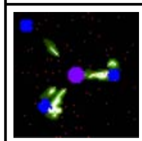
Complex Systems Made Simple

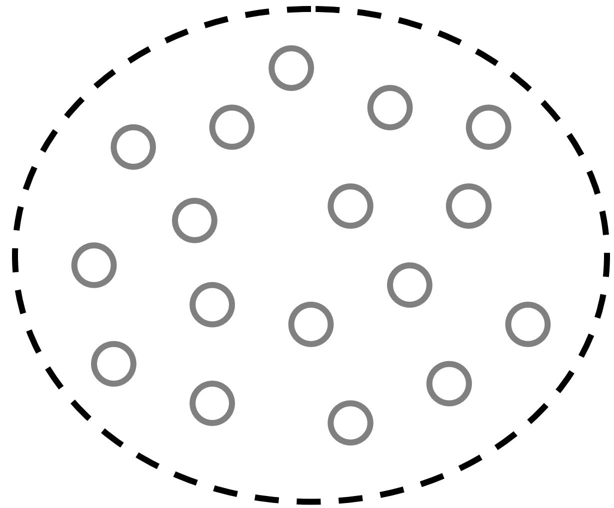
1. Introduction
2. A Complex Systems Sampler
3. **Commonalities**
   a. Common elementary features of complex systems
   b. Common global properties of complex systems
4. NetLogo Tutorial

Complex Systems Made Simple

3. Commonalities

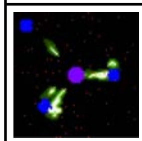
a. Elementary features – *Large number of elements*

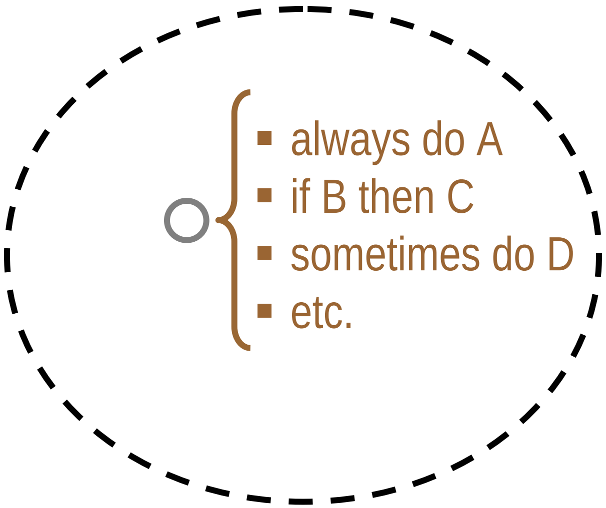
System	*Nodes*
 BZ reaction	*molecules*
 slime mold	*amoebae*
 animal coats	*cells*
 insect colonies	*ants, termites*
 flocking, traffic	*animals, cars*
 swarm sync	*fireflies*



3. Commonalities

a. Elementary features – *Individual behavior rules*

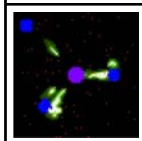
System	*Nodes*	*Rules*
 BZ reaction	*molecules*	*react, diffuse*
 slime mold	*amoebae*	*diffuse, sync, move*
 animal coats	*cells*	*activate, inhibit*
 insect colonies	*ants, termites*	*carry, deposit, follow*
 flocking, traffic	*animals, cars*	*steer, adjust speed*
 swarm sync	*fireflies*	*reset phase/freq*

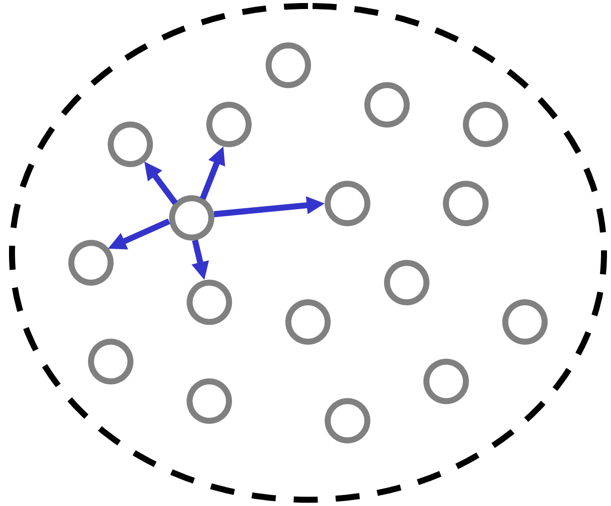


- limited repertoire of fixed and reactive behavior
- note: elements are not *intrinsically* “simple”, only *functionally* at the level of description of the studied process

3. Commonalities

a. Elementary features – *Local interactions: geometric, regular*

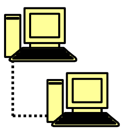
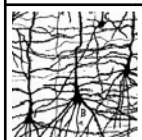
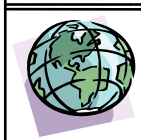
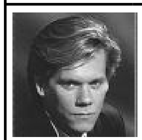
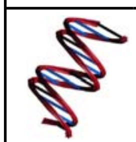
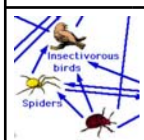
System	*Nodes*	*Edges*
 BZ reaction	*molecules*	*collisions*
 slime mold	*amoebae*	*cAMP*
 animal coats	*cells*	*morphogens*
 insect colonies	*ants, termites*	*pheromone*
 flocking, traffic	*animals, cars*	*perception*
 swarm sync	*fireflies*	*photons ± long-range*

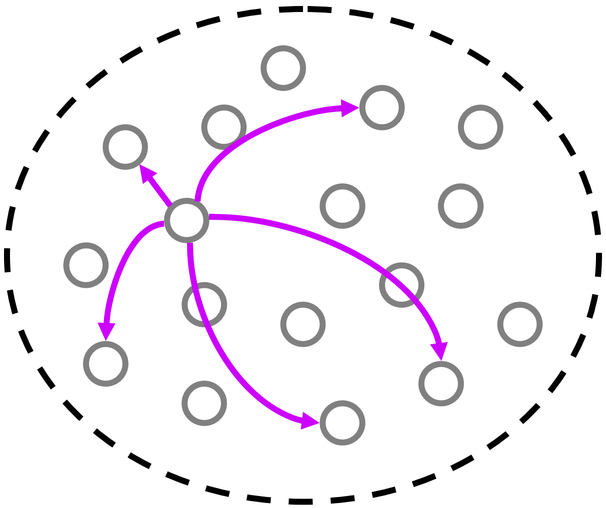


- interactions inside a local neighborhood in 2-D or 3-D geometric space
- limited "visibility" within Euclidean distance
- one-to-one messaging or one-to-many broadcasting

3. Commonalities

a. Elementary features – *Local interactions: Semi-geometric, irregular*

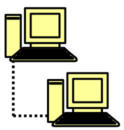
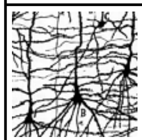
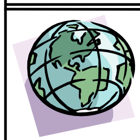
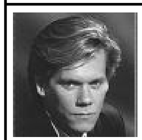
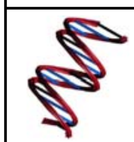
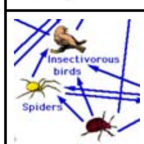
System	*Nodes*	*Edges*
 Internet	*routers*	*wires*
 brain	*neurons*	*synapses*
 WWW	*pages*	*hyperlinks*
 Hollywood	*actors*	*movies*
 gene regulation	*proteins*	*binding sites*
 ecology web	*species*	*competition*

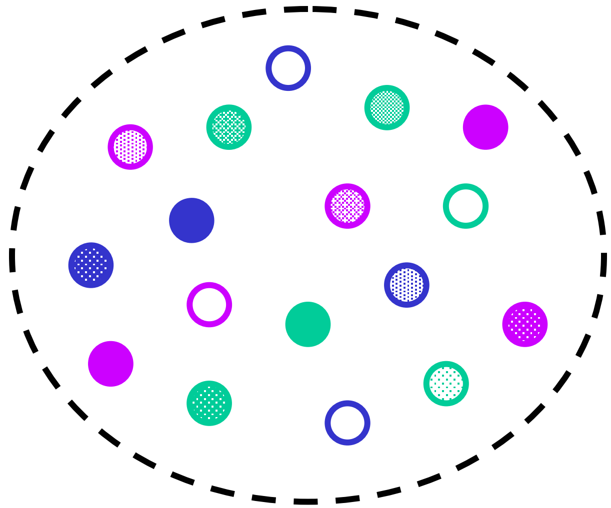


- local neighborhoods can also contain "long-range" links:
  - either "element" nodes located in space
  - or "categorical" nodes not located in space
- still limited "visibility", but not according to distance

3. Commonalities

a. Elementary features – *Node diversity*

System	*Node diversity*	*Node state/ dynamics*
 Internet	*routers, PCs, switches ...*	*routing state/ algorithm*
 brain	*sensory, inter, motor neuron*	*electrical potentials*
 WWW	*commercial, educational ...*	*popularity, num. of visits*
 Hollywood	*traits, talent ...*	*celebrity level, contracts*
 gene regulation	*protein type, DNA sites ...*	*boundness, concentration*
 ecology web	*species traits (diet, reprod.)*	*fitness, density*

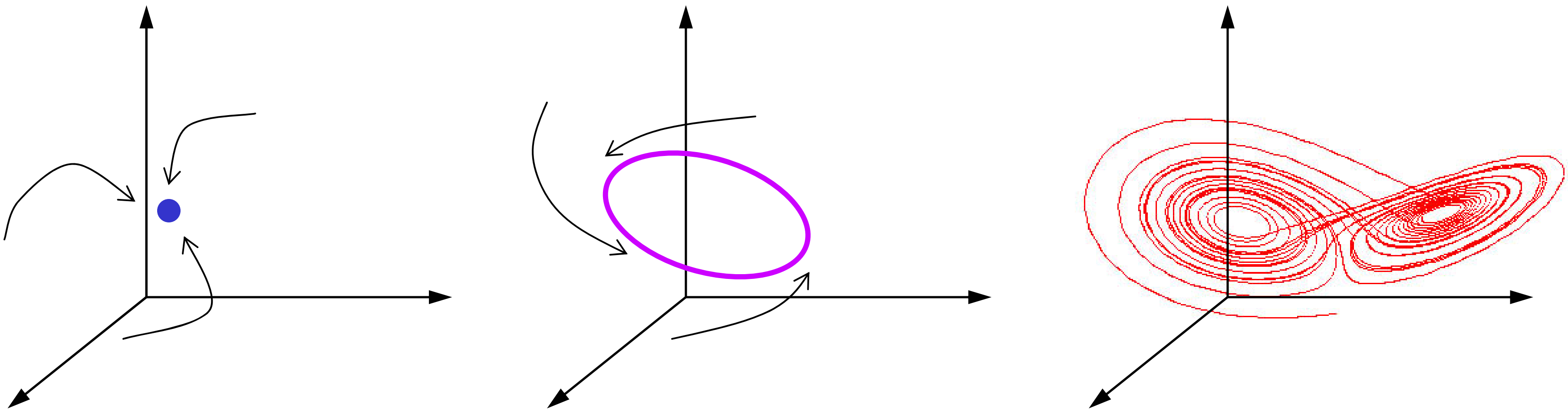


- nodes can be of different subtypes: ●, ●, ●...
- nodes have variable states of activity: ● ● ● ○

3. Commonalities

a. Elementary features – *Node dynamics: individual nodes*

- if each node in the network obey some diff equation, e.g.: $\dfrac{dx}{dt} = f(x)$
- then generally, three possible behaviors in phase space:

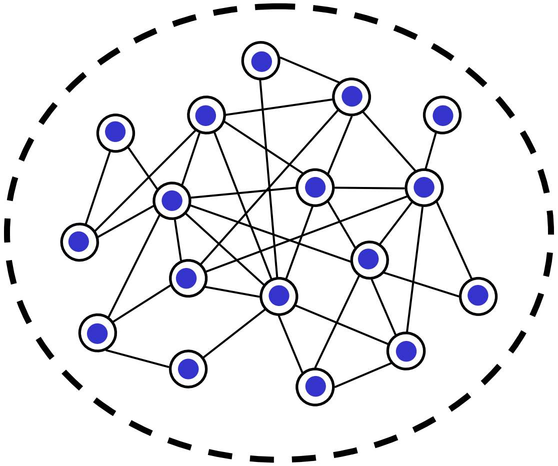


fixed point attractor *limit cycle attractor* *chaotic attractor*

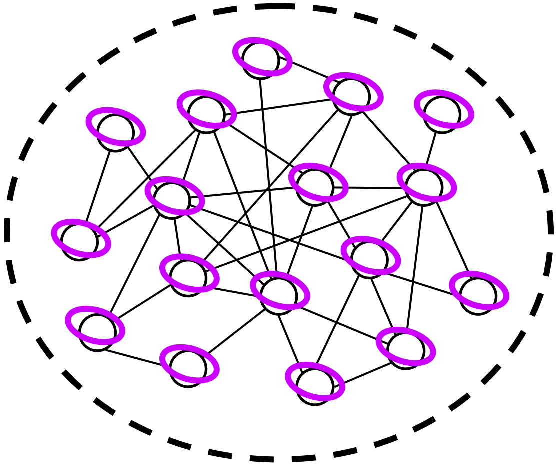
3. Commonalities

a. Elementary features – *Node dynamics: coupled nodes*

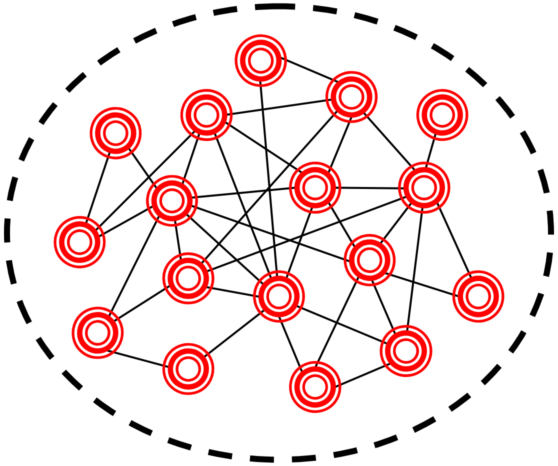
- a complex system is a set of coupled nodes obeying: $\frac{dx_A}{dt} = f(x_A) + \sum_{A \leftarrow B} g(x_A, x_B)$
- generally, three types of node network dynamics:



fixed point node network



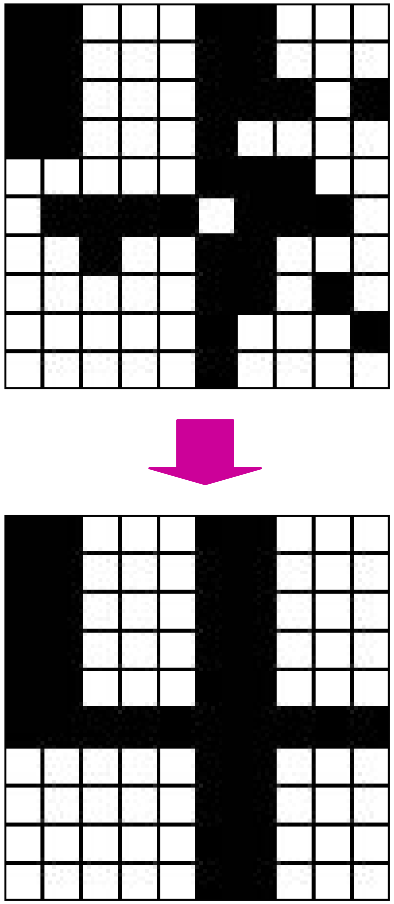
limit cycle node network



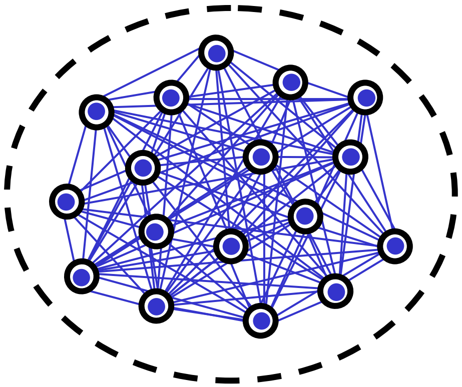
chaotic node network

3. Commonalities

a. Elementary features – *Node dynamics: attractors in full networks*



Pattern retrieval in Hopfield memory:
full graph with Ising-type interactions



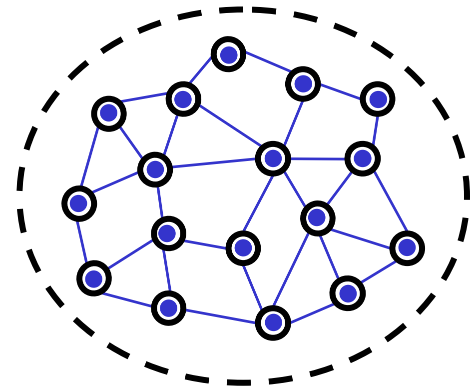
- fixed point nodes
- fully connected network

$\rightarrow$ *a few fixed patterns*
($\approx 0.14\ N$)

3. Commonalities

a. Elementary features – *Node dynamics: attractors in lattice networks*

Pattern formation in animal pigmentation:
2-D lattice with stationary reaction-diffusion
(NetLogo simulation, Uri Wilensky, Northwestern University, IL)

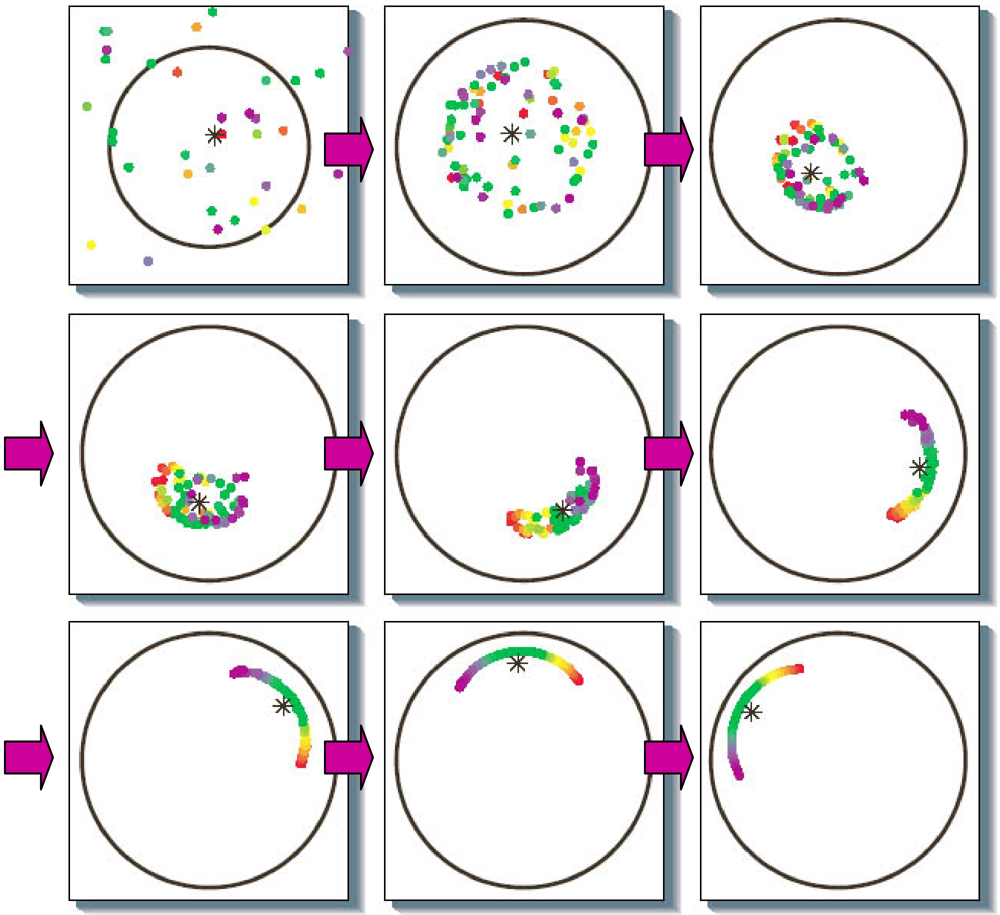


- fixed point nodes
- regular lattice network

→ *a great number of new patterns*

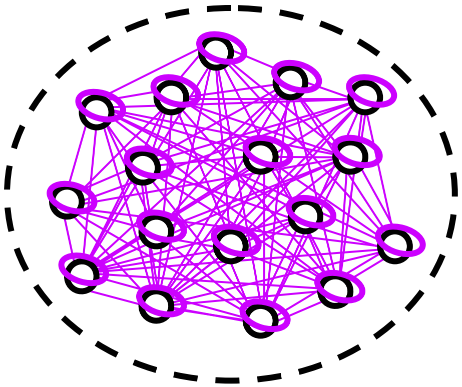
3. Commonalities

a. Elementary features – *Node dynamics: sync in full networks*



Spontaneous synchronization in a network of limit-cycle oscillators with distributed natural frequencies

(Strogatz, 2001)

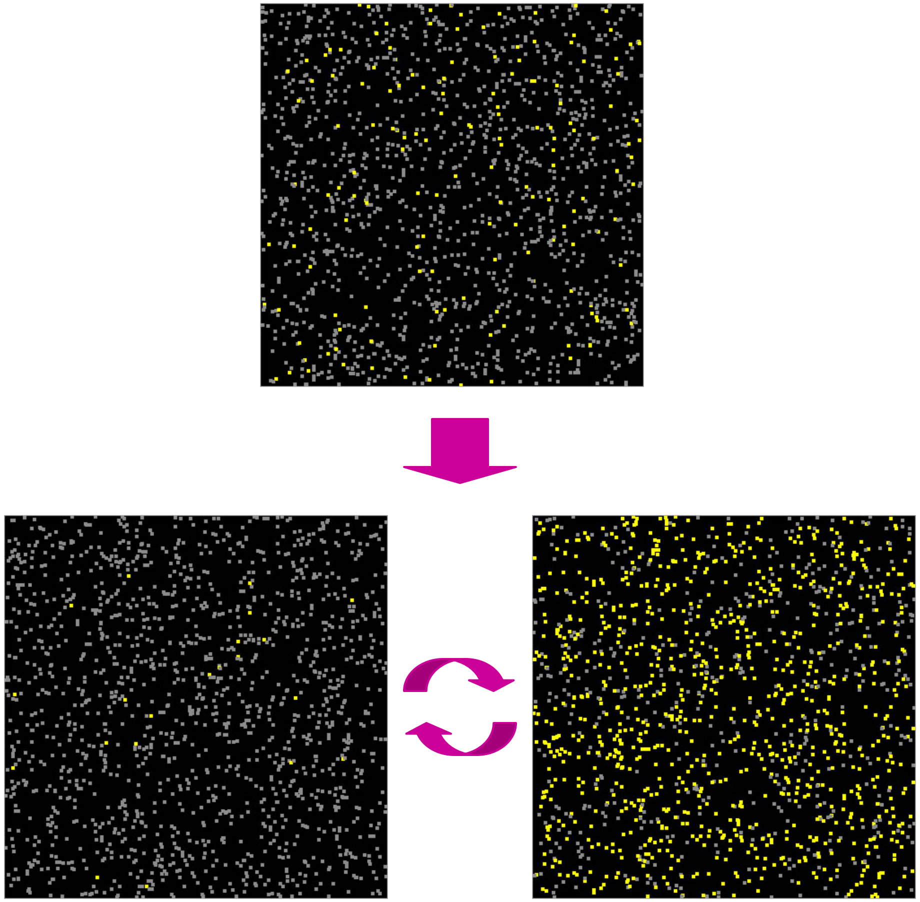


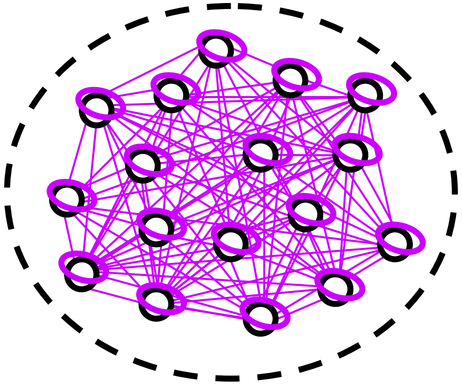
- limit cycle nodes
- fully connected network

→ *global synchronization*

3. Commonalities

a. Elementary features – *Node dynamics: sync in full networks*





- limit cycle nodes
- fully connected network

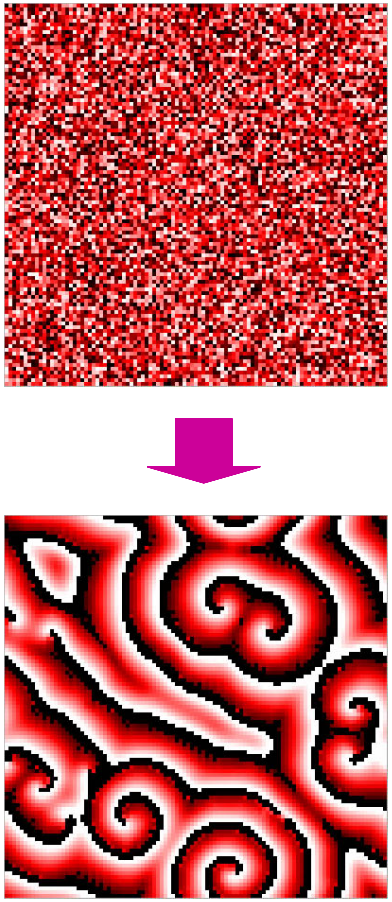
→ *global synchronization*

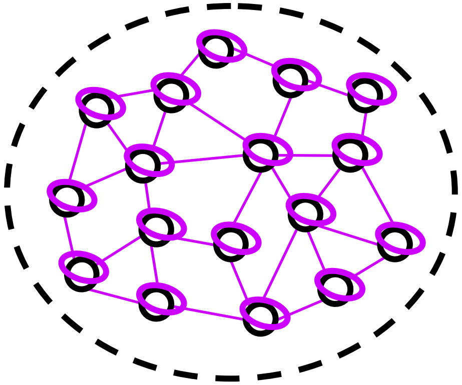
Spontaneous synchronization in a swarm of fireflies: (almost) fully connected graph of independent oscillators

(NetLogo simulation, Uri Wilensky, Northwestern University, IL)

3. Commonalities

a. Elementary features – *Node dynamics: waves in lattice networks*





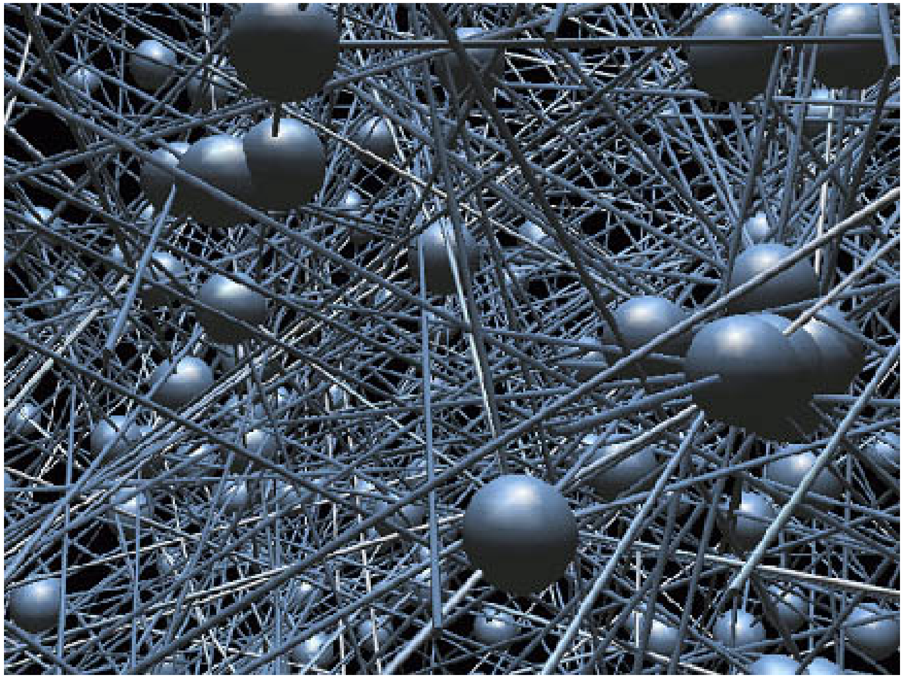
- limit cycle nodes
- regular lattice network

→ *traveling waves*

BZ reaction or slime mold aggregation:
2-D lattice with oscillatory reaction-diffusion
(NetLogo simulation, Uri Wilensky, Northwestern University, IL)

3. Commonalities

a. Elementary features – *Node dynamics: epidemics in complex networks*



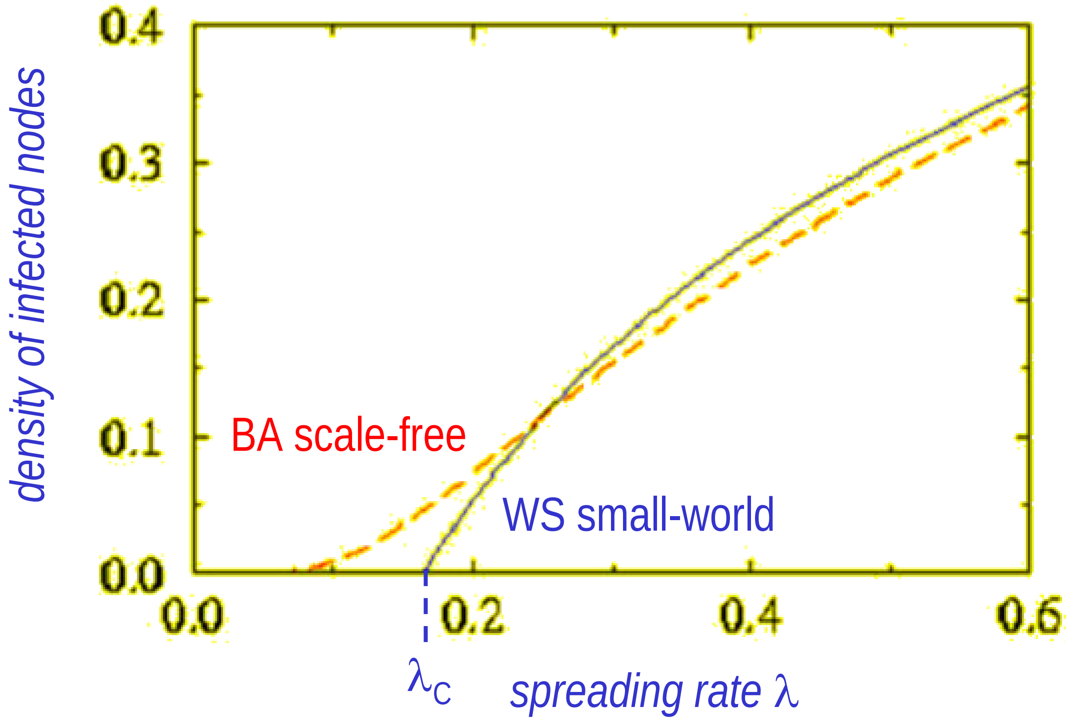
3-D visualization of social links
(A. S. Klovdahl, http://carnap.ss.uci.edu/vis.html)

- understand of beneficial or nefarious activity/failures spread over a network:
  - diseases
  - power blackouts
  - computer viruses
  - fashions, etc.
- *susceptible-infected-susceptible (SIS)* epidemiological model:
  - two node states: infected or susceptible
  - susceptible nodes can get infected with probability ν
  - infected nodes heal and become susceptible again with proba δ

$\rightarrow$ *spreading rate:* $\lambda = \nu / \delta$

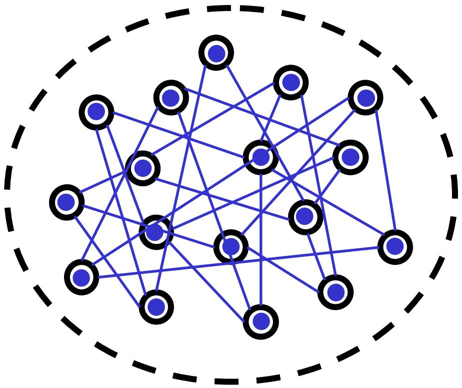
3. Commonalities

a. Elementary features – *Node dynamics: epidemics in complex networks*

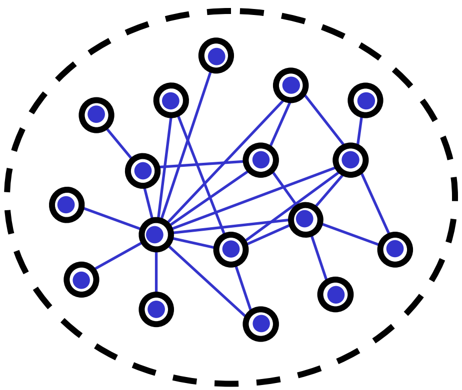


Epidemic on exponential and scale-free networks

(Pastor-Satorras & Vespignani, 2001)



- exponential network
  → *spread with threshold*

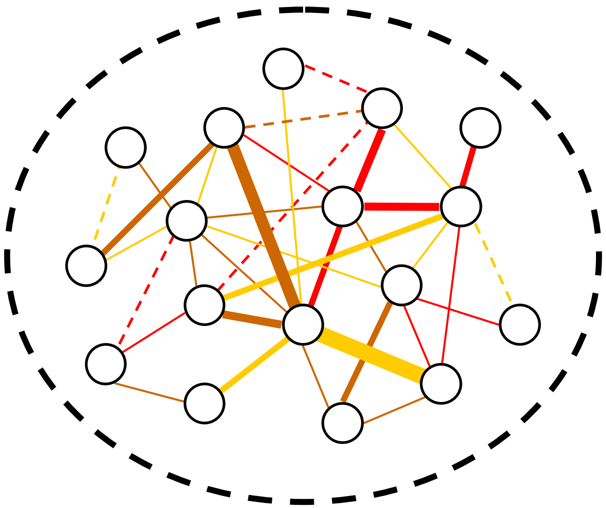


- scale-free network
  → *spread WITHOUT threshold*

3. Commonalities

a. Elementary features – *Link diversity & dynamics*

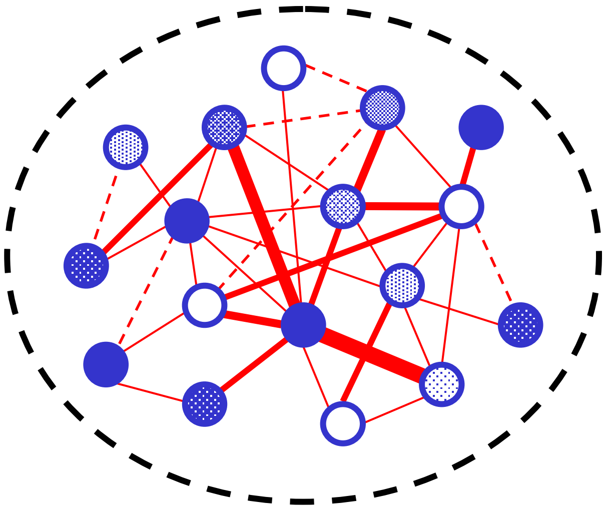
System	*Link diversity*	*Link state/ dynamics*
Internet	*bandwidth (DSL, cable)...*	*--*
brain	*excit., inhib. synapses ...*	*synap. weight, learning*
WWW	*--*	*--*
Hollywood	*theater movie, TV series ...*	*partnerships*
gene regulation	*enhancing, blocking ...*	*mutations, evolution*
ecology web	*predation, cooperation*	*evolution, selection*

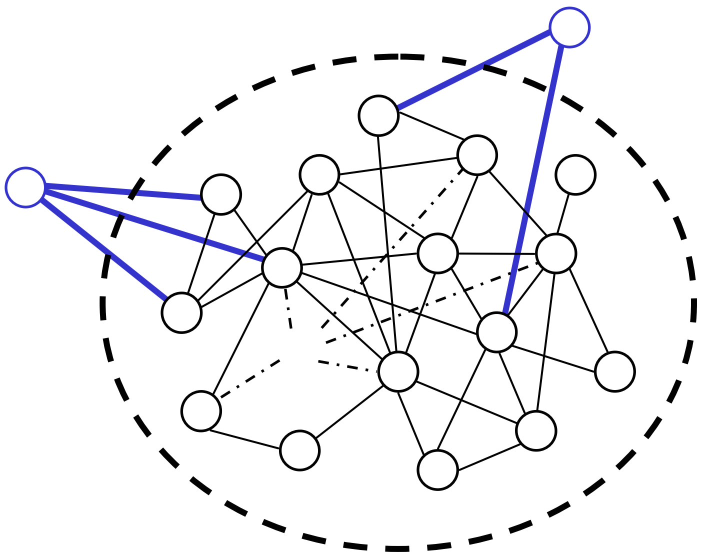


- links can be of different subtypes: , , ...
- links can also have variable weights:

3. Commonalities

a. Elementary features – *Link diversity & dynamics*



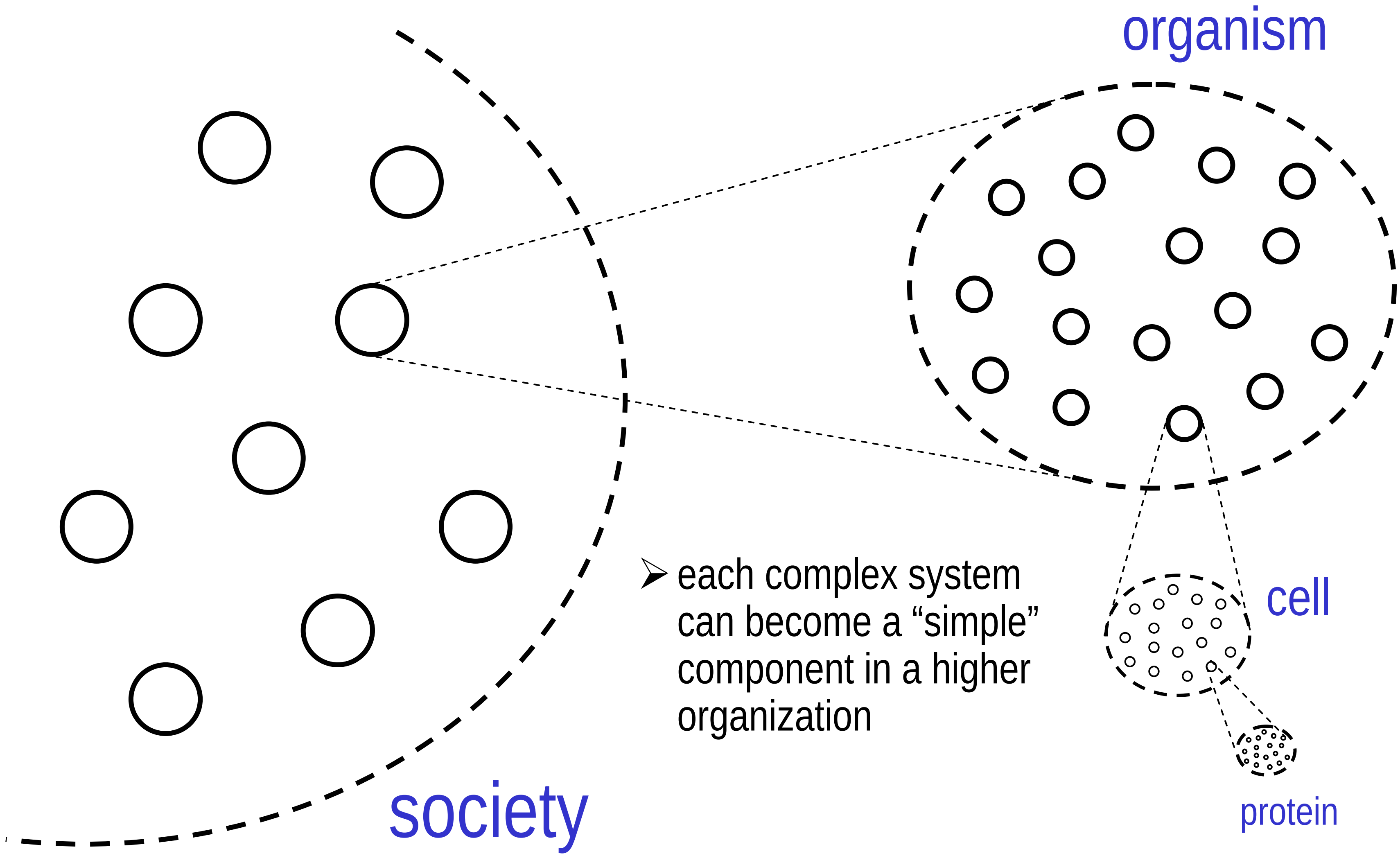


- the *state* of a network generally evolves on two time-scales:
  - fast time scale: node activities
  - slow time scale: connection weights
- examples:
  - neural networks: activities & learning
  - gene networks: expression & mutations

- the ***structural complexity*** of a network can also evolve by adding or removing nodes and edges
- examples:
  - Internet, WWW, actors. ecology, etc.

3. Commonalities

a. Elementary features – *Hierarchy of levels*



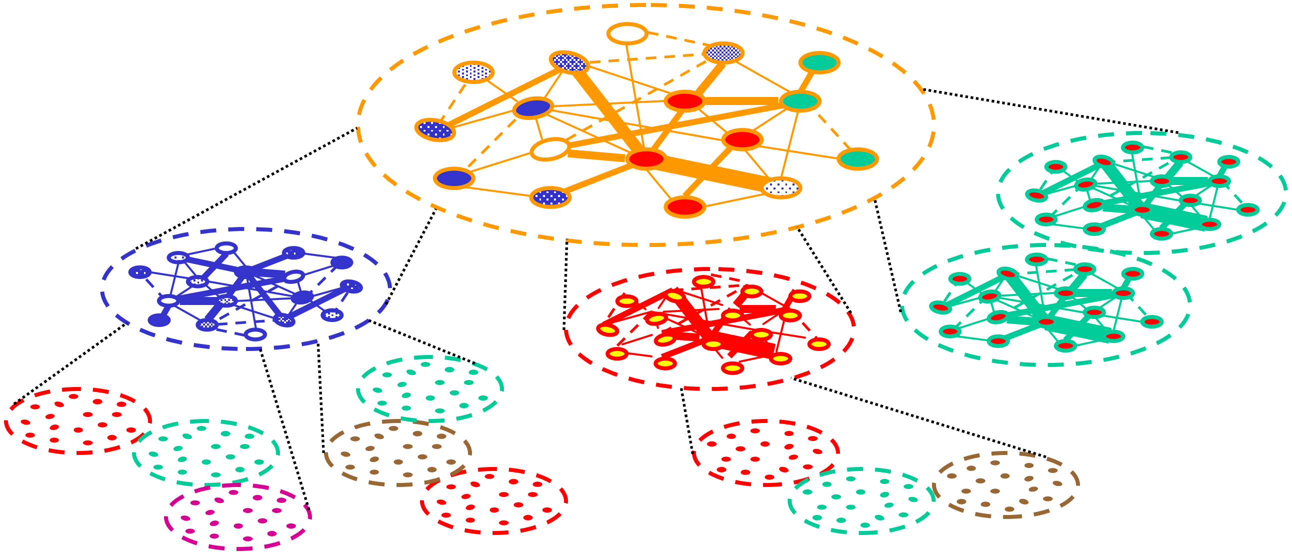
- each complex system can become a "simple" component in a higher organization

3. Commonalities

a. Elementary features – *Heterogeneity, reproducibility*

- ✓ “complex” doesn’t imply “homogeneous”:
  - → *rich agent diversity and pattern heterogeneity, via positions*
- ✓ “complex” doesn’t imply “flat”:
  - → *modular, hierarchical, architecturally detailed (multiscale)*
- ✓ “complex” doesn’t imply “random”:
  - → *reproducible patterns relying on programmable agents*

complex systems are more than spaghetti bowls



Complex Systems Made Simple

1. Introduction

2. A Complex Systems Sampler

3. Commonalities

   a. Common elementary features of complex systems

   b. Common global properties of complex systems

      - *Emergence, self-organization*
      - *Positive feedback, decentralization*
      - *Between simple and disordered*
      - *“More is different”, phase transitions*
      - *Adaptation & evolution*

4. NetLogo Tutorial

3. Commonalities

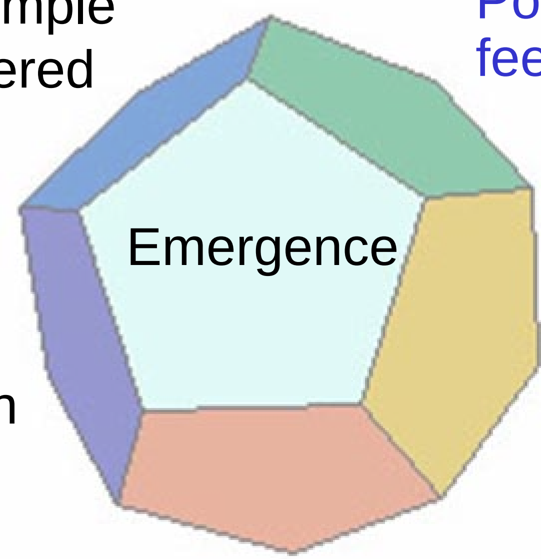
b. Global properties

✓ key concepts ("buzzwords") expressing different facets of CS

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

Between simple and disordered

Positive feedback



Self-organization

Phase transitions

Decentralization

Far from equilibrium

Adaptation

"More is different"

3. Commonalities

b. Global properties – *Emergence*

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

3. Commonalities

b. Global properties – *Self-organization*

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

3. Commonalities

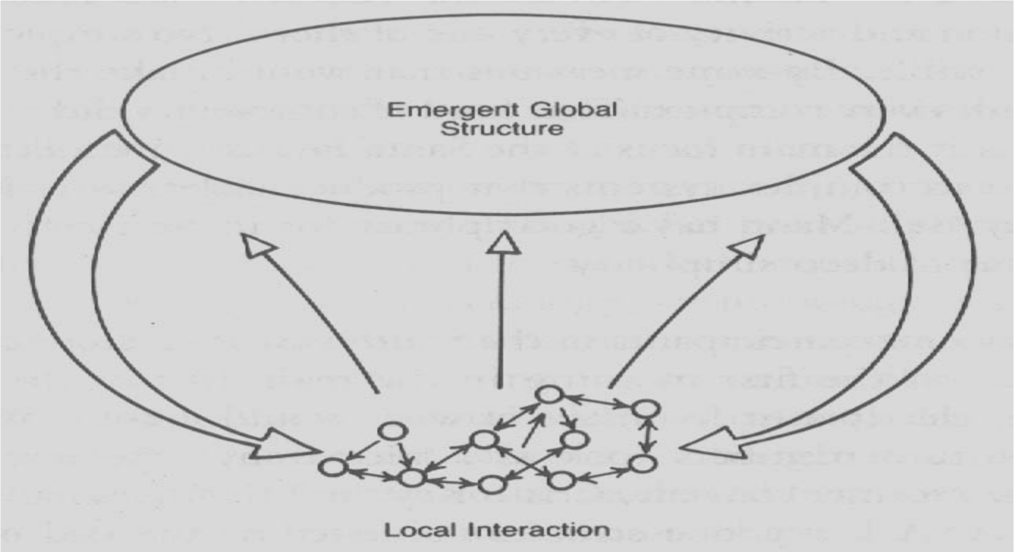
b. Global properties – *Emergence & self-organization*

✓ counter-examples of emergence *without* self-organization

- ex: well-informed leader (orchestra conductor, military officer)
- ex: global plan (construction area), full instructions (orchestra)

✓ immergence: emergent structure feeds back to the elements

- ex: market influences buyers, traffic jam influences drivers



Chris Langton's view of emergence in complex systems
(from "Complexity", Roger Lewin, University of Chicago Press)

3. Commonalities

b. Global properties – *Positive feedback*

✓ positive feedback, circularity

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

→ amplification of fluctuations (nonlinearity)

→ instability of initially homogeneous state

→ broken symmetry

→ creation of structure

3. Commonalities

b. Global properties – *Decentralization*

✓ order without a leader

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

✓ the "invisible hand"

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

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

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

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

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

3. Commonalities

b. Global properties – *Between simple and disordered*

- ✓ Warren Weaver's 1948 classification of scientific activity
  1. Problems of simplicity 1- to few-variable problems of the 17th, 18th and 19th centuries: Newtonian mechanics, electricity, chemistry, etc.
  2. Problems of disorganized complexity million- and billion-variable problems of the 20th century: statistical mechanics (gas, fluid, solid), probability theory, theory of information, etc.
  3. Problems of **organized complexity** ("middle region") dozens or hundreds of *interrelated* variables [21st century problems]: biology, medicine, psychology, economics, social science, etc.
- ✓ the billiards table analogy (from S. Johnson's book *"Emergence"*)
  1. a few balls: individual trajectories from velocities, angles, friction
  2. a million balls: only broad statistical trends (average path, pressure)
  3. a hundred motorized balls obeying simple rules and self-arranging → ??
- ✓ another classification: Wolfram's or Langton's 4 classes of cellular automata

3. Commonalities

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

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

3. Commonalities

b. Global properties – *Decentralization vs. “more is different”?*

✓ recap: decentralization (the “invisible hand”)

- no leader, no designer, no external organizing force that does not belong to the system
- the emergent properties entirely rely on the elements’ behavior and interactions among *themselves*

✓ recap: “more is different”

- ... but these properties cannot be *inferred* or *predicted* just by looking at the elements
- beyond a critical mass and across phase transition lines, the system exhibits *qualitatively new* behaviors

→ only an apparent paradox

- both aspects can, and actually *do* coexist in natural systems
- neither hard-line reductionism (“everything boils down to superstrings”)
- nor “vitalism” or intelligent design (“something else must intervene”)

3. Commonalities

b. Global properties – *“Complexity”: an illusion?*

✓ abundance of autonomous, emergent systems in the environment

- nature: geological patterns, biological cells, organisms, animal societies, ecosystems, etc.
- spontaneously emerging human-made super-structures: cities, markets, Internet, etc.

→ decentralized, unplanned systems are robust, efficient and constitute the overwhelming majority of system types

- it is our artificially centralized, planned engineered systems that are fragile, costly to build, and rare, as they require a higher intelligence to arise

✓ “complexity”, an artifact of our cognitive bias?

- because we are accustomed to the illusion of a central consciousness, we traditionally refer to decentralized systems as “complex”
- but in fact these systems might be ***simpler*** than our familiar engineered devices with their uniquely hierarchical and complicated arrangement