Fifth Annual French Complex Systems Summer School
Institut des Systèmes Complexes, Paris Ile-de-France, July 4-16, 2011

A Tour of Complex Systems

René Doursat

http://iscpif.fr/~doursat

Instructor

René Doursat

Experience

- Fmr. Director, ISC-PIF / Researcher, Ecole Polytechnique (CREA), 2006-
- Visiting Assistant Professor, University of Nevada, Reno, 2004-2006
- *Senior Software Engineer & Architect, Paris and San Francisco, 1995-2004*
- Research Associate, Ecole Polytechnique (CREA), Paris, 1996-1997
- Postdoctoral Fellow, Ruhr-Universität Bochum, Germany, 1991-1995

Education

- HDR Sciences pour l'ingénieur, Université Paris 6 (UPMC), 2010
- Ph.D. in applied math (computational neuroscience), Université Paris 6, 1991
- M.S. in physics, Ecole Normale Supérieure, Paris, 1987

Research interests

- computational modeling and simulation of complex systems, especially neural, biological and social, which can foster novel principles and applications in ICT
- self-organization of *reproducible* and *programmable* structures in (a) large-scale spiking neural dynamics, (b) developmental artificial life, (c) multi-agent networks

Course Contents

➢ What this course is about (dense preview, will be repeated)

- ✓ an *exploration* of various complex systems *objects*:
  - cellular automata, pattern formation, swarm intelligence, complex networks, spatial communities, structured morphogenesis
- ✓ and their common *questions*:
  - emergence, self-organization, positive feedback, decentralization, between simple and disordered, “more is different”, adaptation & evolution
- ✓ by interactive *experimentation* (using NetLogo),
- ✓ introducing *practical* complex systems *modeling* and simulation
- ✓ from a *computational* viewpoint, in contrast with a “mathematical” one (i.e., formal or numerical resolution of symbolic equations),
- ✓ based on discrete *agents* moving in discrete or quasi-continuous space, and *interacting* with each other and their environment

A Tour of Complex Systems

1. Introduction

2. A Complex Systems Sampler

3. Commonalities

4. NetLogo Tutorial

A Tour of Complex Systems

1. Introduction
   a. What are complex systems?
   b. A vast archipelago
   c. Computational modeling
2. A Complex Systems Sampler
3. Commonalities
4. NetLogo Tutorial

A Tour of Complex Systems

1. Introduction

   a. What are complex systems?
      - *Few agents*
      - *Many agents*
      - *CS in this course*

   b. A vast archipelago

   c. Computational modeling

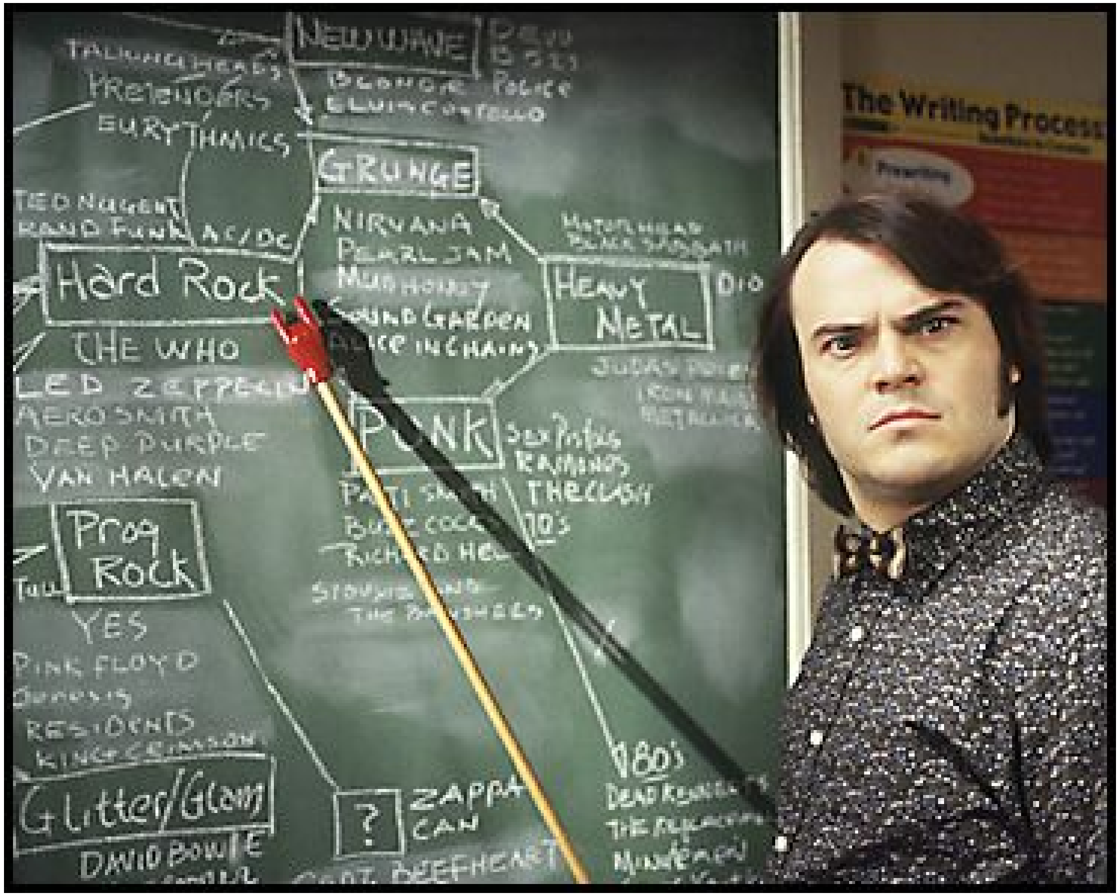
2. A Complex Systems Sampler

3. Commonalities

4. NetLogo Tutorial

1. Introduction — a. What are complex systems?

➢ Any ideas?



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

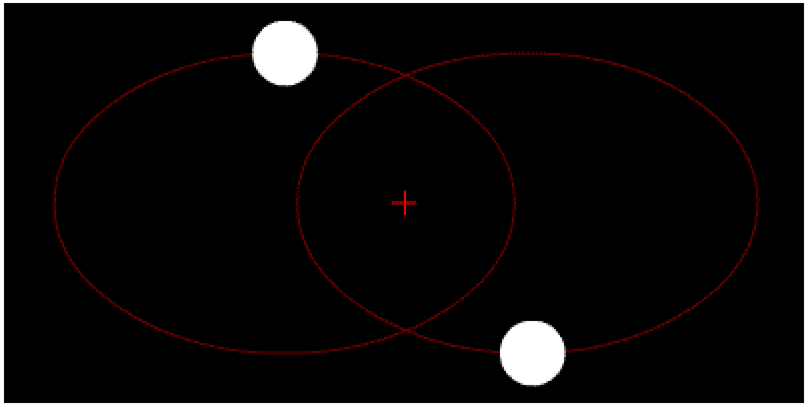
1. Introduction — a. What are complex systems?

➢ Few agents, "simple" emergent behavior

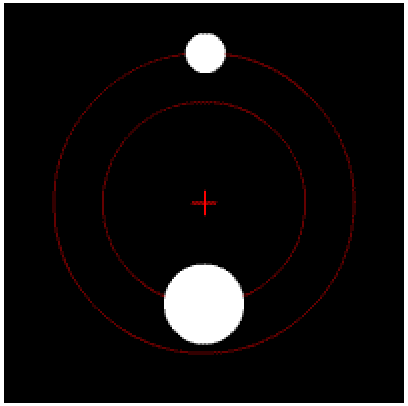
→ *ex: two-body problem*

✓ 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

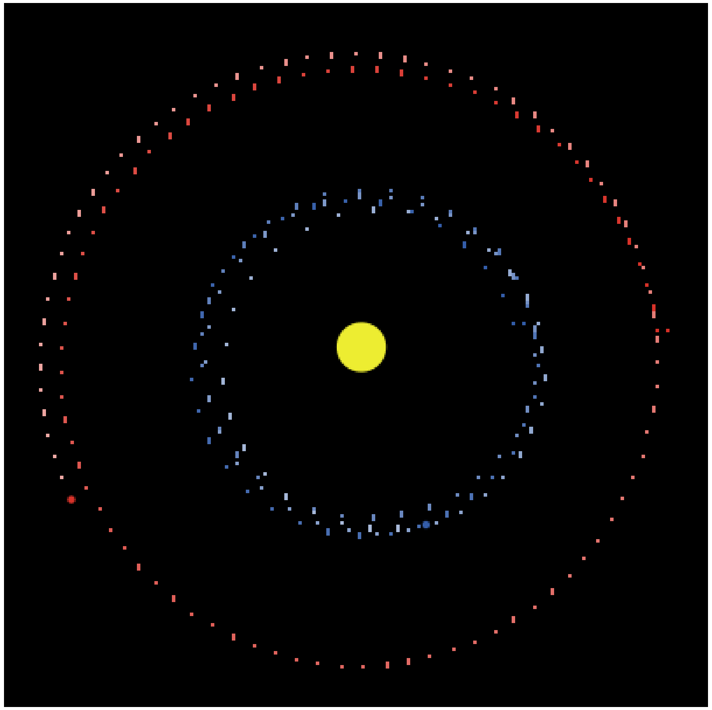


Two bodies with different mass
Wikimedia Commons

1. Introduction — a. What are complex systems?

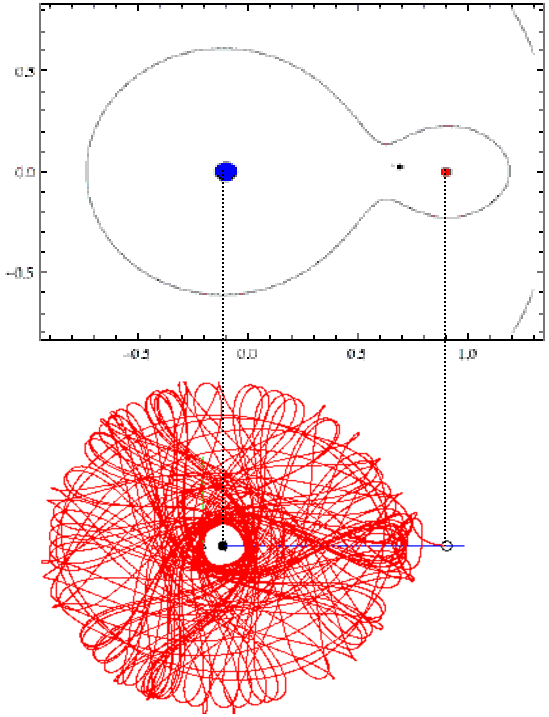
- Few agents, complex emergent behavior
  - → *ex: three-body problem*
  - ✓ generally no exact mathematical solution (even in “restricted” case $m_1 \langle\langle\, m_2 \approx m_3$): must be solved numerically → ***chaotic*** trajectories

NetLogo model: /Chemistry & Physics/Mechanics/Unverified



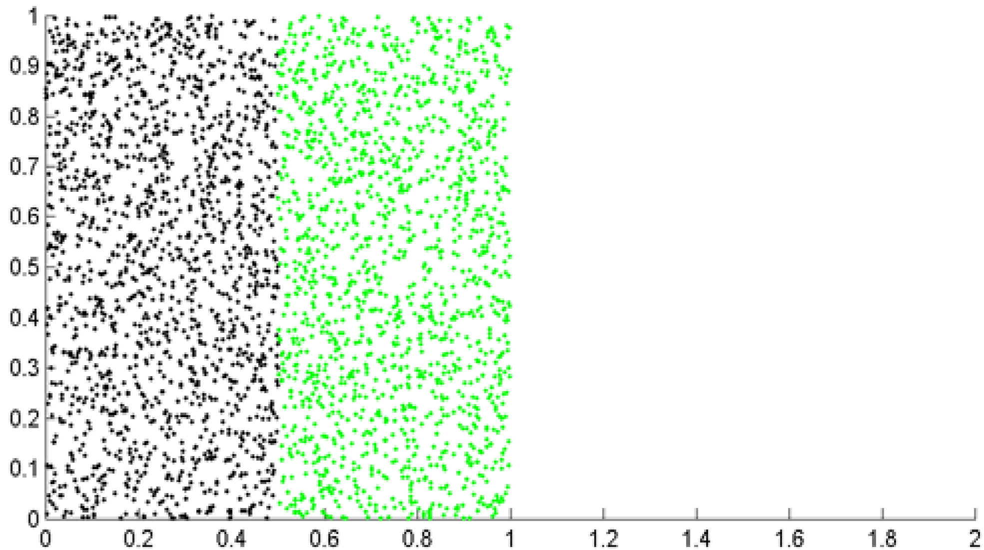
Transit orbit of the planar circular restricted problem

Scholarpedia: Three Body Problem & Joachim Köppen Kiel’s applet



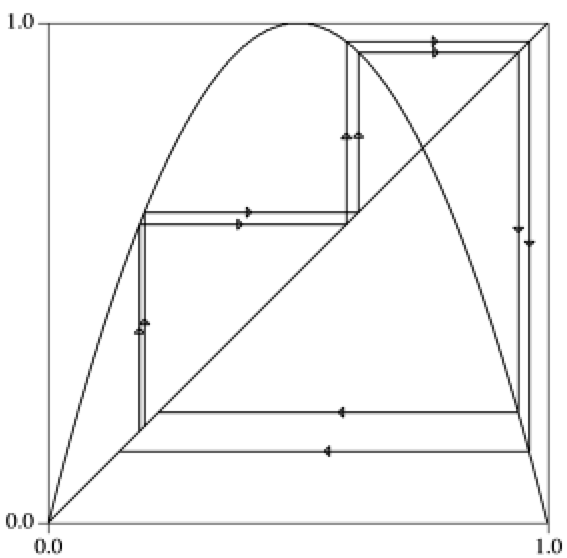
1. Introduction — a. What are complex systems?

- **Few agents, complex emergent behavior**
  - → *ex: more chaos (baker's/horseshoe maps, logistic map, etc.)*
  - ✓ ***chaos*** generally means a ***bounded***, ***deterministic*** process that is ***aperiodic*** and ***sensitive on initial conditions*** → small fluctuations create large variations ("butterfly effect")
  - ✓ even one-variable iterative functions: $x_{n+1} = f(x_n)$ can be "complex"



Baker's transformation

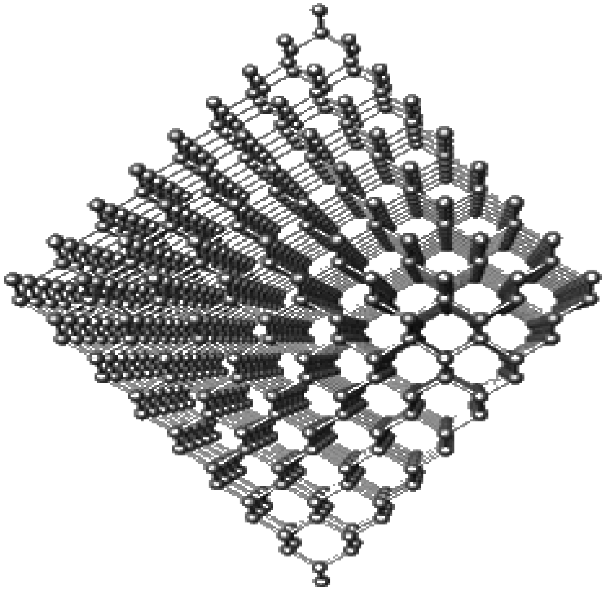
Craig L. Zirbel, Bowling Green State University, OH



Logistic map

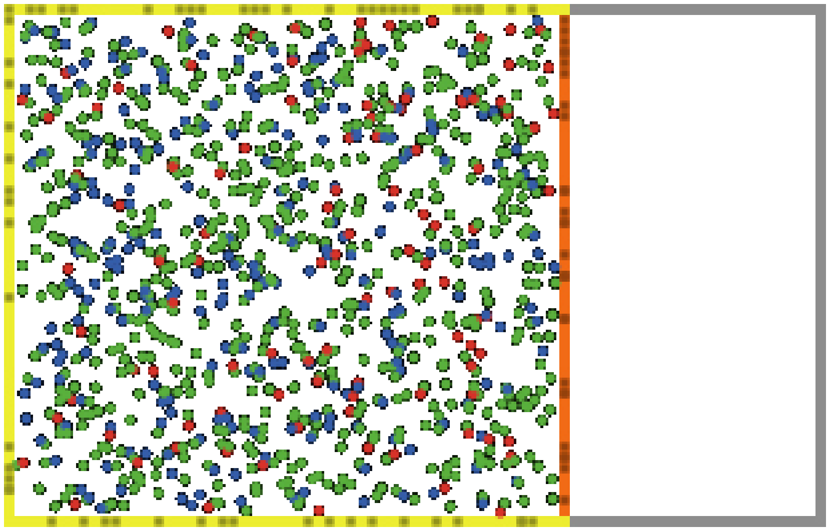
1. Introduction — a. What are complex systems?

- **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

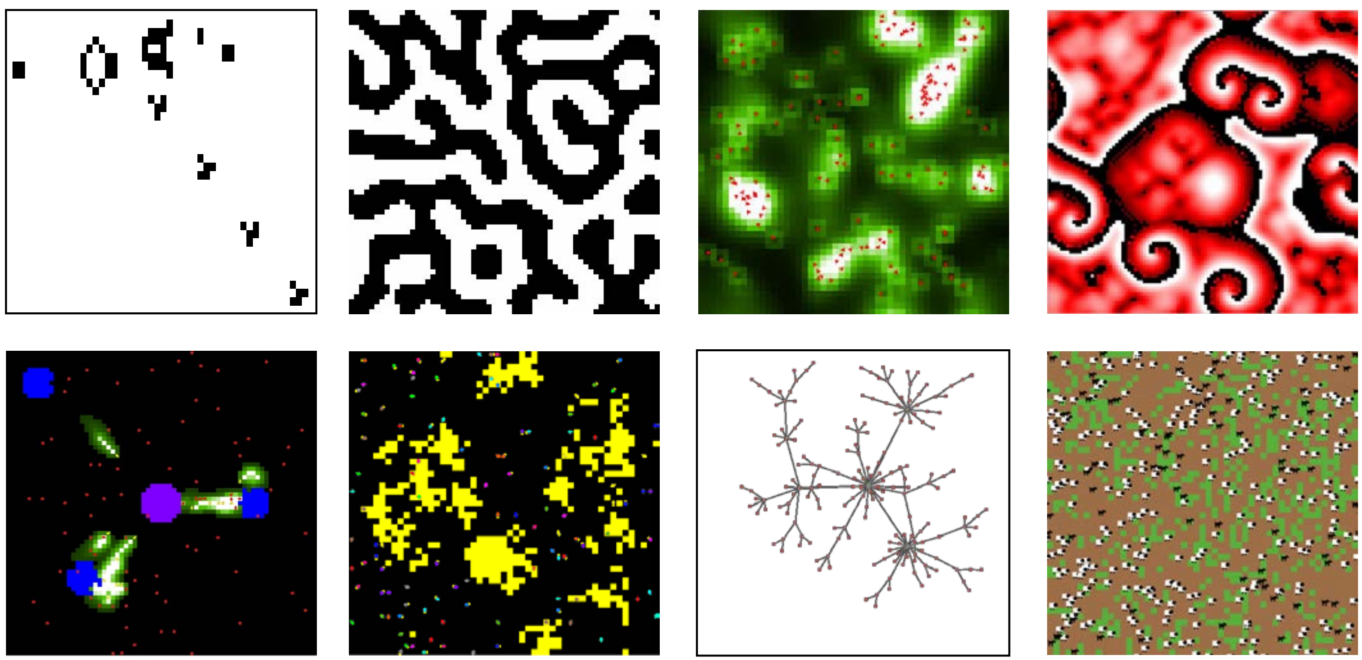


Diamond crystal structure
Tonci Balic-Zunic, University of Copenhagen

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?

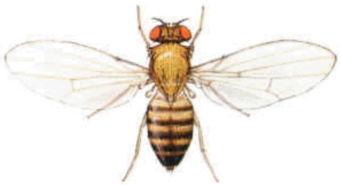
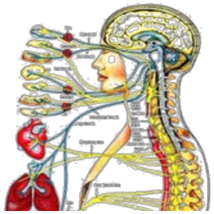
➢ Many agents, complicated rules, complex emergent behavior

→ *natural ex: organisms (cells), societies (individuals + techniques)*

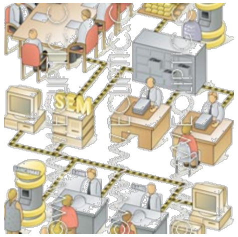
- ✓ agent rules become more "complicated", e.g., ***heterogeneous*** depending on the element's ***type*** and/or ***position*** in the system
- ✓ behavior is also complex but, paradoxically, can become more ***controllable***, e.g., ***reproducible*** and ***programmable***

biological development & evolution

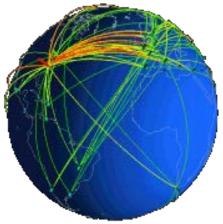


termite mounds



companies



techno-networks

cities

1. Introduction — a. What are complex systems?

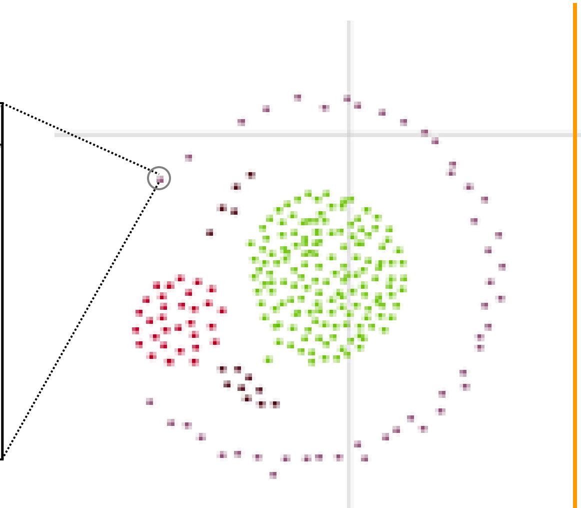
➢ Many agents, complicated rules, complex emergent behavior

→ *ex: self-organized “artificial life”: swarm chemistry, morphogenesis*

✓ in *swarm chemistry* (Sayama 2007), mixed self-propelled particles with different flocking parameters create nontrivial formations

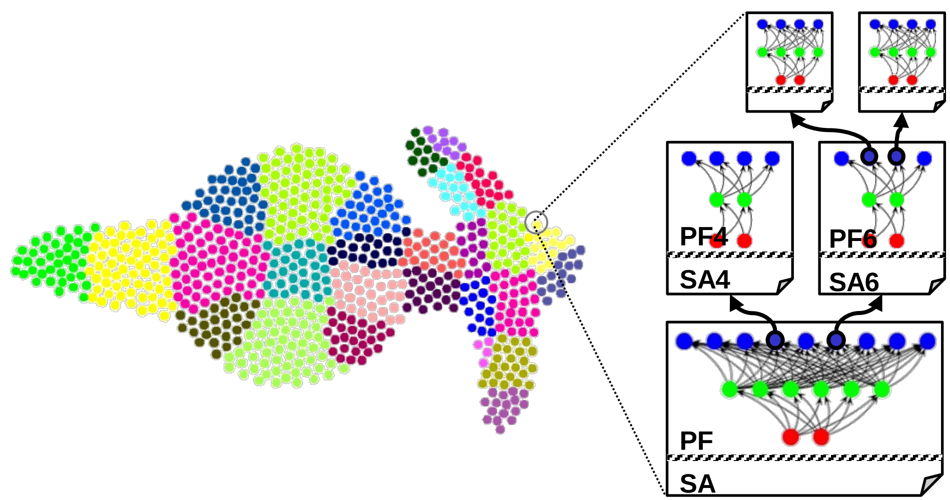
✓ in *embryomorphic engineering* (Doursat 2006), cells contain the same genetic program, but differentiate and self-assemble into specific shapes

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

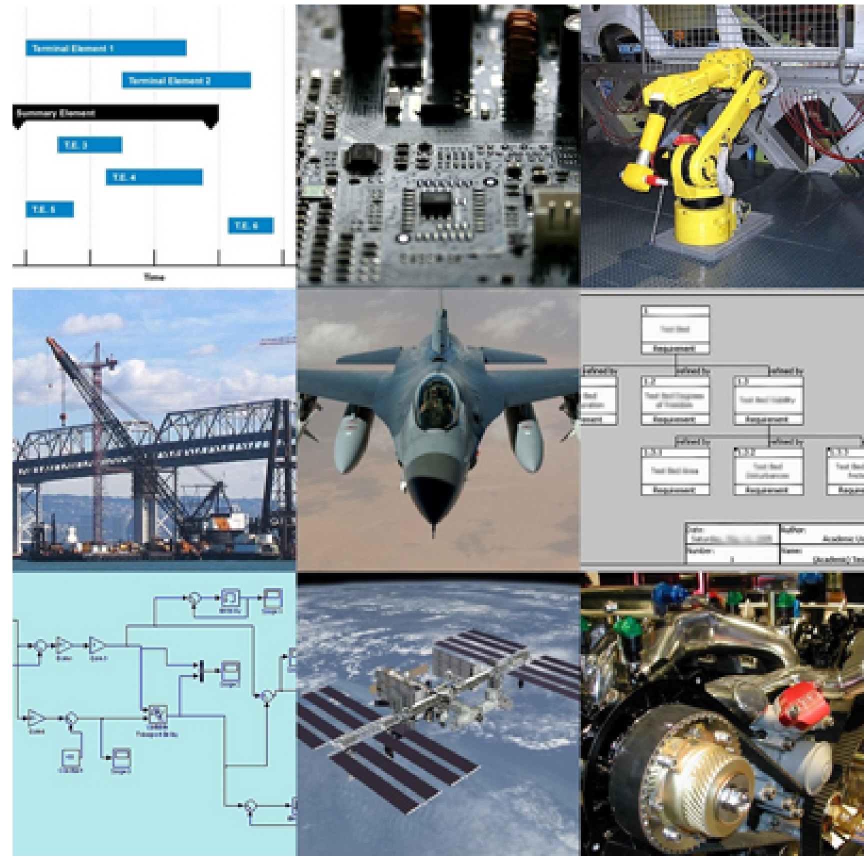
René Doursat, Insitut des Systèmes Complexes, Paris

1. Introduction — a. What are complex systems?

➢ 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

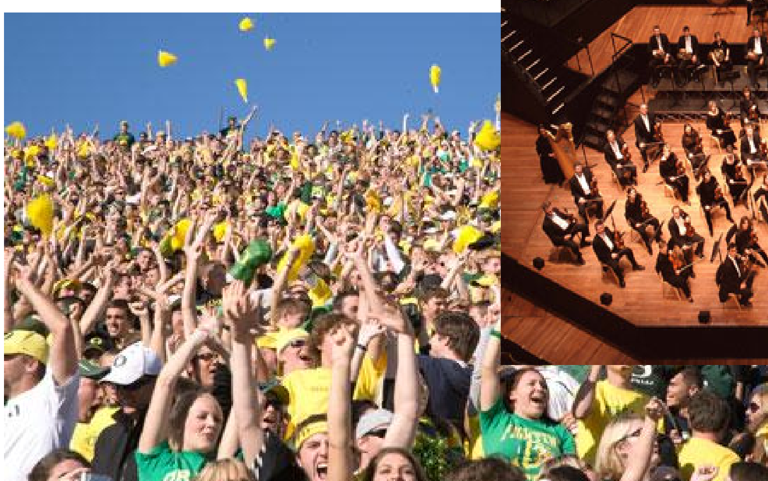


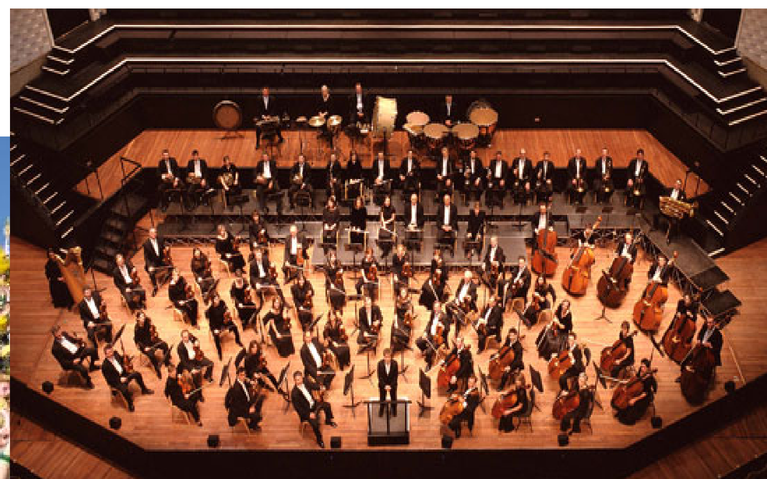
Systems engineering
Wikimedia Commons, http://en.wikipedia.org/wiki/Systems_engineering

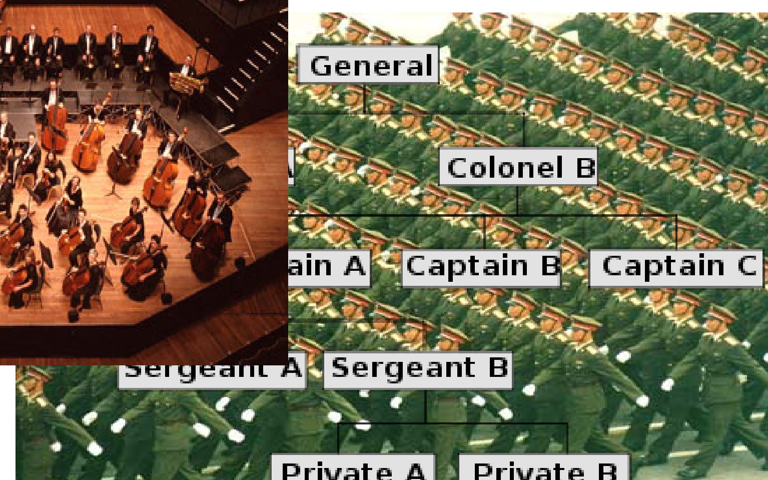
➢ Many agents, complicated rules, "centralized" behavior

→ *spectators, orchestras, military, administrations*

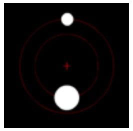
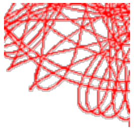
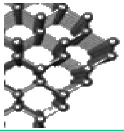
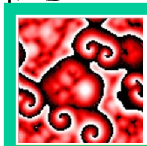
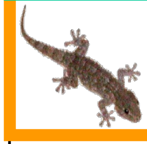
- ✓ people reacting similarly and/or simultaneously to cues/orders coming from a *central cause*: event, leader, plan
- ✓ **hardly "complex" systems:** little decentralization, little emergence, little self-organization





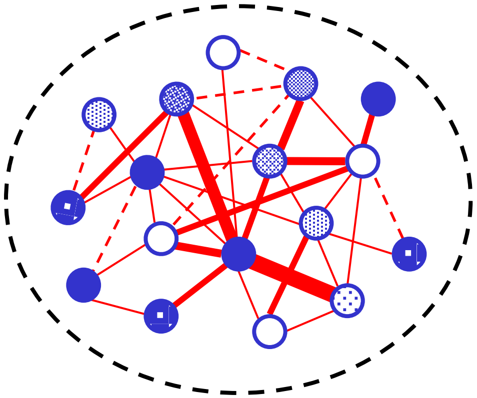


➢ Recap: complex systems in this course

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*

1. Introduction — a. What are complex systems?

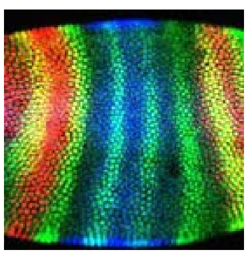
➢ Complex systems in this course



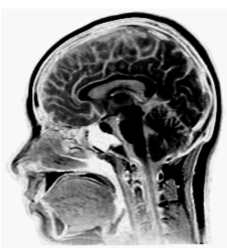
- **large** number of elementary **agents** interacting **locally**
- (more or less) simple individual agent behaviors creating a complex **emergent**, **self-organized** behavior
- *decentralized dynamics: no master blueprint or grand architect*

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

pattern formation
○ = matter



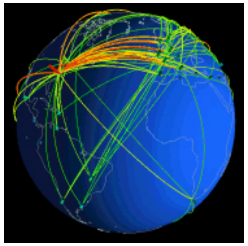
biological development
○ = cell



the brain & cognition
○ = neuron

insect colonies
○ = ant

Internet & Web
○ = host/page

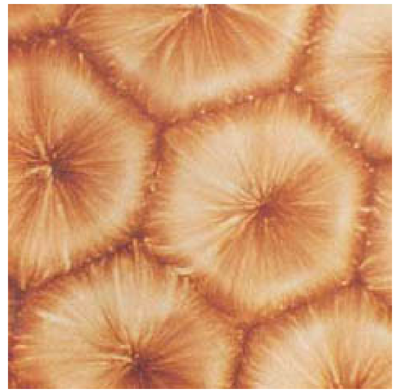


social networks
○ = person

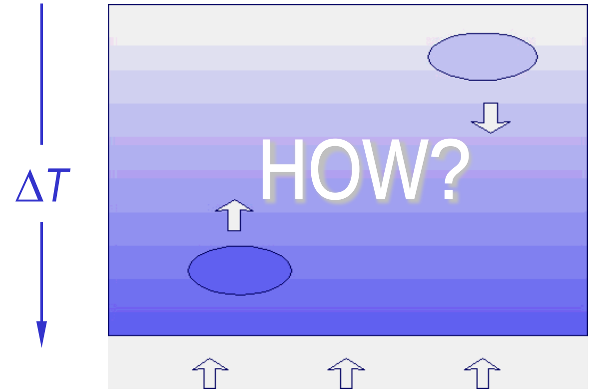
1. Introduction — a. What are complex systems?

Physical pattern formation: Convection cells

Rayleigh-Bénard convection cells in liquid heated uniformly from below
(Scott Camazine, http://www.scottcamazine.com)

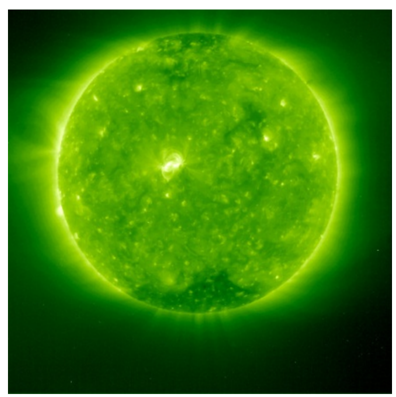


Convection cells in liquid (detail)
(Manuel Velarde, Universidad Complutense, Madrid)

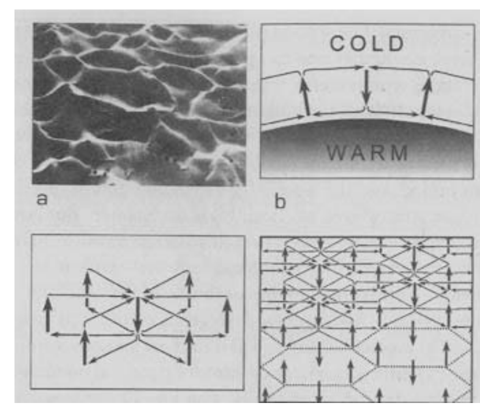


Schematic convection dynamics
(Arunn Narasimhan, Southern Methodist University, TX)

Sand dunes
(Scott Camazine, http://www.scottcamazine.com)



Solar magnetoconvection
(Steven R. Lantz, Cornell Theory Center, NY)



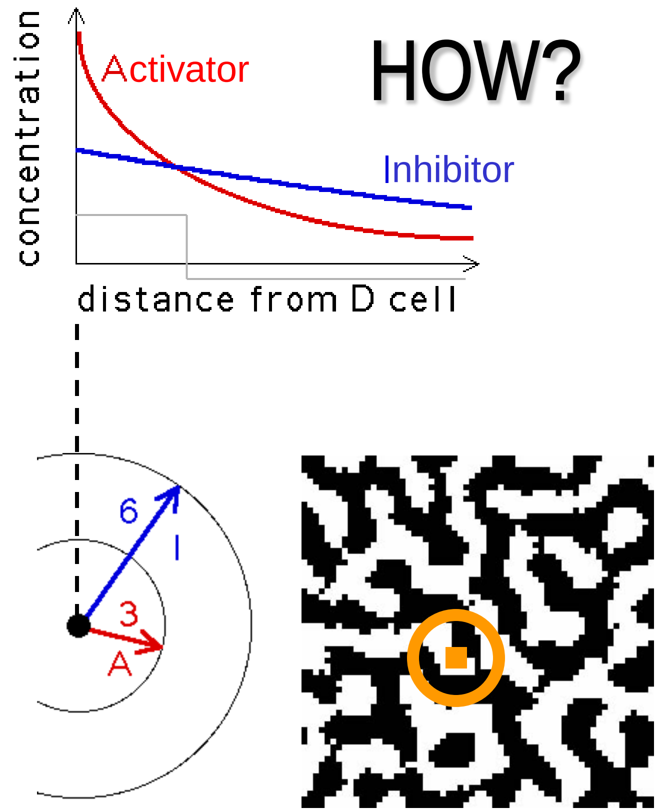
Hexagonal arrangement of sand dunes
(Solé and Goodwin, "Signs of Life", Perseus Books)

- thermal convection, due to temperature gradients, creates stripes and tilings at multiple scales, from tea cups to geo- and astrophysics

1. Introduction — a. What are complex systems?

Biological pattern formation: Animal colors

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

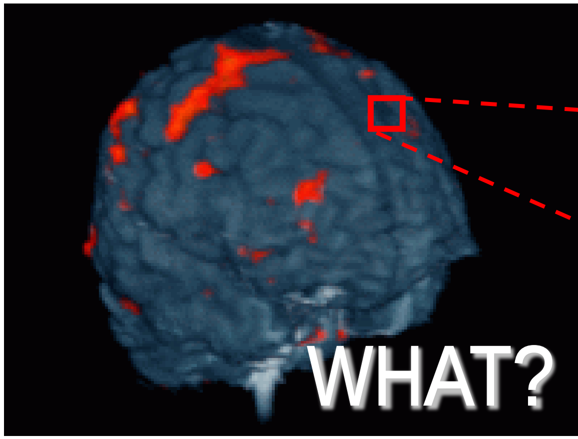


NetLogo fur coat simulation, after David Young's model of fur spots and stripes
(Michael Frame & Benoit Mandelbrot, Yale University)

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

1. Introduction — a. What are complex systems?

Spatiotemporal synchronization: Neural networks

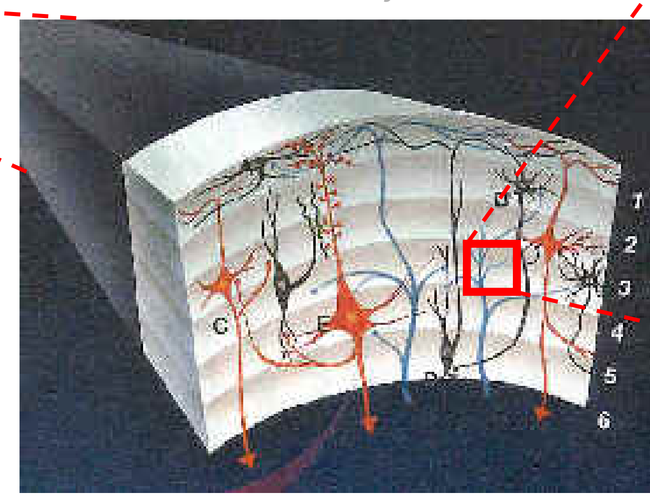


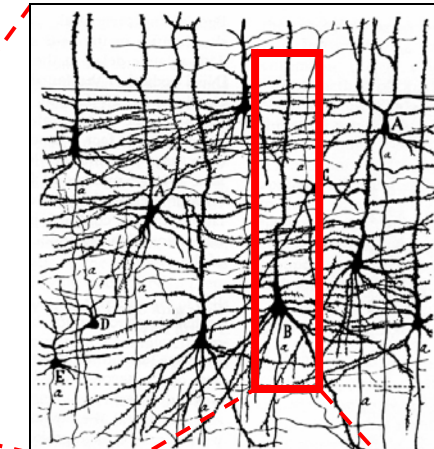
Animation of a functional MRI study
(J. Ellermann, J. Strupp, K. Ugurbil, U Minnesota)

- 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

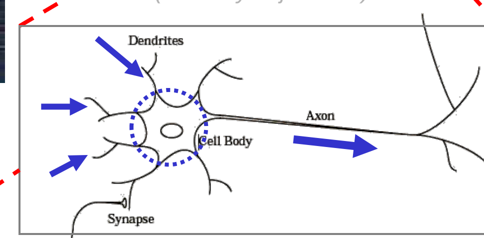
HOW?

Cortical layers

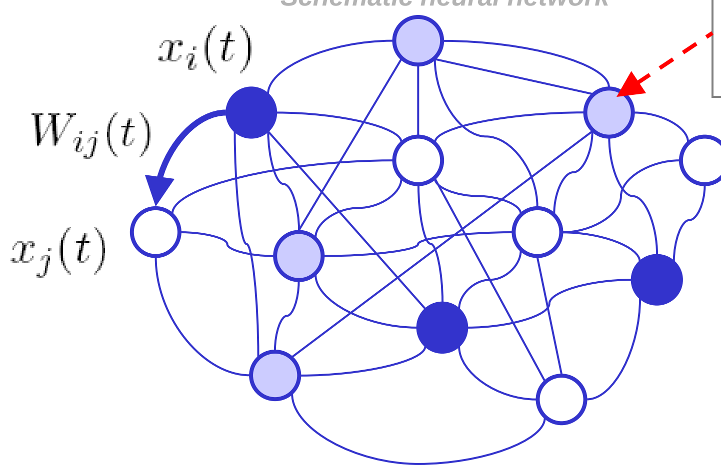


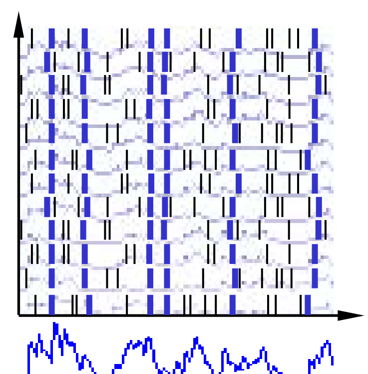


Pyramidal neurons & interneurons
(Ramón y Cajal 1900)



Schematic neural network





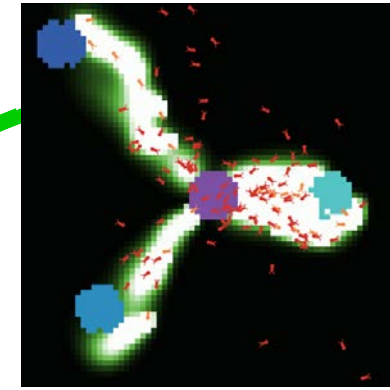
1. Introduction — a. What are complex systems?

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

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

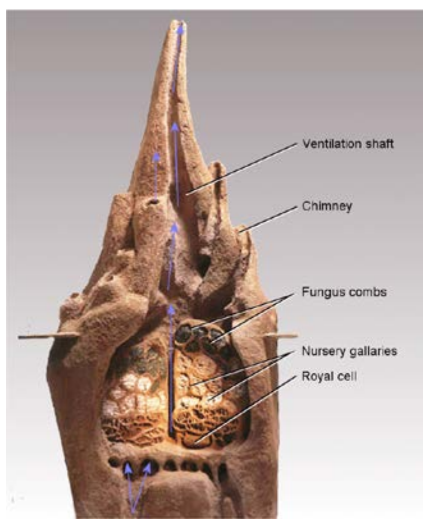
http://picasaweb.google.com/tridentoriginal/Ghana

Harvester ant
(Deborah Gordon, Stanford University)

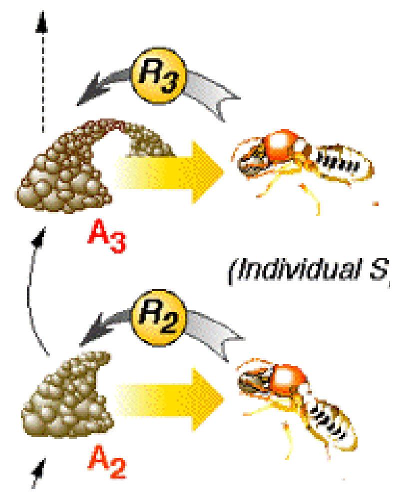


HOW?

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)

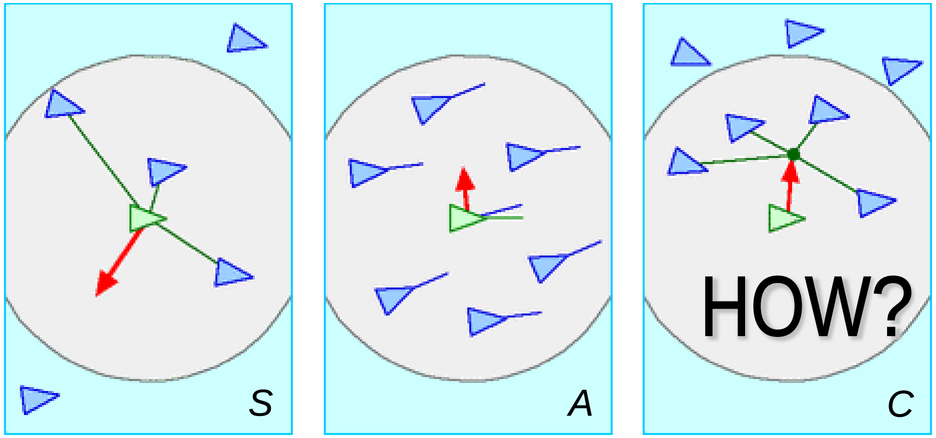
- ants form trails by following and reinforcing each other's pheromone path
- termite colonies build complex mounds by "stigmergy"

1. Introduction — a. What are complex systems?

Collective motion: flocking, schooling, herding

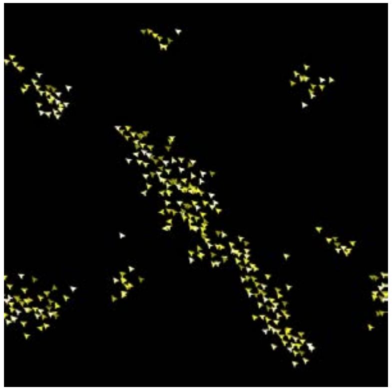
Fish school
(Eric T. Schultz, University of Connecticut)

Bison herd
(Center for Bison Studies, Montana State University, Bozeman)



Separation, alignment and cohesion
("Boids" model, Craig Reynolds, http://www.red3d.com/cwr/boids)

- coordinated collective movement of dozens or 1000s of individuals (confuse predators, close in on prey, improve motion efficiency, etc.)

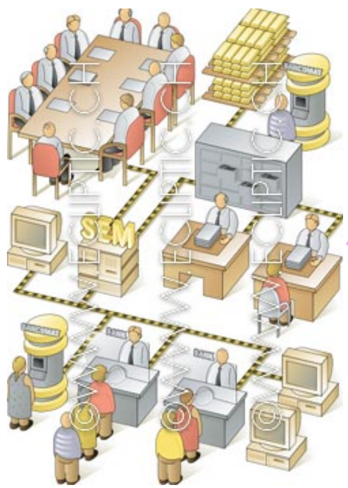


- each individual adjusts its position, orientation and speed according to its nearest neighbors

1. Introduction — a. What are complex systems?

Complex networks and morphodynamics: human organizations

organizations

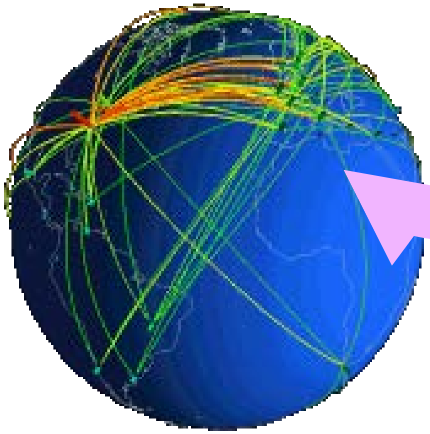


(Thomas Thü Hürlimann, http://ecliptic.ch)

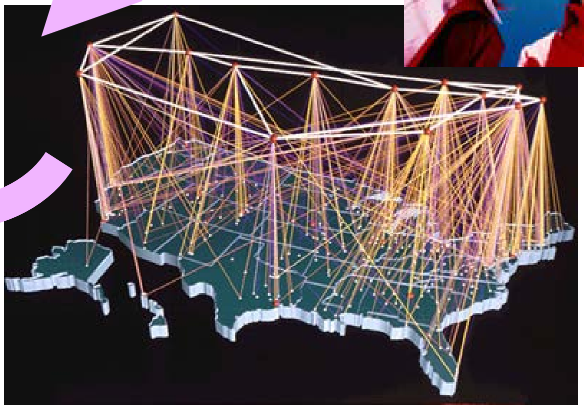
urban dynamics

SimCity (http://simcitysocieties.ea.com)

global connectivity

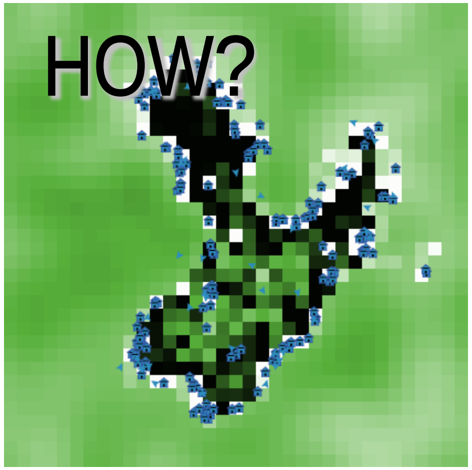


techno-social networks



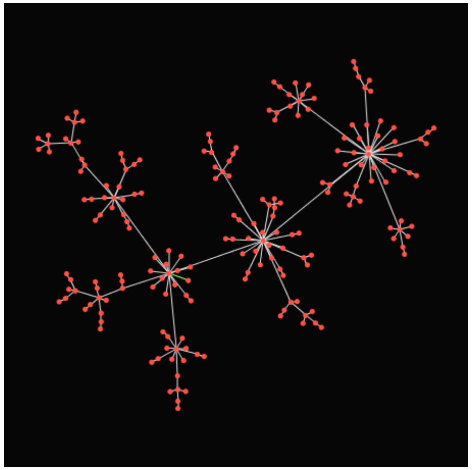
NSFNet Internet (w2.eff.org)

cellular automata model



NetLogo urban sprawl simulation

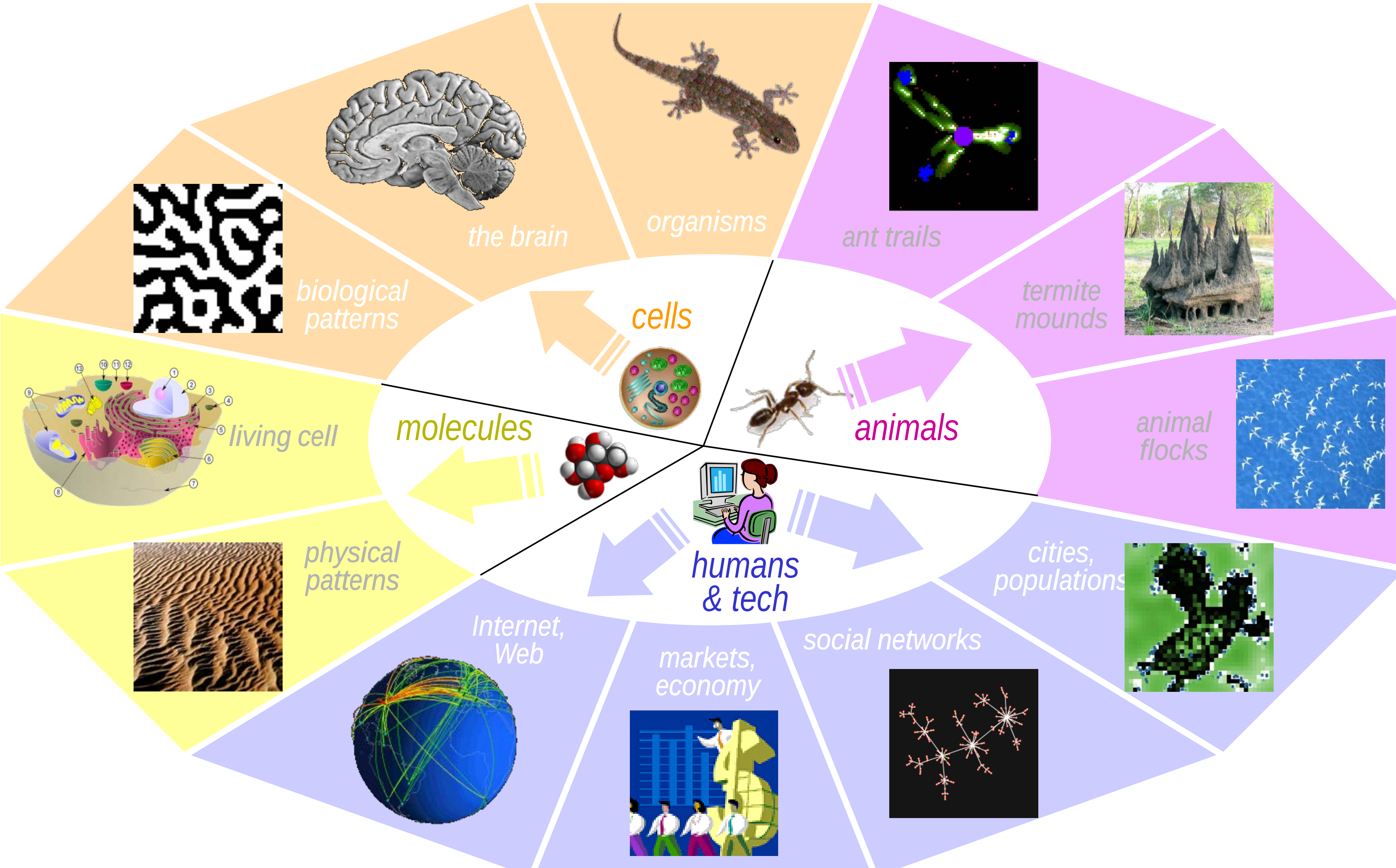
"scale-free" network model



NetLogo preferential attachment simulation

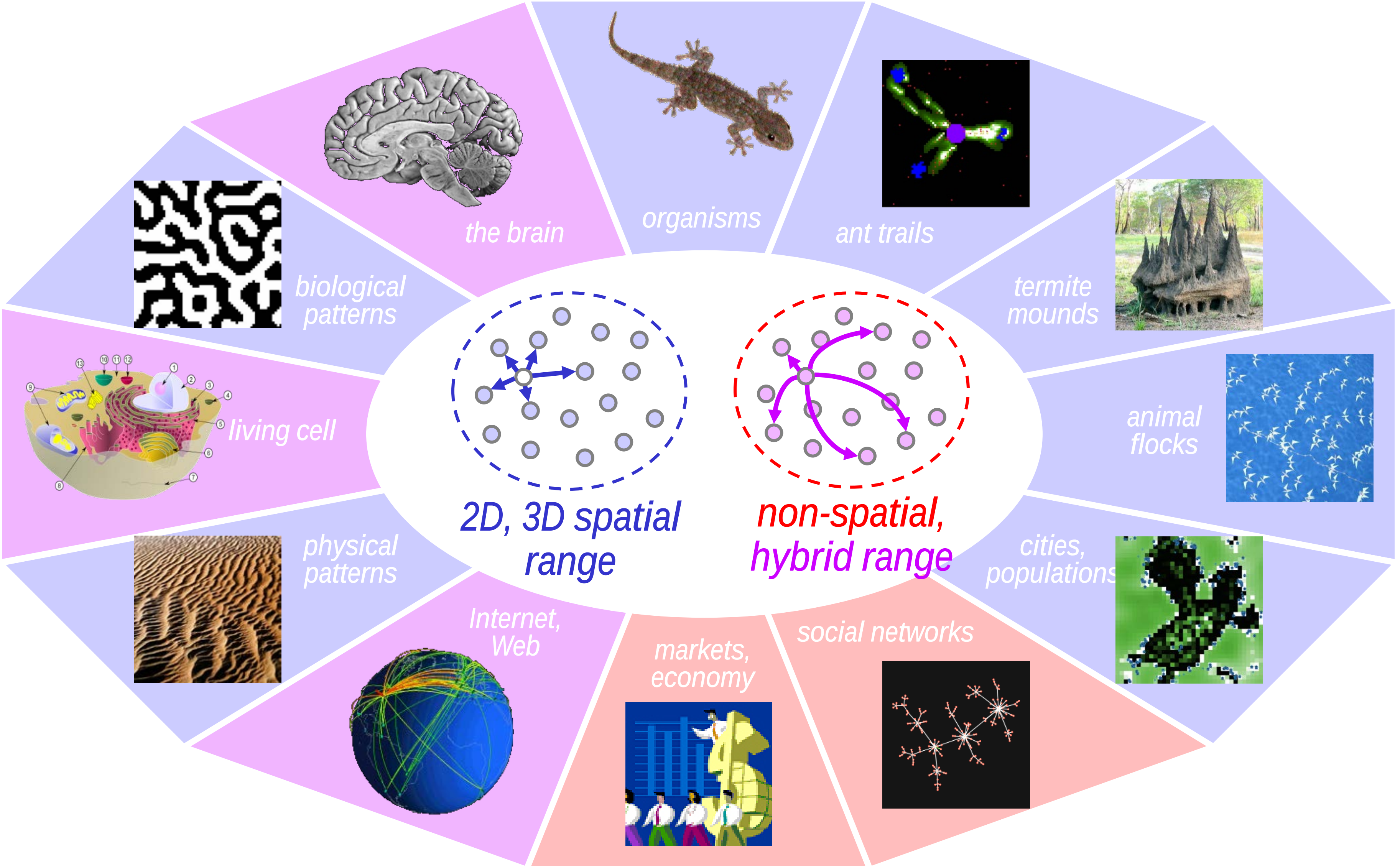
1. Introduction — a. What are complex systems?

Categories of complex systems by agents



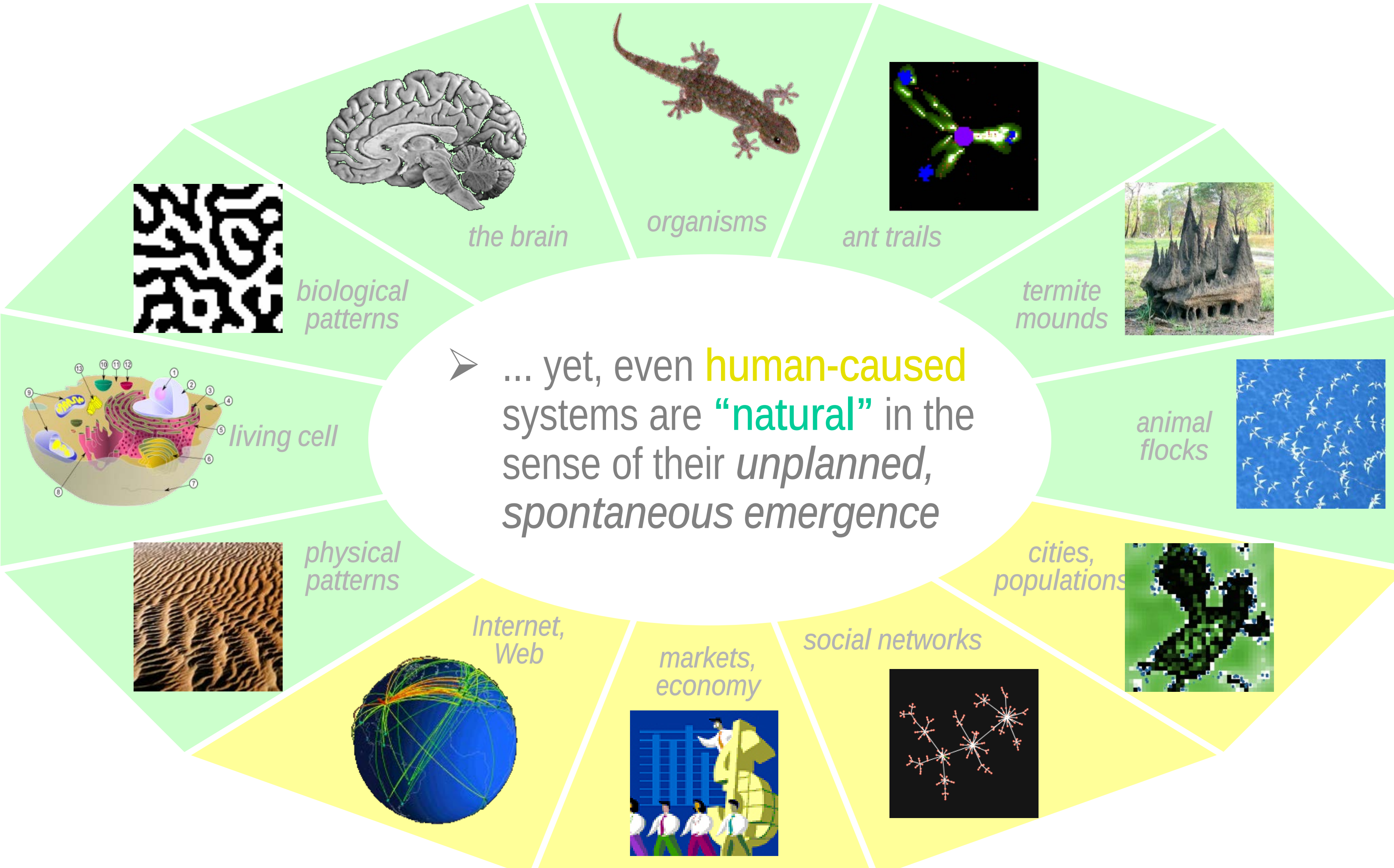
1. Introduction — a. What are complex systems?

Categories of complex systems by range of interactions



1. Introduction — a. What are complex systems?

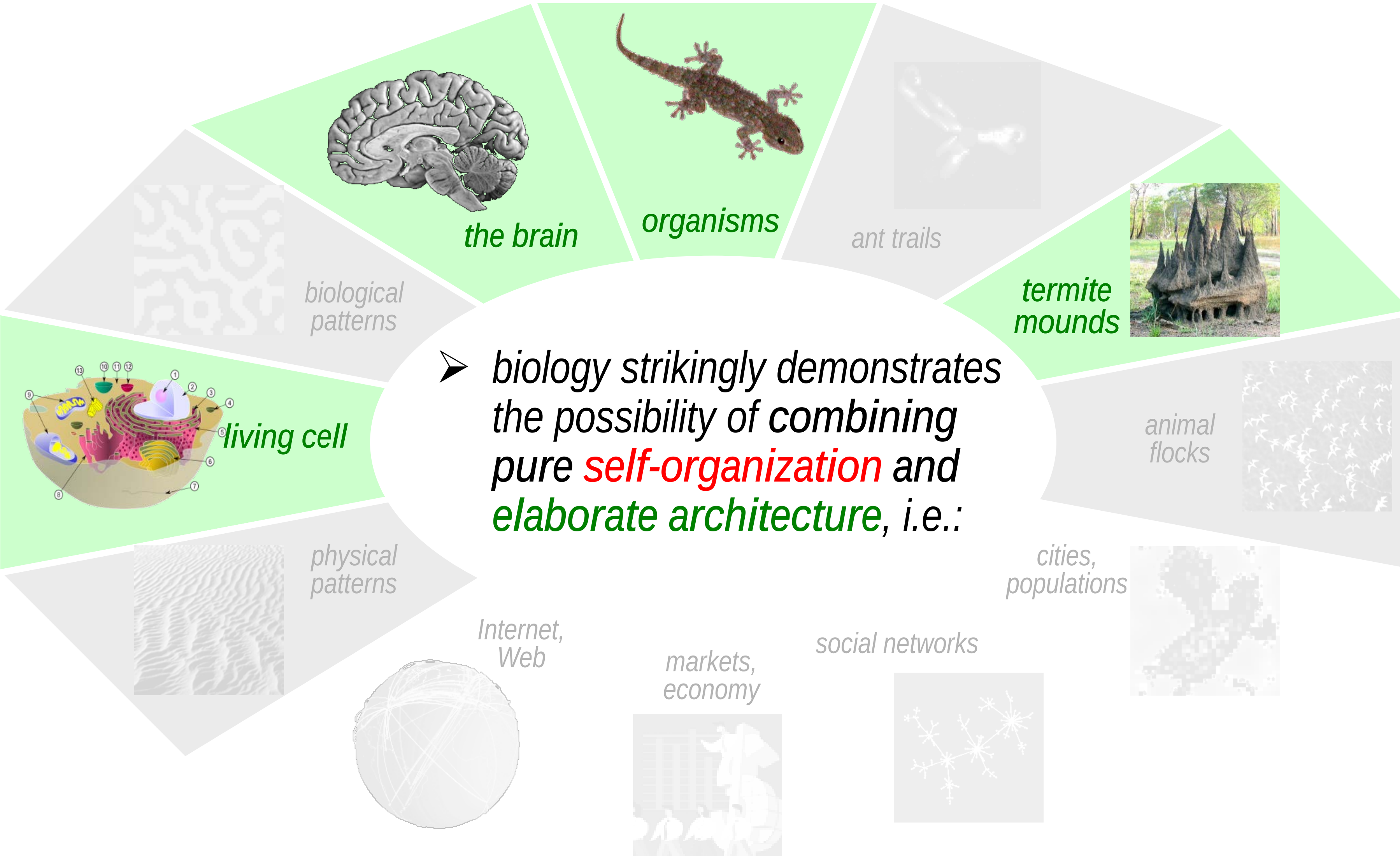
Natural and human-caused categories of complex systems



- ... yet, even human-caused systems are "natural" in the sense of their *unplanned, spontaneous emergence*

1. Introduction — a. What are complex systems?

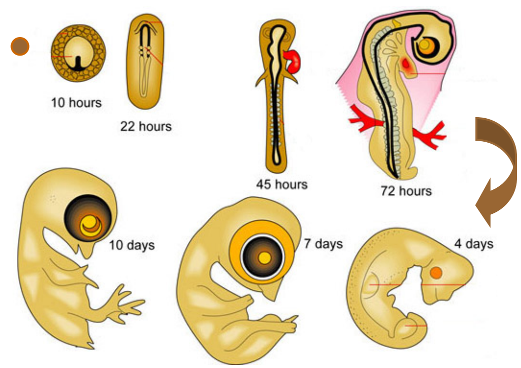
"Simple/random" vs. ***architectured*** *natural complex systems*



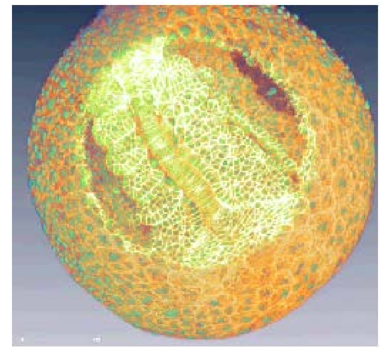
- *biology strikingly demonstrates the possibility of **combining** pure self-organization and elaborate architecture, i.e.:*

1. Introduction — a. What are complex systems?

➢ Ex: Morphogenesis – Biological development



www.infovisual.info

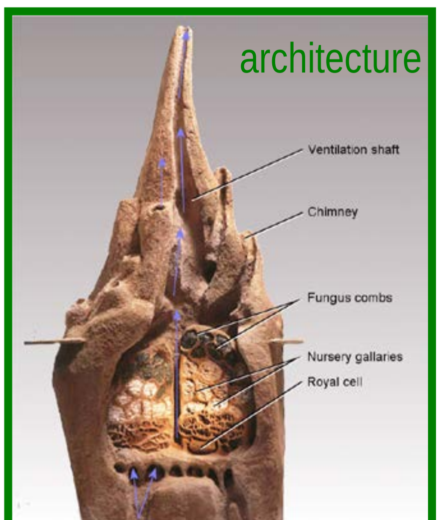


Nadine Peyriéras, Paul Bourgine et al.
(Embryomics & BioEmergences)

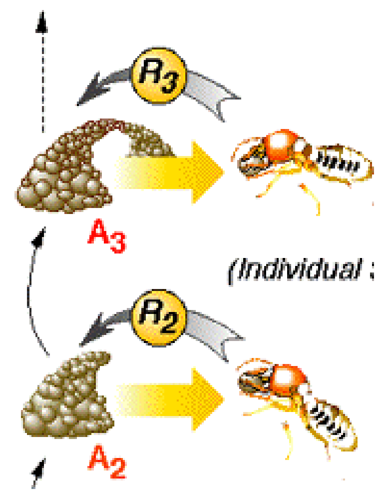
- cells build sophisticated organisms by division, genetic differentiation and biomechanical self-assembly

➢ Ex: Swarm intelligence – Termite mounds

Termite mound
(J. McLaughlin, Penn State University)



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



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

- termite colonies build sophisticated mounds by **"stigmergy"** = loop between modifying the environment and reacting differently to these modifications

1. Introduction — a. What are complex systems?

Human superstructures are "natural" CS

by their unplanned, spontaneous emergence and adaptivity...

geography: cities, populations

people: social networks

wealth: markets, economy

technology: Internet, Web

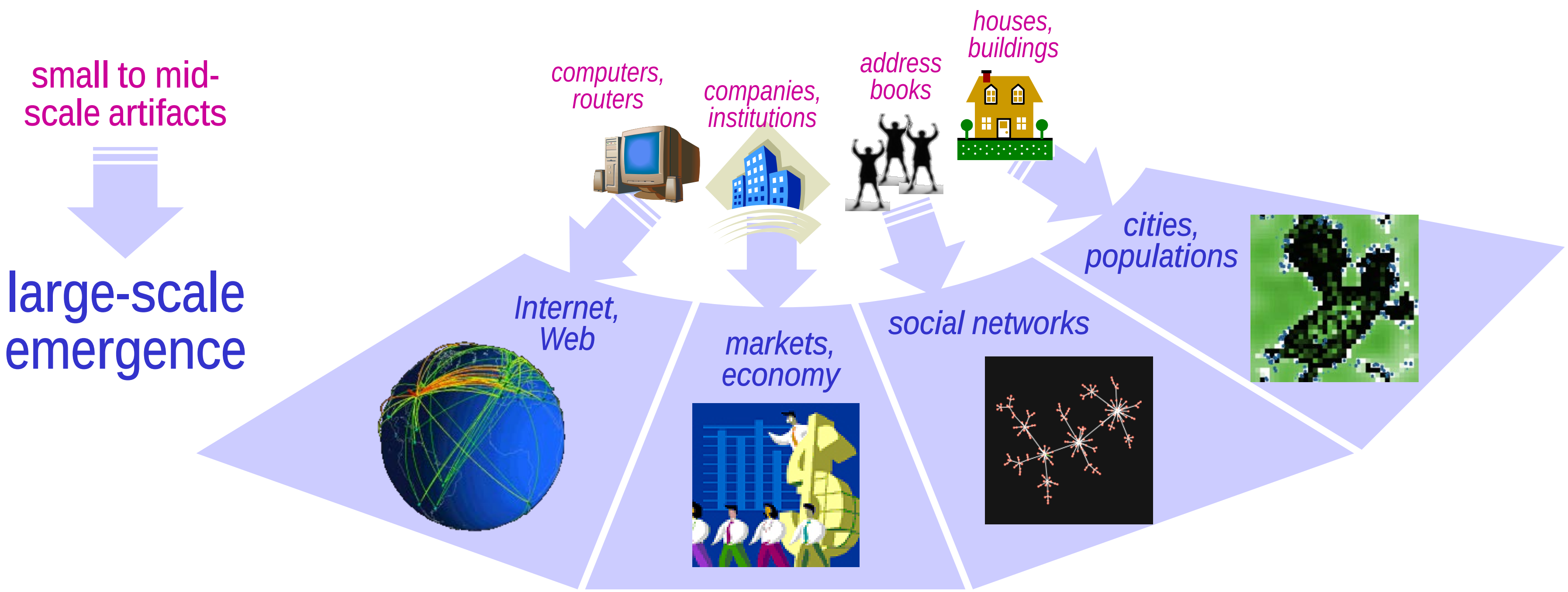
... arising from a multitude of traditionally designed artifacts

houses, buildings

address books

companies, institutions

computers, routers



A Tour of Complex Systems

1. Introduction

   a. What are complex systems?

   b. A vast archipelago

      - *Related disciplines*
      - *Big questions × big objects*
      - *Science ↔ engineering links*

   c. Computational modeling

2. A Complex Systems Sampler

3. Commonalities

4. NetLogo Tutorial

1. Introduction — b. A vast archipelago

➢ Precursor and neighboring disciplines

complexity: measuring the length to describe, time to build, or resources to run, a system

adaptation: change in typical functional regime of a system

systems sciences: holistic (non-reductionist) view on interacting parts

dynamics: behavior and activity of a system over time

multitude, statistics: large-scale properties of systems

- ✓ different families of disciplines *focus* on different aspects
- ✓ (naturally, they intersect a lot: don't take this taxonomy too seriously)

1. Introduction — b. A vast archipelago

➢ 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

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

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

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

1. Introduction — b. A vast archipelago

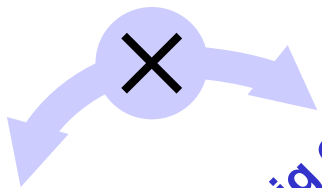
- Sorry, there is no general “complex systems science” or “complexity theory”...
  - ✓ there are a lot of theories and results in related disciplines (“systems theory”, “computational complexity”, etc.), yet
    - such generic names often come from one researcher with one particular view
    - there 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!

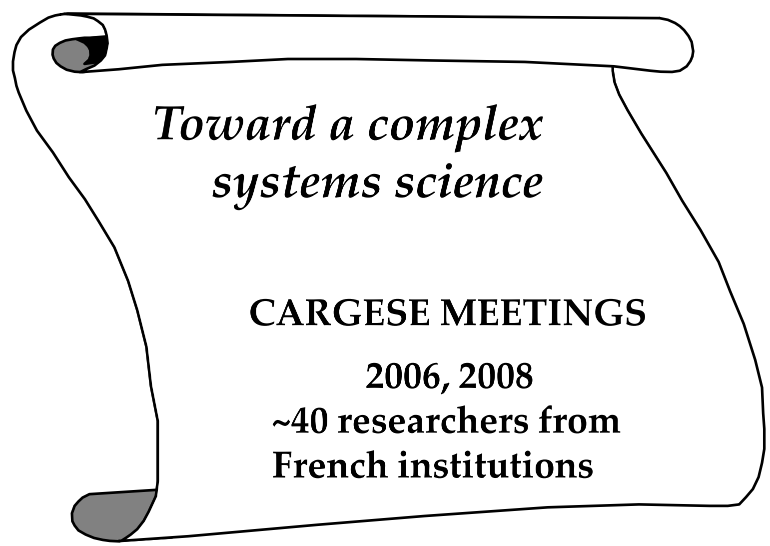
1. Introduction — b. A vast archipelago

➢ The French “roadmap” toward complex systems science

✓ another way to circumscribe complex systems is to list “big (horizontal) questions” and “big (vertical) objects”, and cross them



Big questions \ **Big objects**	subcellular	multicellular / development	physiology	indiv. & social cognition	ecosystems	territorial intell. & sustainability	ubiquitous computing
• reconstruct multiscale dynam.							
• emergence & immergence							
• spatiotemp. morphodynamics							
• optimal control & steering							
• artificial design							
• fluctuations out-of-equilib.							
• adaptation, learning, evolution							

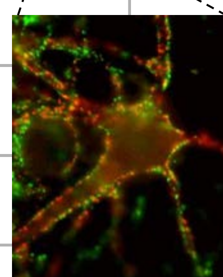


1. Introduction — b. A vast archipelago

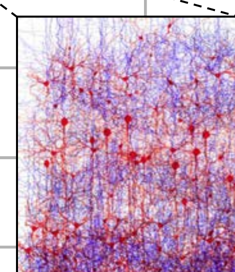
➢ The French “roadmap” toward complex systems science

✓ another way to circumscribe complex systems is to list “big (horizontal) questions” and “big (vertical) objects”, and cross them

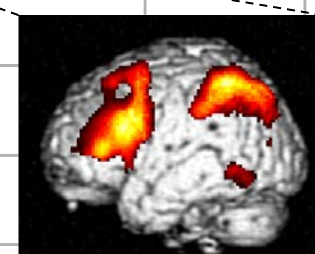
Big questions	**Big objects:** subcellular	multicellular / development	physiology	indiv. & social cognition	ecosystems	territorial intell. & sustainability	ubiquitous computing
• reconstruct multiscale dynam.	**multiscale** →						
• emergence & immergence							
• spatiotemp. morphodynamics							
• optimal control & steering							
• artificial design							
• fluctuations out-of-equilib.							
• adaptation, learning, evolution							



Triller & Dahan



Blue Brain



Laufs et al.

• • •

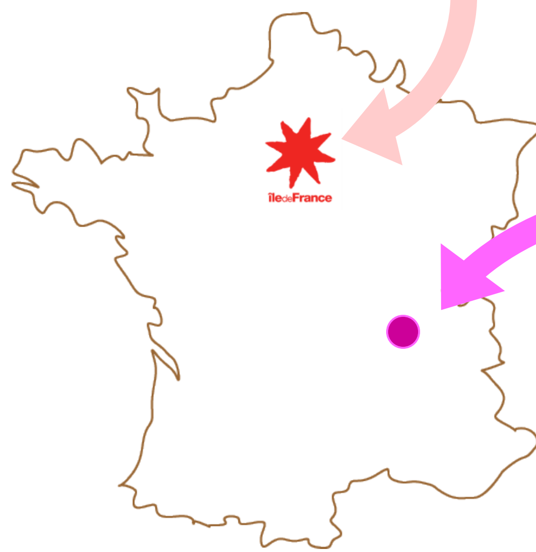
INSTITUT DES SYSTEMES COMPLEXES

Paris Ile-de-France

4^{th} French Complex Systems Summer School, 2010

RNSC

National



IXXI

Lyon Rhône-Alpes

Resident Researchers

Pierre Baudot

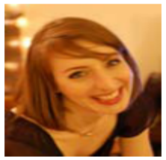
Information Theory - Adaptation - Topology – Thermodynamics of perception.

mathematical neuroscience

René Doursat

Artificial development (self-assembly, pattern formation, spatial computing, evolutionary computation) - Mesoscopic neurodynamics (segmentation, schematization, categorization, perception, cognitive linguistics).

artificial life / neural computing



Marie-Noëlle Comin

Urban systems, networks of cities, innovation, Europe, EU's Framework Programme for Research and Technological Development, converging technologies, NBIC (nanotechnology, biotechnology, information technology and cognitive science).

urban systems / innovation networks

Francesco Ginelli

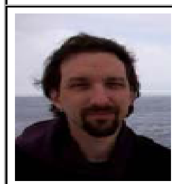
Nonequilibrium statistical mechanics (Active matter, collective motion, flockng, nonequilibrium wetting, directed percolation, long range interactions) - Dynamical system theory (Lyapunov exponents, Lyapunov vectors, synchronization, stable chaos, spatiotemporal chaos, structural stability, hyperbolicity).

statistical mechanics / collective motion

Ivan Junier

Bio-related: Genetic regulation - Cellular organization - DNA/chromatin modeling - -omics (Genomics,Transcriptomics,proteomics,...) - Condensed matter theory - Inference problems in statistical physics - Network analysis (topology, geometry) - Dynamical behaviors of complex systems.
Statistical physics: Out-of equilibrium syste
Thermodynamic description of small syster

structural genomics



Taras Kowaliw

Evolutionary computation, artificial development, computer vision, visualization and electronic art.

computational evolution / development

Telmo Menezes

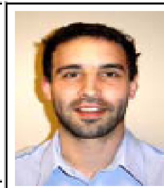
Complex network analysis and simulation - Social networks - Evolutionary search for multi-agent models, Genetic programming applied to programmable networks - Bio-inspired algorithms.

social networks

Bivas Mitra

Peer-to-Peer networks, Blog networks, Complex networks, Statistical mechanics, Networks modeling, Optical networks, Wireless Internet.

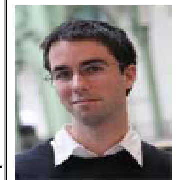
peer-to-peer networks



Romain Reuillon

High performance computing - Grid computing - Scientific workflows - Model exploration - Distributed stochastic simulations - Paralell pseudo-random number generation - Coffee maker.

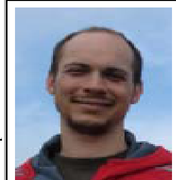
high performance computing



Jean-Baptiste Rouquier

Complex networks: communities, structure, dynamics. Links between fields. Large datasets.
Cellular automata: model of complex systems, perturbation, asynchronism, robustness.

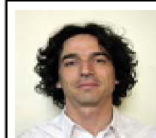
complex networks / cellular automata



Camilo Melani

Grid Computing,Bioemergences Platform (workflow), Mophodynamics reconstruction, Images processing algorithms.

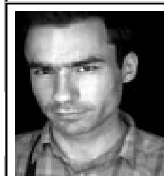
embryogenesis



David Chavalarias

Web mining and Quantitative Epistemology - Cognitive economics and modelling of cultural dynamics - Collective discovery and scientific discovery.

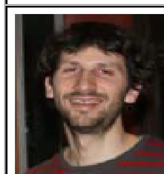
web mining / social intelligence



Srdjan Ostojic

Neuroscience théoriques - Spiking Neurons - Dynamiques Stochastic-ques.

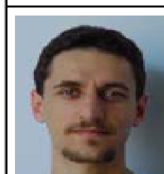
spiking neural dynamics



Andrea Perna

Morphogenesis, Collective behavior, Spatial patterns, Spatial networks.

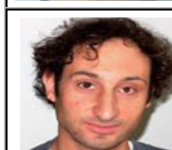
spatial networks / swarm intelligence



Fernando Peruani

Biophysique – Active Matter – Complex Networks.

active matter / complex networks



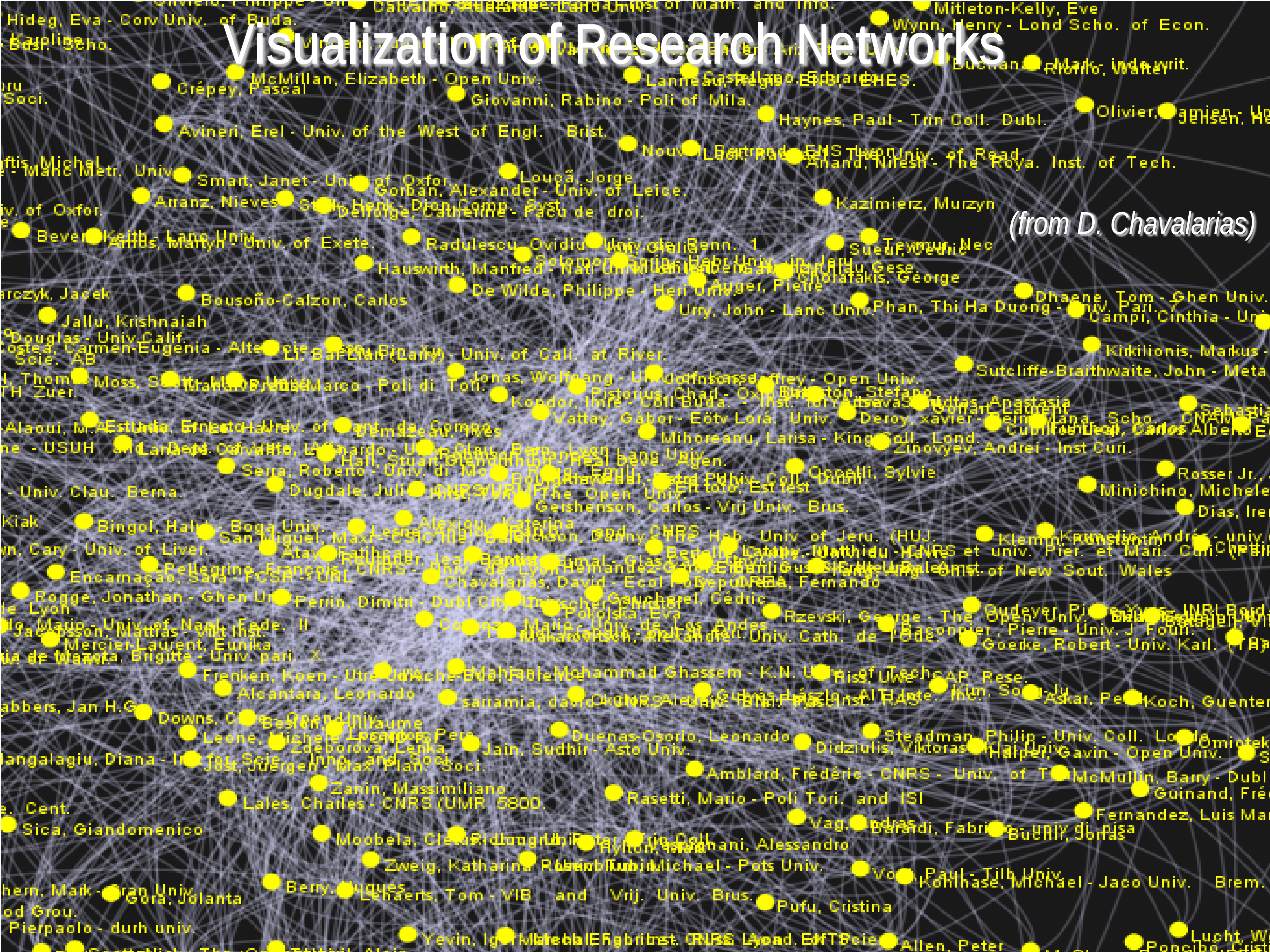
Francesco d'Ovidio

Applied nonlinear dynamics - Transport and mixing in geophysical flows - Interaction of physical and ecological processes in the ocean.

nonlinear dynamics / oceanography

Visualization of Research Networks

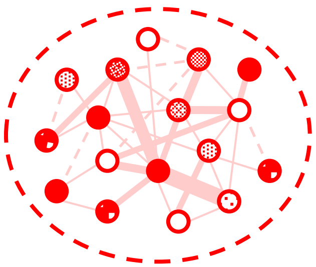
(from D. Chavalarias)



1. Introduction — b. A vast archipelago

➢ The challenges of complex systems (CS) research

Transfers
- among systems

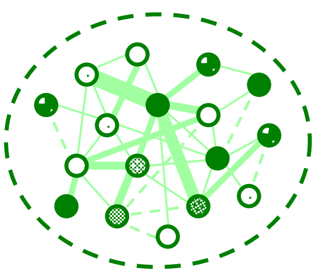


CS science: understanding & modeling "natural" CS

(spontaneously emergent, including human-made)

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

Imports
- observe, model
- control, harness
- design, use



CS (ICT) engineering: designing a new generation of "artificial/hybrid" CS (harnessed & tamed, including nature)

1. Introduction — b. A vast archipelago

➢ Exporting natural CS to artificial disciplines, such as ICT

ex: brain	specific natural or societal complex system	*ex: genes & evolution*
↓	↓	↓
biological neural models	model simulating this system	*laws of genetics*
↓	↓	↓
binary neuron, linear synapse	generic principles and mechanisms (schematization, caricature)	*genetic program, binary code, mutation*
↓	↓	↓
artificial neural networks (ANNs) applied to machine learning & classification	new computational discipline exploiting these principles to solve ICT problems	*genetic algorithms (GAs), evolutionary computation for search & optimization*

1. Introduction — b. A vast archipelago

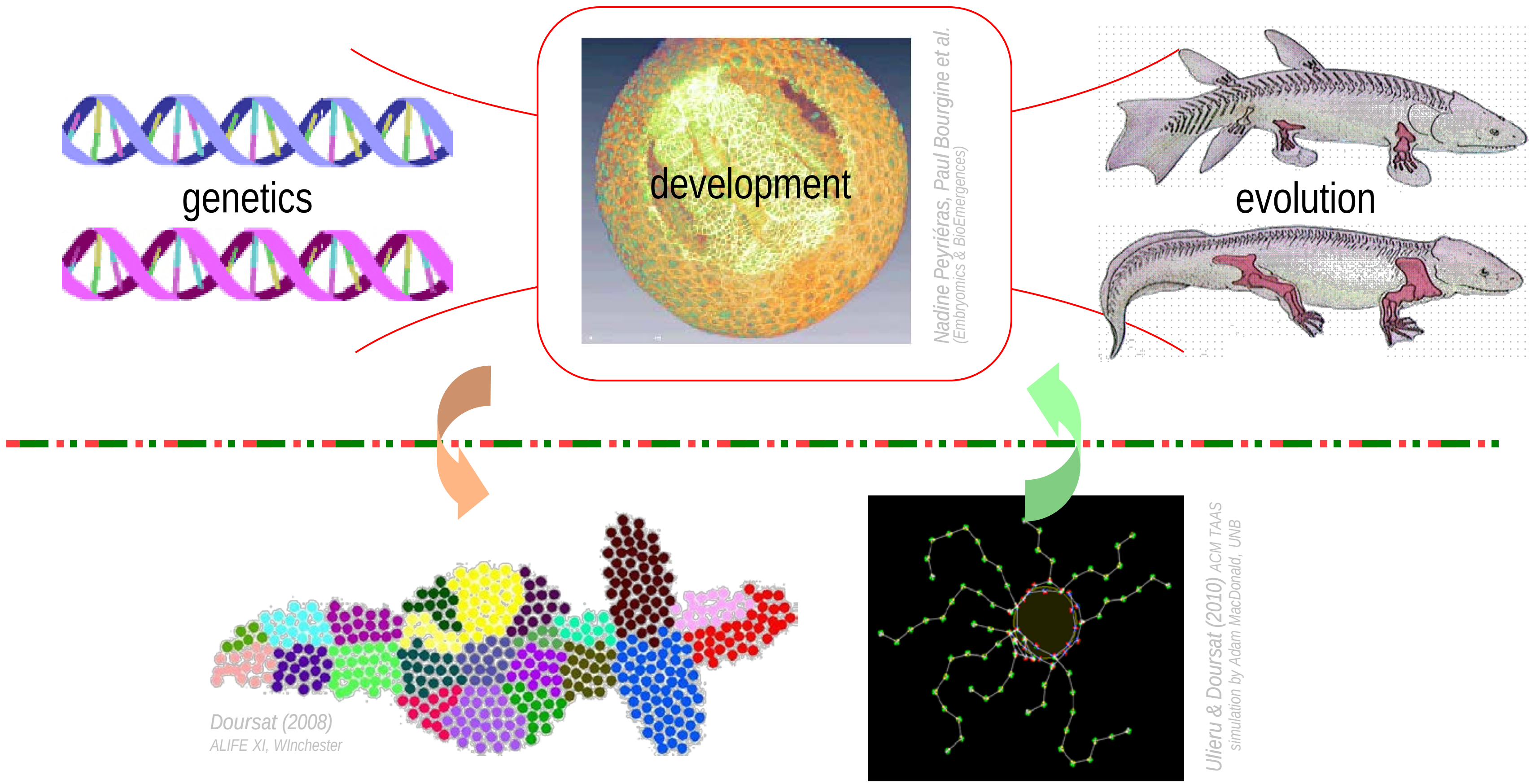
➢ Exporting natural CS to artificial disciplines, such as ICT

ex: ant colonies	specific natural or societal complex system	*ex: bird flocks*
↓	↓	↓
trail formation, swarming	model simulating this system	*3-D collective flight simulation*
↓	↓	↓
agents that move, deposit & follow “pheromone”	generic principles and mechanisms (schematization, caricature)	*“boid”, separation, alignment, cohesion*
↓	↓	↓
ant colony optimization (ACO) applied to graph theoretic & networking problems	new computational discipline exploiting these principles to solve ICT problems	*particle swarm optimization (PSO) “flying over” solutions in high-D spaces*

1. Introduction — b. A vast archipelago

- Another source of inspiration: biological morphogenesis—the epitome of a self-architecting system

  → *exploring computational multi-agent models of evolutionary development ...*



... toward possible outcomes in distributed, decentralized engineering systems

A Tour of Complex Systems

1. Introduction
   a. What are complex systems?
   b. A vast archipelago
   c. Computational modeling
2. A Complex Systems Sampler
3. Commonalities
4. NetLogo Tutorial

1. Introduction — c. Computational modeling

➢ What this course is about

- ✓ an *exploration* of various complex systems *objects* (i.e., made of many agents, with simple or complex rules, and complex behavior):
  - cellular automata, pattern formation, swarm intelligence, complex networks, spatial communities, structured morphogenesis
- ✓ and their common *questions*:
  - emergence, self-organization, positive feedback, decentralization, between simple and disordered, “more is different”, adaptation & evolution
- ✓ by interactive *experimentation* (using NetLogo),
- ✓ introducing *practical* complex systems *modeling* and simulation
- ✓ from a *computational* viewpoint, in contrast with a “mathematical” one (i.e., formal or numerical resolution of symbolic equations),
- ✓ based on discrete *agents* moving in discrete or quasi-continuous space, and *interacting* with each other and their environment

1. Introduction — c. Computational modeling

➢ What this course is *not*

- ✓ a technical course about the archipelago of related disciplines
  - an information theory / computational complexity class
  - a dynamical systems / chaos / fractals / stochastic processes class
  - a systems engineering / control theory class
  - a graph theory / networks / statistical physics class
- ✓ a technical course about big questions × big objects
  - a fluid dynamics class
  - a condensed matter class
  - an embryology class
  - a neuroscience class
  - an entomology class
  - a sociology class
  - an economics class
  - ...

you can wake up now

... but what about the math?

➢ Existence of macro-equations for some dynamic systems

- ✓ we are typically interested in obtaining an explicit description or expression of the behavior of a whole system over time
- ✓ in the case of dynamical systems, this means *solving* their evolution rules, traditionally a set of ***differential equations*** (DEs)
- ✓ either *ordinary* (O)DEs of *macro-variables* in *well-mixed* systems
  - ex: in chemical kinetics, the law of mass action governing concentrations:

    $\alpha A + \beta B \rightarrow \gamma C$ described by $d[A]/dt = -\alpha k\, [A]^\alpha\, [B]^\beta$
  - ex: in economics, (simplistic) laws of gross domestic product (GDP) change:

    $dG(t)/dt = \rho\, G(t)$
- ✓ or *partial* (P)DEs of *local variables* in *spatially extended* systems
  - ex: heat equation: $\partial u/\partial t = \alpha \nabla^2 u$, wave equation: $\partial^2 u/\partial t^2 = c^2 \nabla^2 u$
  - ex: Navier-Stokes in fluid dynamics, Maxwell in electromagnetism, etc.

1. Introduction — c. Computational modeling

➢ Existence of macro-equations and an analytical solution

- ✓ in some cases, the explicit formulation of an exact solution can be found by calculus, i.e., the *symbolic manipulation of expressions*
  - ex: geometric GDP growth $\Rightarrow$ exponential function

    $dG(t)/dt = \rho\, G(t) \quad \Rightarrow \quad G(t) = G(0)\, e^{-\rho\, t}$

  - ex: heat equation $\Rightarrow$ linear in 1D borders; widening Gaussian around Dirac

    $\partial u/\partial t = \alpha\, \partial^2 u/\partial^2 x$ and $u(x,0) = \delta(x) \quad \Rightarrow \quad \boxed{u(x,t) = \frac{1}{\sqrt{4\pi k t}} \exp\left(-\frac{x^2}{4kt}\right)}$

- ✓ calculus (or analysis) relies on known shortcuts in the world of mathematical "regularities", i.e., mostly the family of continuous, derivable and integrable functions that can be expressed symbolically

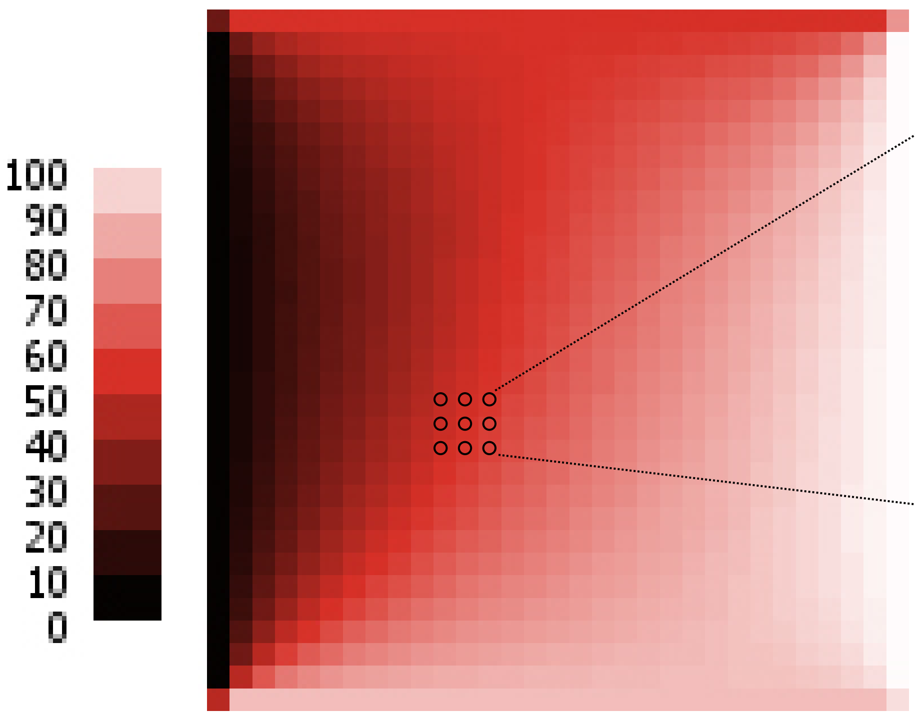
$\rightarrow$ *unfortunately, although vast, this family is in fact very small compared to the immense range of dynamical behaviors that natural complex systems can exhibit!*

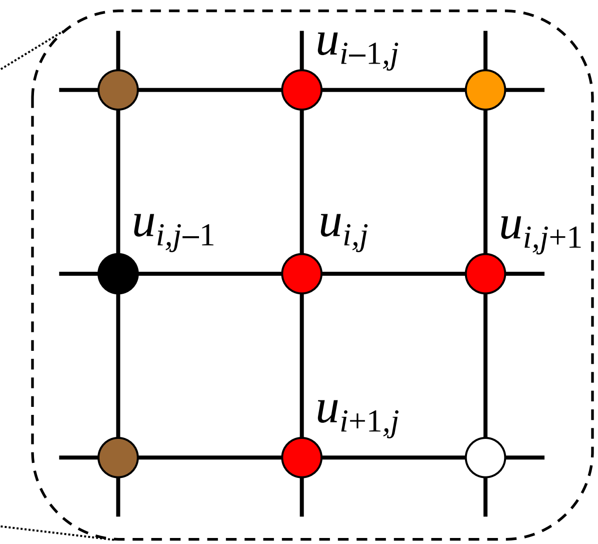
1. Introduction — c. Computational modeling

➢ Existence of macro-equations but no analytical solution

- ✓ when there is no symbolic resolution of an equation, *numerical analysis* involving algorithms (step-by-step recipes) can be used
- ✓ it involves the discretization of space into cells, and time into steps

NetLogo model: /Chemistry & Physics/Heat/Unverified/Heat Diffusion





$\partial u/\partial t = \alpha \nabla^2 u$ by forward Euler $\Rightarrow$

$$\Delta u_{i,j} = \alpha\left(u_{i,j-1} + u_{i,j+1} + u_{i-1,j} + u_{i+1,j} - 4u_{i,j}\right)$$

1. Introduction — c. Computational modeling

➢ Absence of macro-equations

- ✓ *"The study of non-linear physics is like the study of non-elephant biology."* —Stanislaw Ulam
  - the physical world is a fundamentally *non-linear* and *out-of-equilibrium* process
  - focusing on linear approximations and stable points is missing the big picture in most cases

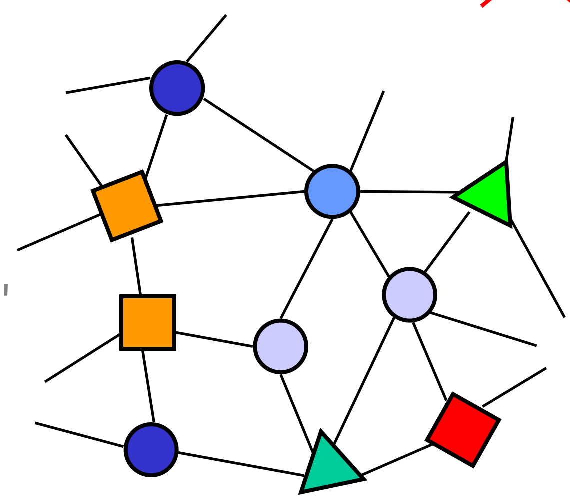
- ✓ let's push this quip: *"The study of non-analytical complex systems is like the study of non-elephant biology."* —??
  - complex systems have their own "elephant" species, too: dynamical systems that can be described by diff. eqs or statistical laws

  → *most real-world complex systems do not obey neat macroscopic laws*

➢ Where global ODEs and spatial PDEs break down...

ex: embryogenesis

- ✓ systems that *no macroscopic quantity* suffices to explain ~~(ODE)~~
  - no law of "concentration", "pressure", or "gross domestic product"
  - even if global metrics can be designed to give an indication about the system's dynamical regimes, they rarely obey a given equation or law
- ✓ systems that require a *non-Cartesian* decomposition of space ~~(PDE)~~
  - network of irregularly placed or mobile *agents*
- ✓ systems that contain ***heterogeneity***
  - segmentation into different *types of agents*
  - at a fine grain, this would require a "patchwork" of regional equations (ex: embryo)
- ✓ systems that are dynamically *adaptive*
  - the topology and strength of the interactions depend on the short-term activity of the agents and long-term "fitness" of the system in its environment

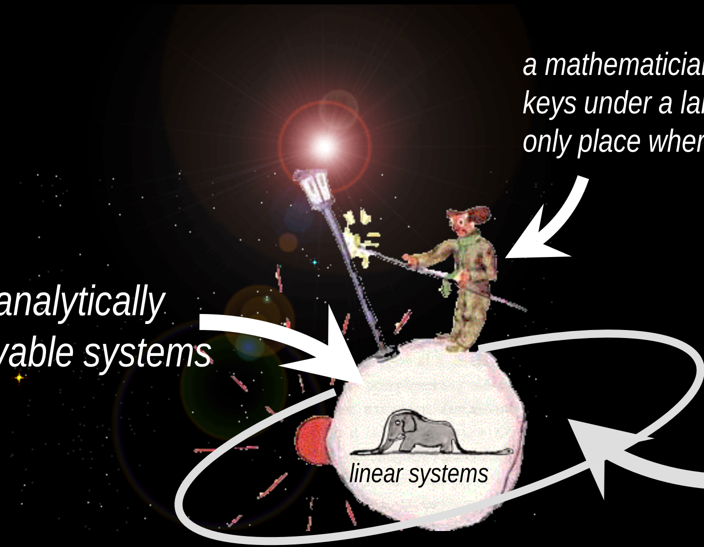


1. Introduction — c. Computational modeling

➢ The world of complex systems modeling

a mathematician (physicist?) looking for his keys under a lamp post, because this is the only place where there is (analytical) light

analytically solvable systems



analytically expressable, numerically solvable systems

all the rest:

non-analytically expressable systems

⇒ computational models

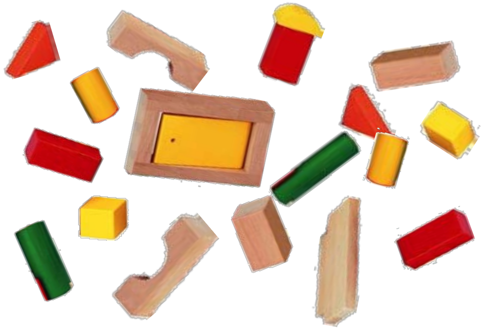
The Lamplighter & the Elephant-Digesting Boa, from "The Little Prince"
Antoine de Saint-Exupéry

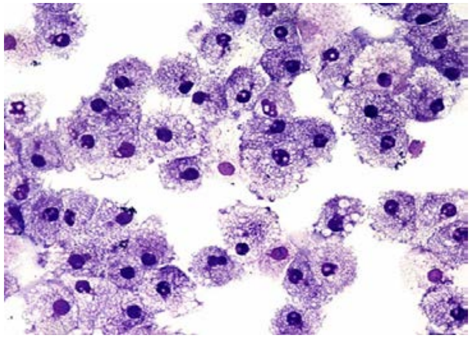
1. Introduction — c. Computational modeling

➢ The world of computational (agent) modeling

- ✓ not a cold and dark place!... it is teeming with myriads of *agents* that carry (micro-)*rules*

a computer scientist (physicist?) populating the world with agents

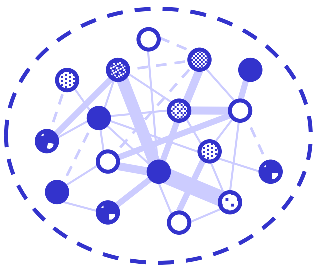




- ✓ the operational concept of “agent” is inspired from “social” groups: people, insects, cells, modules: agents have *goals* and *interactions*

1. Introduction — c. Computational modeling

- ABM meets MAS: two (slightly) different perspectives

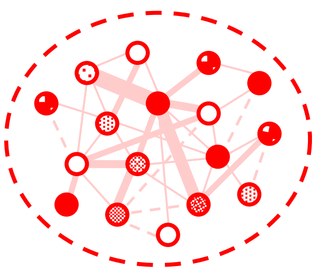


CS science: understand "natural" CS

→ *Agent-Based Modeling (ABM)*

... "Multi Agent-Based Modeling and Simulation Systems" (MABMSS)??

computational complex systems



CS engineering: design a new generation of "artificial" CS → *Multi-Agent Systems (MAS)*

✓ but again, don't take this distinction too seriously! they overlap a lot

1. Introduction — c. Computational modeling

➢ ABM: the modeling perspective from CA & social science

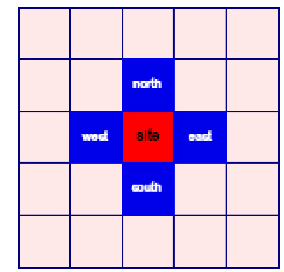
- ✓ *agent-* (or individual-) ***based modeling*** (ABM) arose from the need to model systems that were too complex for analytical descriptions

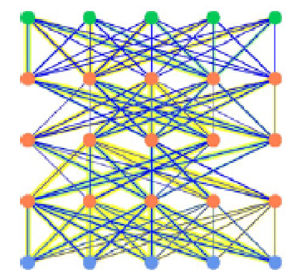
- ✓ one origin: cellular automata (CA)
  - von Neumann self-replicating machines → Ulam's "paper" abstraction into CAs → Conway's *Game of Life*
  - based on ***grid*** topology

- ✓ other origins rooted in economics and social sciences
  - related to "methodological individualism"
  - mostly based on grid and ***network*** topologies

- ✓ later: extended to ecology, biology and physics
  - based on grid, network and 2D/3D ***Euclidean*** topologies

→ *the rise of fast computing made ABM a practical tool*



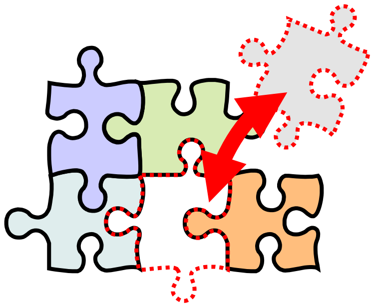


Macal & North
Argonne National Laboratory

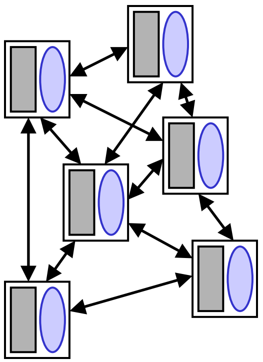
1. Introduction — c. Computational modeling

➢ MAS: the engineering perspective from computer sci. & AI

- ✓ in software engineering, the need for clean *architectures*
  - historical trend: breaking up big monolithic code into *layers*, *modules* or *objects* that communicate via application programming *interfaces* (APIs)
  - this allows fixing, upgrading, or replacing parts without disturbing the rest
- ✓ in AI, the need for *distribution* (formerly “DAI”)
  - break up big systems into smaller units creating a decentralized computation: *software/intelligent agents*



- ✓ difference with object-oriented programming:
  - agents are “proactive” / autonomously threaded
- ✓ difference with distributed (operating) systems:
  - agents don’t appear transparently as one coherent system



→ *the rise of pervasive networking made distributed systems both a necessity and a practical technology*

1. Introduction — c. Computational modeling

- **MAS: the engineering perspective from computer sci. & AI**
  - ✓ emphasis on software agent as a *proxy* representing human users and their interests; users state their prefs, agents try to satisfy them
    - ex: internet agents searching information
    - ex: electronic broker agents competing / cooperating to reach an agreement
    - ex: automation agents controlling and monitoring devices
  - ✓ main tasks of MAS programming: agent design and society design
    - an agent can be ± reactive, proactive, deliberative, social (Wooldridge)
    - an agent is caught between (a) its own (complicated) goals and (b) the constraints from the environment and exchanges with the other agents

→ *slight contrast between the MAS and ABM philosophies*

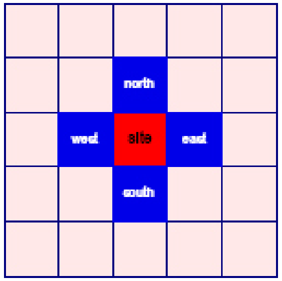
- MAS: focus on few "heavy-weight" (big program), "selfish", intelligent agents – ABM: many "light-weight" (few rules), highly "social", simple agents
- MAS: focus on game theoretic gains – ABM: collective emergent behavior

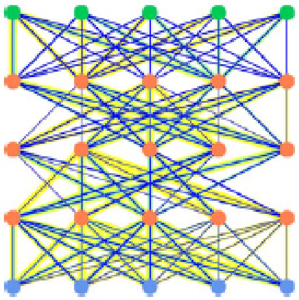
1. Introduction — c. Computational modeling

➢ An agent in this course

- ✓ a (small) program deemed “local” or “autonomous” because it has
  - its own scheduling (execution process or thread)
  - its own memory (data encapsulation)
  - ... generally simulated in a virtual machine
- ✓ this agent-level program can consist of
  - *a set of dynamical equations (“reactive”)* ***at the microscopic level***
  - *a set of logical rules (AI)... or a mix of both*
- ✓ peer-to-peer interactions among agents under different topologies

Hugo Weaving as Agent Smith
The Matrix Revolutions, Warner Bros.

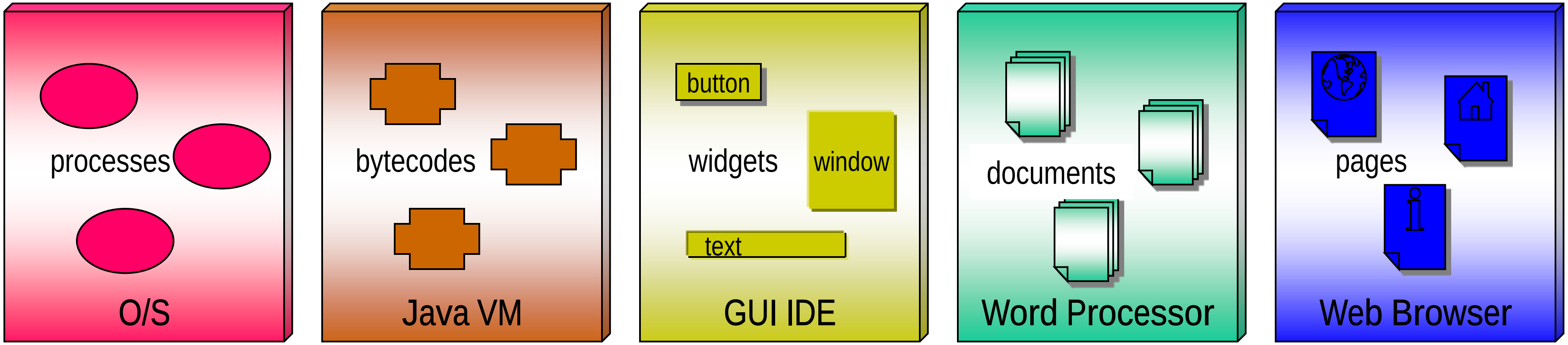




1. Introduction — c. Computational modeling

➢ Agent virtual machines or “platforms”

✓ just like there are various middleware-componentware frameworks...



✓ ... there are also ABM platforms, e.g., *NetLogo*, *Swarm*, or *Repast*