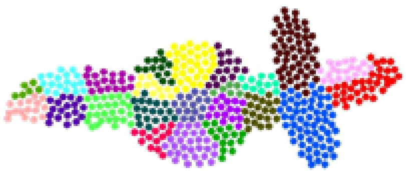
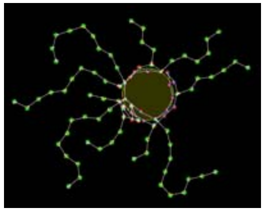
LSE COMPLEXiTY research seminar



Complex systems as



"self-made puzzles" that can be programmed

Lessons from biological morphogenesis

René Doursat

http://doursat.free.fr

INSTITUT DES SYSTEMES COMPLEXES

ISC PARIS ÎLE DE FRANCE

INSTITUT DES SYSTEMES COMPLEXES
Paris Ile-de-France

INSTITUT DES SYSTEMES COMPLEXES PARIS ÎLE DE FRANCE

ISC

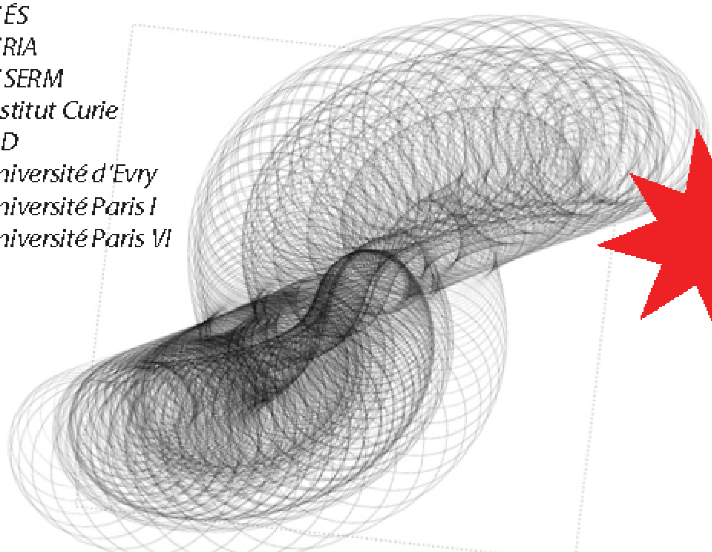
"Une action de coordination régionale"

L'Institut des Systèmes Complexes, Paris Île-de-France (ISC-PIF) rassemble des chercheurs issus de disciplines différentes qui souhaitent travailler ensemble sur les grandes questions posées par les systèmes complexes.

Véritable tête de pont d'un réseau qui regroupe tous les acteurs académiques et privés concernés par la science des systèmes complexes, l'ISC-PIF crée des liens nouveaux au-delà des frontières des laboratoires et des centres R&D.

Nos Partenaires

Région Île-de-France
CNRS
CEA
École Polytechnique
EHESS
ENS Ulm
EPHE
Genopole
IHÉS
INRIA
INSERM
Institut Curie
IRD
Université d'Evry
Université Paris I
Université Paris VI



Feuille de route

L'action de coordination régionale « systèmes complexes » a pour but d'identifier et de structurer le réseau francilien de la recherche en systèmes complexes. Fruit des premières années d'investigation, une feuille de route a été rédigée par 70 scientifiques. Cette dernière permet aujourd'hui de rassembler un grand nombre de chercheurs autour des thèmes les plus prometteurs. Elle participe à la définition des programmes et des appels de l'ANR et de l'Union Européenne.

Les événements « systèmes complexes »

Qu'ils soient sous forme de **séminaires, ateliers, colloques ou conférences**, les événements organisés par l'ISC-PIF n'ont qu'un but : créer un espace de travail de haut niveau sur des problèmes pointus et d'actualité en science des systèmes complexes. Ces événements sont organisés, co-organisés ou co-animés par les chercheurs invités et partenaires de l'ISC-PIF, tout au long de l'année.

Des actions de formation et de recherche

Les **écoles d'été internationales**, co-organisées entre les différents instituts, ont pour but de former les chercheurs de différents horizons scientifiques souhaitant se familiariser avec la science des systèmes complexes. Les cours sont enregistrés et disponibles en ligne pour une diffusion maximale. L'une des spécificités de ces écoles est leur interdisciplinarité, rendue indispensable par celle des systèmes complexes. Au cours de l'année, des **instituts thématiques** d'une semaine sont également organisés par l'ISC-PIF. Ces cours, enseignés par d'excellents conférenciers invités spécialement pour l'occasion, sont un moyen important de faire le point sur les avancées et directions à privilégier.
L'ISC-PIF encourage également le développement de **Masters et doctorats européens « systèmes complexes »** et soutient le projet d'une **Université ouverte des systèmes complexes** au niveau européen, pour faire face aux importants besoins de formation interdisciplinaire.

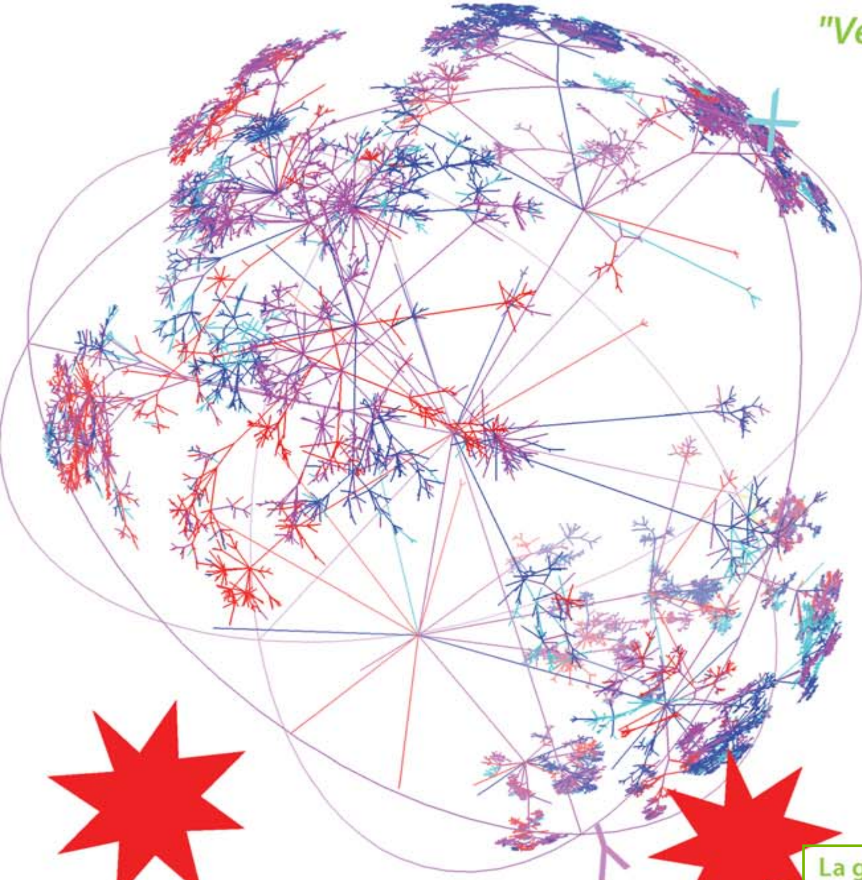
Un portail interactif

L'ISC-PIF offre un portail interactif (*iscpif.fr*) qui est le lieu où chaque chercheur, chaque équipe, chaque centre peut s'identifier comme appartenant à la communauté des systèmes complexes et se fédérer avec les autres au sein d'un espace créatif commun pour **élaborer et partager des contenus scientifiques**. Cet espace créatif s'intègre dans un réseau européen multi-site *(csregistry.org)* qui partage la même volonté de servir les acteurs de la science des systèmes complexes.

http://iscpif.fr

INSTITUT DES SYSTEMES COMPLEXES PARIS ÎLE DE FRANCE

"Vers un réseau francilien de recherche avancée"



Mise en réseau des équipes de recherche

L'ISC développe une stratégie de **mise en réseau des équipes de recherche** et de leurs locaux, distribués sur l'ensemble de la région avec un centre à Paris. L'ensemble des équipes de recherche est intégré dans **un système de visioconférence** pour faciliter les interactions et créer des liens dans les réseaux scientifiques, indépendamment de la distance géographique ou de l'appartenance institutionnelle et disciplinaire. Grâce **aux antennes ISC-PIF,** un cap sera franchi. En effet, ces antennes hébergeront des projets de recherche et de nouvelles équipes, qui pourront ensuite se développer au sein des partenaires. C'est là un rôle majeur de l'institut. Une antenne a déjà été installée au CEA sur le plateau de Saclay, qui connaît un développement scientifique très fort. D'autres antennes seront installées en 2009 et 2010 à l'Ecole Polytechnique, au CNRS de Gif-sur-Yvette, et chez d'autres partenaires.

Un soutien direct aux chercheurs

Le programme de **recrutement de chercheurs invités** sur appel d'offre international se poursuit en 2009 et renforce le développement de recherches à la frontière des sciences. La venue de jeunes chercheurs de haut niveau, sur une période de deux ou trois ans, est l'un des meilleurs moyens de maintenir l'activité de recherche de l'institut et de préparer des vagues successives de projets. L'**appel à idées** est une autre forme de soutien de chercheurs grâce au financement initial de projets innovants et ambitieux, sortant des cadres traditionnels des agences de moyens. Ces projets interdisciplinaires portent sur l'organisation de réseaux de recherche ou des événements (colloques, réunions) dans le domaine des systèmes complexes. L'appel d'offre est ouvert à l'ensemble du territoire.

Les relations avec l'industrie

En 2009, l'ISC-PIF renforce ses relations avec l'industrie grâce à un double programme : le montage de **contrats d'intérêt commun avec les industriels**, et le projet de **Fondation des Systèmes Complexes**. Cette dernière est complémentaire de l'institut car elle vise à favoriser les relations entre des chercheurs du réseau ISC et les industriels. Ces partenariats offriront de nouveaux crédits à moyen terme à des programmes scientifiques qui ont une valeur fondamentale pour la science mais également un potentiel applicatif pour l'industrie, tout en répondant aux grands enjeux sociétaux sur la santé, l'écologie, l'économie, etc.

La grille de calcul

Une stratégie de mise en réseau des plate-formes expérimentales permet de partager de puissants moyens en calcul et des logiciels libres autour du portail de l'ISC-PIF. La **grille « systèmes complexes » francilienne**, installée en 2008, s'intègre dans la Grille Île-de-France (GRIF), elle-même immergée dans le réseau européen GEANT. Cet outil d'envergure autorise le traitement de très grandes masses de données, telles celles nécessaires pour la reconstruction des dynamiques multi-échelles, de la modélisation et des simulations de grandes dimensions. L'ISC-PIF a pour ambition de devenir le moteur d'un vaste mouvement francilien de partage et d'utilisation de la grille de calcul et de son extension nationale et européenne.

http://iscpif.fr

Systems that are self-organized and architectured

the challenge for complex systems: integrate a true ***architecture***

the challenge for complicated systems: integrate ***self-organization***

free self-organization

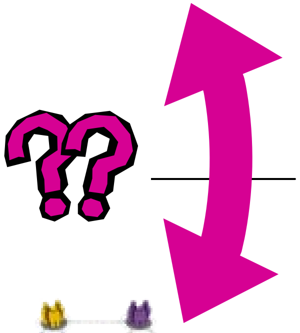
deliberate design

designed self-organization / self-organized design

Toward programmable self-organization

➢ Self-organized systems

- ✓ a myriad of self-positioning agents
- ✓ collective order is not imposed from outside (only influenced)
- ✓ comes from purely *local* information & interaction around each agent
- ✓ no agent possesses the global map or goal of the system
- ✓ but every agent may contain all the *rules* that contribute to it



➢ Structured systems

- ✓ true *architecture*: non-trivial, complicated morphology
  - *hierarchical*, multi-scale: regions, parts, details, agents
  - *modular*: reuse, quasi-repetition
  - *heterogeneous*: differentiation & divergence in the repetition
- ✓ *random* at the microscopic level, *but reproducible* (quasi deterministic) at the mesoscopic and macroscopic levels

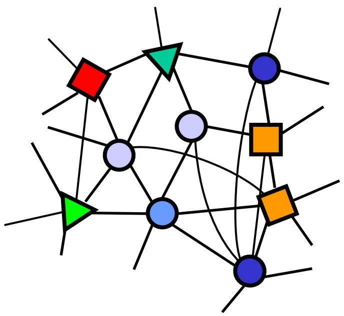
Self-made puzzles that can be programmed

1. Techno-social networks and multi-agent modeling
2. Complex systems: from statistical to morphological
3. Harnessing complexity by "meta-design"
4. A possible direction: morphogenetic engineering
5. Toward programmable networks

Overview

➢ Harnessing complex techno-social systems

ubiquitous computing & communication capabilities create entirely *new myriads of user-device interactions* from the bottom up



explosion in size and complexity of techno-social networks in all domains: energy, education, healthcare, business, defense

de facto complex systems with spontaneous collective behavior that we don’t quite understand or control yet

time to design new collaborative rules and technologies to harness this decentralization and emergence

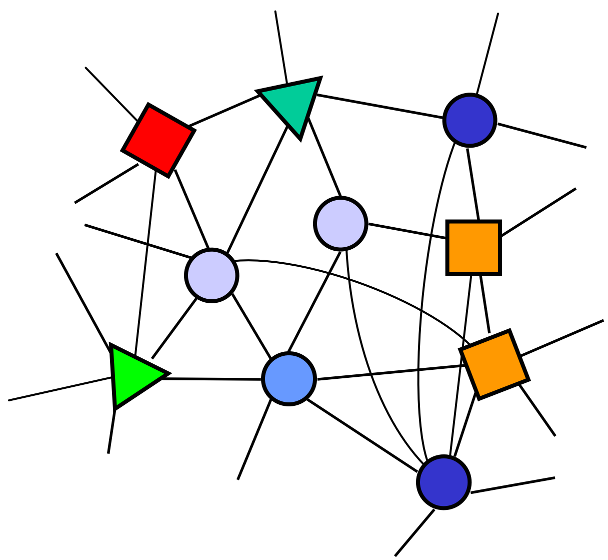
Complex techno-social systems

➢ The rise of techno-social networks

- ✓ explosion in size and complexity of networked techno-social systems in all domains of society:
  - healthcare
  - education
  - business
  - energy & environment
  - defense & security
  - etc.
- ✓ opened the door to entirely new forms of social organization characterized by a increasing degree of **decentralization** and **self-organization**

Complex techno-social systems

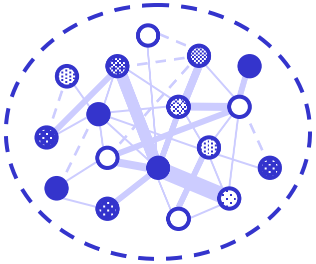
- **De facto distribution over a myriad of users and devices**
  - ✓ ubiquitous computing and communication capabilities connect people and infrastructures in unprecedented ways
  - ✓ complex techno-social systems based on bottom-up interactions among a myriad of artifacts and **humans** ...



  - ✓ ... via computing hardware, and **software agents**

Complex techno-social systems

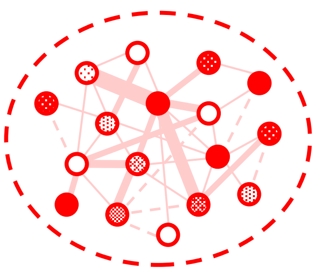
- Understanding → guiding, causing, designing



Understanding "natural" (spontaneous) emergence

→ *Agent-Based Modeling (ABM)*

designing complex techno-social systems



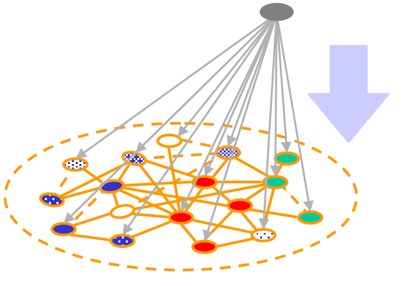
Guiding & causing a new "artificial" emergence

→ *Multi-Agent Systems (MAS)*

Complex techno-social systems

➢ Users: decentralized read-write access to information

- ✓ first, information was centralized in a few hands (news, experts)
  - printing, moving, physically exchanging
- ✓ then, Internet made its access ("reading") decentralized
  - staying home, browsing, downloading in electronic format
- ✓ now, **creation** of information ("writing") is also decentralized
  - blogs, wikis, sharing, social networking
- ✓ shift of the center of mass in many domains
  - ... from a centralized hierarchy (oligarchy) of providers of *data, knowledge, management, information, energy, etc.*
  - ... to a densely heterarchy of proactive participants: *patients, students, employees, users, consumers, etc.*



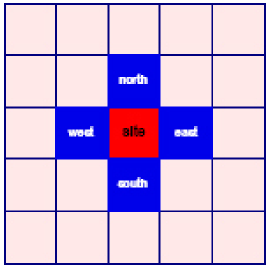
→ *creates full-fledged complex systems of two-way interactions among multiple users, via distributed software applications*

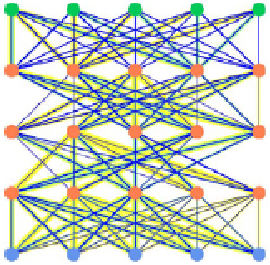
Complex techno-social systems

➢ Users: the modeling perspective of the social sciences

- ✓ *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*



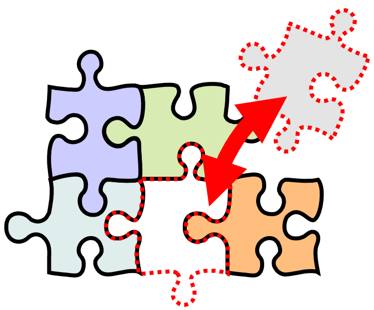


Macal & North
Argonne National Laboratory

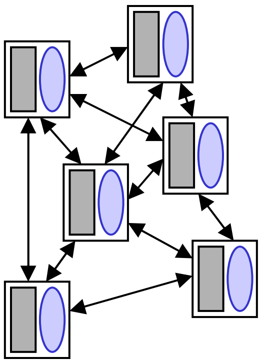
Complex techno-social systems

➢ Software & devices: decentralized computation

- ✓ 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 "intelligent" systems into smaller, less exhaustive units: *software / intelligent agents*



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



Complex techno-social systems

➢ Software: the multi-agent perspective of computer science

- ✓ 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 (sophisticated) 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

Why multi-agent modeling?

- **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.

Why multi-agent 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 ⇒ exponential function

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

    - ex: heat equation ⇒ linear in 1D borders; widening Gaussian around Dirac

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

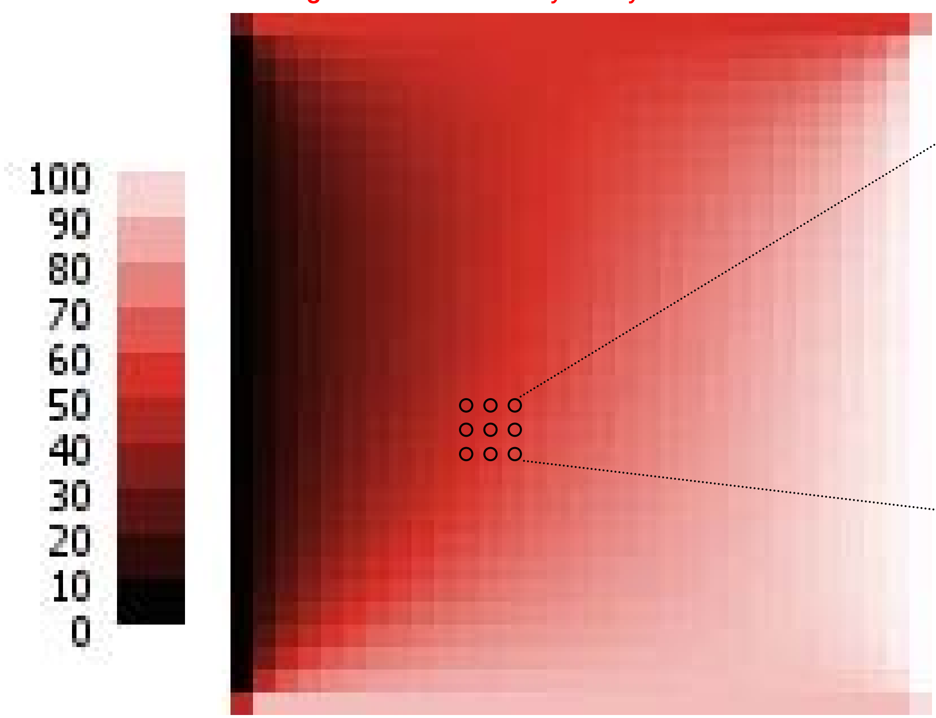
  - ✓ calculus (or analysis) relies on known shortcuts in the world of mathematical "regularities", i.e., the family of continuous, derivable and integrable functions that can be expressed symbolically

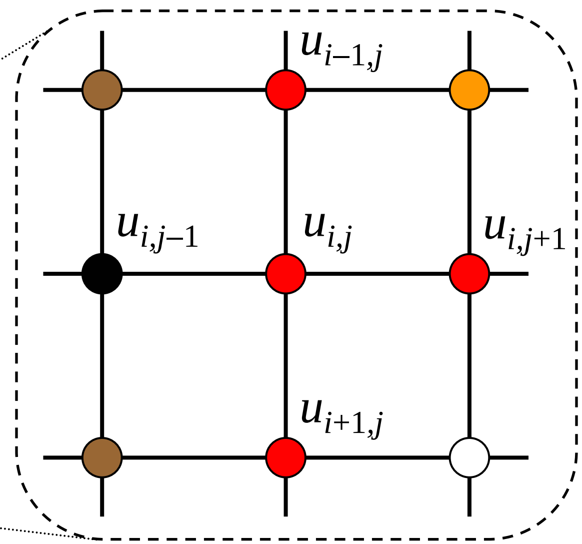
→ *unfortunately, although vast, this family is in fact very small compared to the immense range of dynamical behaviors that natural complex systems can exhibit!*

Why multi-agent 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 $\Rightarrow$

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

Why multi-agent 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

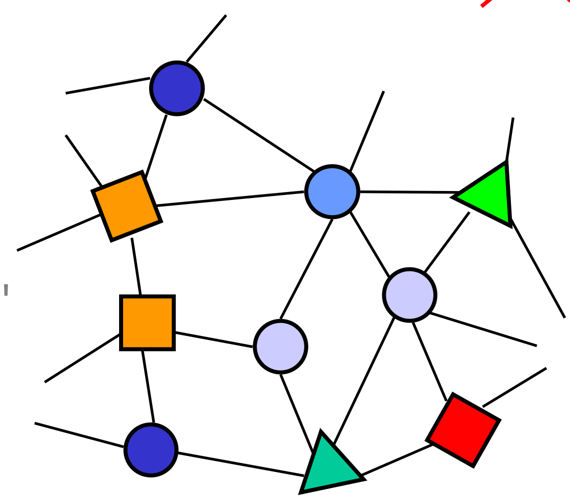
- ✓ let's push this quip: *"The study of non-analytical complex systems is like the study of non-elephant biology."* —??
  - complex systems have their own "elephant" species, too: dynamical systems that can be described by diff. eqs or statistical laws
  - many real-world complex systems do not obey neat macroscopic laws

Why multi-agent modeling?

- **Where global ODEs and spatial PDEs break down...**

morphogenesis

- ✓ 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

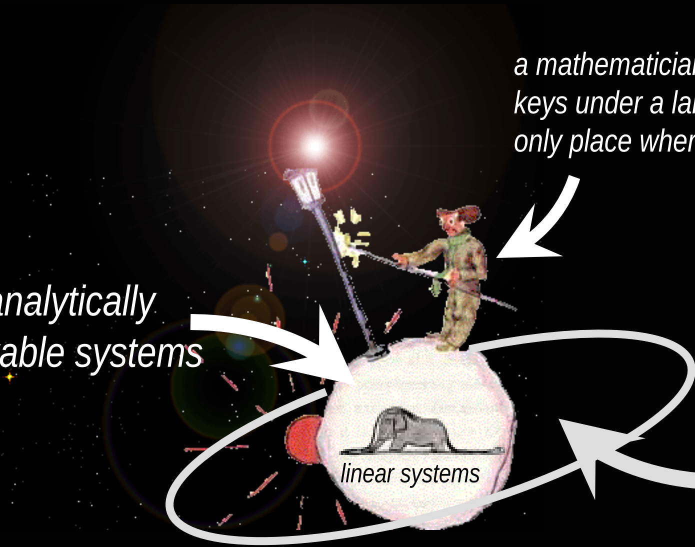


Why multi-agent modeling?

- 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

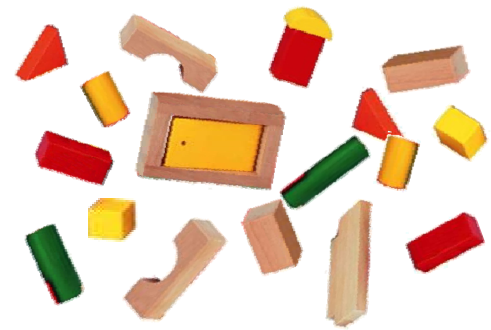
⇒ computational models

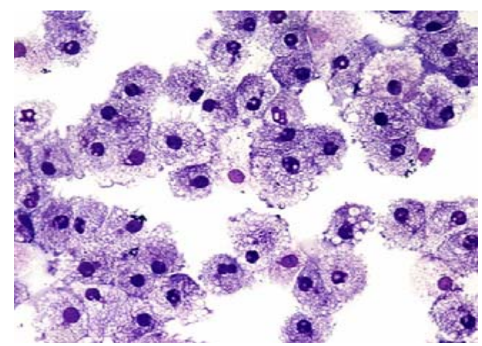
The Lamplighter & the Elephant-Digesting Boa, from "The Little Prince"
Antoine de Saint-Exupéry (born in Lyon)

Why multi-agent modeling?

- The world of multi-agent (computational) 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





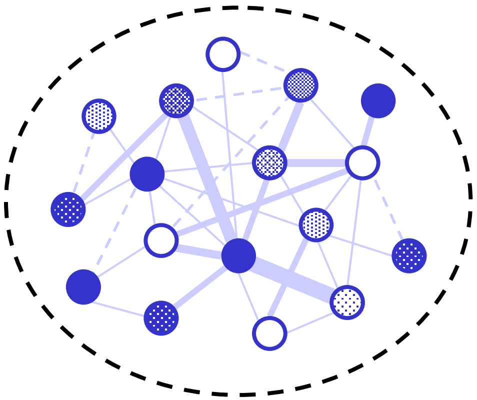
  - ✓ the operational concept of "agent" is inspired from "social" groups: people, insects, cells, modules: agents have *goals* and *interactions*

Self-made puzzles that can be programmed

1. Techno-social networks and multi-agent modeling
2. Complex systems: from statistical to morphological
3. Harnessing complexity by "meta-design"
4. A possible direction: morphogenetic engineering
5. Toward programmable networks

Complex systems

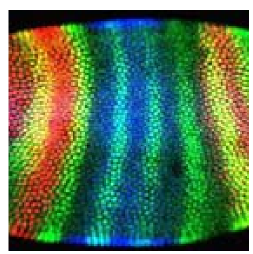
➢ We are faced with complex systems in many domains



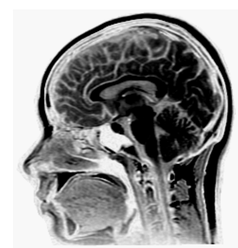
- **large** number of elementary **agents** interacting **locally**
- simple individual behaviors creating a complex **emergent** collective behavior
- *decentralized dynamics: no master blueprint or grand architect*
- **self-organization** and **evolution** of innovative order

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

pattern formation
○ = matter

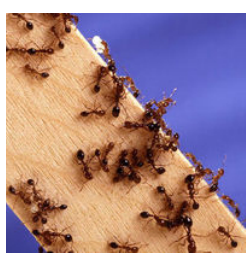


biological development
○ = cell

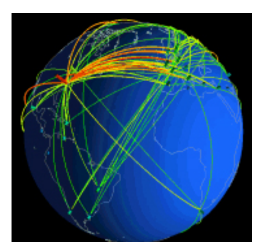


the brain & cognition
○ = neuron

insect colonies
○ = ant



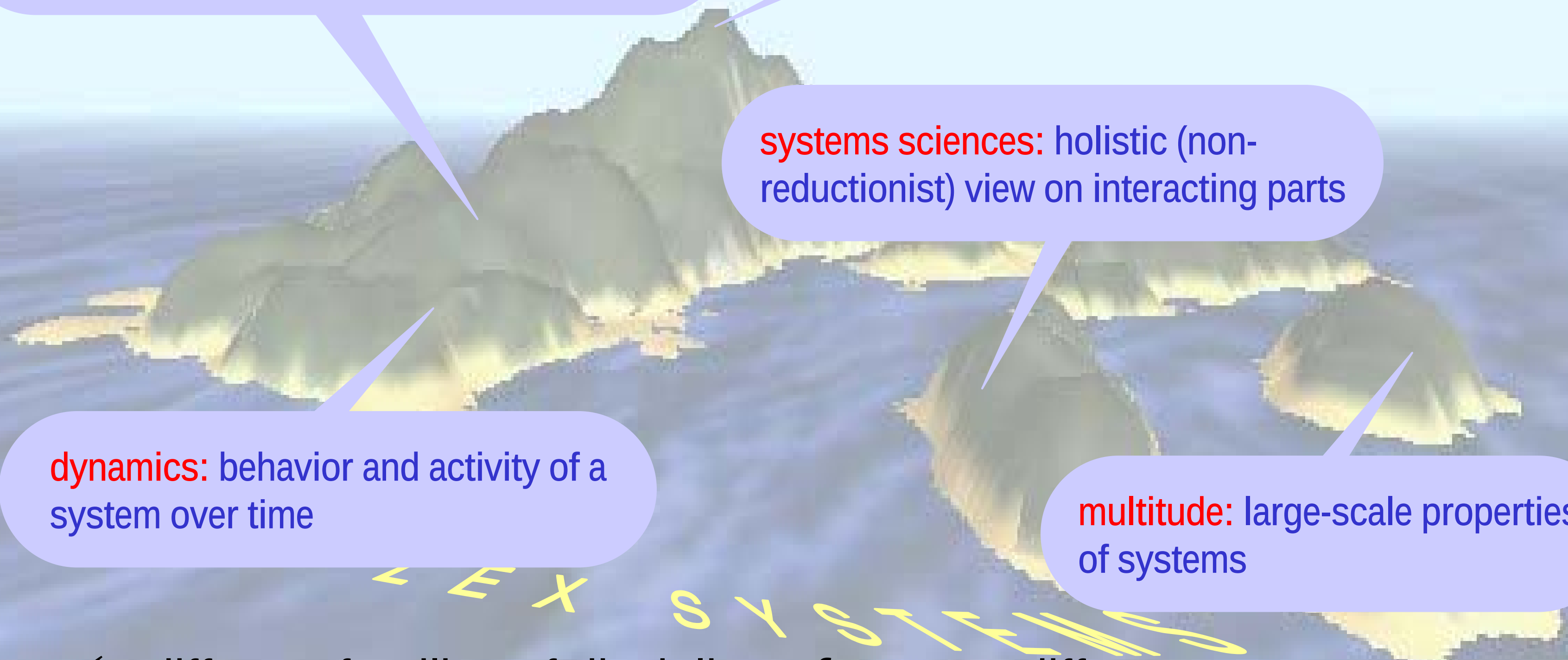
Internet & Web
○ = host/page



social nets economy
○ = person

Complex systems: 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: large-scale properties of systems

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

Complex systems: 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)

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

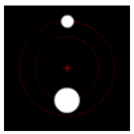
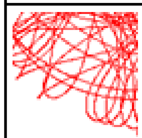
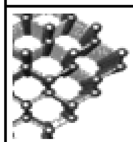
multitude: large-scale properties of systems
- graph theory & networks
- statistical physics
- agent-based modeling
- distributed AI systems

Complex systems: 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 author 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

Complex systems

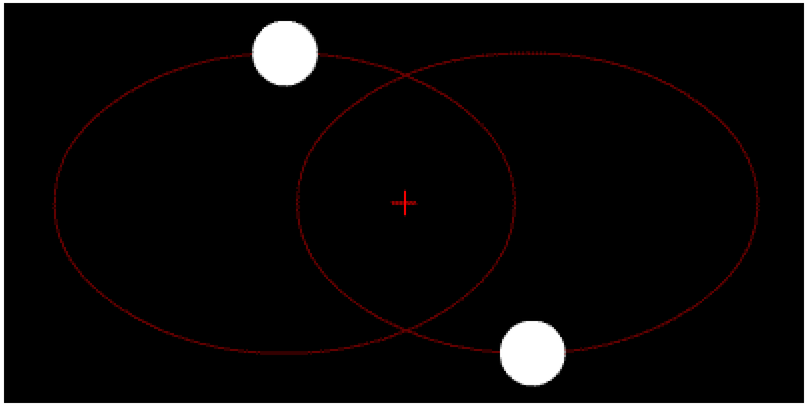
➢ A brief taxonomy of systems

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*

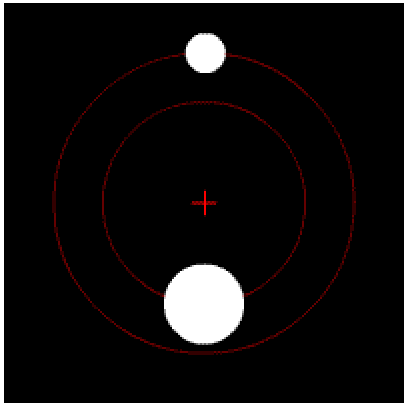
Complex systems

- **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

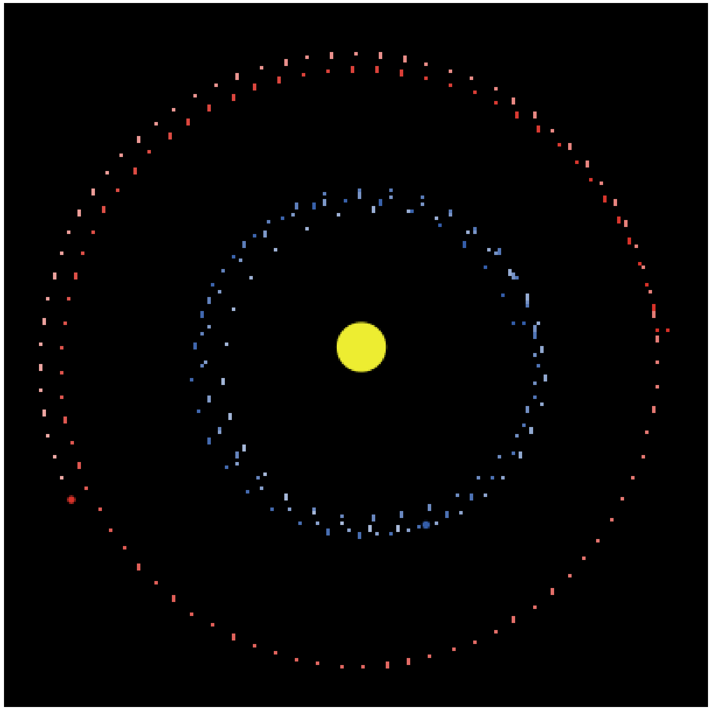


Two bodies with different mass
Wikimedia Commons

Complex systems

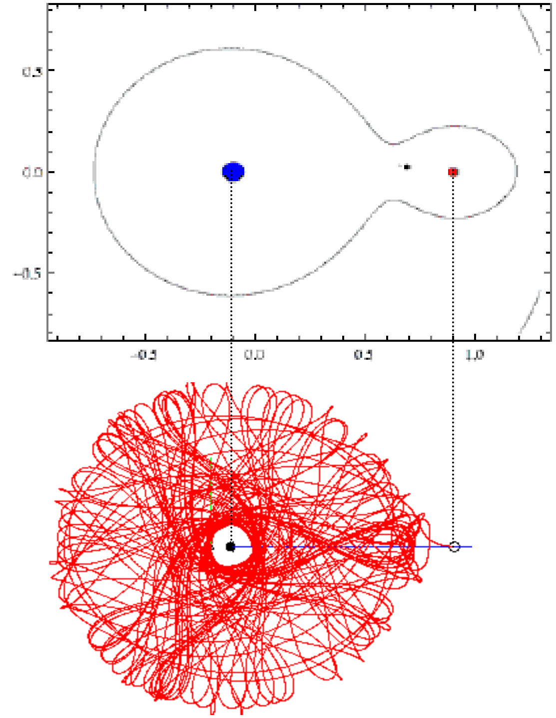
- **Few agents, complex emergent behavior**
  - → *ex: three-body problem*
  - ✓ generally no exact mathematical solution (even in "restricted" case $m_1 \langle\langle\, m_2 \approx m_3$): must be solved numerically → ***chaotic*** trajectories

NetLogo model: /Chemistry & Physics/Mechanics/Unverified



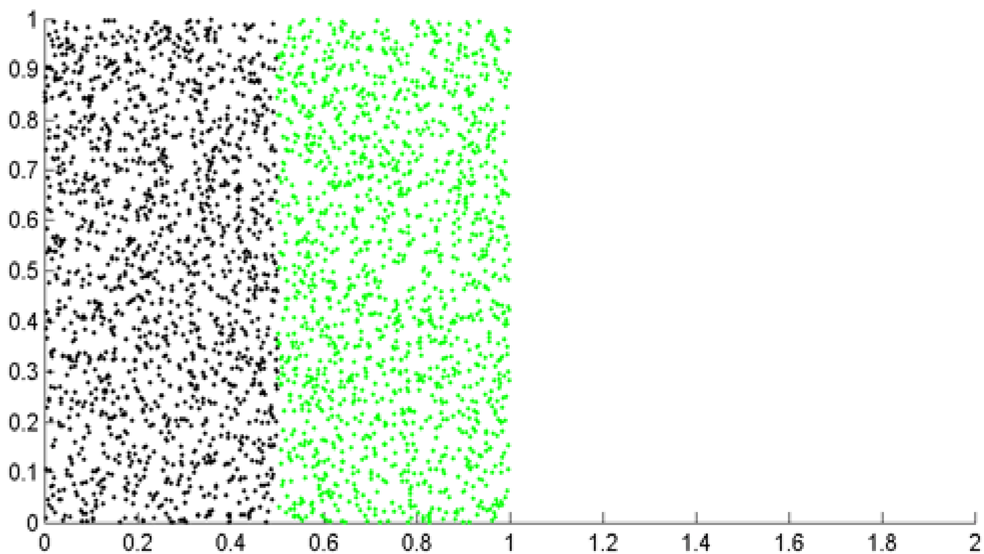
Transit orbit of the planar circular restricted problem

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

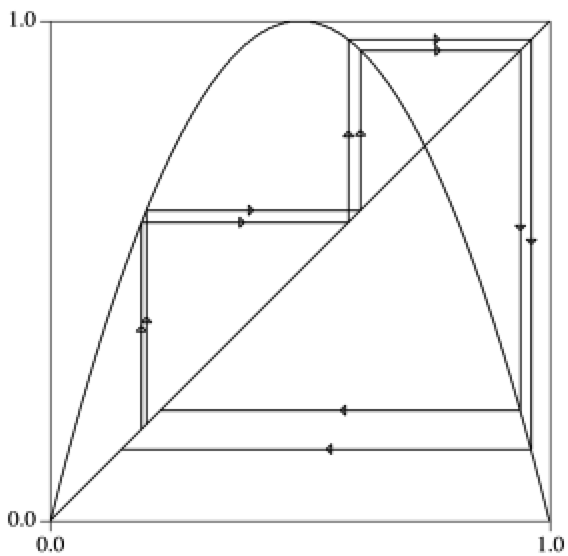


Complex systems

- 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"



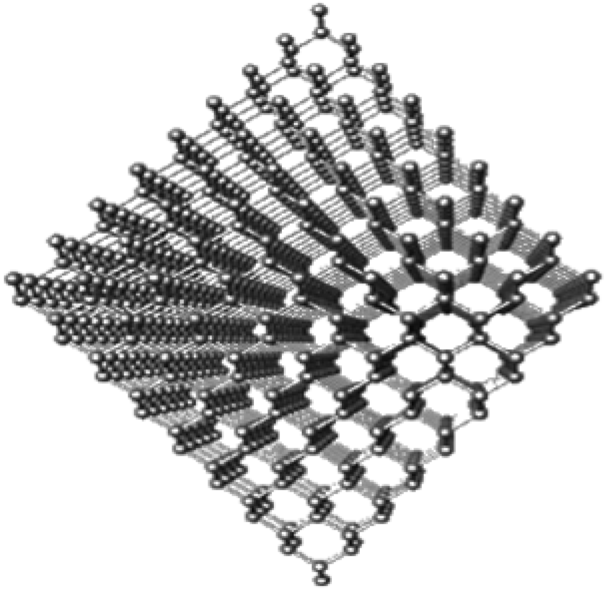
Baker's transformation
Craig L. Zirbel, Bowling Green State University, OH



Logistic map

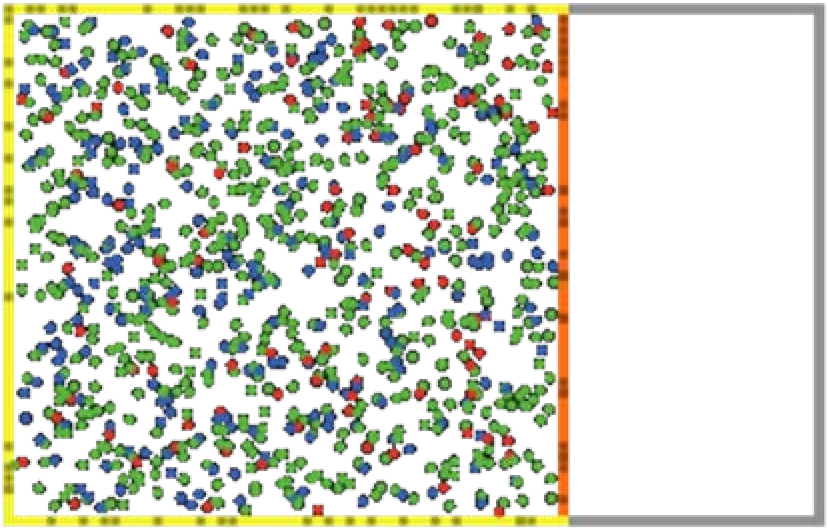
Complex systems

- 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



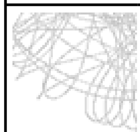
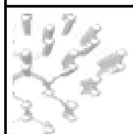
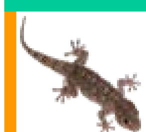
Diamond crystal structure
Tonci Balic-Zunic, University of Copenhagen

NetLogo model: /Chemistry & Physics/GasLab Isothermal Piston



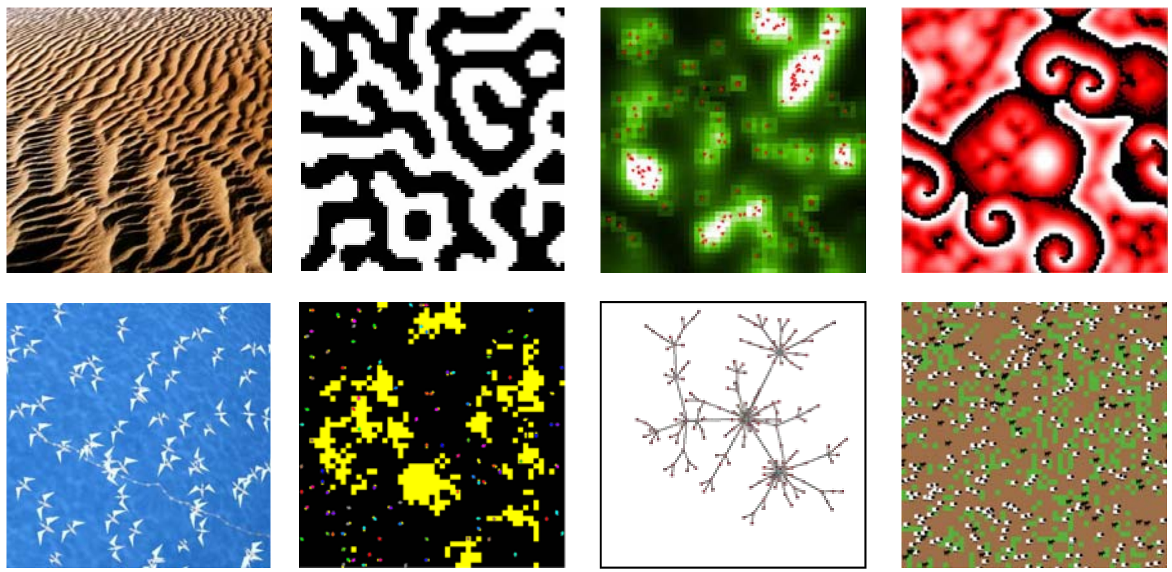
"Statistical" vs. "morphological" complex systems

➢ A brief taxonomy of systems

	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*	*sophisticated*	*complex*	*YES – reproducible and heterogeneous*

"Statistical" (self-similar) systems

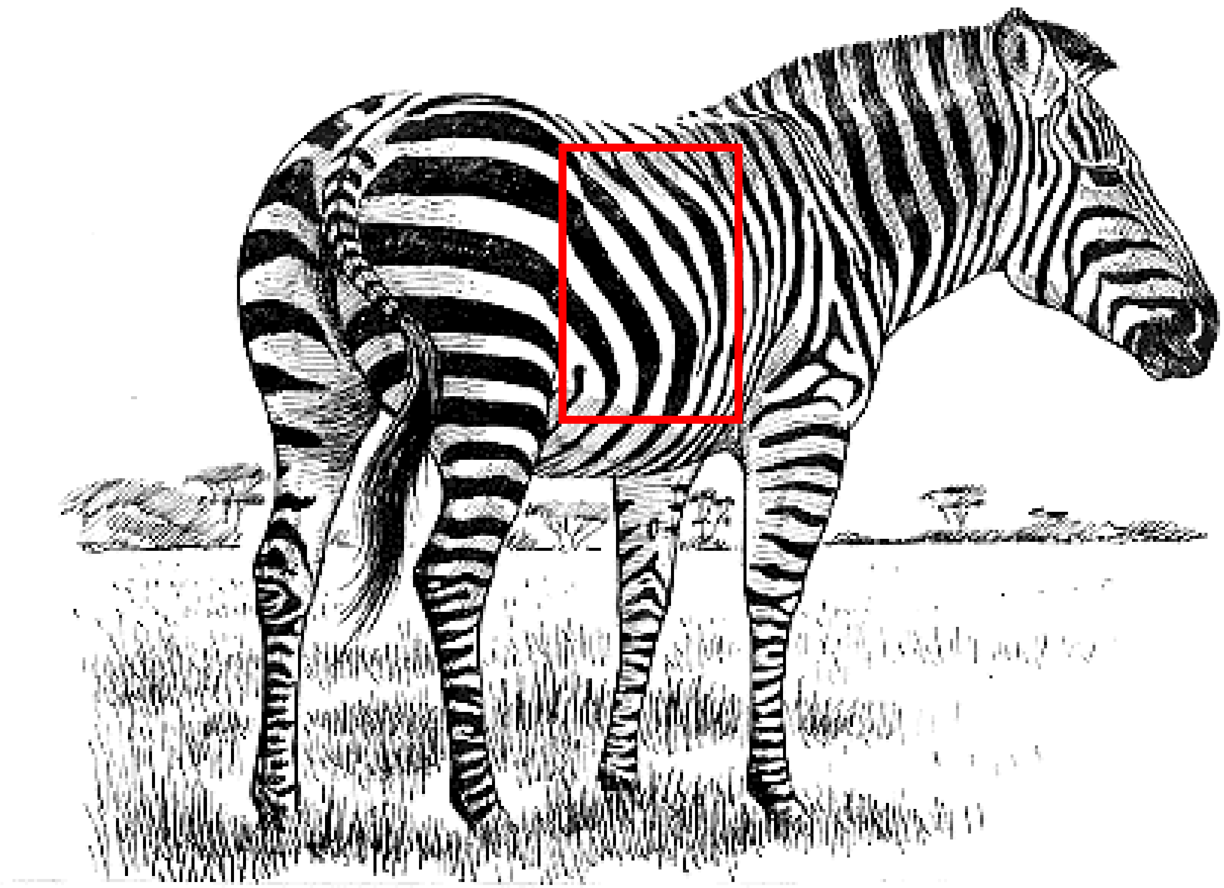
- **Many agents, simple rules, "complex" emergent behavior**
  - → *the "clichés" of complex systems: diversity of pattern formation (spots, stripes), swarms (clusters, flocks), complex networks, etc.*



- ✓ yet, often like "textures": repetitive, statistically *uniform*, information-poor
- ✓ spontaneous order arising from amplification of *random* fluctuations
- ✓ *unpredictable* number and position of mesoscopic entities (spots, groups)

"Morphological" (self-dissimilar) systems

compositional systems: pattern formation ≠ morphogenesis



"The stripes are easy, it's the horse part that troubles me"

—attributed to A. Turing, after his 1952 paper on morphogenesis

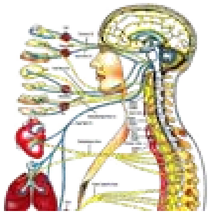
"Morphological" (self-dissimilar) systems

- Many agents, sophisticated rules, complex emergence
  - → *natural ex: organisms (cells)*

plants

vertebrates

arthropods



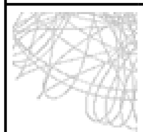
humans

- ✓ mesoscopic organs and limbs have intricate, *nonrandom* morphologies
- ✓ development is highly *reproducible* in number and position of body parts
- ✓ *heterogeneous* elements arise under information-rich genetic control

- Biological organisms are self-organized *and* structured
  - ✓ because the pieces of the puzzle (agent rules) are more "sophisticated" (than inert matter): depend on agent's *type* and/or *position* in the system
  - ✓ the system is truly more complicated but, paradoxically, can also lend itself better to *control* and *programming*

"Complicated" (social) systems

➢ A brief taxonomy of systems

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*
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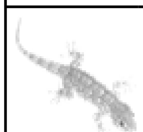
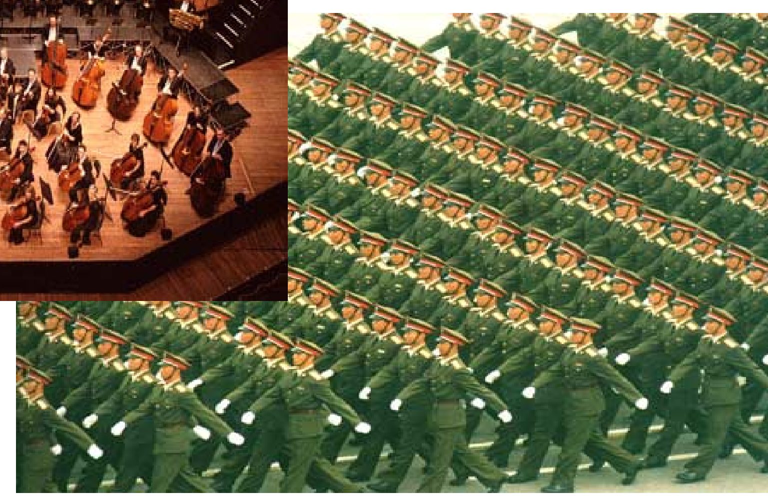
 structured morphogenesis	*many*	*sophisticated*	*complex*	*YES – reproducible and heterogeneous*
 machines, crowds with leaders	*many*	*sophisticated*	*"simple"*	*NO – not self-organized*

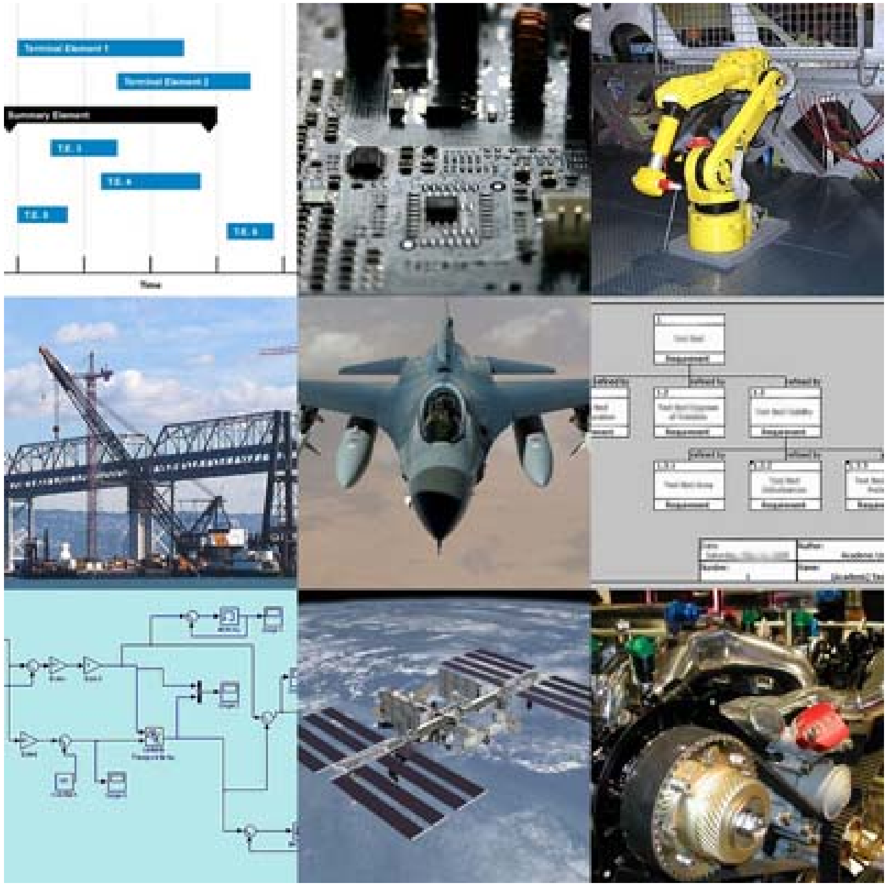
"Complicated" (social) systems

- Many agents, sophisticated rules, "simple" emergent behavior
  - → *social example: crowds, orchestras, armies*
  - ✓ humans reacting similarly and/or simultaneously to a complicated set of stimuli coming from a *centralized* leader, plan or event
  - → ***absence of*** *(or little)* ***self-organization***



"Complicated" (technical) systems

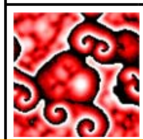
- Many agents, sophisticated rules, "simple" emergent behavior
  - → *technical examples: electronics, machines, aircrafts, civil eng.*
  - ✓ complicated, multi-part devices designed by engineers to behave in a limited and *predictable* (reliable, controllable) number of ways "I don't want my airplane to be creatively emergent"
  - → ***absence of self-organization*** (components do not assemble or evolve by themselves)



Systems engineering
Wikimedia Commons

Complex systems

➢ A brief taxonomy of systems

Category	*Agents / Parts*	*Local Rules*	*Emergent Behavior*	*A "Complex System"?*
✓ the challenge of "statistical" systems: integrate an *architecture* ✓ the challenge of "complicated" systems: integrate *self-organization*				
 patterns, swarms, complex networks	*many*	*simple*	*"complex"*	*YES – but mostly random and uniform*
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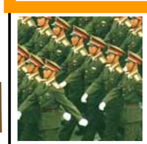
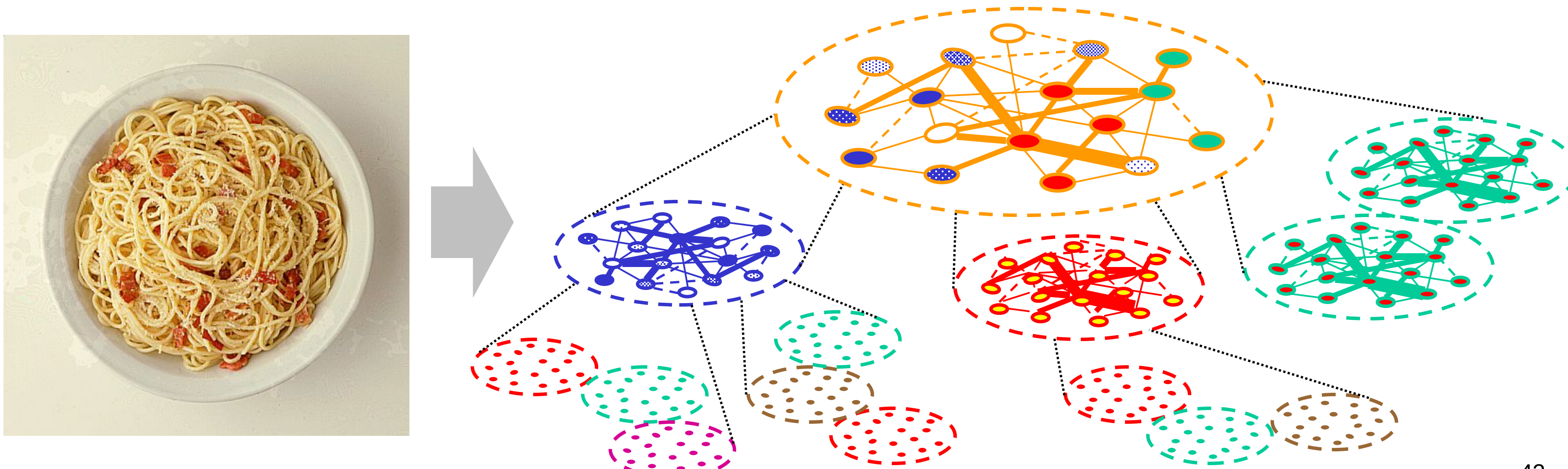
 machines, crowds with leaders	*many*	*sophisticated*	*"simple"*	*NO – not self-organized*

Beyond statistics: heterogeneity, modularity, reproducibility

- Complex systems can be much more than a "soup"
  - ✓ "complex" doesn't necessarily imply "homogeneous"...
    → ***heterogeneous** agents and diverse patterns, via positions*
  - ✓ "complex" doesn't necessarily imply "flat" (or "scale-free")...
    → ***modular**, hierarchical, detailed architecture (at specific scales)*
  - ✓ "complex" doesn't necessarily imply "random"...
    → ***reproducible** patterns relying on programmable agents*

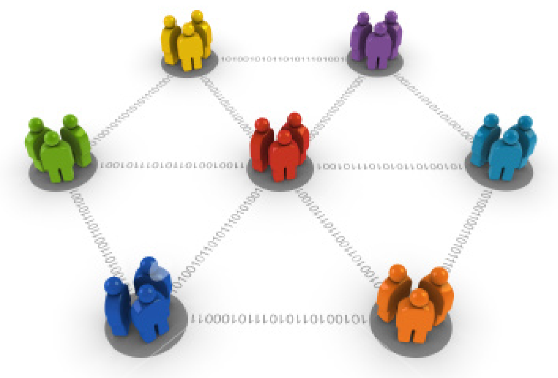


Self-made puzzles that can be programmed

1. Techno-social networks and multi-agent modeling
2. Complex systems: from statistical to morphological
3. Harnessing complexity by "meta-design"
4. A possible direction: morphogenetic engineering
5. Toward programmable networks

Complex techno-social systems

- The "New Deal" of the ICT age: complex behavior
  - ✓ characterized by diverse and specialized eNetworked proactive participants



  - ✓ as complex systems, techno-social networks exhibit self-organization and unpredictability
  - ✓ spontaneously appearance of collective behavior, but traditional organizations are not prepared for it
  - ✓ this spontaneous trend that has preceded our ability as designers to comprehend and control it

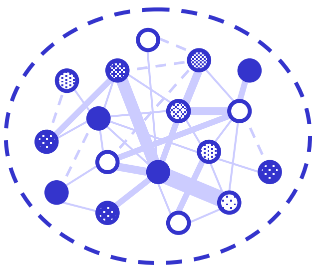
Complex techno-social systems

- A challenge *and* an opportunity for design & engineering
  - fundamental challenge for traditional engineering based on
    - requirement specification
    - hierarchical, top-down management
  - but also opening new opportunities for exploiting the formidable potential of ICT advances
  - beyond blogging, wikis, e-mail and file sharing, invent a new generation of collaborative techno-social rules & technologies
  - import the desirable properties of natural complex systems
    - (semi-)autonomy
    - homeostasis
    - dynamic adaptation
    - long-term evolution

From natural CS to designed CS (and back)

- The challenges of complex systems (CS) research

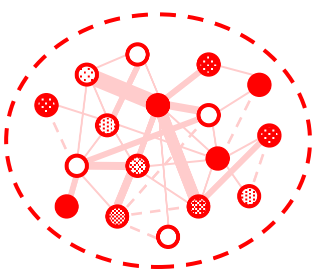
Transfers
- among systems



CS science: *understanding "natural" CS*
(i.e., spontaneously emergent, including human activity)
→ Agent-Based Modeling (ABM)

Exports
- decentralisation
- <u>autonomy</u>, homeostasis
- learning, evolution

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

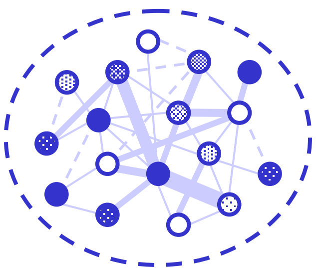


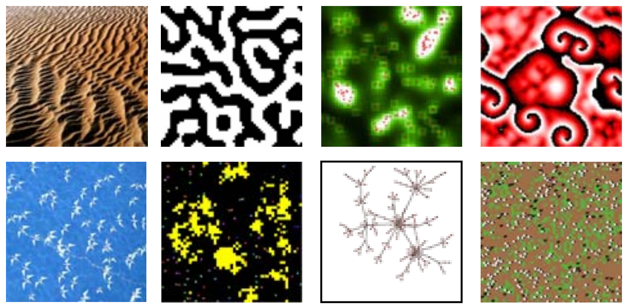
CS engineering: *designing a new generation of "artificial" CS (i.e., harnessed & tamed, including nature)*
→ Multi-Agent Systems (MAS)

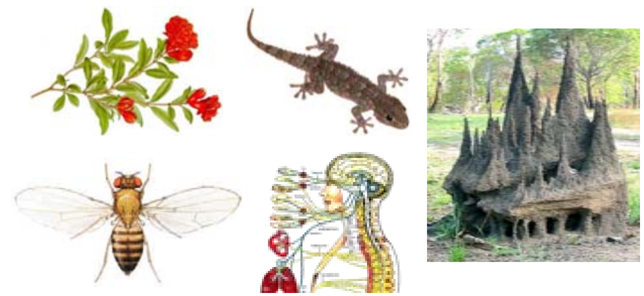
From natural CS to designed CS

➢ Two influences from natural CS

statistical systems | morphological systems

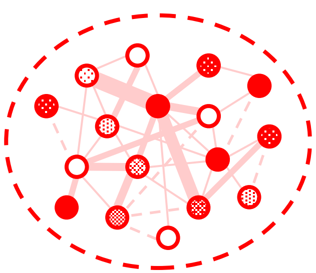






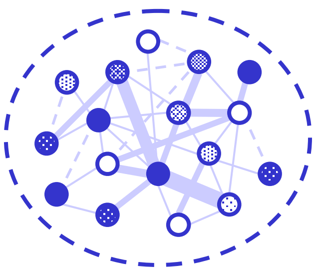
- uniform
- random
- unpredictable details

- heterogeneous
- programmable
- reproducible

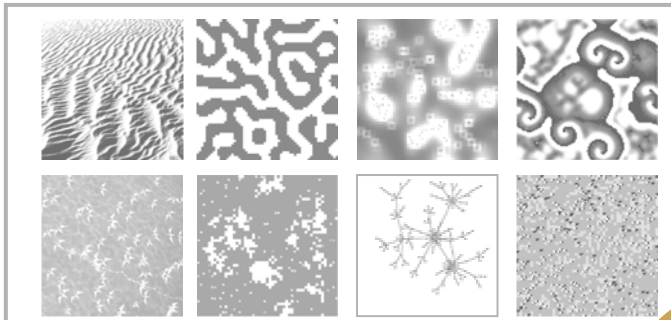


From natural CS to designed CS

➢ Transfer from morphological to techno-social systems



statistical systems



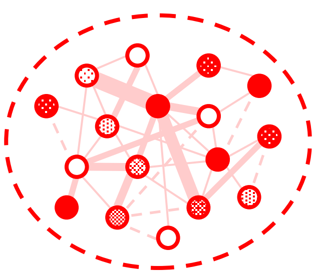
- uniform
- random
- unpredictable details

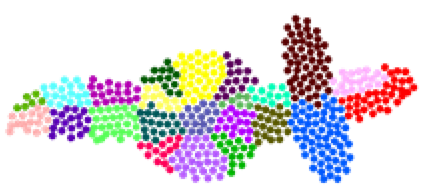
morphological systems

- heterogeneous
- programmable
- reproducible

ex: HIBIE (Harvard) = $125M

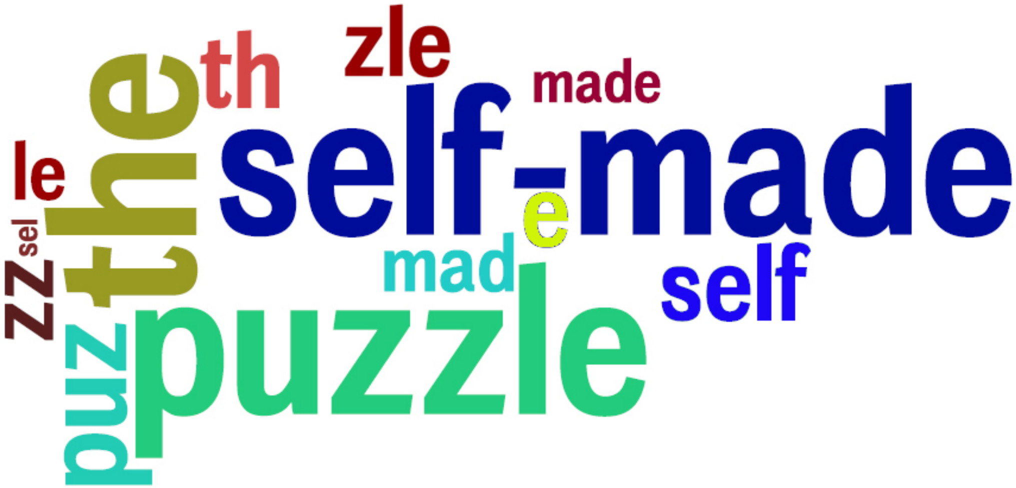
?





amorphous/spatial computing, autonomic networks, modular/swarm robotics, programmable matter

The "self-made puzzle": from genotype to phenotype



a. Construe systems as *self-assembling puzzles*

b. Design and *program their pieces* (the "genotype")

c. Let them evolve by *variation* of the pieces and *selection* of the architecture (the "phenotype")

- Genotype (DNA): rules at the *micro* level of agents
  - ✓ *search* and *connect* to other agents
  - ✓ *interact* with them over those connections
  - ✓ *modify* one's internal state (differentiate) and rules (evolve)
  - ✓ provide a specialized *fonction*
- Phenotype: collective behavior, visible at the *macro* level

Emergent engineering

- Harnessing, not dreading complex systems
  - ✓ the need to develop a sense of capability and security in the changing context
  - ✓ instead of clinging to a traditionally totalistic control that is inexorably vanishing...
  - ✓ ... focus rather on establishing conditions in which complexity can develop and evolve
  - ✓ focus on endogenous and local control

→ *future complex techno-social engineering should be less about direct design than developmental and evolutionary "meta-design"*

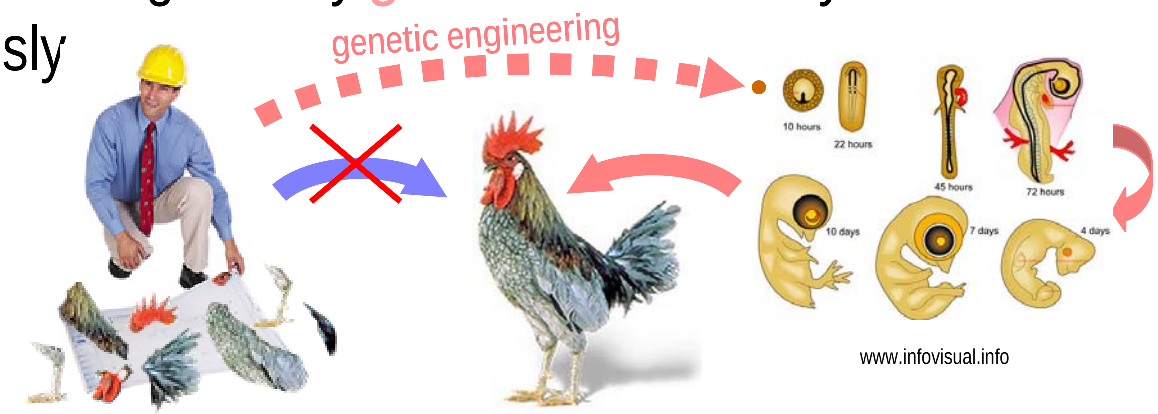
The challenge of designing complexity

➢ From design to meta-design

- ✓ organisms endogenously *grow* but artificial systems *are built* exogenously

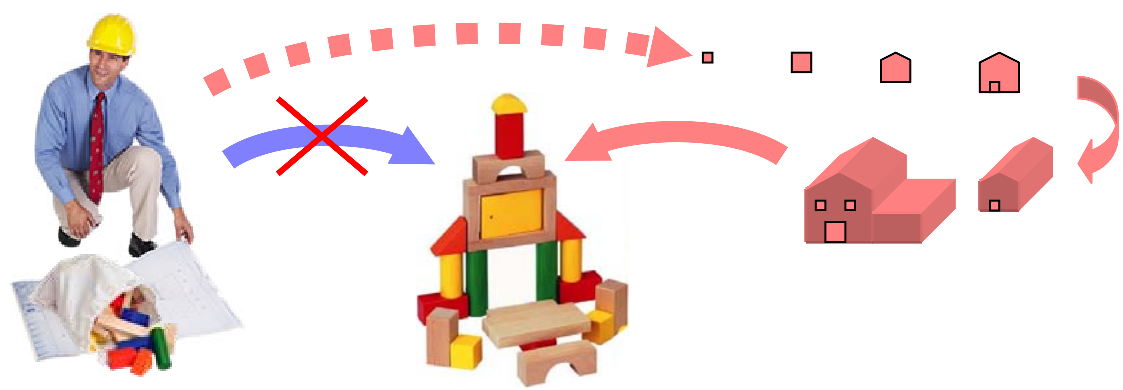
systems design

systems "meta-design"



- ✓ future designers should "step back" from their creation and only set *generic* conditions for systems to self-assemble and evolve

don't build the system from the top (phenotype), program the components from the bottom (genotype)



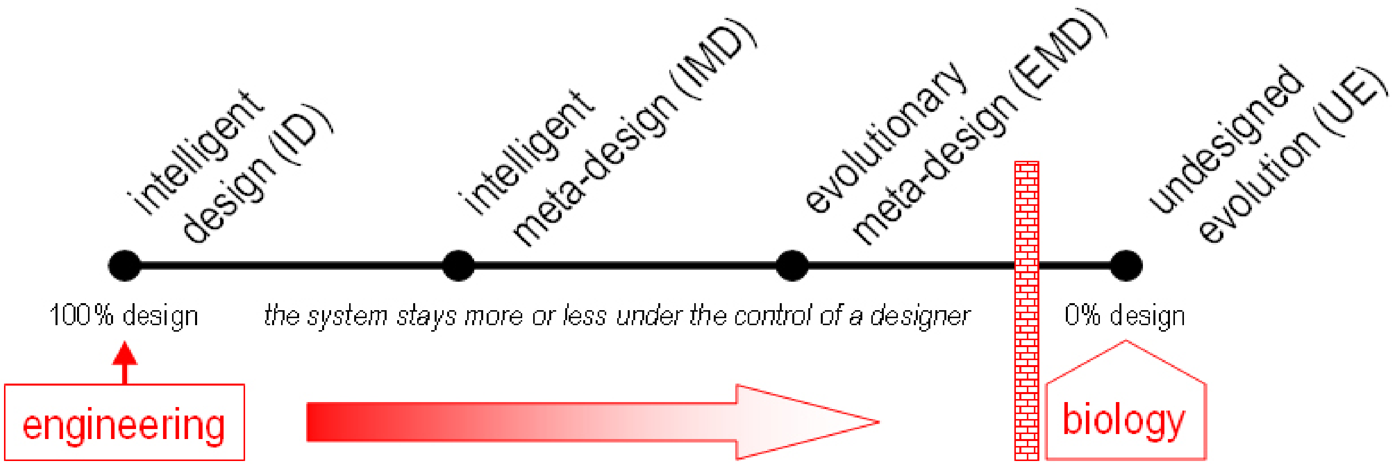
Bio-inspired emergent engineering

➢ Natural adaptive systems as a new paradigm for TS

- ✓ natural complex adaptive systems, biological or social, can become a new and powerful source of inspiration for future IT in its transition toward autonomy
- ✓ "emergent engineering" will be less about direct design and more about developmental and evolutionary meta-design
- ✓ it will also stress the importance of constituting fundamental laws of *development* and developmental *variations* before these variations can even be selected upon in the evolutionary stage
- ✓ it is conjectured that fine-grain, *hyperdistributed* systems will be uniquely able to provide the required "solution-rich" space for successful evolution by selection

The meta-design of complexity

➢ Pushing design toward evolutionary biology



intelligent "hands-on" design		intelligent & evolutionary "meta-design"
heteronomous order	▪	autonomous order
centralised control	▪	decentralised control
designer as a micromanager	▪	designer as a lawmaker
rigidly placing components	▪	allowing fuzzy self-placement
sensitive to part failures	▪	insensitive to part failures
need to control and redesign	▪	prepare for adaptation & evolution
complicated systems: planes, computers	▪	*complex* multi-component systems

Paradoxes in approaching complexity

- The paradoxes of complex systems engineering
  - can autonomy be planned?
  - can decentralization be controlled?
  - can evolution be designed?

  - ✓ can we expect specific characteristics from systems that we otherwise let free to assemble and invent themselves?

  - ✓ ultimate goal: "design-by-emergence" of pervasive computing and communication environments able to address and harness complexity

Not science *versus* policy-making…

… but the science *of* policy-making

ESRC Energy Seminar, March 2009, LSE's Second Life retreat

Self-made puzzles that can be programmed

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4. A possible direction: morphogenetic engineering
5. Toward programmable networks

Quick preview of multi-agent embryogenesis

➢ An *abstract* (computational) approach to development

- ✓ as a fundamentally *spatial* phenomenon
- ✓ highlighting the *broad principles* – necessary to absorb and integrate the data – and proposing a *computational* model of these principles

➢ Broad principles

1. *biomechanics* → collective motion → "sculpture" of the embryo
2. *gene regulation* → gene expression patterns → "painting" of the embryo

\+ *coupling* between shapes and colors

➢ Multi-agent models

- ✓ best positioned to integrate both
- ✓ account for heterogeneity, modularity, hierarchy
- ✓ each agent carries a set of *biomechanical* and *regulatory* rules

Morphogenesis couples assembly and patterning

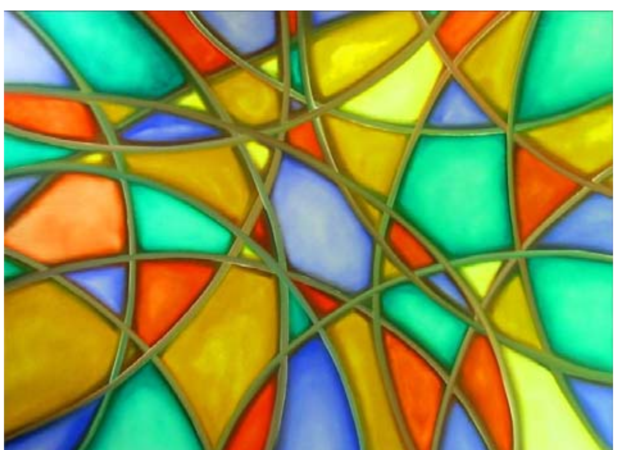
➢ Sculpture → forms

Ádám Szabó, *The chicken or the egg* (2005)
http://www.szaboadam.hu

"shape from patterning"

- ✓ the forms are "sculpted" by the self-assembly of the elements, whose behavior is triggered by the colors

➢ Painting → colors



"patterns from shaping"

- ✓ new color regions appear (domains of genetic expression) triggered by deformations

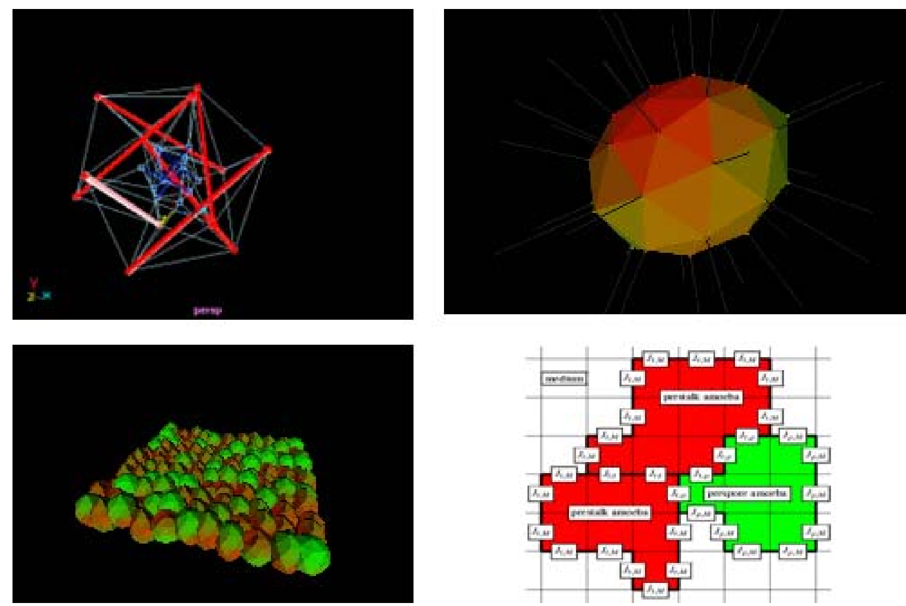
Niki de Saint Phalle

Embryogenesis couples mechanics and regulation

➢ Cellular mechanics

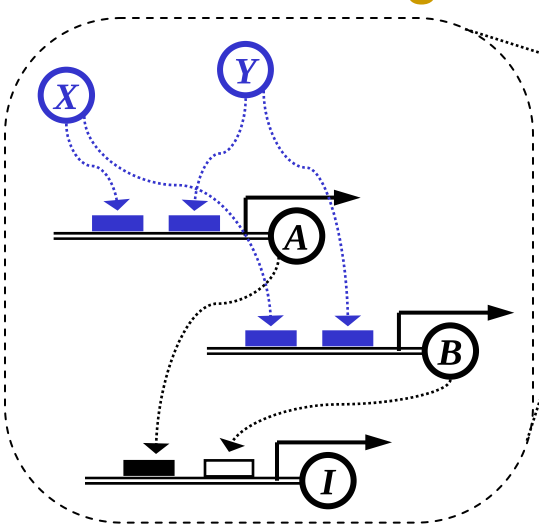
- ✓ adhesion
- ✓ deformation / reformation
- ✓ migration (motility)
- ✓ division / death

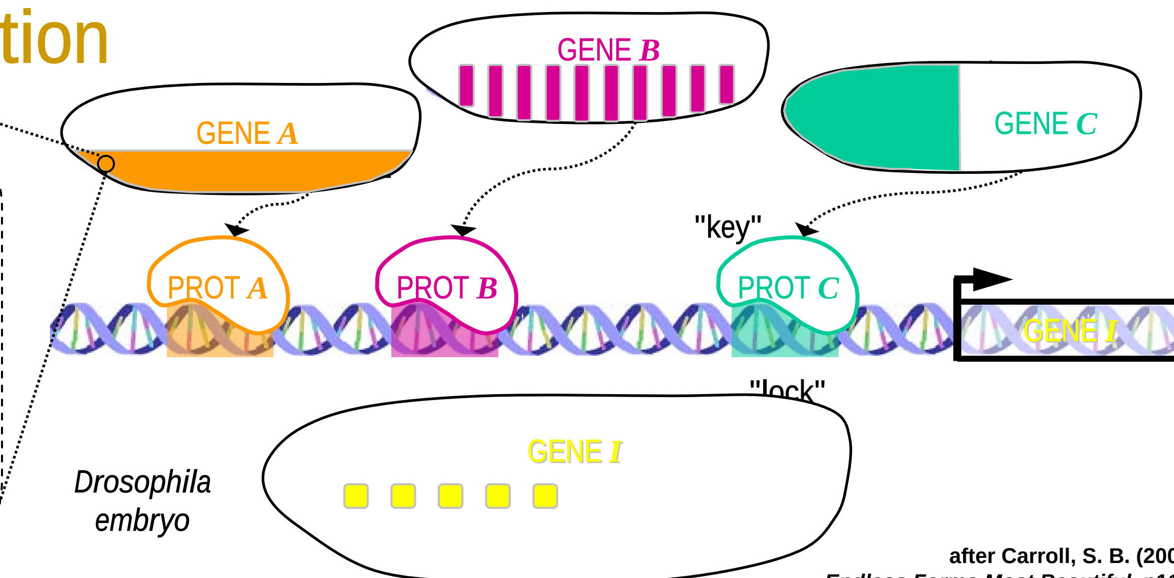
tensional integrity (Ingber)



cellular Potts model (Graner, Glazier, Hogeweg)

➢ Genetic regulation



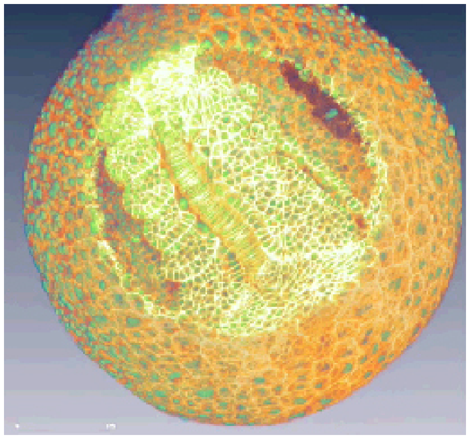


after Carroll, S. B. (2005)
Endless Forms Most Beautiful, p117

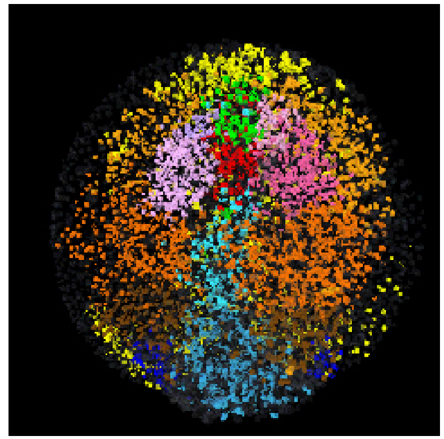
Embryogenesis couples motion and patterns

➢ Collective motion regionalized into patterns

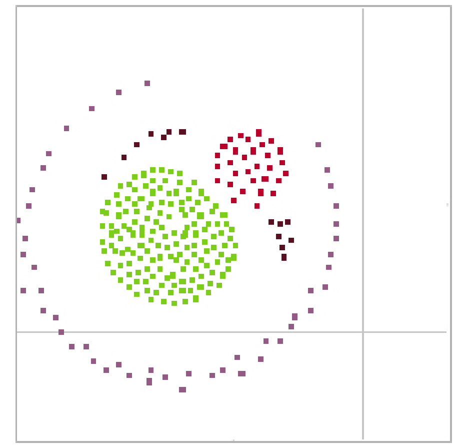
Nadine Peyriéras, Paul Bourgine, Thierry Savy,
Benoît Lombardot, Emmanuel Faure et al.
Embryomics & BioEmergences



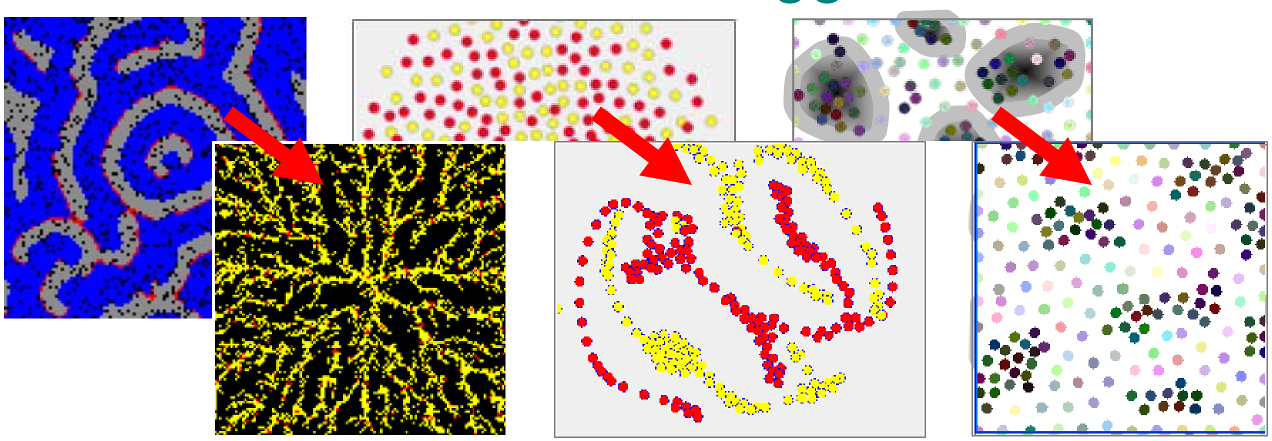
zebrafish



Hiroki Sayama (Swarm Chemistry)
http://bingweb.binghamton.edu/~sayama/SwarmChemistry/



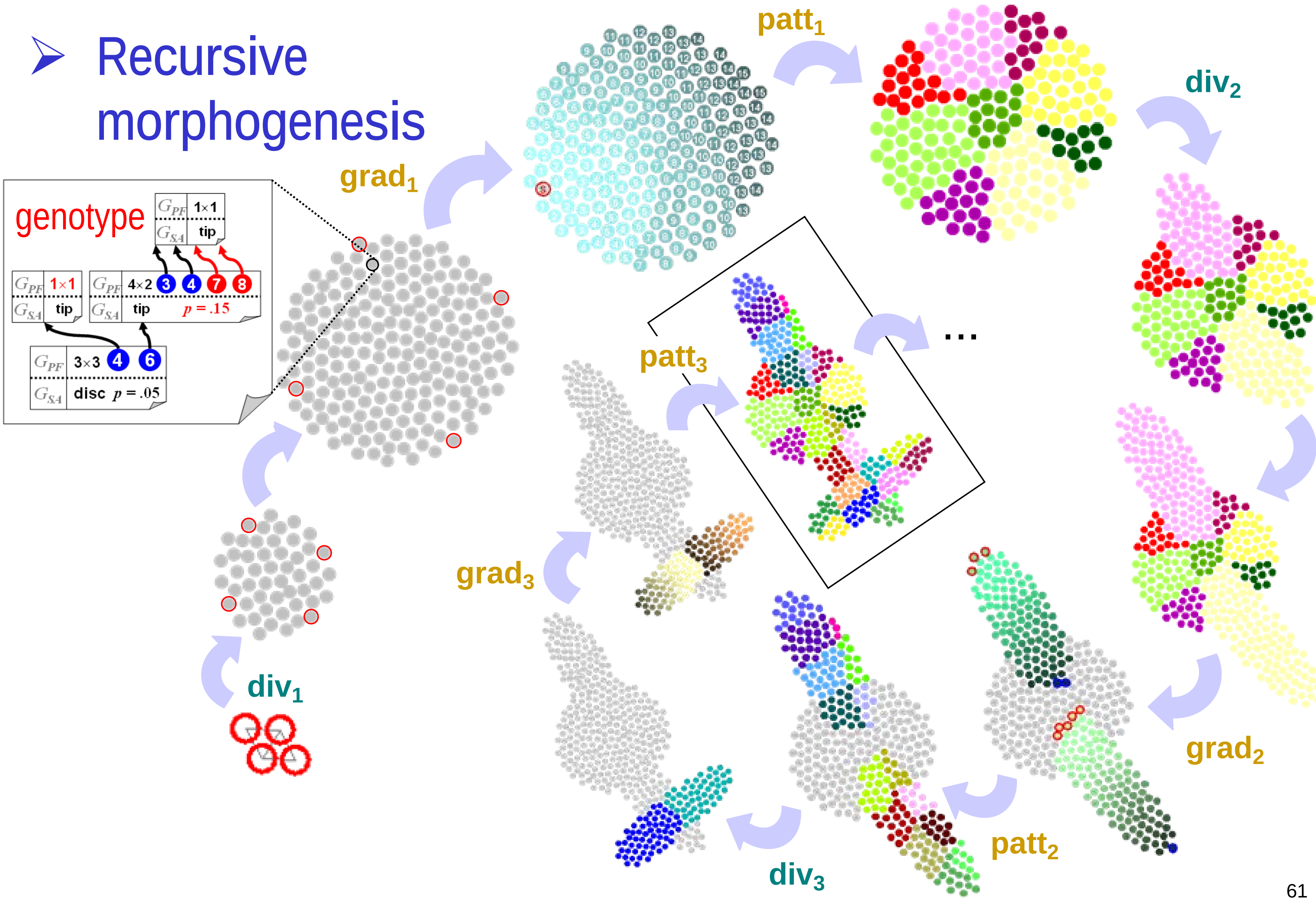
➢ Pattern formation that triggers motion



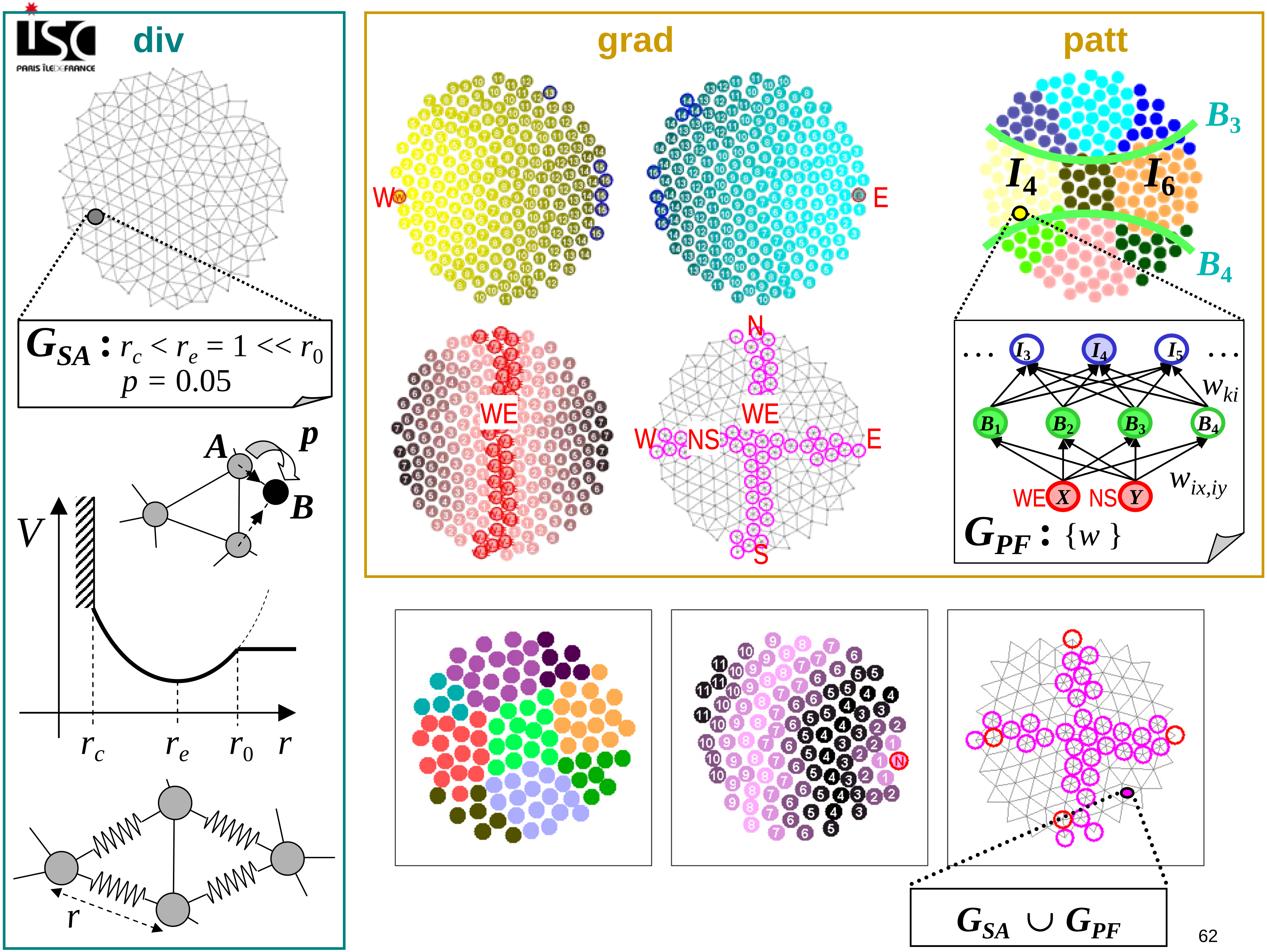
http://zool33.uni-graz.at/schmickl

Exemple of hybrid mesoscopic model

- Recursive morphogenesis



René Doursat, ALife XI (2008)



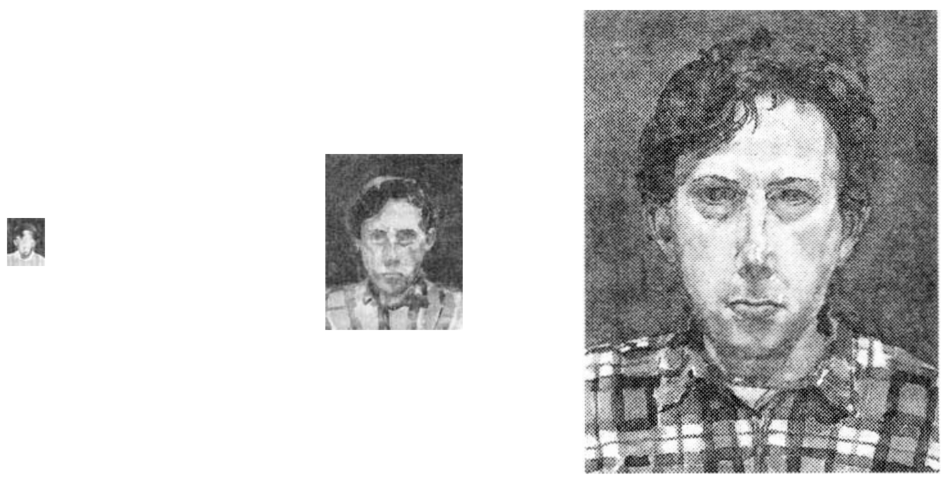
div
grad
patt
PARIS ÎLE DE FRANCE
W
E
WE
N
NS
S
B_3
B_4
I_4
I_6
G_{SA} : $r_c < r_e = 1 << r_0$
$p = 0.05$
A
B
p
V
r_c
r_e
r_0
r
. . . I_3 I_4 I_5 . . .
w_{ki}
B_1 B_2 B_3 B_4
$w_{ix,iy}$
WE X NS Y
G_{PF} : $\{w\}$
$G_{SA} \cup G_{PF}$

Hierarchical morphogenesis

➢ Morphological refinement by iterative growth

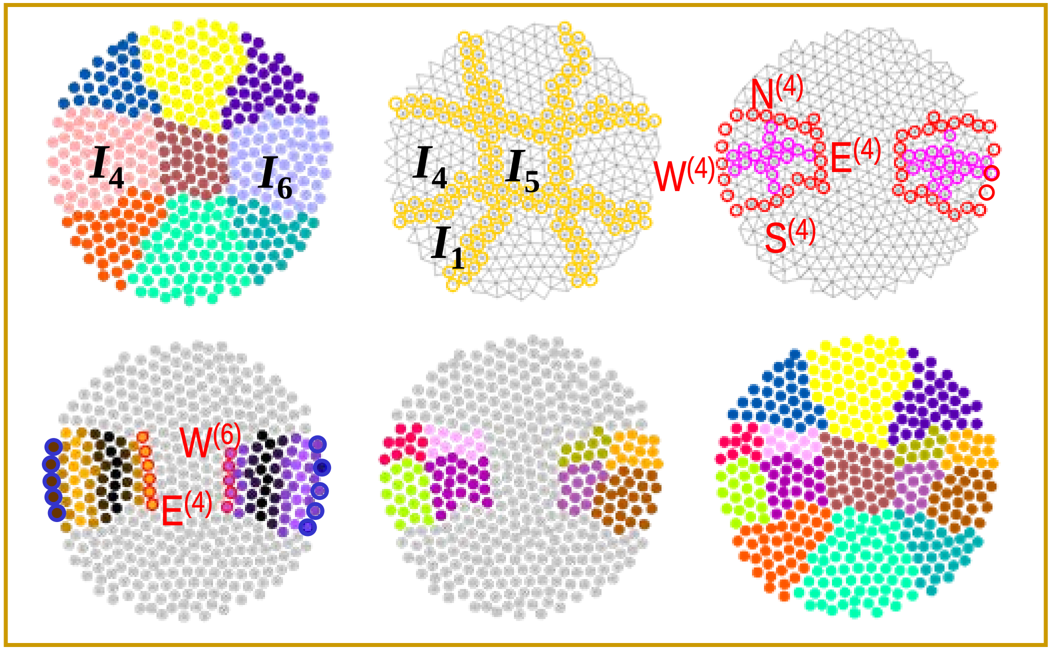
- ✓ details are not created in one shot, but gradually added. . .

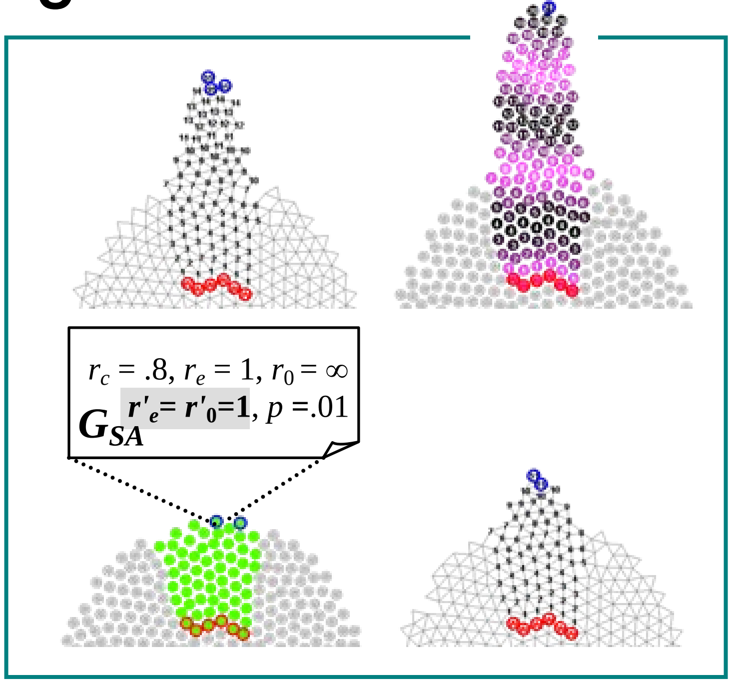
- ✓ . . . while, at the same time, the canvas grows

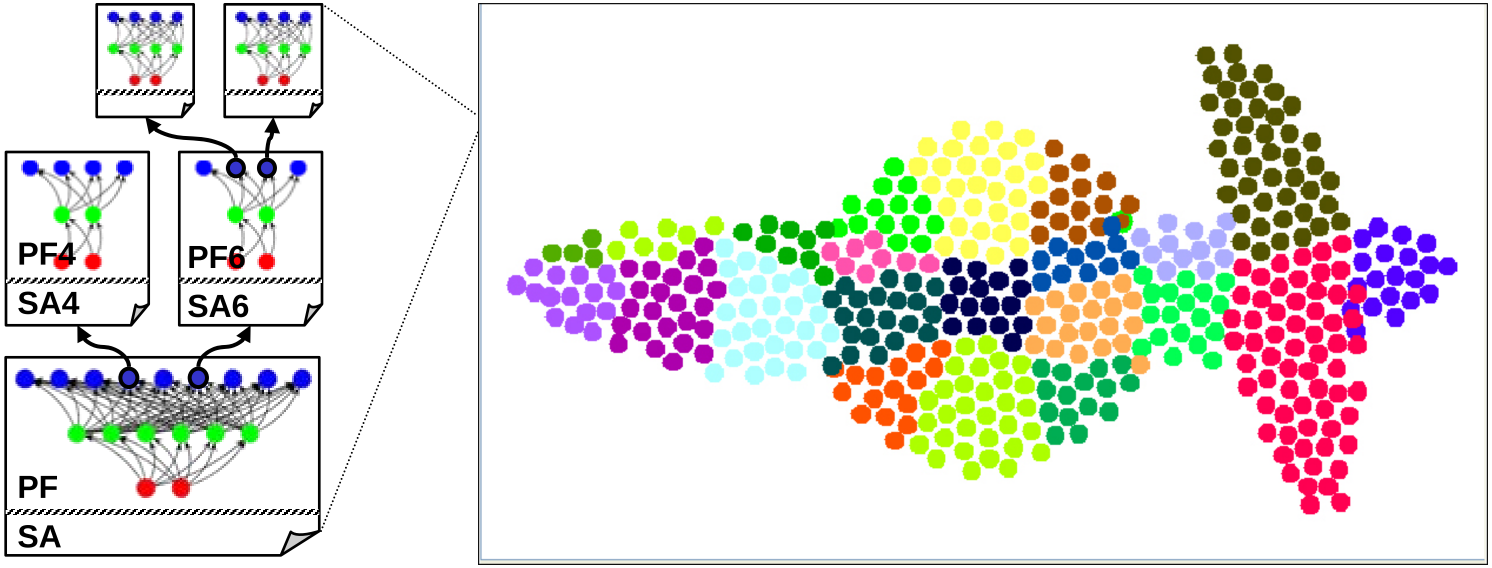


from Coen, E. (2000)
The Art of Genes, pp131-135

Hierarchical morphogenesis



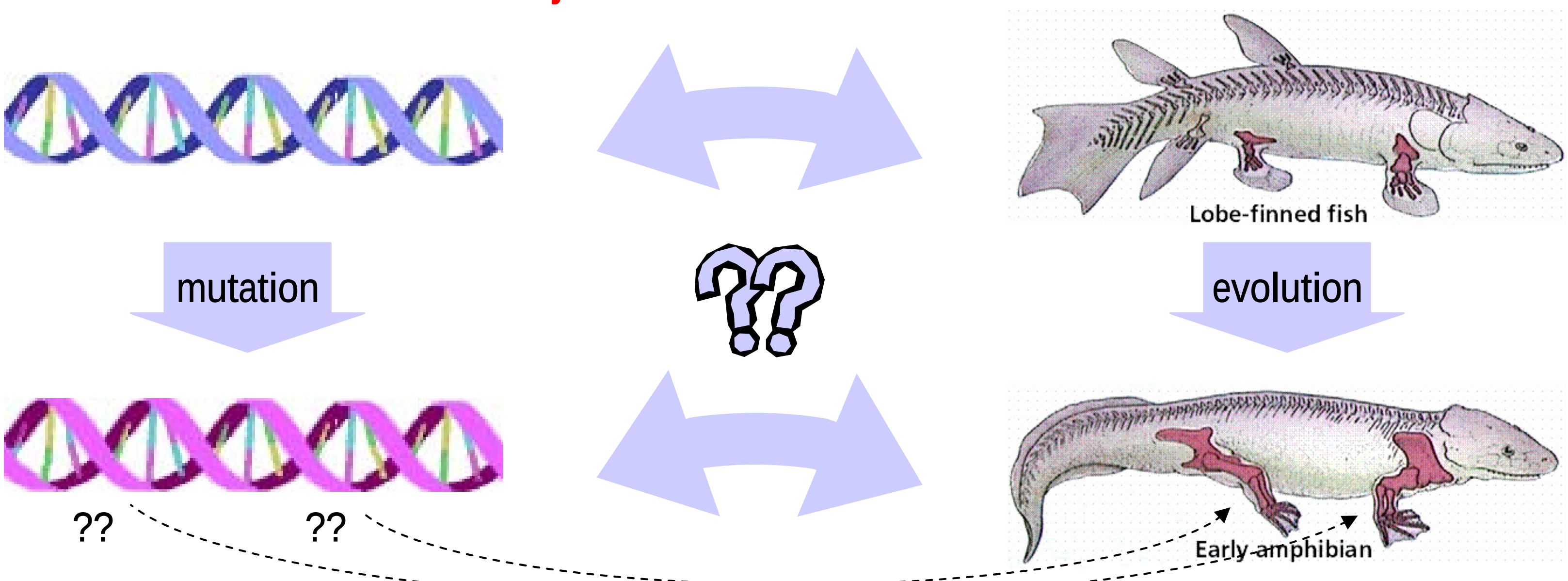




Evolutionary development (evo-devo)

➢ Development: the missing link of the Modern Synthesis

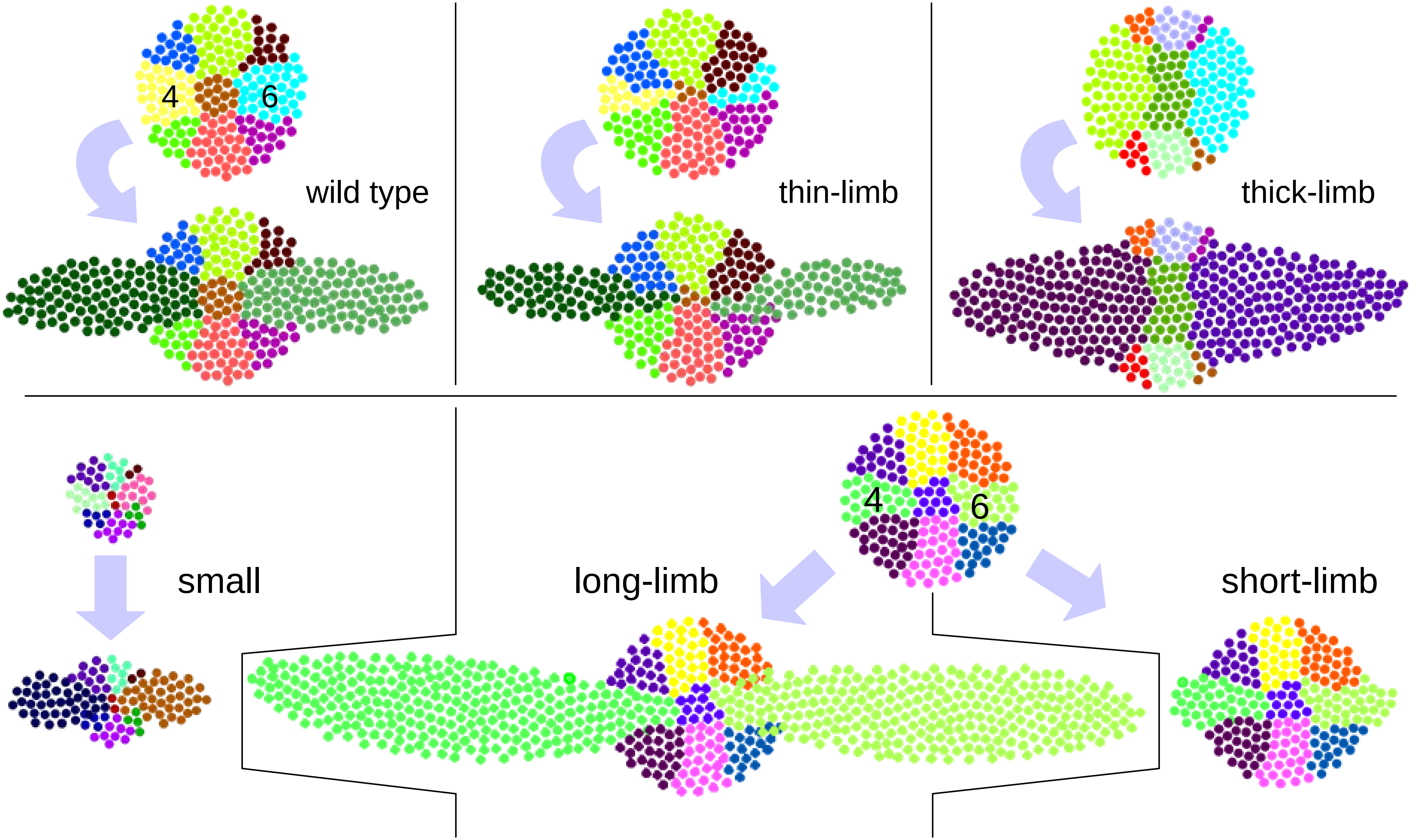
- ✓ biology's "Modern Synthesis" demonstrated a fundamental correlation between genotype and phenotype, yet the molecular and cellular mechanisms of development are still unclear
- ✓ the genotype-phenotype link cannot remain an abstraction if we want to understand evolution as *producing innovation by variation* and not just as a selection force



Purves et al., *Life: The Science of Biology*

Multi-agent evolutionary development (evo-devo)

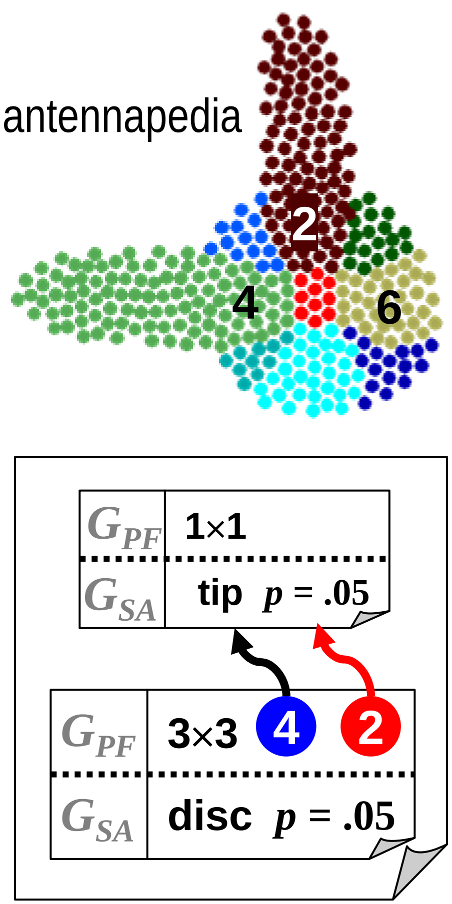
➢ Genotype mutations → phenotype variations (*quantitative*)



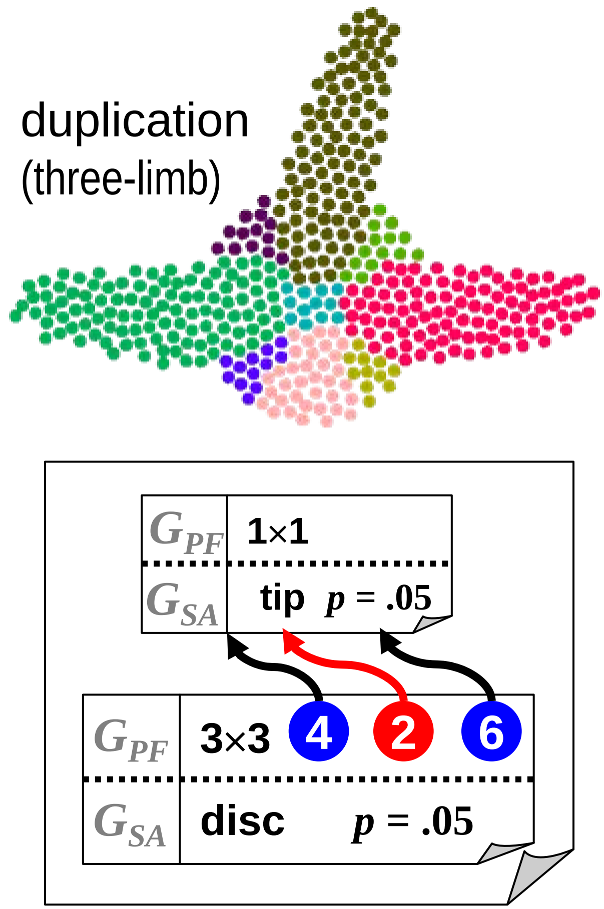
Multi-agent evolutionary development (evo-devo)

➢ Genotype mutations → phenotype variations (*qualitative*)

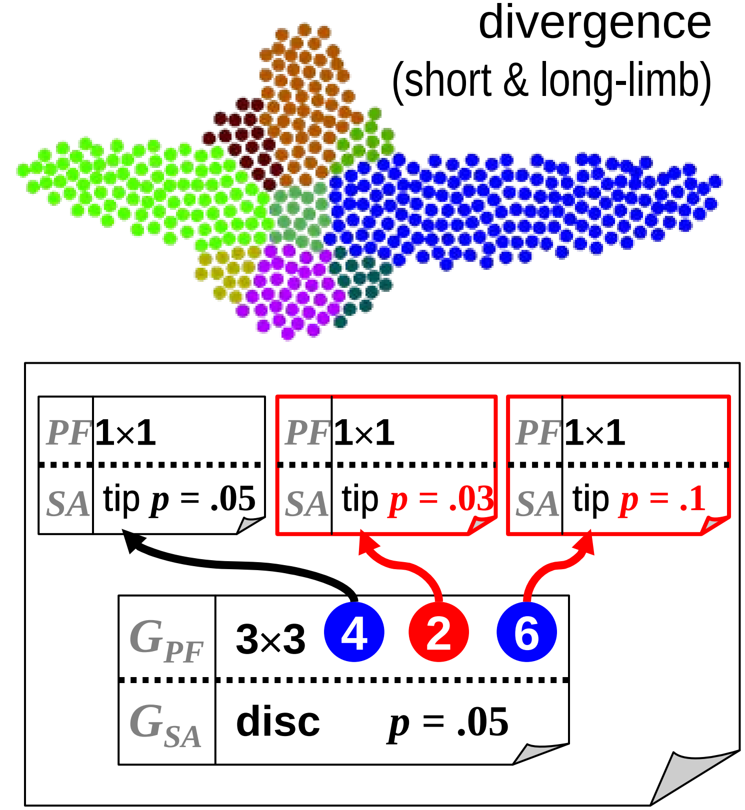
antennapedia



homology by <u>duplication</u>

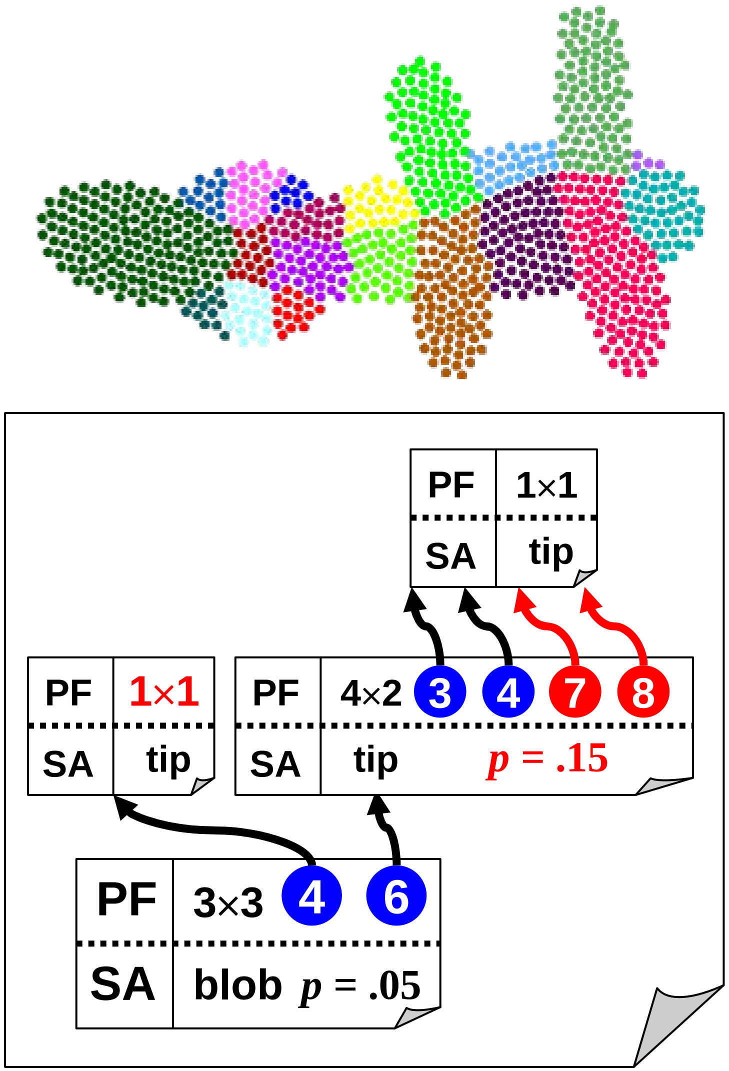


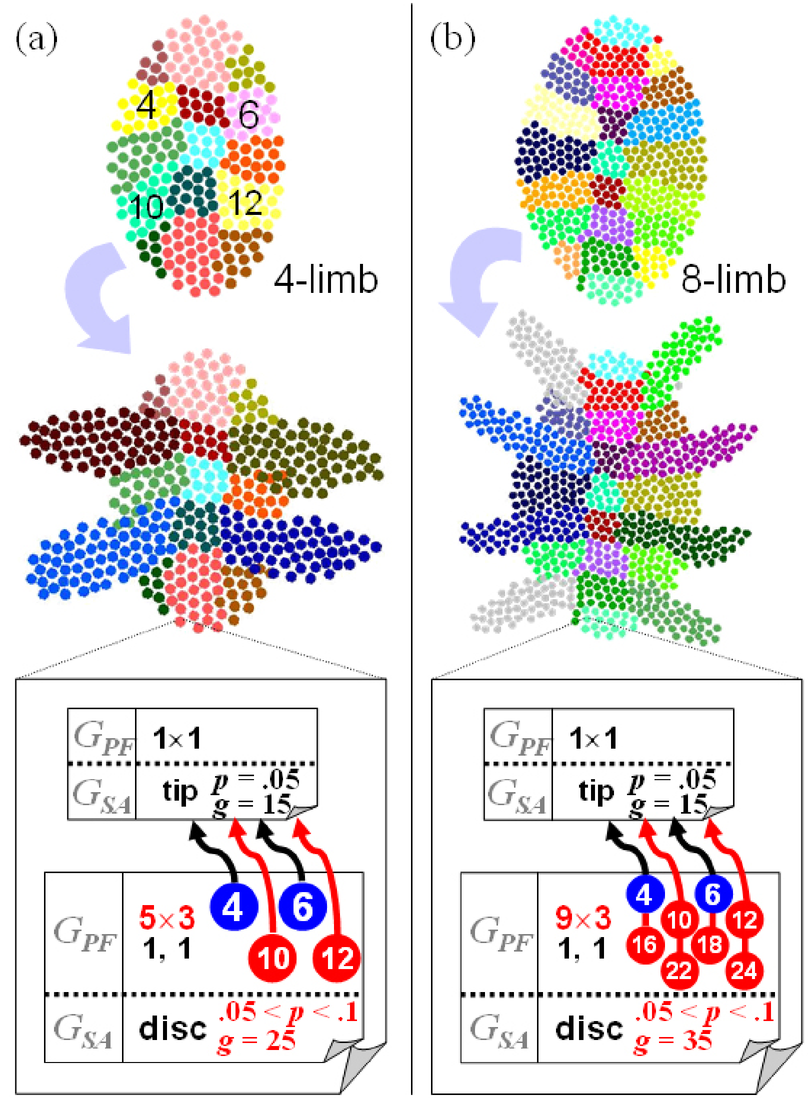
<u>*divergence*</u> of the homology



Multi-agent evolutionary development (evo-devo)

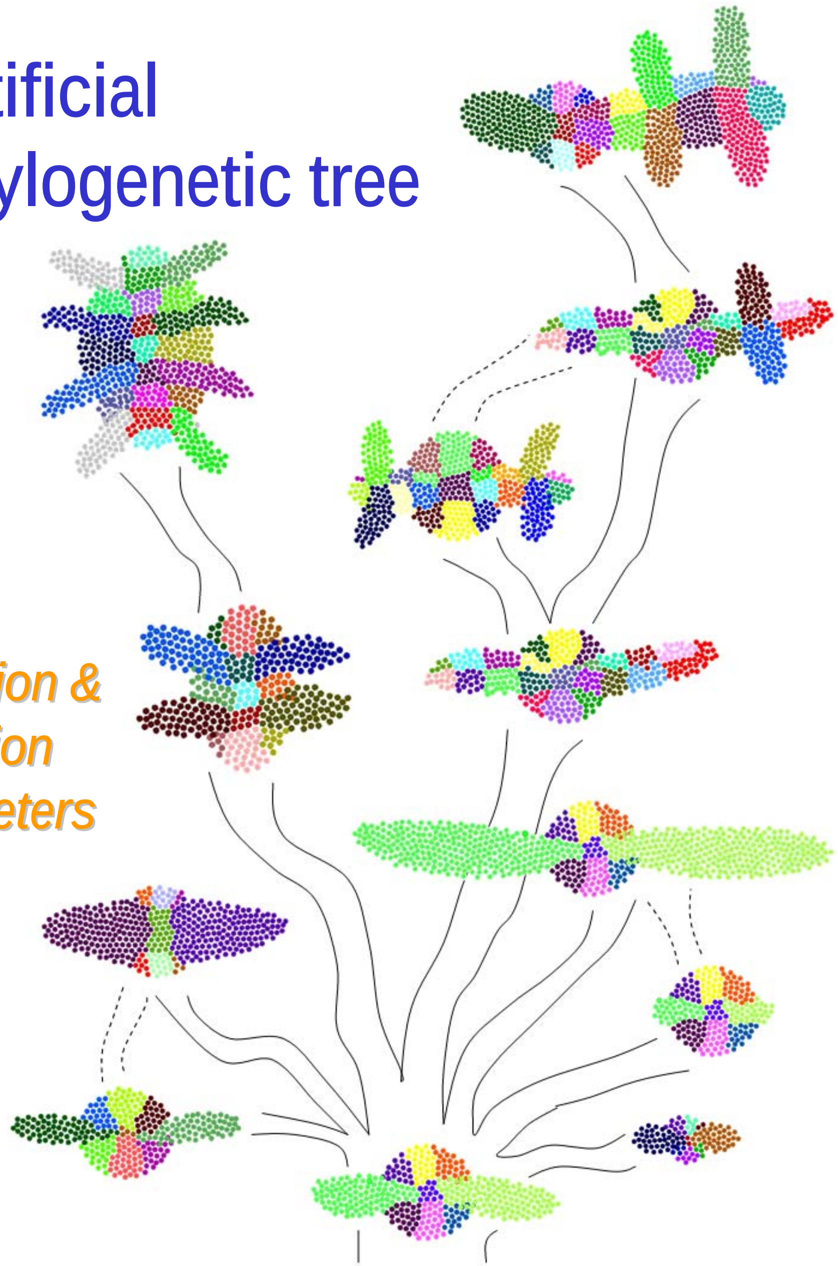
➢ Genotype mutations → phenotype variations (*qualitative*)





Multi-agent evolutionary development (evo-devo)

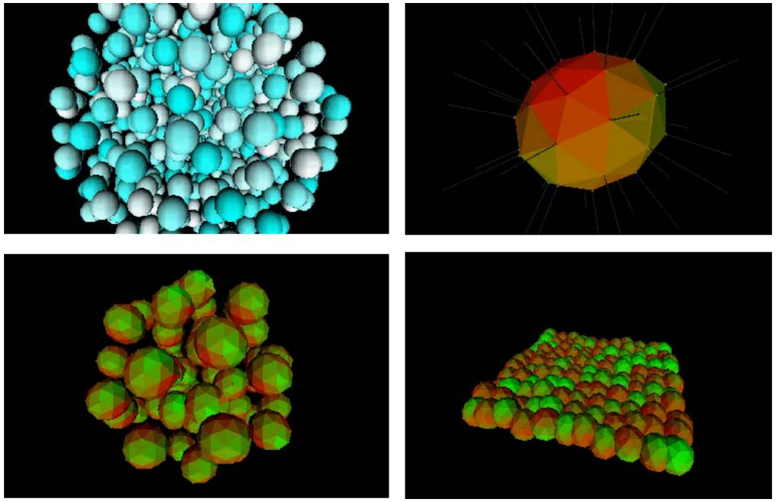
- Artificial phylogenetic tree



optimization & validation of parameters

future directions:

- better biomechanics (3D) : cytoskeleton, migration
- better gene regulation



Morphogenetic Engineering Workshop, Paris 2009

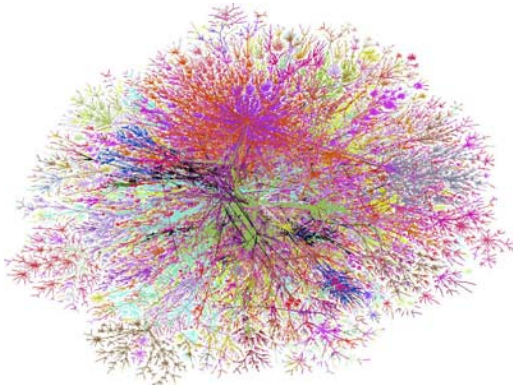
http://www.iscpif.fr/MEW2009

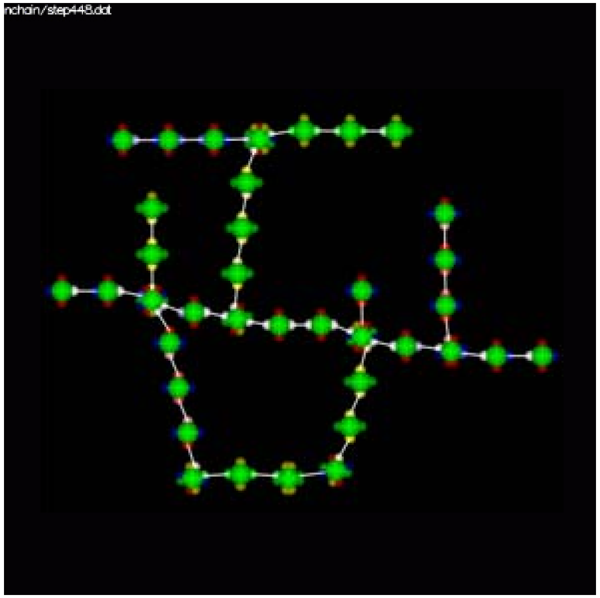
Exporing various engineering approaches to the artificial design and implementation of autonomous systems capable of developing complex, heterogeneous morphologies

Self-made puzzles that can be programmed

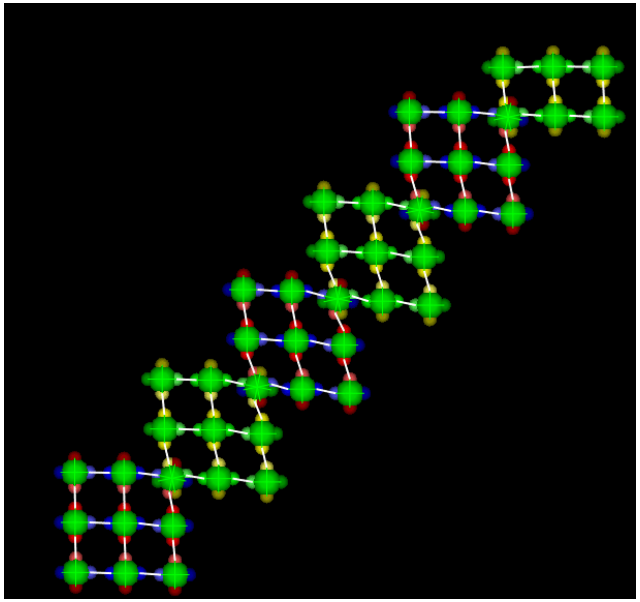
1. Techno-social networks and multi-agent modeling
2. Complex systems: from statistical to morphological
3. Harnessing complexity by "meta-design"
4. A possible direction: morphogenetic engineering
5. Toward programmable networks

From "scale-free" to structured networks

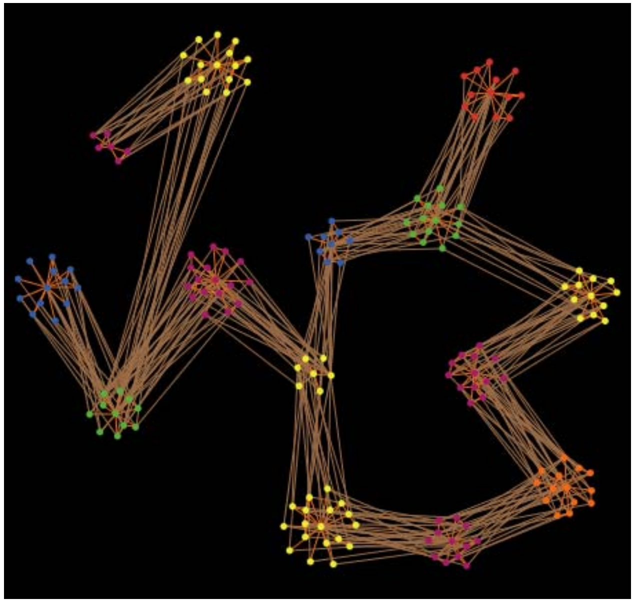




single-node
composite branching



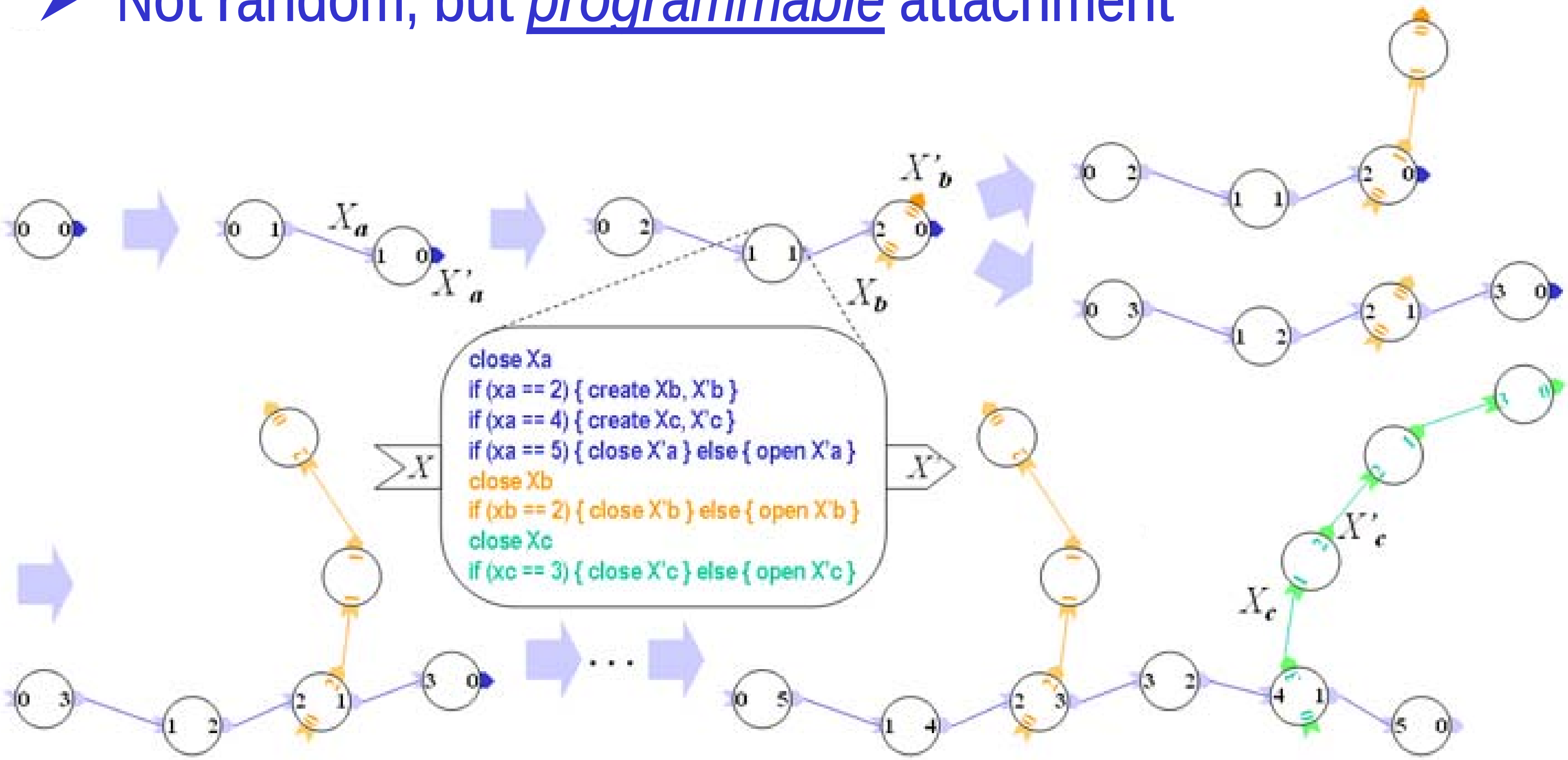
iterative lattice pile-up



clustered
composite branching

Self-knitting networks

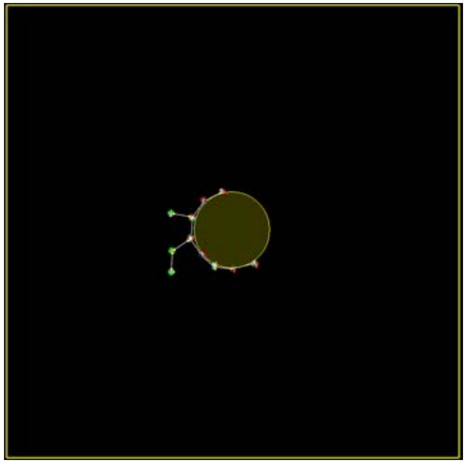
➤ Not random, but ***programmable*** attachment

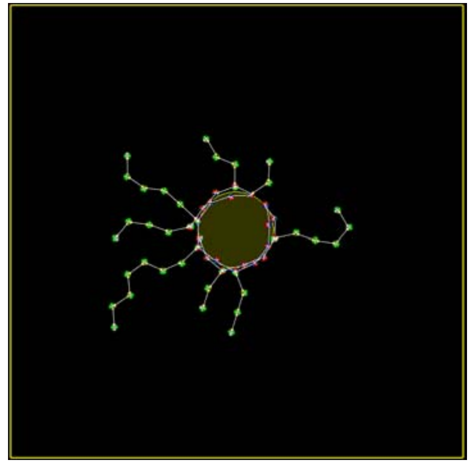


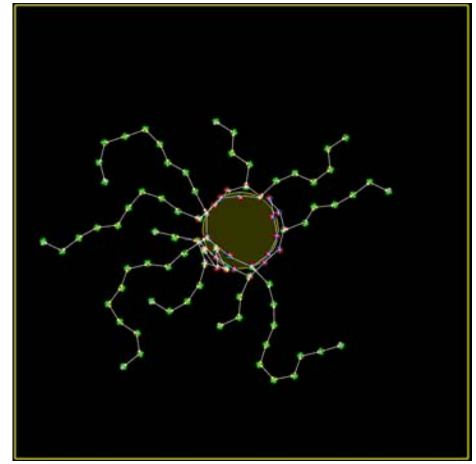
✓ a generalisation of morphogenesis in *n* dimensions

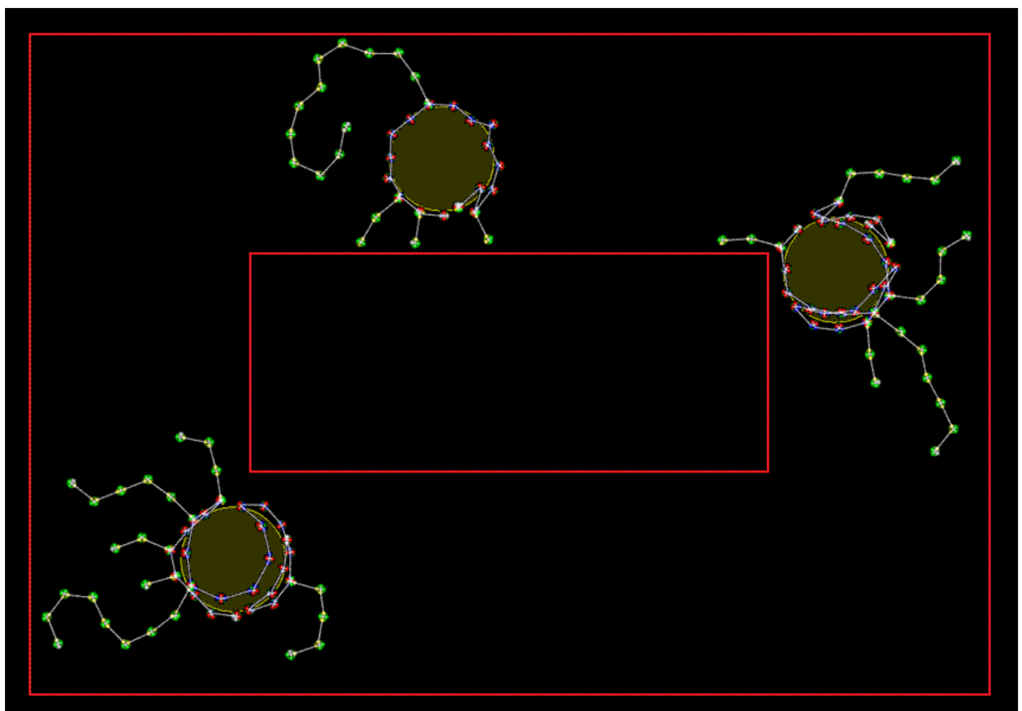
✓ the node routines are the *"genotype"* of the network

Order influenced (not imposed) by the environment









- Collaboration with Prof. Mihaela Ulieru, Canada Research Chair (UNB)
- Some simulations by Adam MacDonald (MS student at UNB), based on his software "Fluidix" (http://www.onezero.ca)

Application to techno-social networks

➢ Two applications under work

- ✓ energy grid
  - ▪ fight global warming & save energy

    ⇒ develop renewable energy sources

    ⇒ encourage "*prosumer*" initiatives (solar panels, wind turbines, etc.)

    ⇒ ***decentralise*** energy generation

    → *encourage* ***coalition*** *of users into communities to smooth consumption*

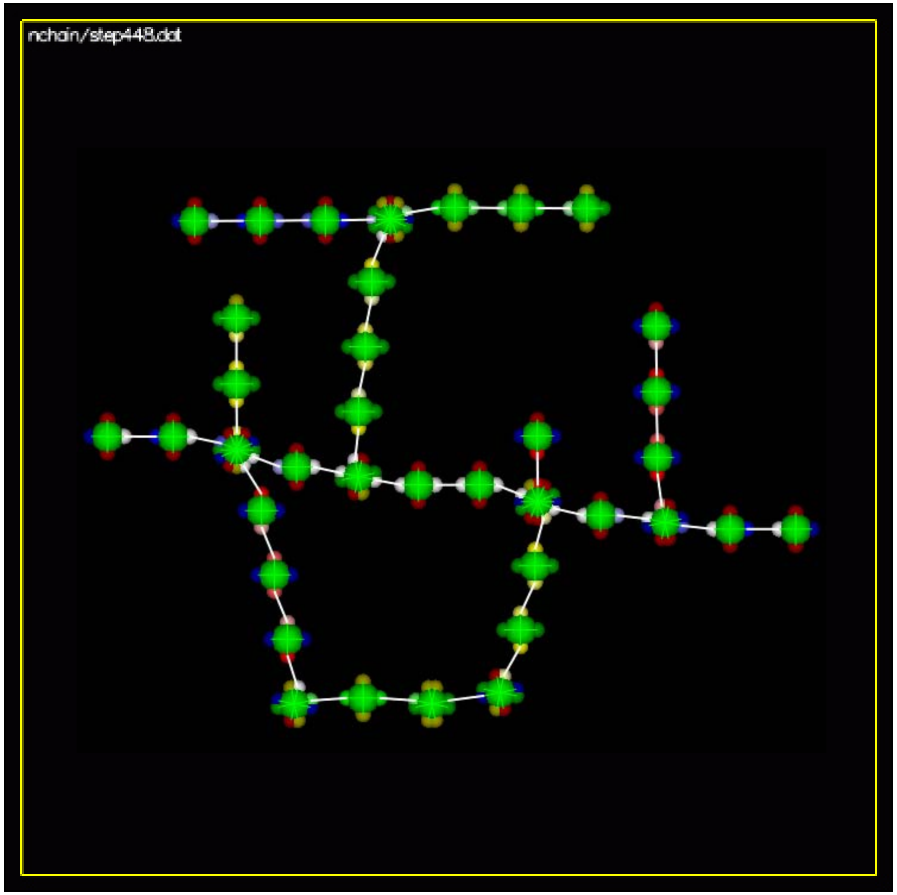
- ✓ security "ecosystems"
  - ▪ dynamic, on-the-fly creation of targeted, efficient, short-lived meta-organisations
  - ▪ working towards achieving a common goal, such as crisis resolution

    → *autonomous agents* ***coordinate*** *in various ways and decide how resources will be distributed*

submitted grant proposals
- EnergyWeb (FP7 ICT)
- BIONEXT (COST)

Abstract model of self-made network

- Formation of a specific, reproducible structure
  - ✓ nodes attach randomly, but only to a few available ports

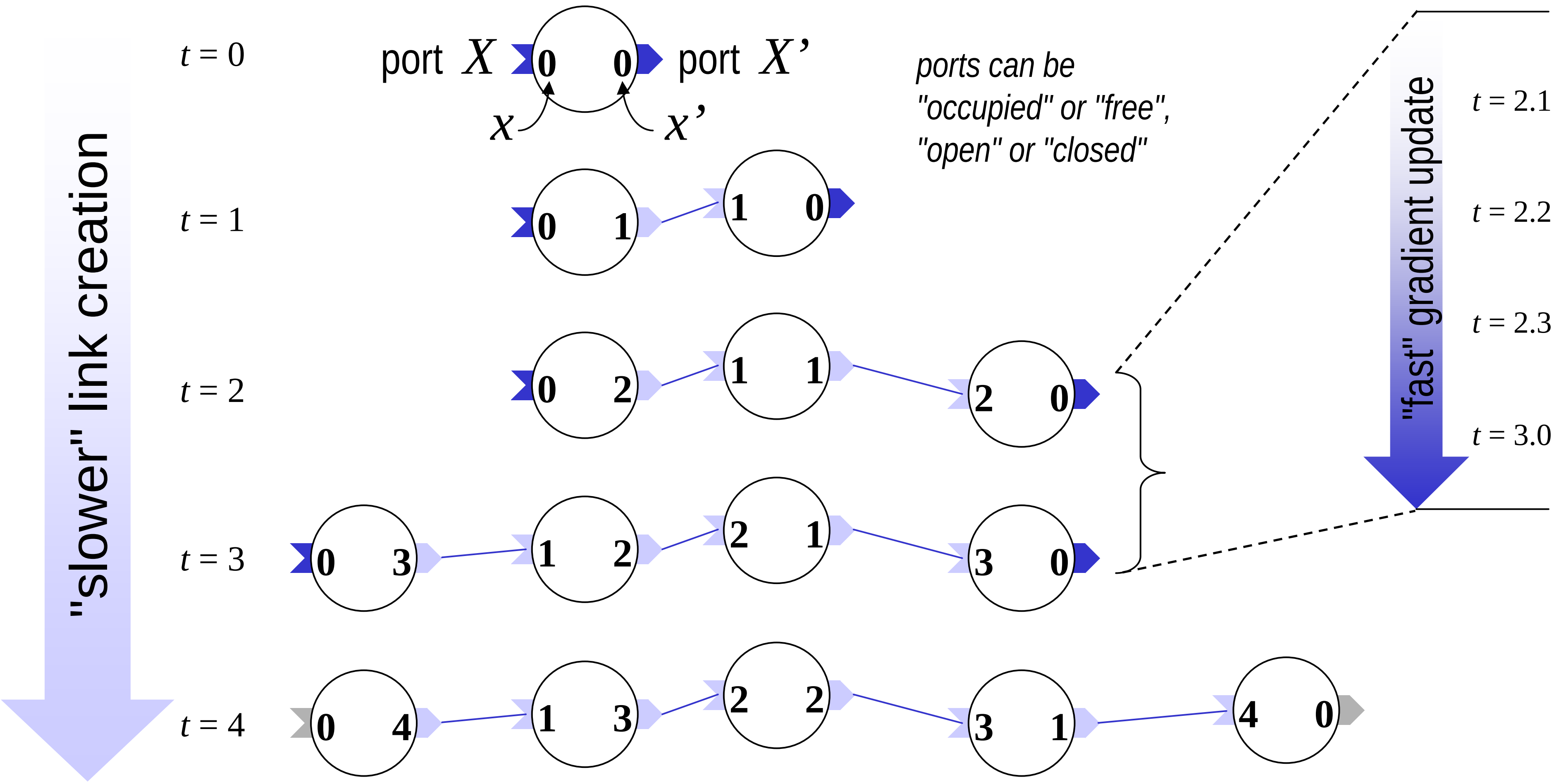


1. Chains
2. Lattices
3. Clusters
4. Modules

Abstract model of self-made network

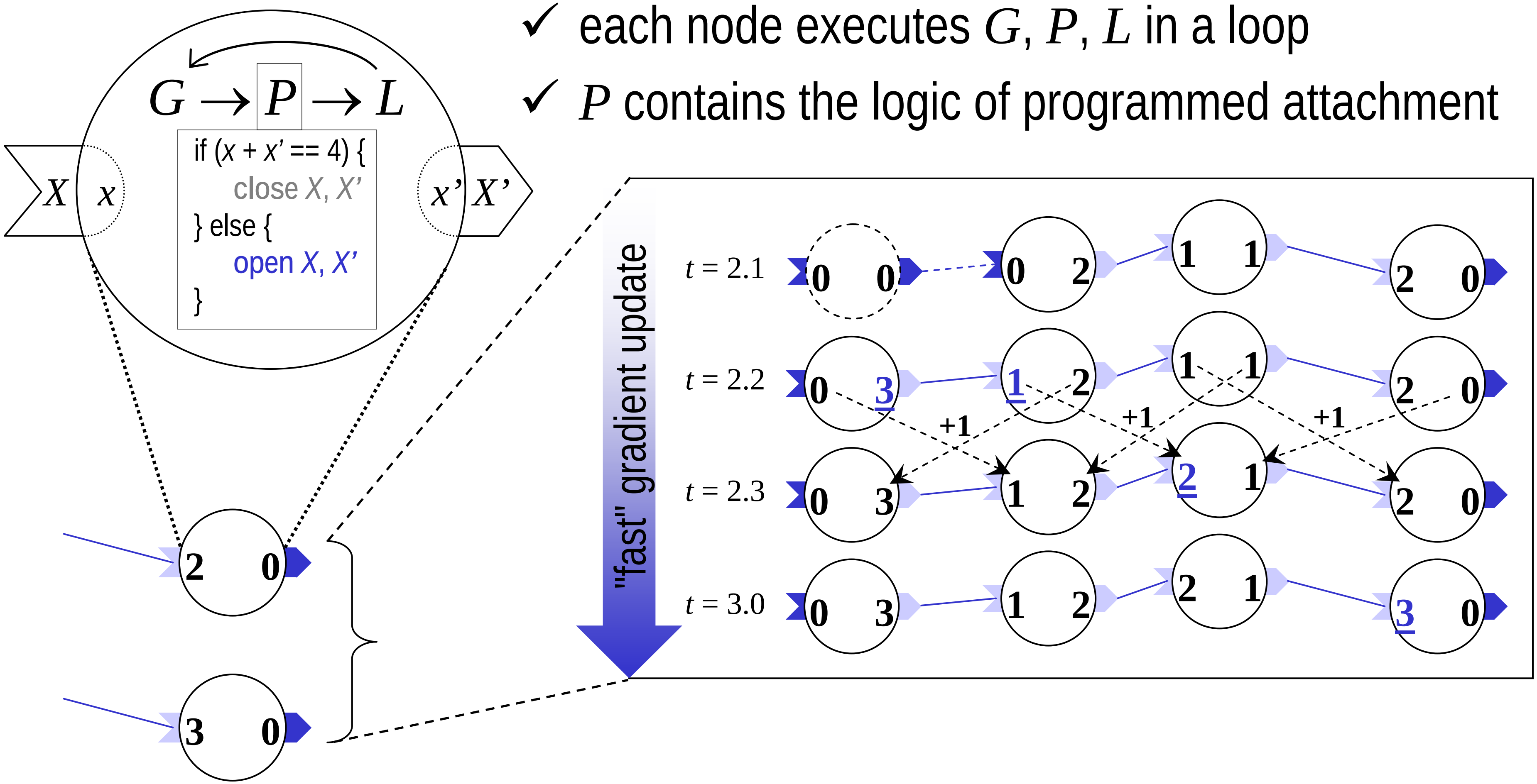
Simple chaining

- ✓ link creation (L) by programmed port management (P)



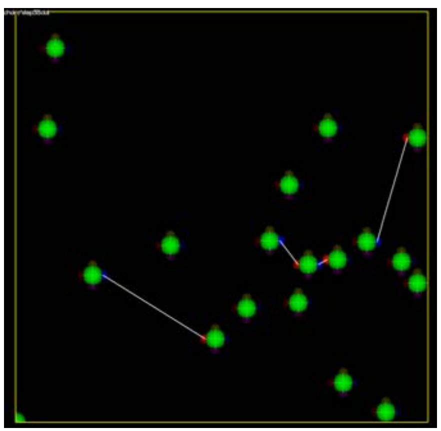
Abstract model of self-made network

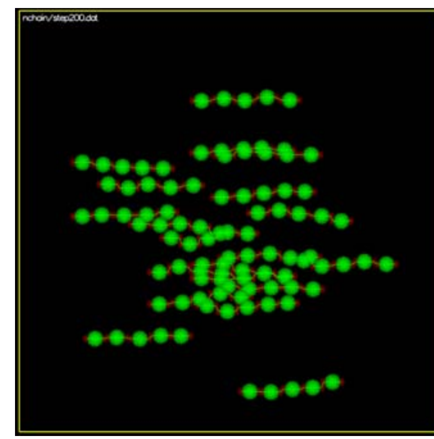
- Simple chaining
  - ✓ port management (P) relies on gradient update (G)
  - ✓ each node executes G, P, L in a loop
  - ✓ P contains the logic of programmed attachment



Abstract model of self-made network

- Simple chaining

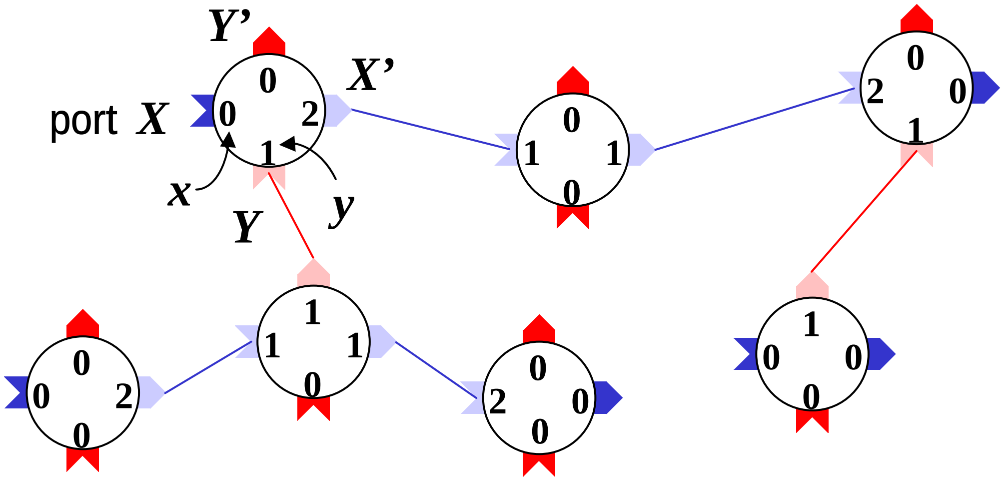




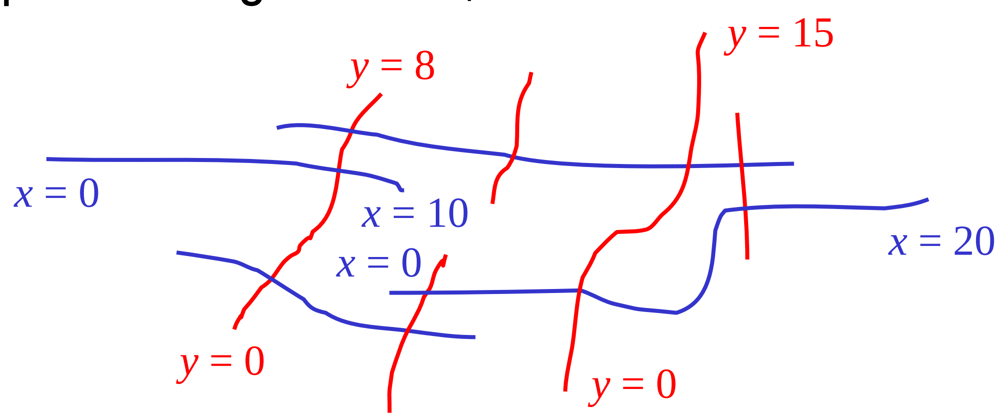
Abstract model of self-made network

Lattice formation by guided attachment

- *two* pairs of ports: (X, X') and (Y, Y')



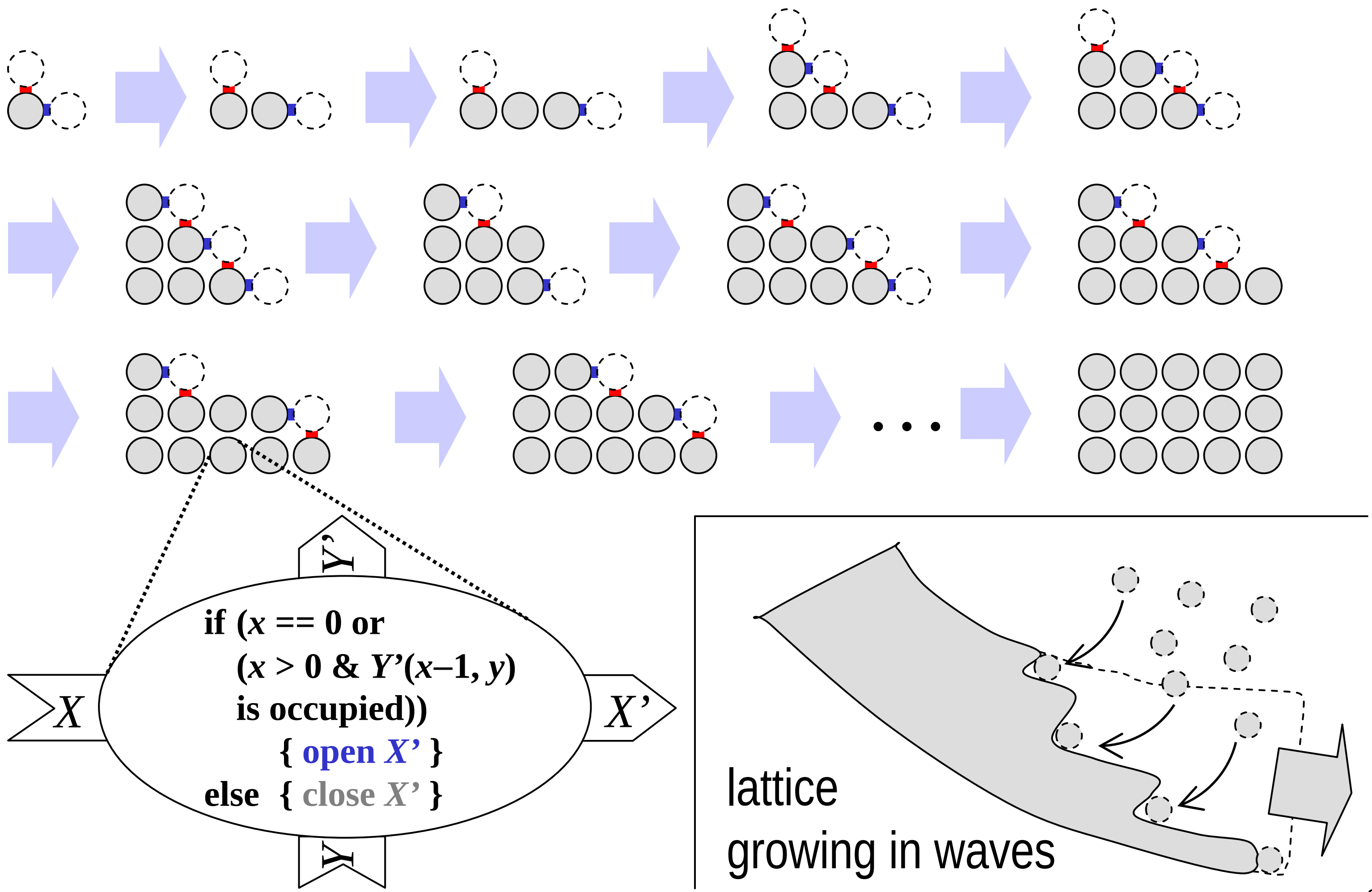
- without port management *P*, chains form and intersect randomly



Abstract model of self-made network

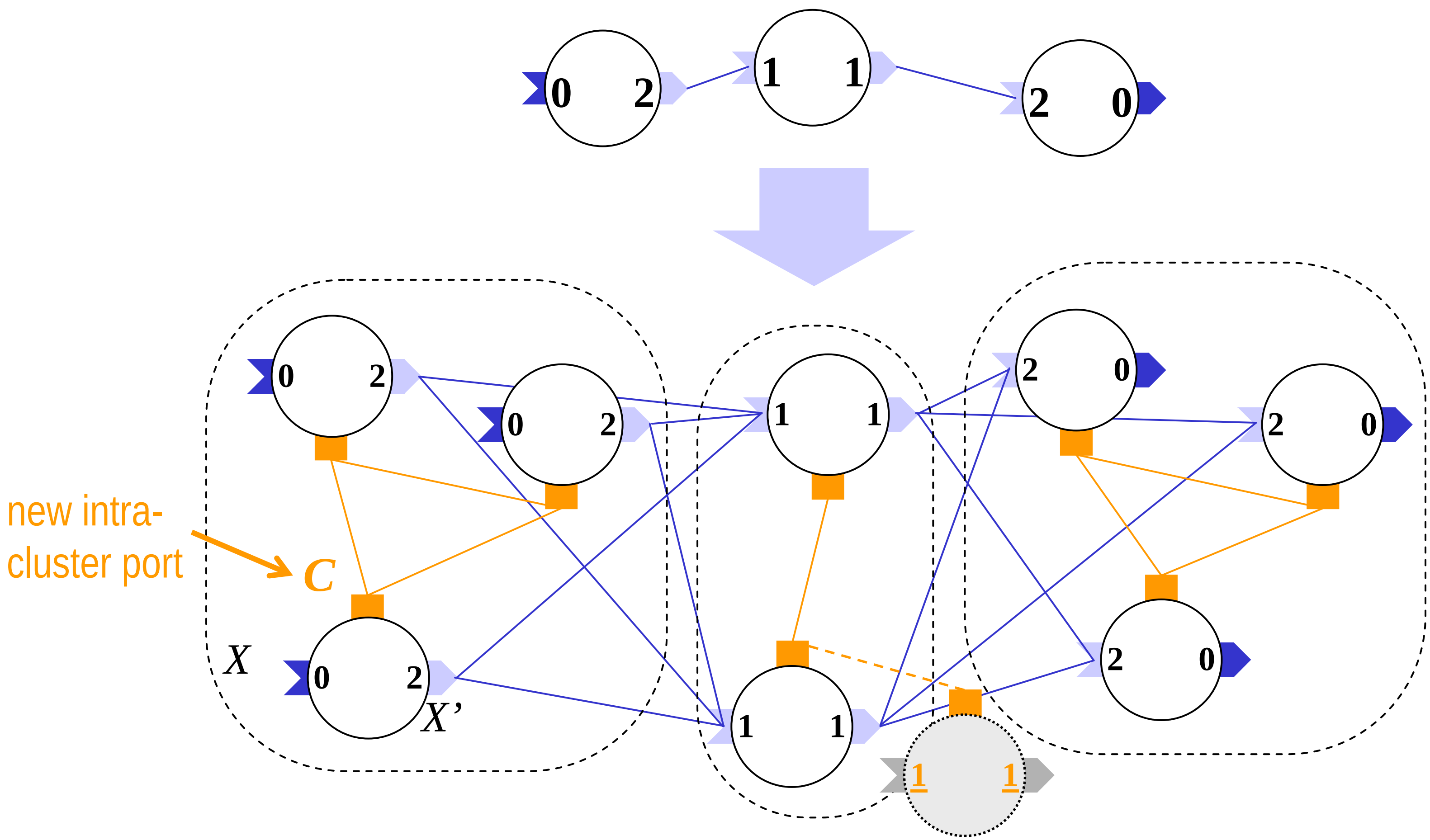
➢ Lattice formation by guided attachment

- ✓ only specific spots are open, similar to beacons on a landing runway



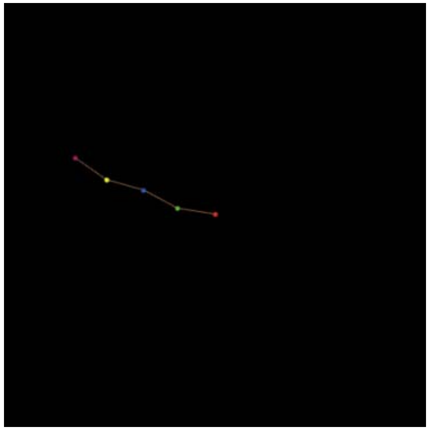
Abstract model of self-made network

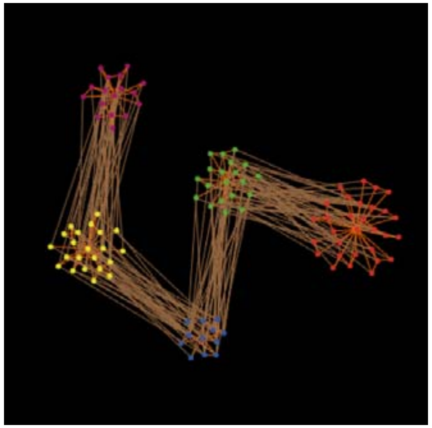
- **Cluster chains and lattices**
  - ✓ several nodes per location: reintroducing randomness but only within the constraints of a specific structure



Abstract model of self-made network

- Cluster chains and lattices

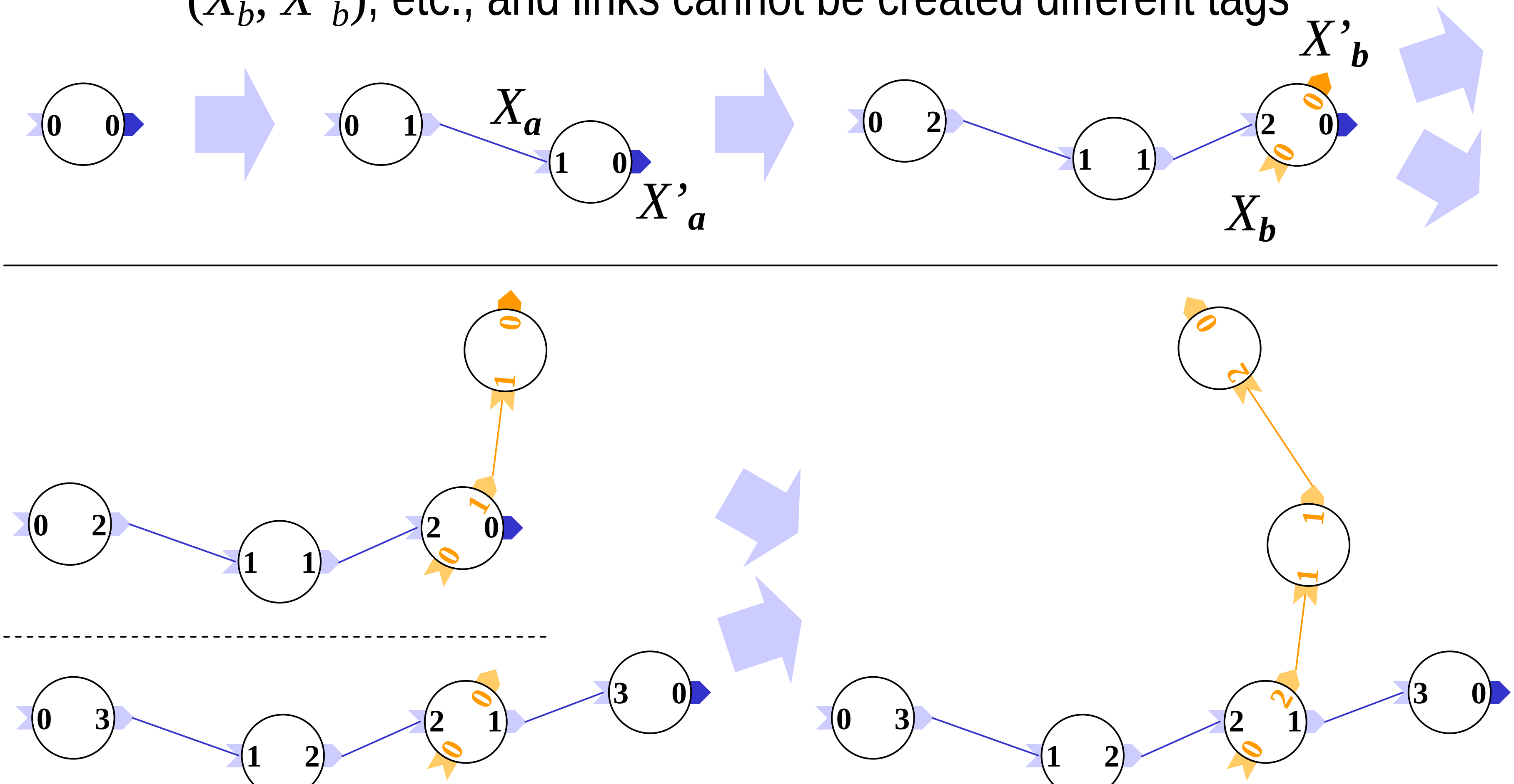




Abstract model of self-made network

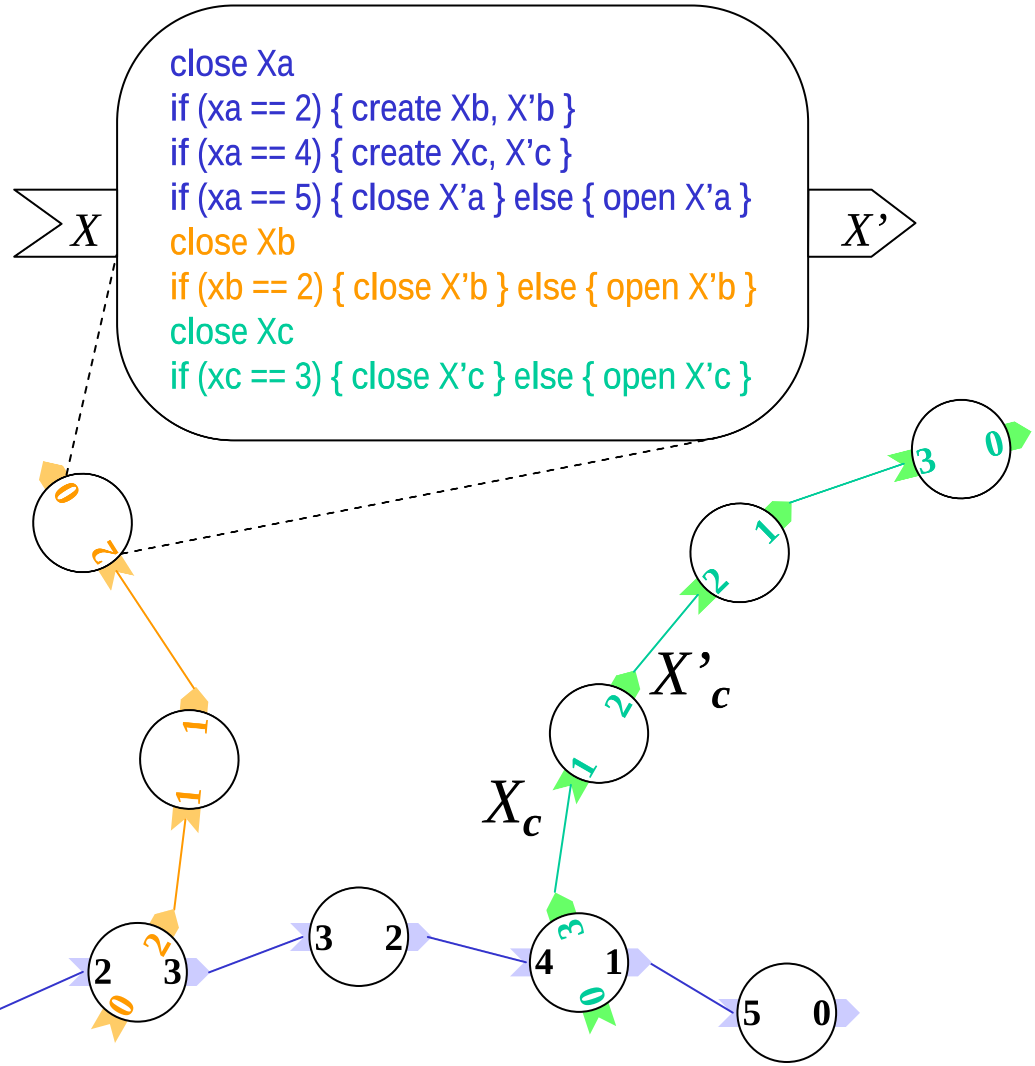
➢ Modular structures by local gradients

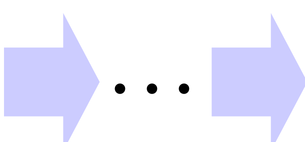
- ✓ modeled here by different coordinate systems, (X_a, X'_a), (X_b, X'_b), etc., and links cannot be created different tags



Abstract model of self-made network

- Modular structures by local gradients
  - the node routines are the *"genotype"* of the network





Toward concrete applications

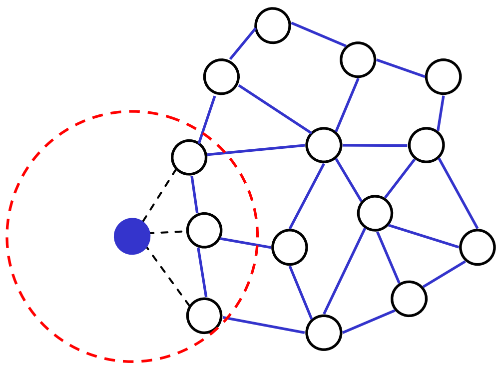
➢ Four notions to expand the model

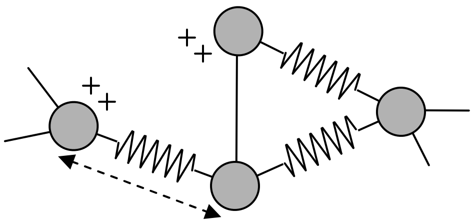
- ✓ model so far...
  - abstract principles of self-made networks
  - purely *endogenous* ability to form precise configurations
  - foundations for the emergence of *programmable* structures that are neither repetitive nor imposed by the environment
- ✓ ... must now be completed with more notions:
  1) ***physical space:*** *distance-dependent attachment*
  2) ***external events:*** *boundary conditions, exogenous constraints*
  3) ***agent functionality:*** *type-dependent attachment & function*
  4) ***action plans:*** *on-the-fly rule compilation & broadcast*

Toward concrete applications

1) Physical space

- ✓ real-world networks generally combine non-spatial & Euclidean topologies
- ✓ when agents and devices interact in real space, take into account metric distance:
  - in addition to gradient values $(x, x', y, y', \ldots)$ nodes carry a real vector $\mathbf{r} = (r_x, r_y, r_z)$
  - limits the scope of pre-attachment detection (nodes can only see "nearby" nodes)
  - gives a mechanical meaning to nodes and links, for example through force-based layout

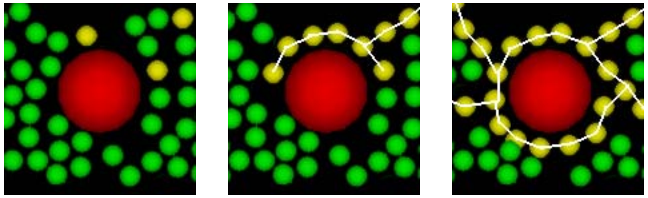




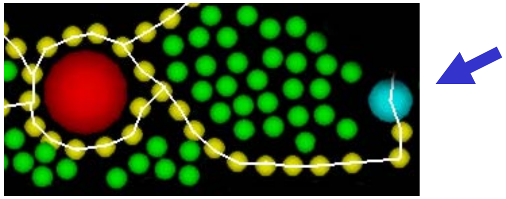
Toward concrete applications

2) External events

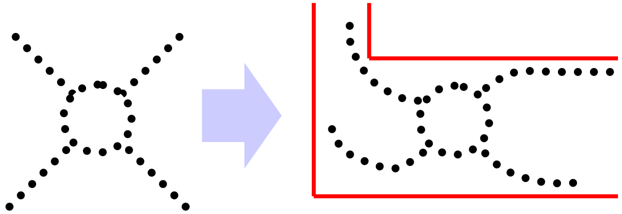
- ✓ the propensity to create structured formations must also be influenced and modified by the environment
- ✓ the internal dynamics must interact with an external dynamics of boundary conditions, events, landmarks, etc.
  - *triggers* — "seed" points can aggregate structure growth (e.g., via "event-driven" ports searching external stimuli)



  - *attractors* — chains can grow like trails aiming toward target points (e.g., via "tropism" rules that bias attachment, and "pull" in a given direction)



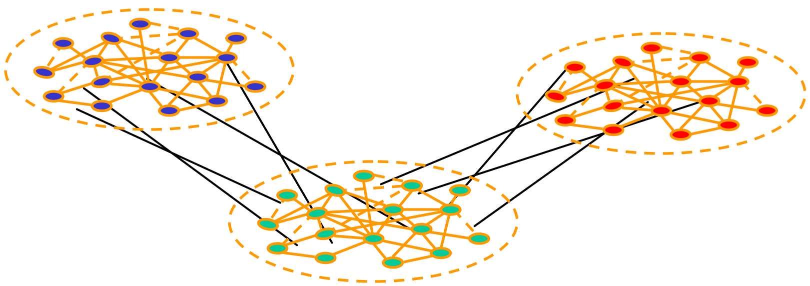
  - *obstacles* — once immersed in space, an ideal structure must adapt and bend around obstacles

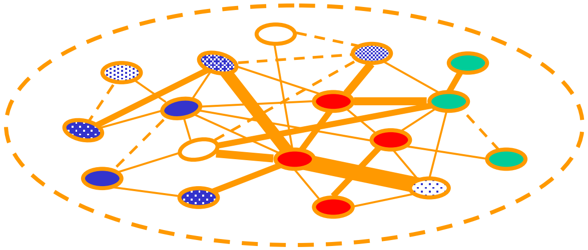


Toward concrete applications

3) Agent functionality

- ✓ diversity of *functional* roles that agents may have, in addition to their self-assembly capabilities
- ✓ natural heterogeneity of agents could be reflected in the model by a heterogeneity of ports and gradients, and diversified attachment rules that depend on predefined agent types
- ✓ this could result in various types of subnetworks, e.g.:
  - "intra-category" subnetworks linking agents of similar expertise
  - "inter-category" subnetworks combining agents of different expertise into mixed clusters

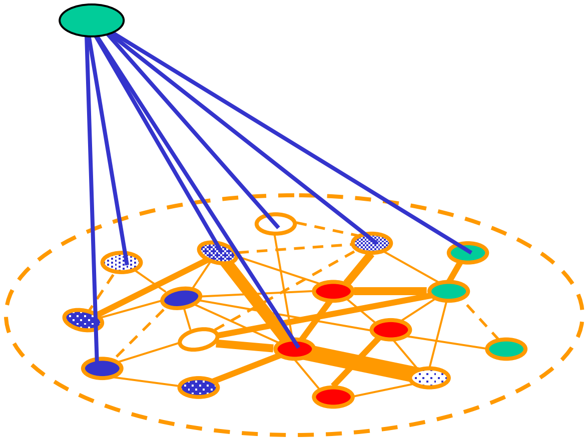




Toward concrete applications

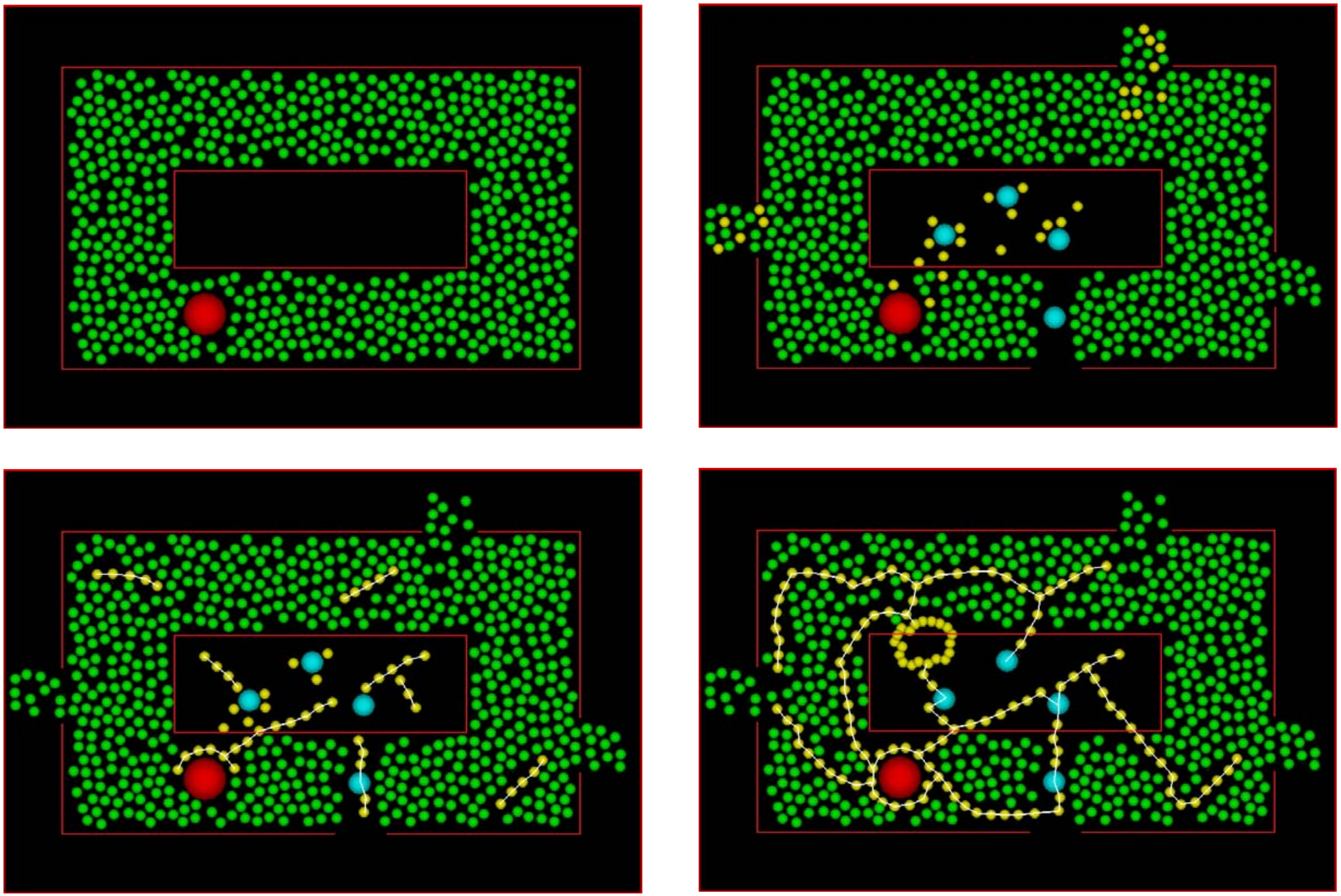
4) Action plans

- ✓ effective network deployment cannot exclusively rely on peer-to-peer self-organization at the local level
- ✓ techno-social networks still need global monitoring and orchestration
  - for that, high-level action plans could set the global course of the action, while low-level implementation details would be carried out by individual agents
  - action plans could be compiled down into local rules of attachment and broadcast to all agents
  - thus, the network could adapt to new events by ***reprogramming the agents on the fly*** to create new formations



Toward concrete applications

➢ Possible example: self-organized security (SOS) scenario



(mockup screens: not a simulation ... yet)

Self-made puzzles that can be programmed

1. Techno-social networks and multi-agent modeling
2. Complex systems: from statistical to morphological
3. Harnessing complexity by "meta-design"
4. A possible direction: morphogenetic engineering
5. Toward programmable networks