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Paradox in Approaching Complexity

From Natural to Engineered Complex Systems

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From Natural to Engineered Complex Systems

1. Approaching and harnessing complexity

The new techno-social networks are de facto complex systems (of users and devices)

They exhibit spontaneous collective behavior that we don’t quite understand or control yet

It is time to design new collaborative technologies to harness this decentralization and emergence

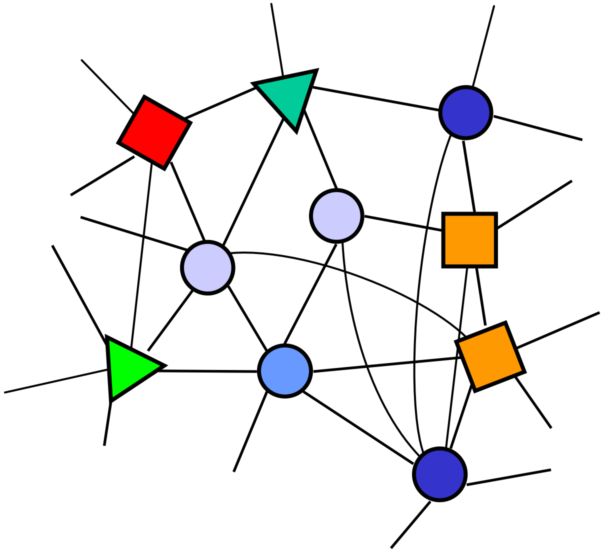
2. A possible direction: morphogenetic engineering

Techno-social systems

- The rise of complex techno-social networks
  - explosion in size and complexity of networked ICT systems in all domains of society (exemplified in this conference):
    - 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**

Techno-social systems

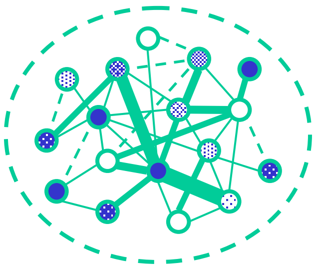
- De facto distribution over a myriad of users and devices
  - ✓ ubiquitous computing and communication capabilities connect people and infrastructures in unprecedented ways
  - ✓ complex techno-social systems based on bottom-up interactions among a myriad of artifacts and **humans** ...



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

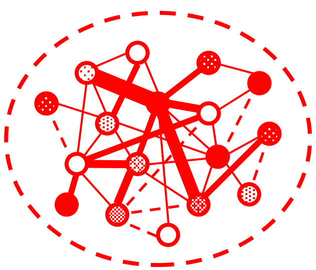
Techno-social systems

- Understanding & causing → designing



Understanding "natural" (spontaneous) emergence
→ *Agent-Based Modeling (ABM)*

designing complex ICT systems



Causing new "artificial" emergence
→ *Multi-Agent Systems (MAS)*

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 of providers:
      data, knowledge, command, information, energy, etc.
    - to a densely heterarchy of proactive participants:
      patients, students, soldiers, users, consumers, etc.

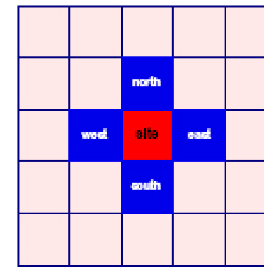
→ *creates full-fledged complex systems of two-way interactions among multiple users, via distributed software applications*

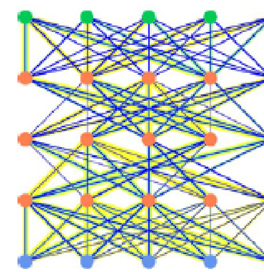
Techno-social systems

➢ 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 from 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*

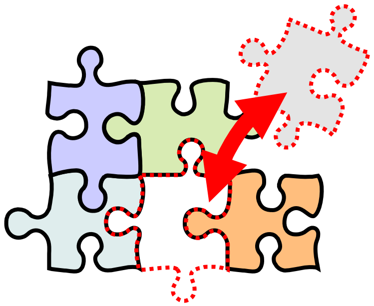




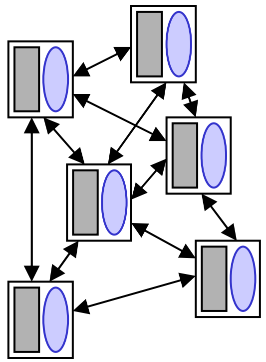
Macal & North
Argonne National Laboratory

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***



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



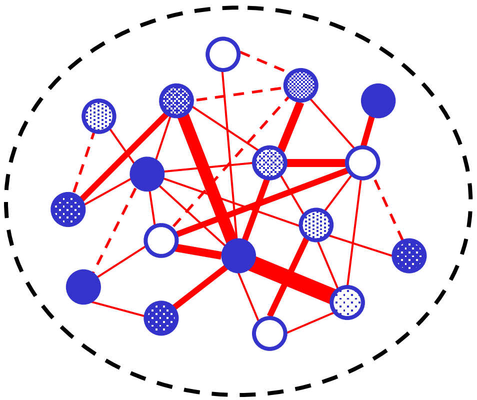
→ *the rise of pervasive networking made distributed systems a necessity and a practical technology*

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
  - → *contrast with the ABM philosophy*
    - focus on few “heavy-weight” (big program), “selfish”, intelligent agents, as opposed to many “light-weight” (few rules), highly “social”, simple agents
    - focus on game theoretic gains, as opposed to collective emergent behavior

Complex systems

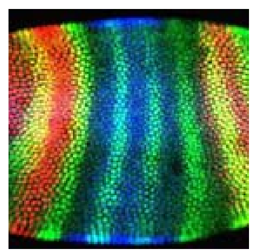
➢ Complex systems



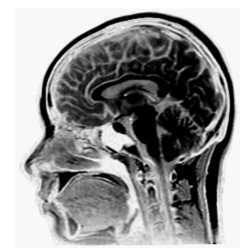
- **large** number of elementary **agents** interacting **locally**
- more or less simple individual agent behaviors creating a complex emergent **self-organized** behavior
- **decentralized** dynamics: no master blueprint or architect
- **self-organization** and **evolution** of innovative order

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

pattern formation
○ = matter

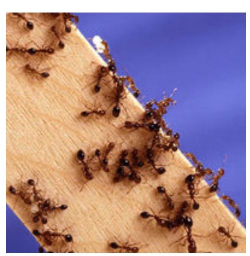


biological development
○ = cell

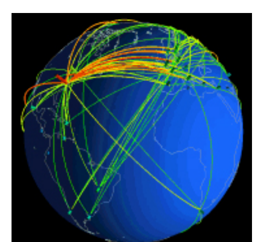


the brain & cognition
○ = neuron

insect colonies
○ = ant



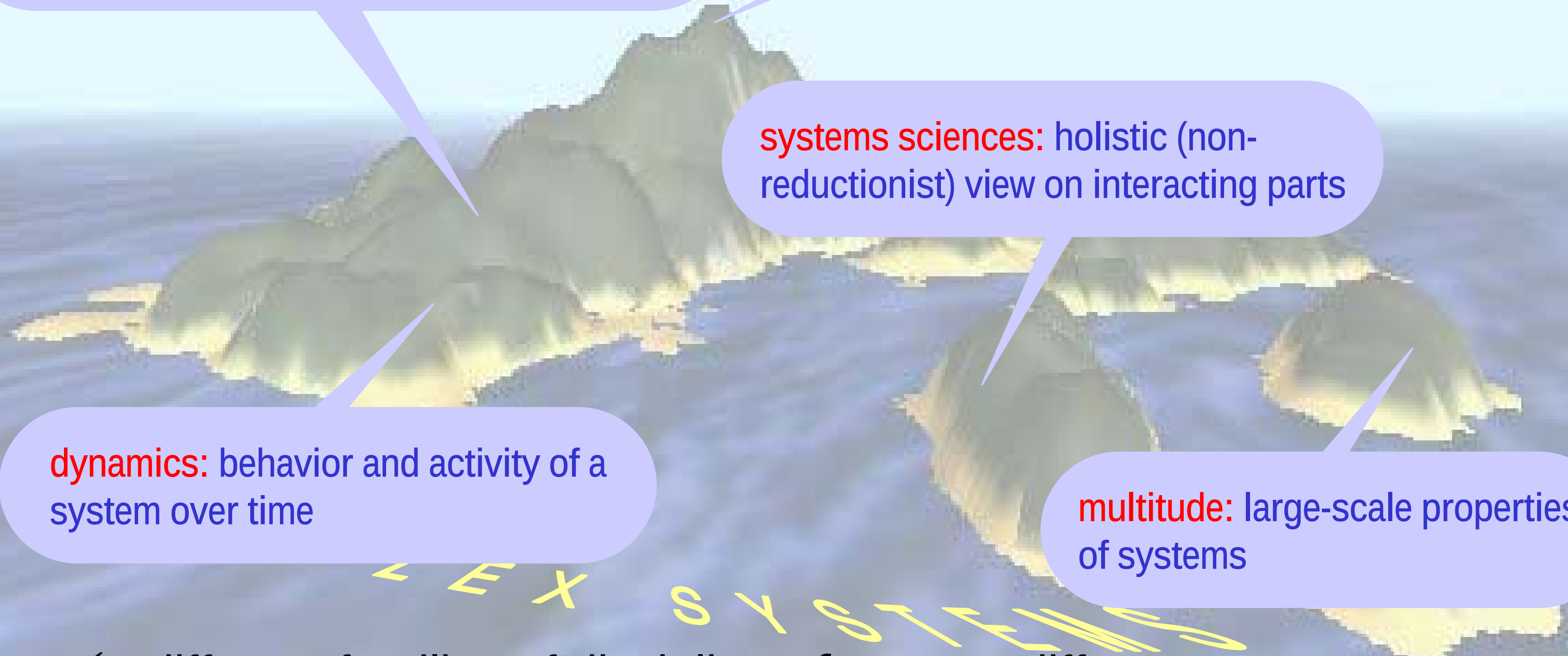
Internet & Web
○ = host/page



social networks
○ = person

Complex systems: a vast archipelago

➢ Precursor and neighboring disciplines



adaptation: change in typical functional regime of a system

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

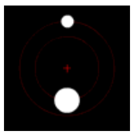
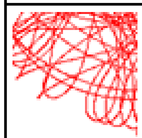
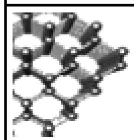
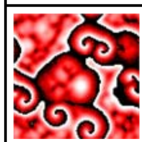
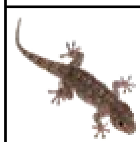
- graph theory & networks
- statistical physics
- agent-based modeling
- distributed AI systems

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"?*
 two-body problem	*few*	*simple*	*simple*	*NO*
 three-body pb, 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*
 machines, crowds with leaders	*many*	*sophisticated*	*"simple"*	*COMPLICATED – not self-organized*

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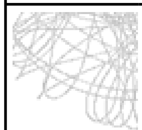
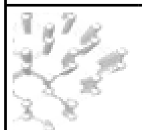
 three-body pb, low-D chaos	*few*	*simple*	*complex*	*NO – too small*
 crystal, gas	*many*	*simple*	*simple*	*NO – few params suffice to describe it*
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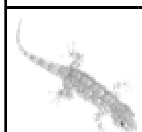 structured morphogenesis	*many*	*sophisticated*	*complex*	*YES – reproducible and heterogeneous*
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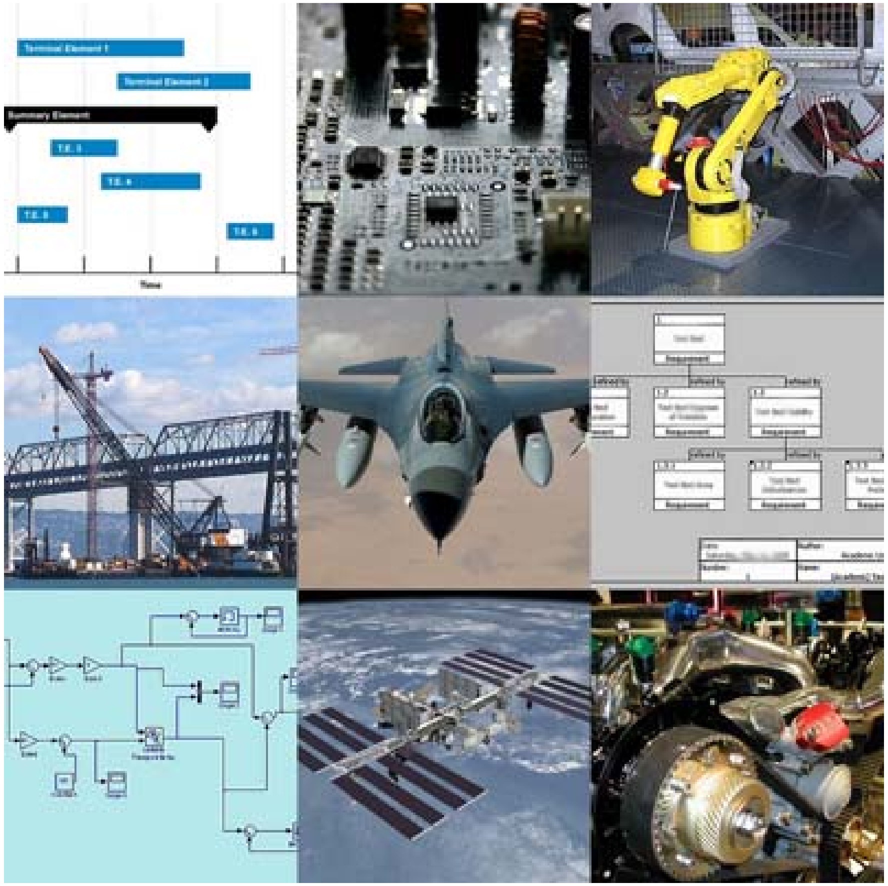
Complicated systems

- Many agents, complex rules, "simple" emergent behavior
  - → *techno example: electronics, machines, aircrafts, civil constructions*
  - ✓ 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)



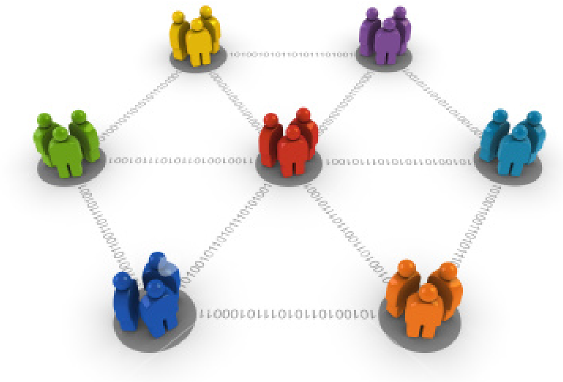
Systems engineering
Wikimedia Commons

Complicated systems

- Many agents, complex 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 self-organization*** *(or only little)*

Complex techno-social systems

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



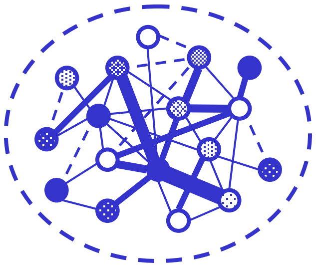
  - ✓ as complex systems, techno-social networks exhibit self-organization and unpredictability
  - ✓ spontaneously appearance of collective behavior, but traditional organizations are not prepared for it
  - ✓ this spontaneous trend that has preceded our ability as designers to comprehend and control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

Complex techno-social systems

- A challenge & an opportunity for 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 technologies
  - import the desirable properties of natural complex systems
    - (semi-)autonomy
    - homeostasis
    - dynamic adaptation
    - long-term evolution

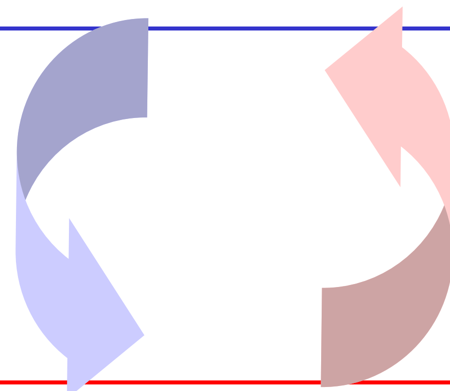
Complex systems research

- The challenges of complex systems (CS) research



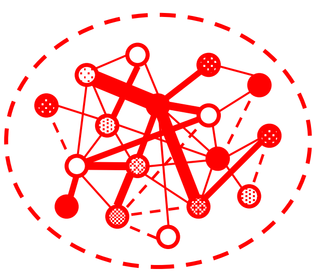
CS science: understanding "natural" CS

(i.e. spontaneously emergent, including human activity)



Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

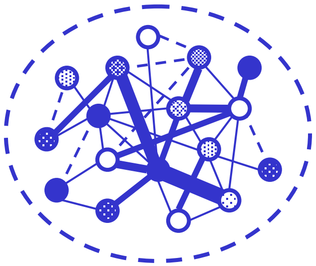
Imports
- observe, model
- control, harness
- design, use



CS engineering: creating a new generation of "artificial" CS (i.e. harnessed, including nature)

Complex systems research

- ABM meets MAS: merging two perspectives

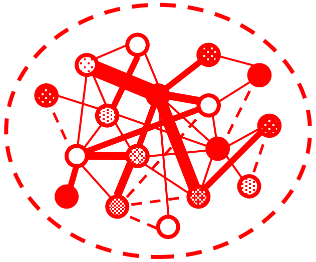


CS science: understanding "natural" CS

→ *Agent-Based Modeling (ABM)*

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

designing complex ICT systems



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

Emergent engineering

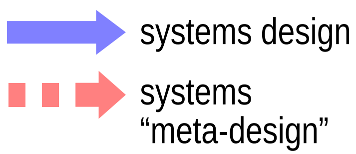
- Harnessing, not dreading complex systems
  - ✓ the need to develop a sense of capability and security in the changing context
  - ✓ instead of clinging to a traditionally totalistic control that is inexorably vanishing...
  - ✓ ... focus rather on establishing conditions in which complexity can develop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

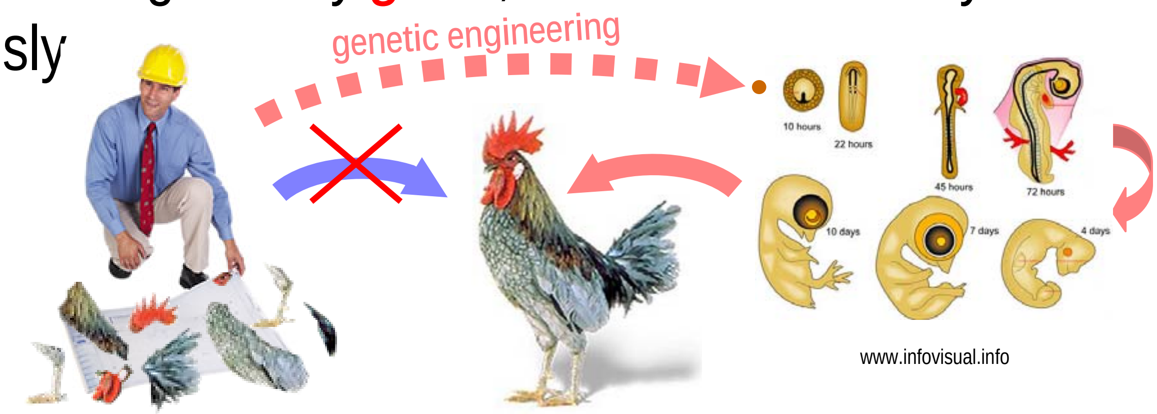
→ *future complex ICT engineering should be less about direct design than developmental and evolutionary “meta-design”*

The challenge of designing complexity

➢ Toward "meta-design"

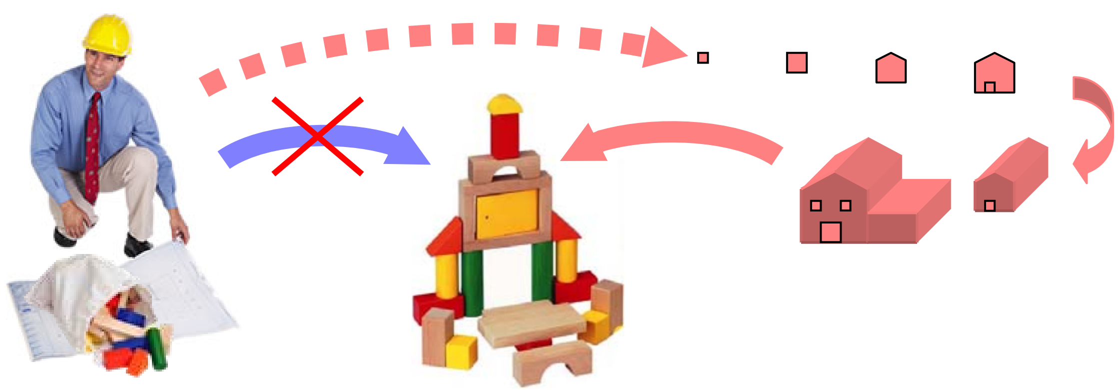
- ✓ organisms endogenously *grow*, whereas artificial systems *are built* exogenously





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

don't build the system (phenotype), <u>program the agents</u> (developmental genotype)—see, e.g., "artificial embryogeny"

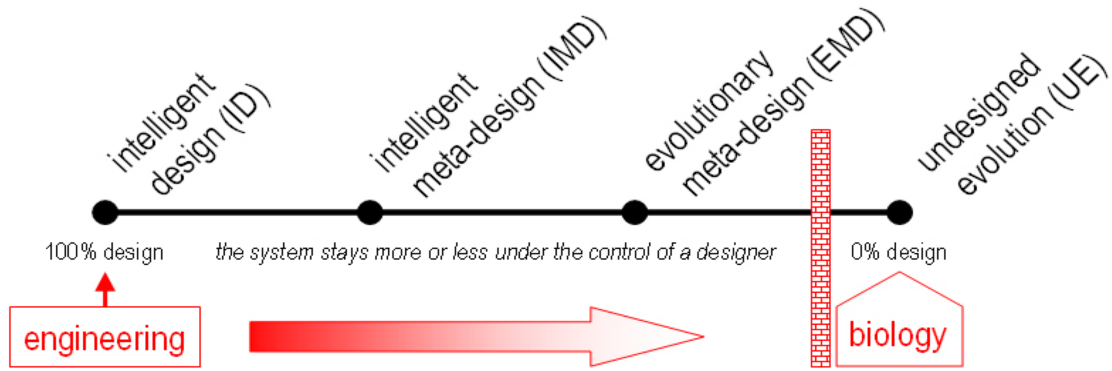


Bio-inspired emergent engineering

- Natural adaptive systems as a new paradigm for ICT
  - ✓ 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

Evolutionary meta-design

➢ Pushing engineering toward evolutionary biology



intelligent design		intelligent & evolutionary “meta-design”
heteronomous order	▪	autonomous order
centralized control	▪	decentralized control
manual, extensional design	▪	automated, intentional design
engineer as a micromanager	▪	engineer as a lawmaker
rigidly placing components	▪	allowing fuzzy self-placement
tightly optimized systems	▪	hyperdistributed & redundant systems
sensitive to part failures	▪	insensitive to part failures
need to control	▪	prepare to adapt & self-regulate
need to redesign	▪	prepare to learn & evolve
complicated systems: planes, ~~computers~~	▪	*complex* systems: Web, market ... computers?

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

From Natural to Engineered Complex Systems

1. Approaching and harnessing complexity

2. A possible direction: morphogenetic engineering

   a. Consider systems as self-made puzzles

   b. Design and program the pieces (“genotype”)

   c. Evolve by variation of the pieces & selection of the architecture (“phenotype”)

From flocks to shapes

uncontrolled
self-organization

controlled
self-made puzzle

From “statistical” to “morphological” complex systems

- A brief taxonomy of systems

Category	*Agents / Parts*	*Local Rules*	*Emergent Behavior*	*A “Complex System”?*
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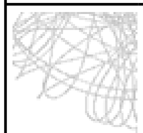
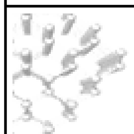
 three-body pb, low-D chaos	*few*	*simple*	*complex*	*NO – too small*
 crystal, gas	*many*	*simple*	*simple*	*NO – few params suffice to describe it*
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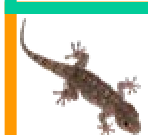 structured morphogenesis	*many*	*sophisticated*	*complex*	*YES – reproducible and heterogeneous*
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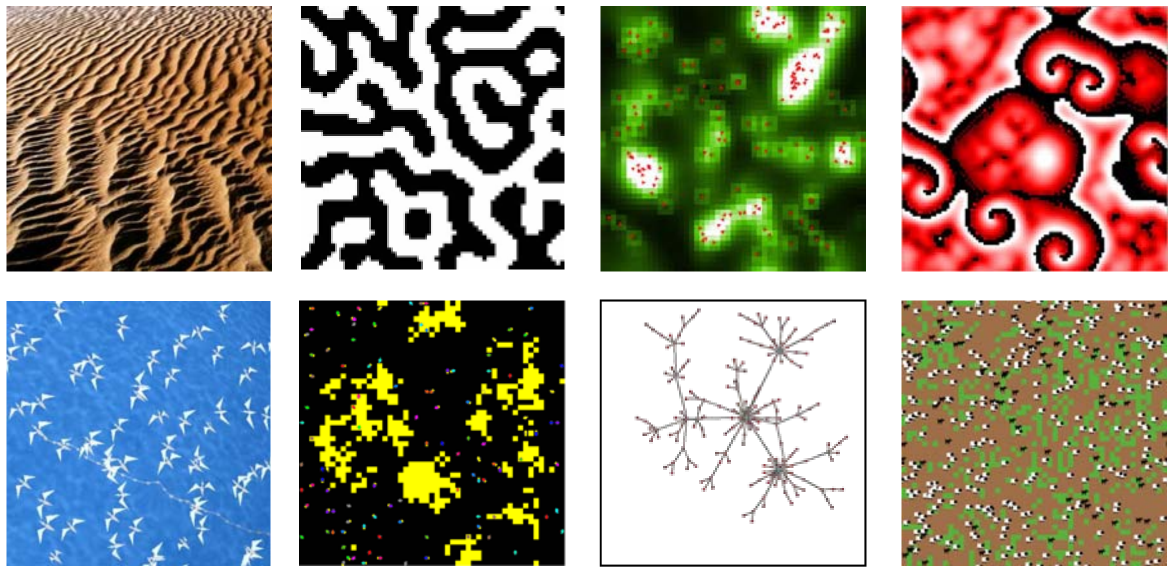
Statistical (self-similar) systems

- 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)

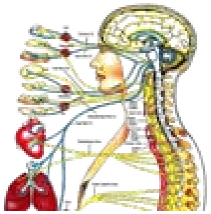
Morphological (self-dissimilar) systems

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

plants

vertebrates

arthropods

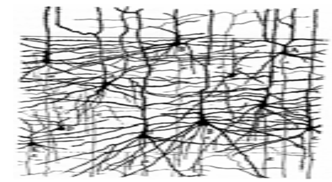


humans

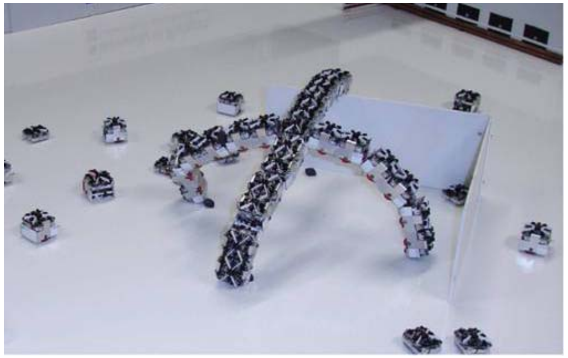
  - ✓ mesoscopic organs and limbs have intricate, *nonrandom* morphologies
  - ✓ development is highly *reproducible* in number and position of body parts
  - ✓ *heterogeneous* elements arise under information-rich genetic control
- ➢ Biological organisms are self-organized *and* structured
  - ✓ because agent rules are more “sophisticated”: they can depend on the agent’s *type* and/or *position* in the system
  - ✓ the outcome (development) is truly complex but, paradoxically, can also be more *controllable* and *programmable*

The need for morphogenetic abilities: self-architecturing

- Model natural systems → transfer to artificial systems
  - ✓ need for morphogenetic abilities in biological modeling
    - organism development
    - brain development

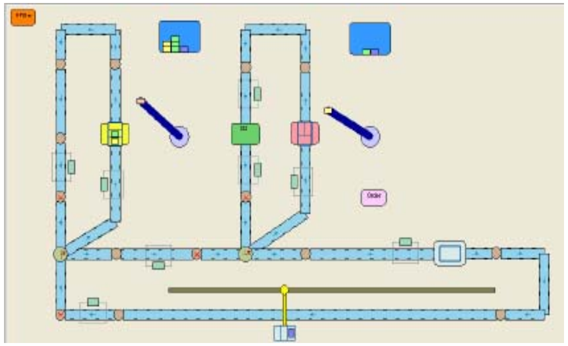


  - ✓ need for morphogenetic abilities in computer science & AI
    - self-forming robot swarm
    - self-architecturing software
    - self-connecting micro-components



http://www.symbrion.eu

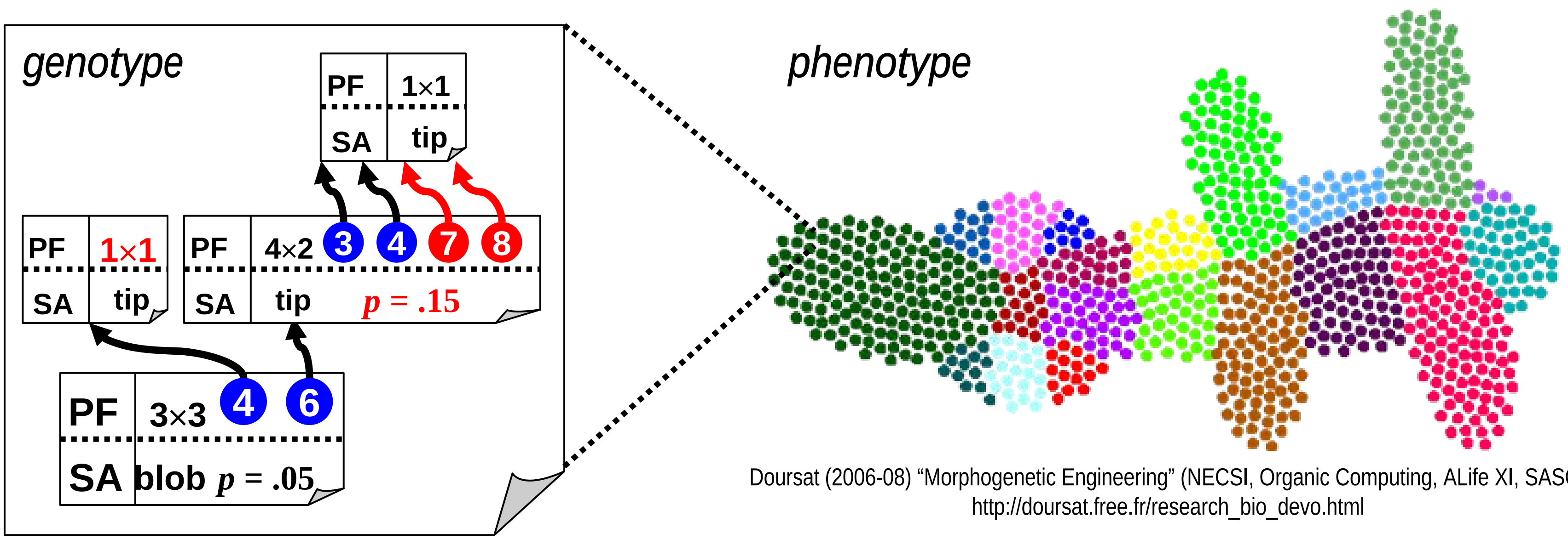
  - ✓ need for morphogenetic abilities in techno-social eNetworked systems
    - self-reconfiguring manufacturing plant
    - self-stabilizing energy grid
    - self-deploying emergency taskforce



MAST agents, Rockwell Automation Research Center
{pvrba, vmarik}@ra.rockwell.com

The self-made puzzle: from genotype to phenotype

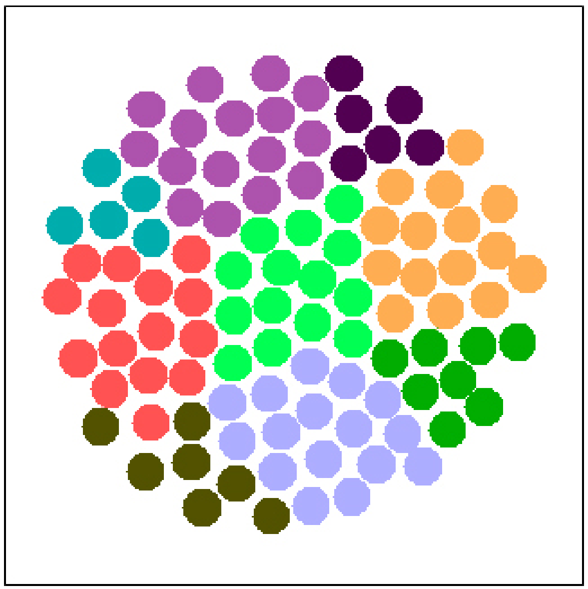
- Genotype (DNA): rules at agents' *microlevel* on how to
  - ✓ *search* and *connect* to other agents
  - ✓ *interact* with them over these connections
  - ✓ *change* one's internal state and rules, i.e., *differentiate*
  - ✓ carry out some specialized *function*
- Phenotype: collective behavior visible at the *macrolevel*



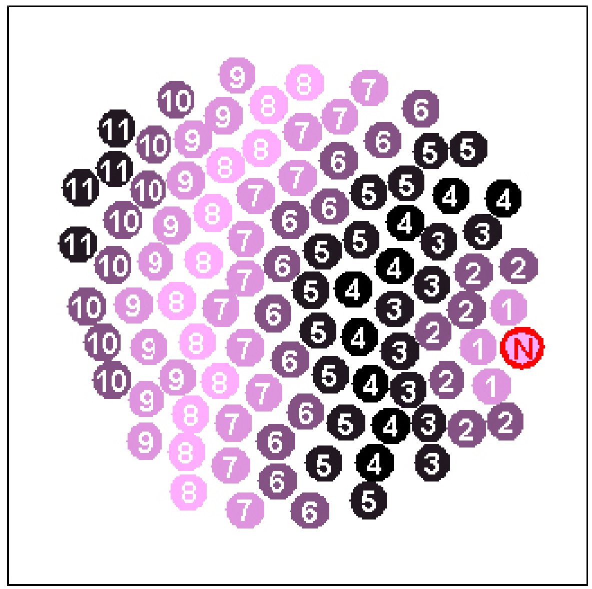
Doursat (2006-08) "Morphogenetic Engineering" (NECSI, Organic Computing, ALife XI, SASO)
http://doursat.free.fr/research_bio_devo.html

A model of programmable morphogenesis

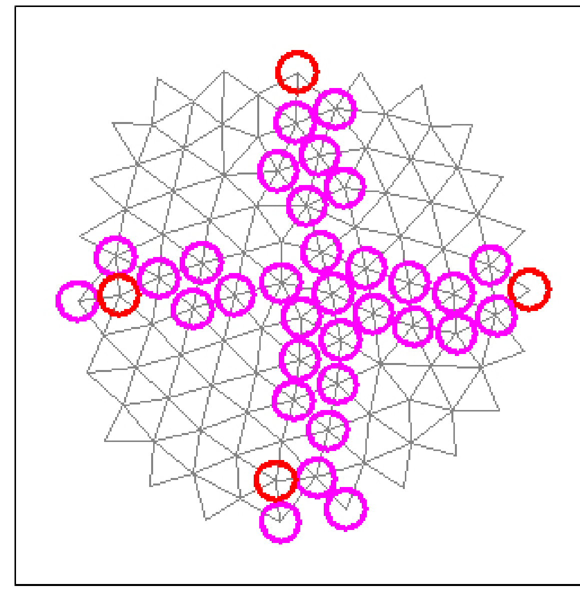
- Simultaneous growth *and* patterning on 1 level
  - ✓ example of simulation: 3 movies showing the same development highlighting 3 different internal states (in different embryos)



highlighting
gene patterning (PF-II)



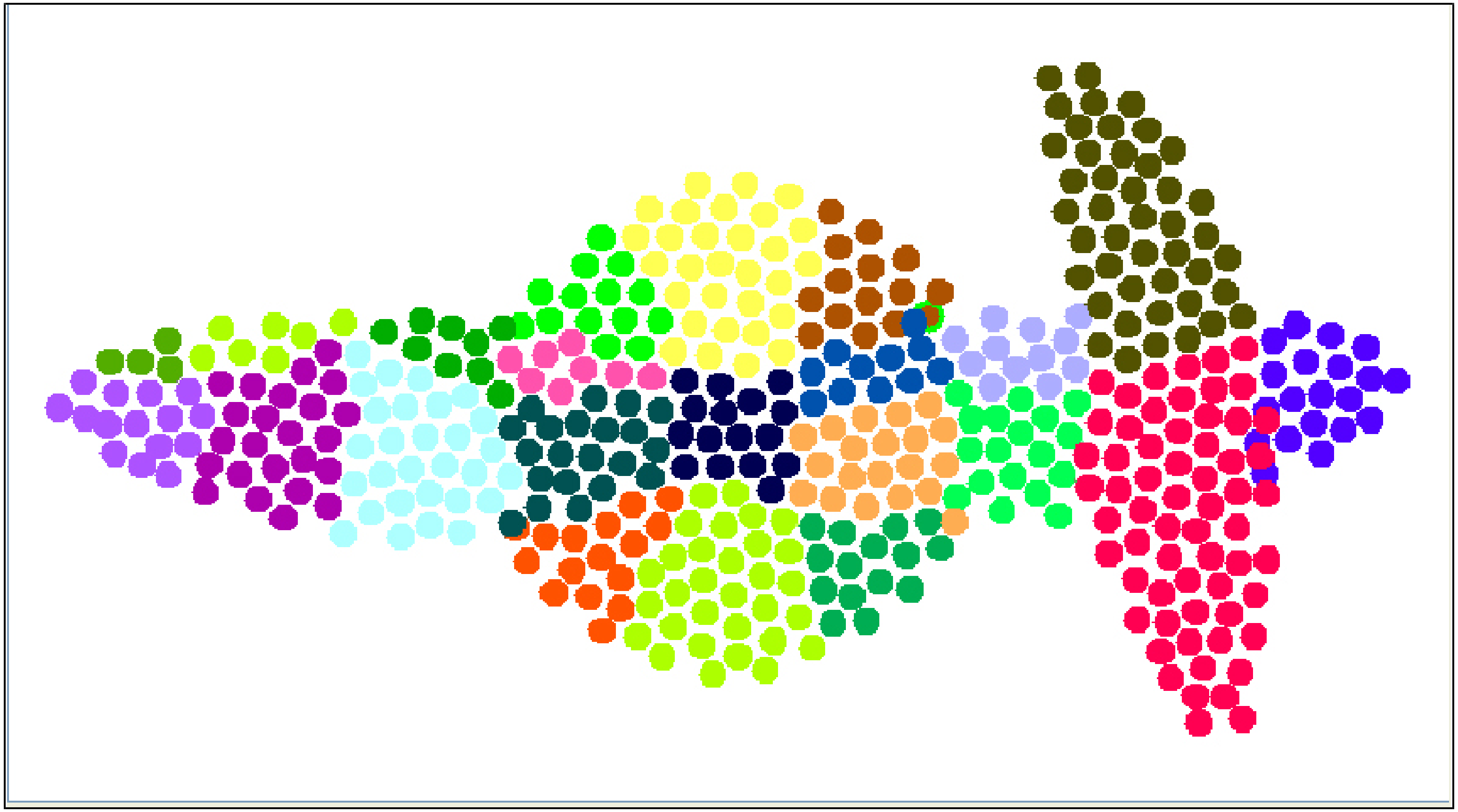
highlighting
gradient formation (PF-I)



highlighting
lattice (SA) with gradient lines

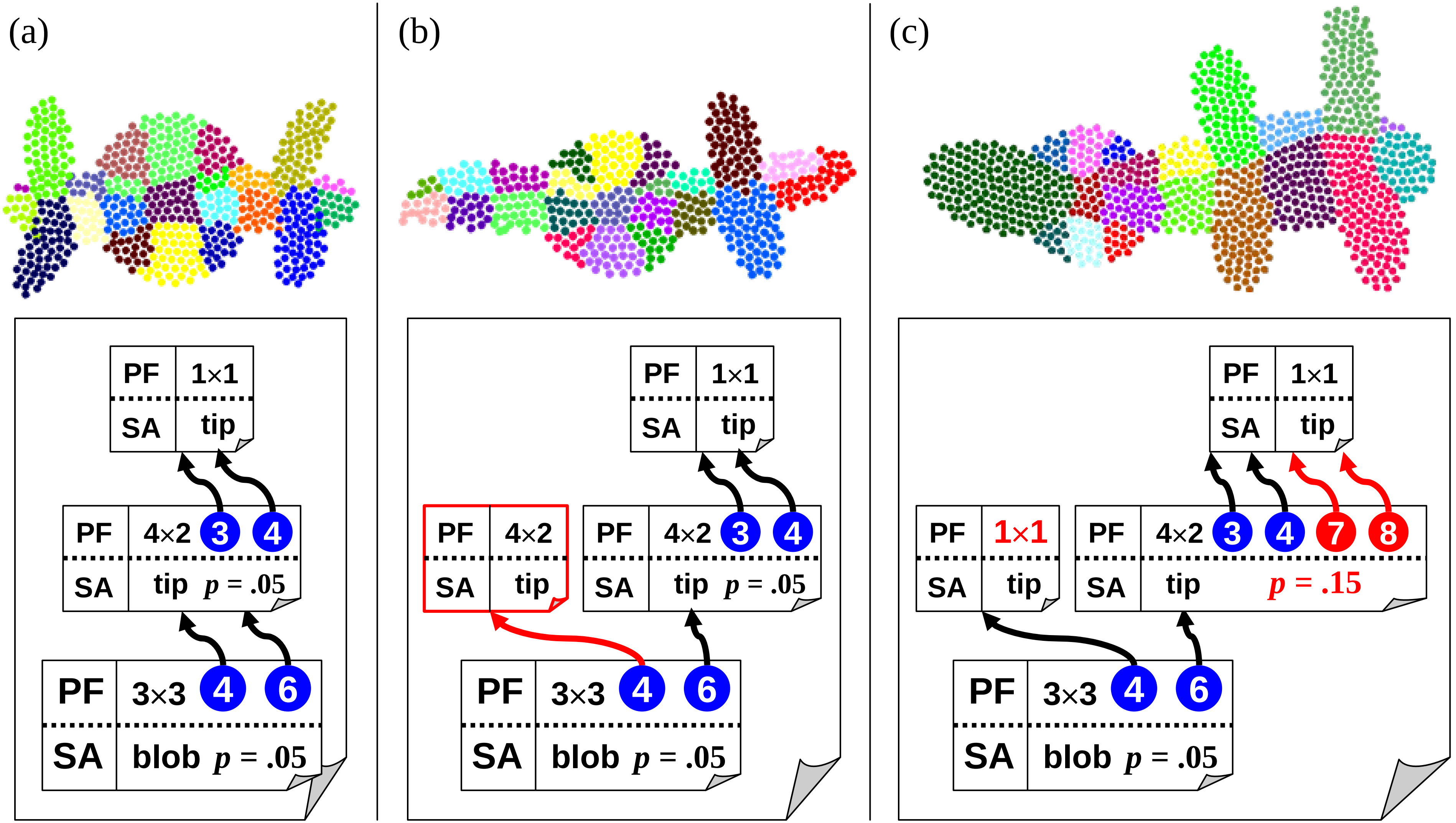
A model of programmable morphogenesis

- Modular growth *and* patterning on 3 levels



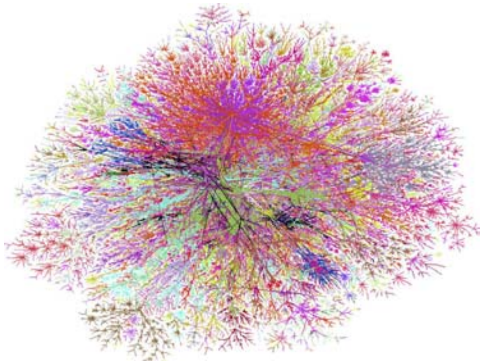
Evolutionary morphological meta-design

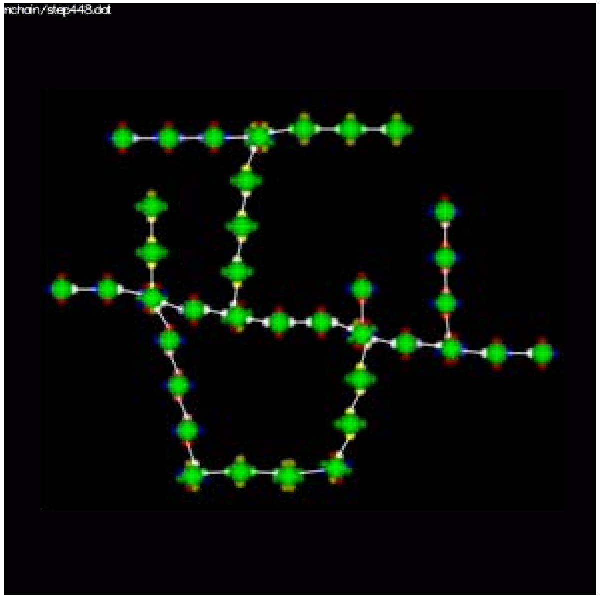
➢ Evolution of modular growth and patterning



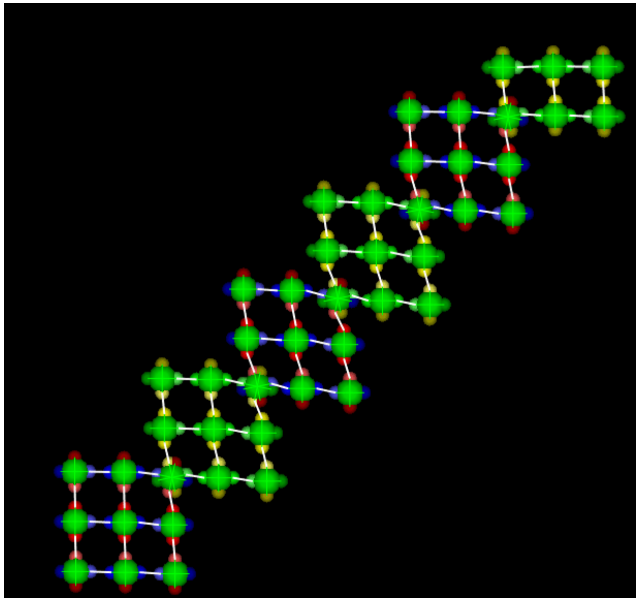
From scale-free to structured networks

- Extension of 2-D morphogenesis to N-D network topologies

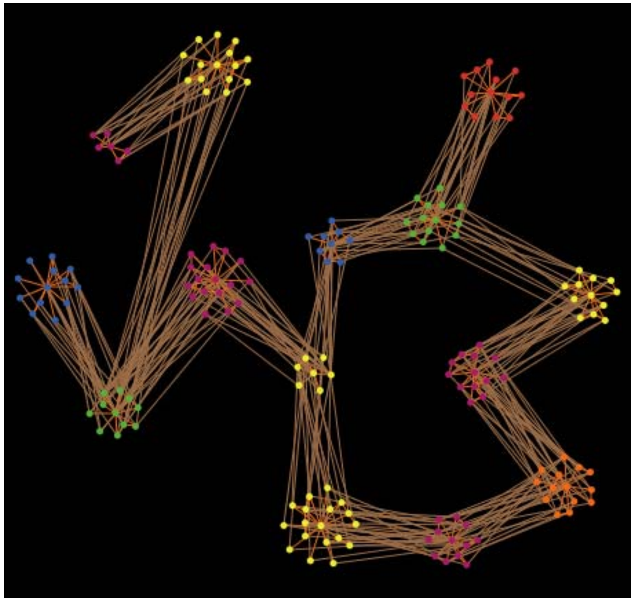




single-node
composite branching



iterative lattice pile-up



clustered
composite branching

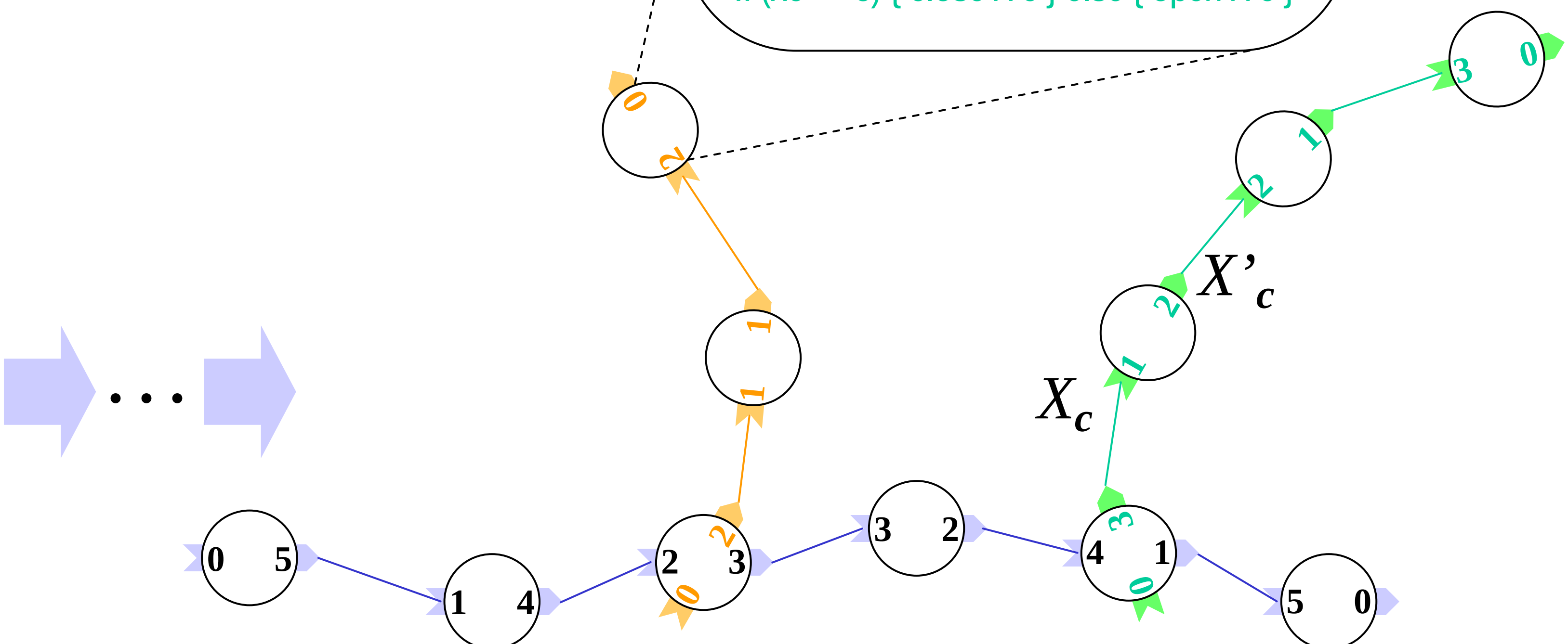
A model of programmable complex networks

- Modular network architectures by local gradients
  - the node routines are the *“genotype”* of the network

X

```
close Xa
if (xa == 2) { create Xb, X’b }
if (xa == 4) { create Xc, X’c }
if (xa == 5) { close X’a } else { open X’a }
close Xb
if (xb == 2) { close X’b } else { open X’b }
close Xc
if (xc == 3) { close X’c } else { open X’c }
```

X’



From Natural to Engineered Complex Systems

1. Approaching and harnessing complexity

2. A possible direction: morphogenetic engineering

Thank you