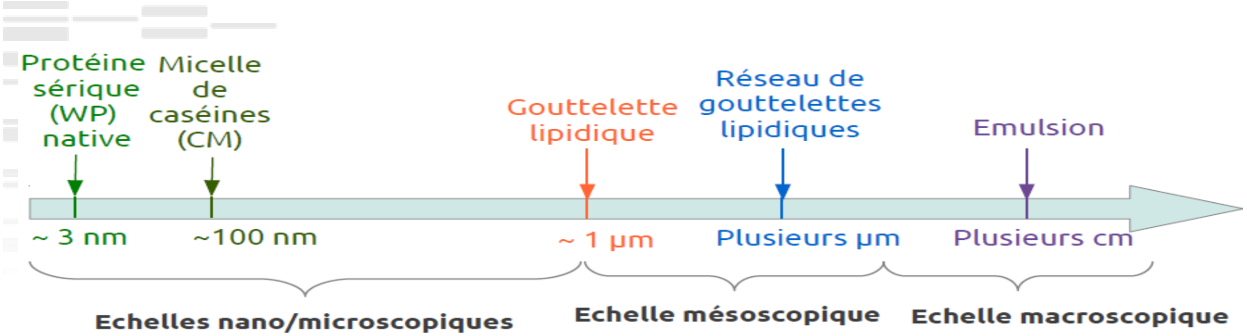
Comment faire émerger la structure ?

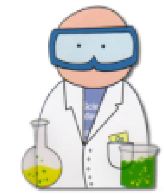
[Foucquier et al., 2012]
[Descamps et al.,in press]
[Jelinko, 2013]

Characterisation of the different scales







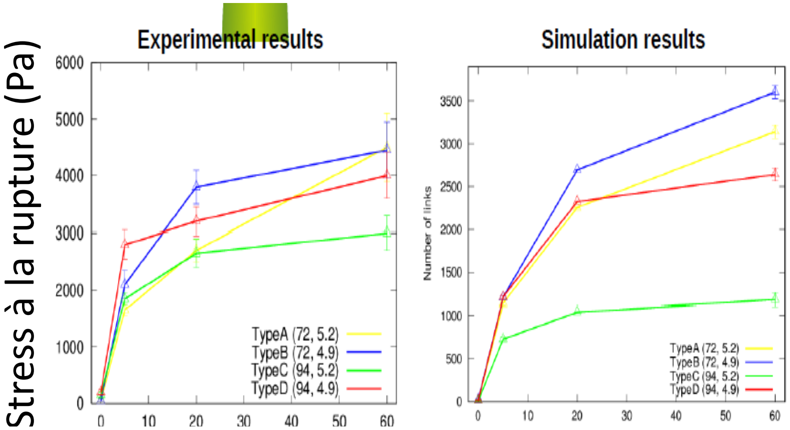


1 µ m

1 volume unitaire env.

20*20*20 µ m3

Texture



Pression homogénéisation(Mpa) //
Nombre de liens

Simulations **M3**

Simulations **M2**

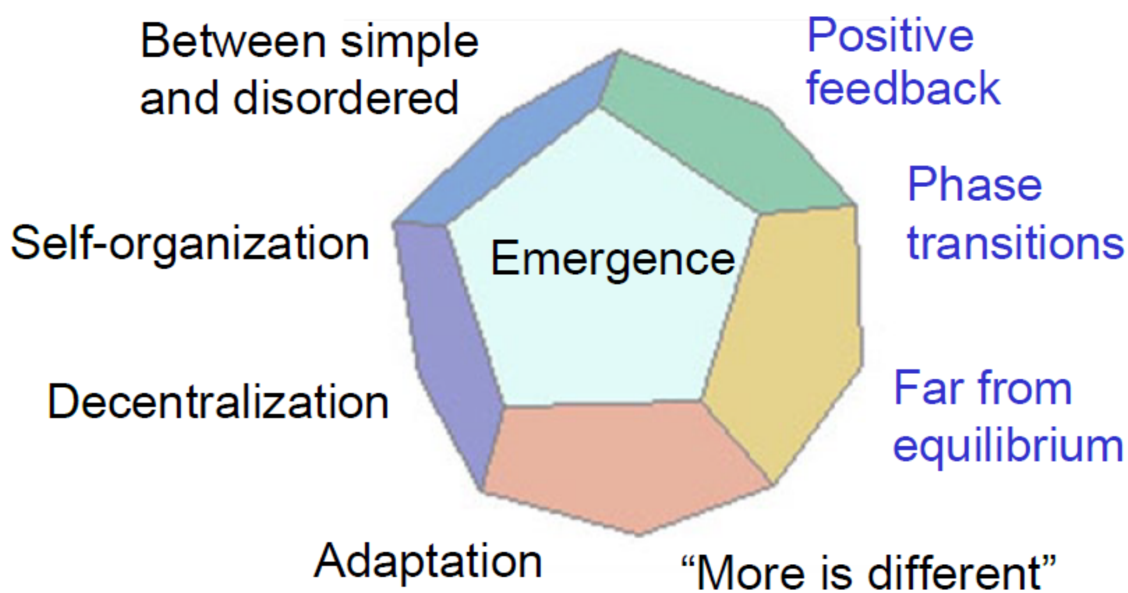
- **Sorry, there is no general "complex systems science" or "complexity theory"...**
  - there are a lot of theories and results in related disciplines ("systems theory", "computational complexity", etc.), yet
    - such generic names often come from one researcher with one particular view
    - there is no unified viewpoint on ***complex systems***, *especially autonomous*
    - in fact, there is not even any agreement on their ***definition***
  - we are currently dealing with an intuitive set of criteria, more or less shared by researchers, but still hard to formalize and quantify:
    - complexity
    - emergence
    - self-organization
    - multitude / decentralization
    - adaptation, etc.

... but don't go packing yet!

b. Global properties

✓ key concepts (“buzzwords”) expressing different facets of CS

- some have different definitions across disciplines; no global agreement
- others have a clearer meaning but different weights in “making” CS
- terms overlapping but not equivalent; yet, often grouped or interchanged



b. Global properties – *Emergence*

- ✓ the system has properties that the elements do not have
  - ex: microscopic units form macroscopic patterns (convection rolls, spiral waves, stripes, spots)
  - ex: “ignorant” individuals make intelligent collective decisions (insect colonies, neurons, market traders)
- ✓ these properties cannot be easily inferred or ***deduced***
  - ex: liquid water or ice emerging from H_2O molecules
  - ex: cognition and consciousness emerging from neurons
- ✓ different properties can emerge from the same elements/rules
  - ex: the same molecules of water combine to form liquid or ice crystals
  - ex: the same cellular automaton rules change behavior from initial state
- ✓ global properties can constitute local rules at a higher level: jumping from level to level through emergence

b. Global properties – *Self-organization*

- ✓ the organization or “order” of the system increases internally without external intervention
  - ex: aggregating processes (slime mold, pigmentation spots, termite heaps, flocks, etc.)
- ✓ order can be quantified using an “order parameter”
  - ex: cluster rate in aggregation
  - ex: long-range spatiotemporal correlations (spiral waves, synchrony)
- ✓ crucial to the notion of ***self***-organization are the interactions ***among*** elements (vs. interaction with an external cause)
  - either directly: element ↔ element
  - or indirectly: element ↔ environment ↔ element (“stigmergy” in social insects)

b. Global properties – *Positive feedback*

✓ positive feedback, circularity

- ex: ants bring more pheromone where there is pheromone
- ex: termites bring pellets of soil where there is a heap of soil
- ex: pigmented cells differentiate next to other pigmented cells
- ex: fireflies want to synchronize with the swarm's flashes
- ex: cars speed up where there are fast cars in front of them
- ex: traders prefer buying stock that goes up
- ex: the media talk about what is currently talked about in the media

→ amplification of fluctuations (nonlinearity)

→ instability of initially homogeneous state

→ broken symmetry

→ creation of structure

b. Global properties – *Decentralization*

✓ order without a leader

- ex: the central amoeba in spiral waves is *not* a pacemaker
- ex: the queen ant is *not* a manager
- ex: the first bird in a V-shaped flock is *not* a leader

✓ the "invisible hand"

- distribution: each element carry a small piece of the global information
- ignorance: elements don't have explicit knowledge or goals about the group
- parallelism: elements act simultaneously

✓ decentralized processes are far more abundant than leader-guided processes, in nature and human societies

✓ ... and yet, the notion of decentralization is still counterintuitive

- many decentralized phenomena are still poorly understood
- a "leader-less" or "designer-less" explanation still meets with resistance

→ mostly due to human perceptual bias toward an identifiable source or primary cause

b. Global properties – *“More is different”, phase transitions*

- ✓ Philip W. Anderson’s 1972 slogan “More is different”
  - criticism of the reductionist/constructionist hard line: “after discovering the fundamental laws, it is just a matter of reconstructing from them”
  - ...however, particle physics does not help solid state physics or biology!
  - reconstructionism crashes on the cliffs of *scale* and *complexity*
  - hierarchy levels of science show *qualitative* leaps (*new* properties)
  - psychology is not just applied biology, biology is not applied chemistry
  - ...yet again, this does *not* imply any unknown external or mysterious force; only a fundamental limitation in our analytical tools
- ✓ notion of “critical mass”
  - ex: need enough ants for a pheromone trail to form
  - ex: need enough chemical types for an autocatalytic set to appear
- ✓ phase transitions in parameter space
  - broken symmetries
  - most interesting: transition from randomness or chaos to order

b. Global properties – *"Complexity": an illusion?*

- ✓ abundance of autonomous, emergent systems in the environment
  - nature: geological patterns, biological cells, organisms, animal societies, ecosystems, etc.
  - spontaneously emerging human-made super-structures: cities, markets, Internet, etc.
- → decentralized, unplanned systems are robust, efficient and constitute the overwhelming majority of system types
  - it is our artificially centralized, planned engineered systems that are fragile, costly to build, and rare, as they require a higher intelligence to arise
- ✓ "complexity", an artifact of our cognitive bias?
  - because we are accustomed to the illusion of a central consciousness, we traditionally refer to decentralized systems as "complex"
  - but in fact these systems might be ***simpler*** than our familiar engineered devices with their uniquely hierarchical and complicated arrangement

➢ Precursor and neighboring disciplines

complexity: measuring the length to describe, time to build, or resources to run, a system
- information theory (Shannon; entropy)
- computational complexity (P, NP)
- Turing machines & cellular automata

adaptation: change in typical functional regime of a system
- evolutionary methods
- genetic algorithms
- machine learning

→ *Toward a unified "complex systems" science and engineering?*

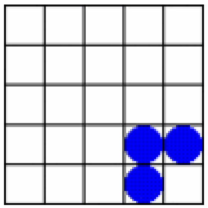
systems sciences: holistic (non-reductionist) view on interacting parts
- systems theory (von Bertalanffy)
- systems engineering (design)
- cybernetics (Wiener; goals & feedback)
- control theory (negative feedback)

dynamics: behavior and activity of a system over time
- nonlinear dynamics & chaos
- stochastic processes
- systems dynamics (macro variables)

multitude, statistics: large-scale properties of systems
- graph theory & networks
- statistical physics
- agent-based modeling
- distributed AI systems

Un petit texte de Pierre Duhem, *La Théorie Physique*, p. 284 pour mieux comprendre :

Edgar Morin, philosophe et sociologue, propose dans son ouvrage *Introduction à la pensée complexe, de grouper les connaissances dans une approche globale.*

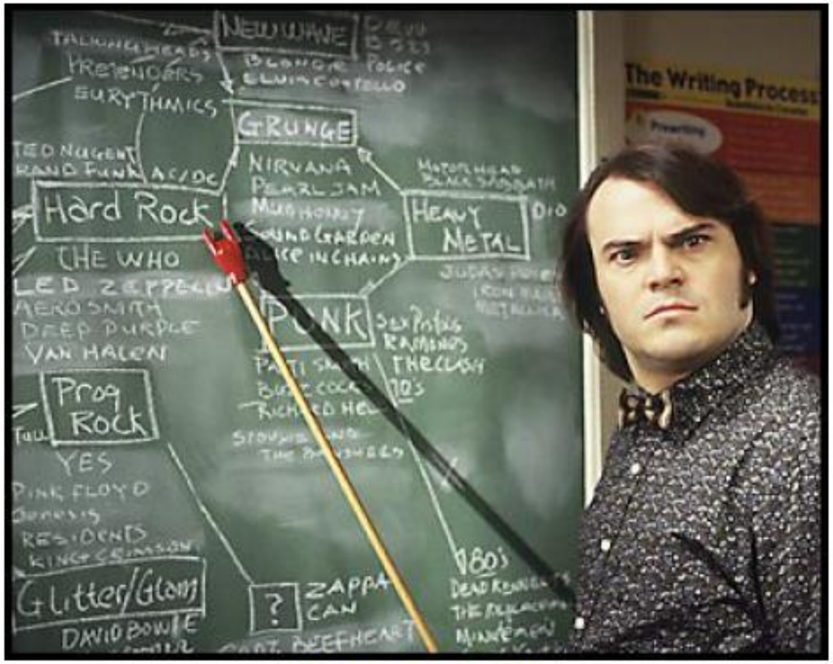


Holisme

"La Physique n'est pas une machine qui se laisse démonter ; on ne peut pas essayer chaque pièce isolement et attendre, pour l'ajuster, que la solidité en ait été minutieusement contrôlée ; la science physique, c'est un système que l'on doit prendre tout entier ; c'est un organisme dont on ne peut faire fonctionner une partie sans que les parties les plus éloignées de celle-la entrent en jeu, les unes plus, les autres moins, toutes à quelque degré. Si quelque gène, quelque malaise se révèle, dans ce fonctionnement, c'est par l'effet produit sur le système tout entier que le physicien devra deviner l'organe qui a besoin d'être redressé ou modifié, sans qu'il lui soit possible d'isoler cet organe et de l'examiner à part".

Réductionnisme

Le Réductionnisme c'est l'anti-holisme : on décompose les choses pour étudier chaque éléments indépendamment puis ayant compris le fonctionnement des divers éléments, on les assemble pour comprendre le système de base étudié (la sociologie à partir de la psychologie, l'écologie à partir de la biologie, la thermodynamique à partir de la physique statistique, etc.). C'est-à-dire que ici toutes les parties sont inférieures à la somme du tout, c'est le **principe de contrainte** contrairement à la citation du début s'apparentant au **principe d'émergence**.



The School of Rock (2003)
Jack Black, Paramount Pictures

The End

Simulations:

Presentation sur netlogo de fur mammal: régler des w différents

3 variables: distance activation, distance inhibition et w (poids sur l’impact de l’inhibition si sup 1 inhibition plus d’impact
Les cellules colorées (activées) pour le mammifère sont en blanc dans le modèle

Présentation des colonies de fourmis et programme. Jouer sur la position de la nourriture et l’équilibre renforcement et évaporation des odeurs

Mettre une video sur le cerveau et/ou le TD