# Complex Systems Made Simple

# Complex Systems Made Simple

1. Introduction

2. A Complex Systems Sampler
   a. Cellular automata:
      - *Game of life*
      - *1-D binary automata*
   b. Pattern formation
   c. Swarm intelligence
   d. Complex networks
   e. Spatial communities
   f. Structured morphogenesis

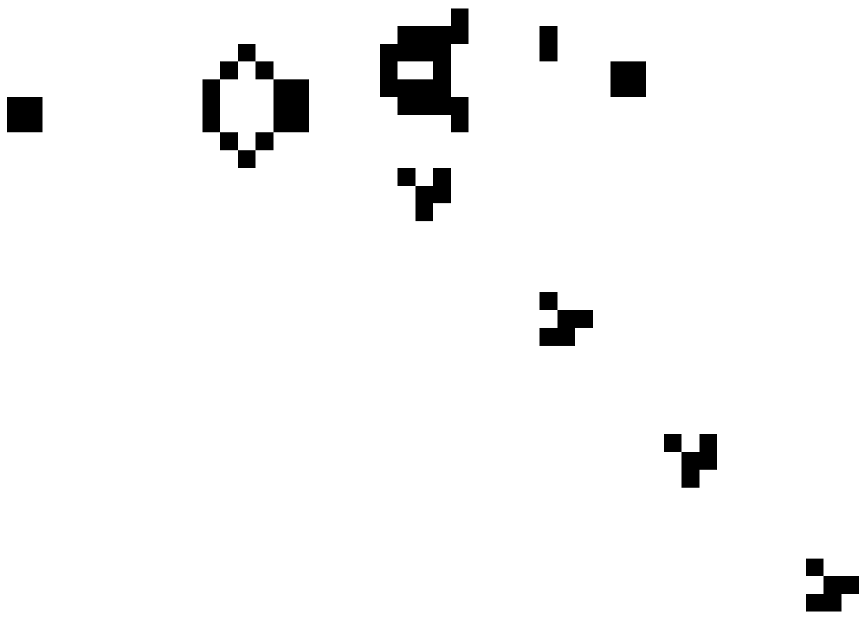
3. Commonalities

4. NetLogo Tutorial

# 2. A Complex Systems Sampler

## a. Cellular automata – *Game of life*

NetLogo model: /Computer Science/Cellular Automata/Life



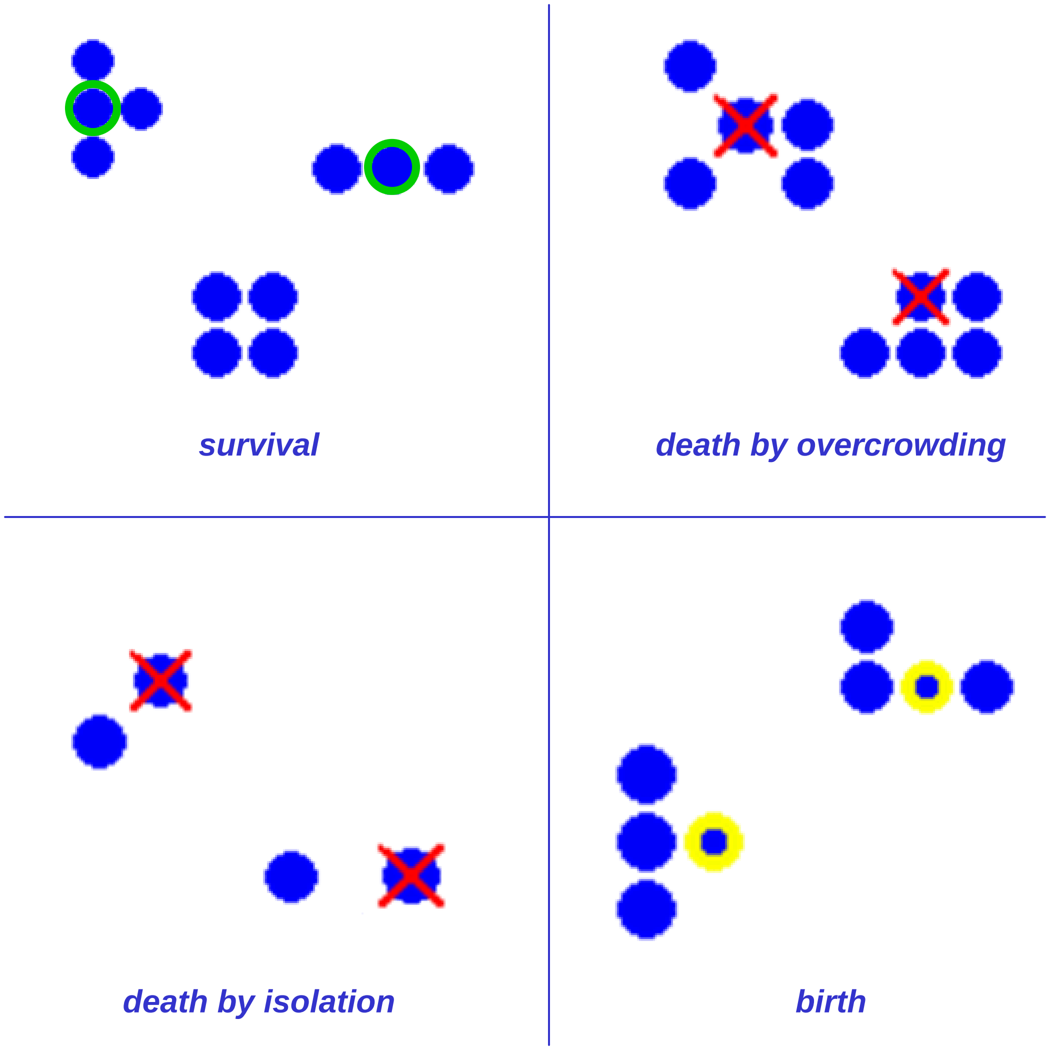
***Bill Gosper's Glider Gun***
*(Wikipedia, "Conway's Game of Life")*

### History

- most famous cellular automaton
- designed by John H. Conway in 1970
- in an attempt to find a simpler self-replicating machine than von Neumann's 29-state cells
- very simple set of rules on black and white pixels
- creates small "autonomous", "life-like" patterns (static, repeating, translating, etc.) on the few-pixel scale

# 2. A Complex Systems Sampler

## a. Cellular automata – *Game of life*



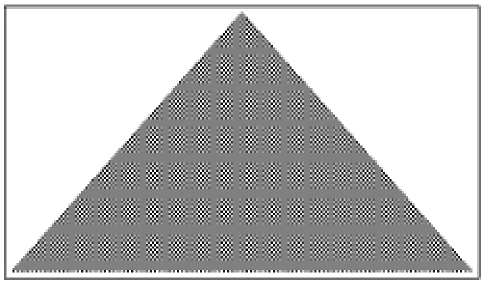

### Rules of the game

- survival: a live cell with 2 or 3 neighboring live cells survives for the next generation
- death by overcrowding: a live cell with 4 of more neighbors dies
- death by loneliness: a live cell with 1 neighbor or less dies
- birth: an empty cell adjacent to exactly 3 live cells becomes live

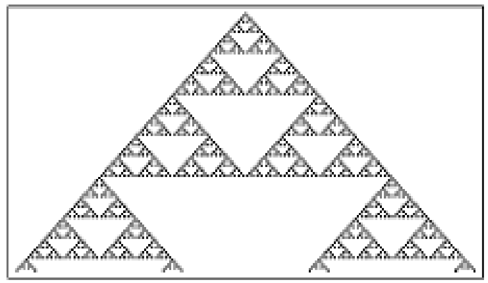
# 2. A Complex Systems Sampler

## a. Cellular automata – *1-D binary automata*

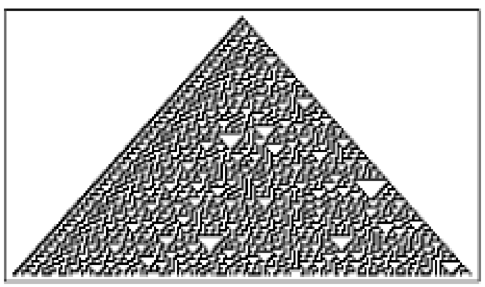
NetLogo model: /Computer Science/Cellular Automata/CA 1D Elementary



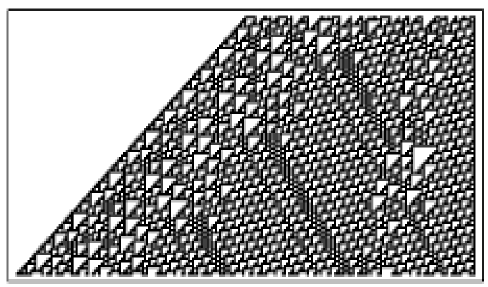
***repeating: Rule 250***



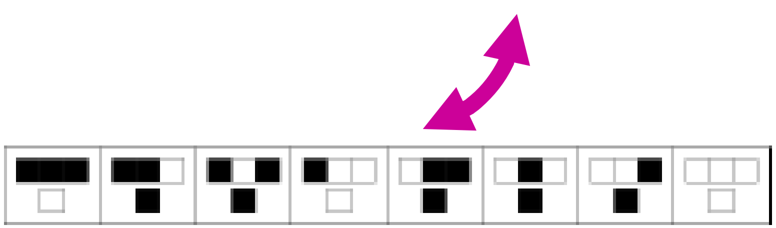
***nesting: Rule 90***



***randomness: Rule 30***



***localized structures: Rule 110***



### History

- “elementary CAs” = black and white pixels on one row
- like the Game of Life, simple rules depending on nearest neighbors only (here, 2)
- total number of rules = 2^(2^3) = 256
- Wolfram’s attempt to classify them in four major groups:
  - repetition
  - nesting
  - [apparent] randomness
  - localized structures (“complex”)

# 2. A Complex Systems Sampler

## a. Cellular automata

### Concepts collected from these examples

- large number of elements = pixels
- ultra-simple local rules
- emergence of macroscopic structures (patterns >> pixels)
- complex & diverse patterns (self-reproducible, periodic, irregular)

# Complex Systems Made Simple

1. Introduction

2. A Complex Systems Sampler

   a. Cellular automata

   b. **Pattern formation:**
      - *Physical: convection cells*
      - *Biological: animal colors; slime mold*
      - *Chemical: BZ reaction*

   c. Swarm intelligence

   d. Complex networks

   e. Spatial communities

   f. Structured morphogenesis

3. Commonalities

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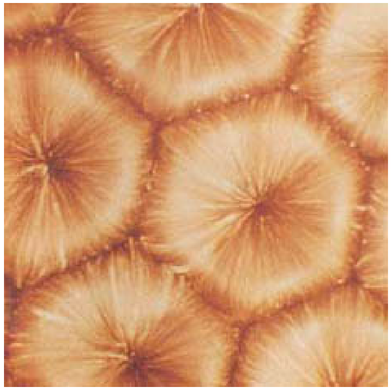
# 2. A Complex Systems Sampler

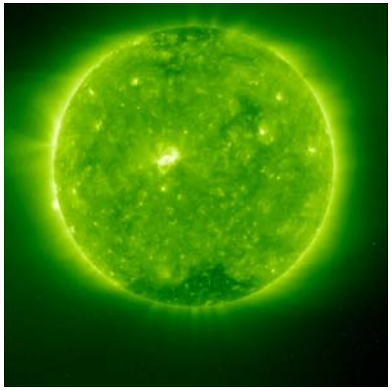
## b. Pattern formation – *Physical: convection cells*

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



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

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



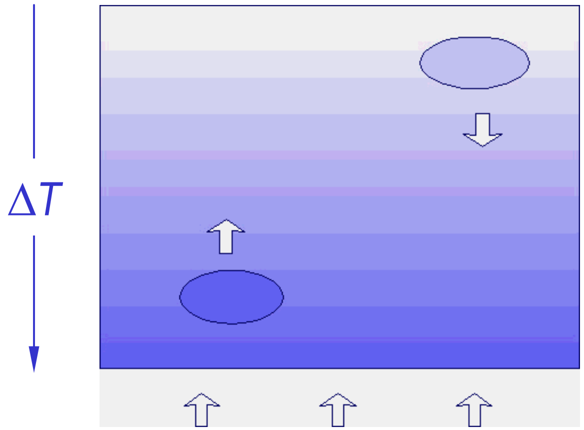
***Solar magnetoconvection***
*(Steven R. Lantz, Cornell Theory Center, NY)*

### Phenomenon

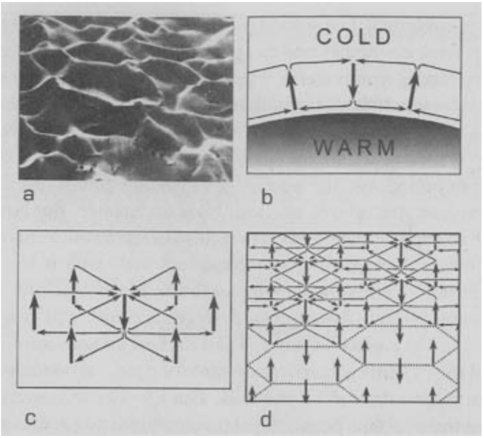
- "thermal convection" is the motion of fluids caused by a temperature differential
- observed at multiple scales, whether frying pan or geo/astrophysical systems
- spontaneous symmetry-breaking of a homogeneous state
- formation of stripes and cells, several order of magnitudes larger than molecular scale

# 2. A Complex Systems Sampler

## b. Pattern formation – *Physical: convection cells*




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



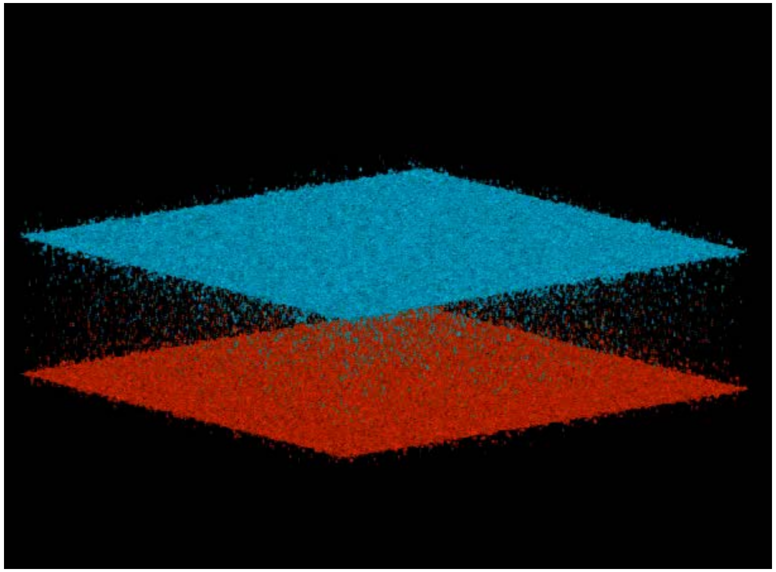

***Hexagonal arrangement of sand dunes***
*(Solé and Goodwin, "Signs of Life", Perseus Books)*

### Mechanism

- warm fluid is pushed up from the bottom by surrounding higher density (buoyancy force)
- cold fluid sinks down from the top due to surrounding lower density
- accelerated motion
- viscosity and thermal diffusion normally counteract buoyancy...
- ... but only up to a critical temperature differential $\Delta T_c$
- beyond $\Delta T_c$ buoyancy takes over and breaks up the fluid into alternating rolls

# 2. A Complex Systems Sampler

## b. Pattern formation – *Physical: convection cells*



***Convection dynamics***
*(Stéphane Labrosse, Institut de Physique du Globe, Paris)*

### Modeling & simulation

- surfaces of constant temperatures (red for hot, blue for cold)
- visualization of ascending and descending currents
- notice the moving cell borders at the top
- marginal case of multi-agent modeling:
  - top-down modeling by discretization of macroscopic differential equations
  - extremely fine-grain and dense distribution of agents = fixed grid

# 2. A Complex Systems Sampler

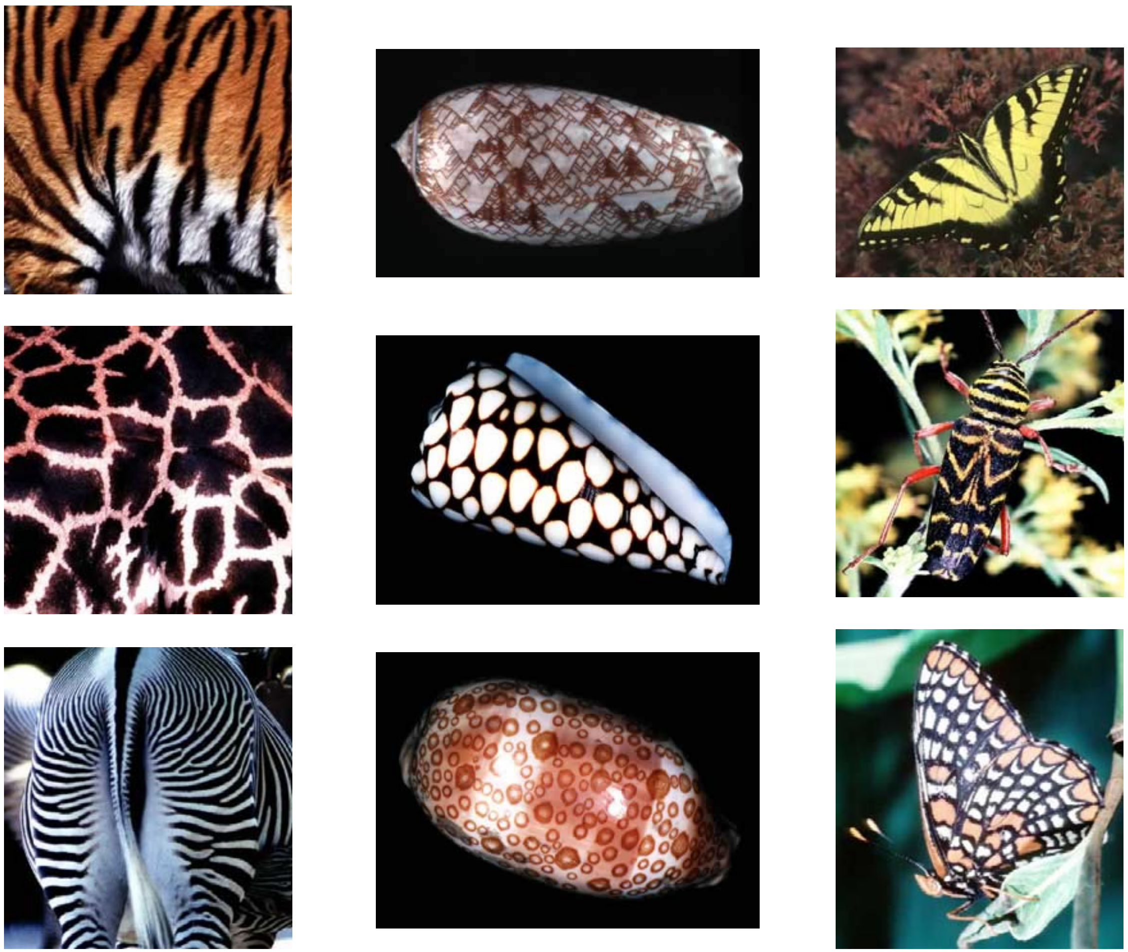
## b. Pattern formation – *Physical: convection cells*

## Concepts collected from this example

- large number of elementary constituents
- emergence of macroscopic structures (convection cells >> molecules)
- self-arranged patterns
- amplification of small fluctuations (positive feedback, symmetry breaking)
- phase transition
- far from equilibrium

# 2. A Complex Systems Sampler

## b. Pattern formation – *Biological: animal colors*



***Mammal fur, seashells, and insect wings***

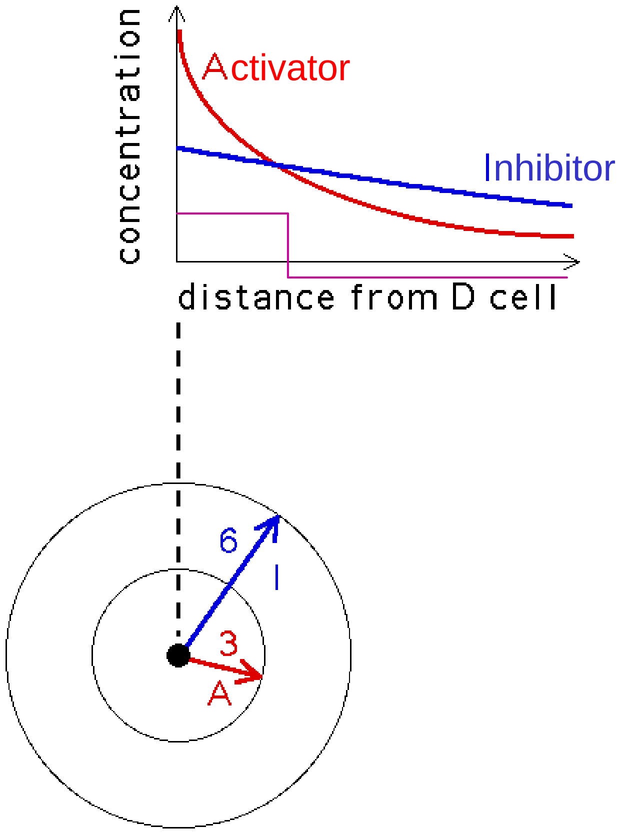
*(Scott Camazine, http://www.scottcamazine.com)*

### Phenomenon

- rich diversity of pigment patterns across species
- evolutionary advantage:
  - warning
  - camouflage, mimicry
  - sexual attraction
  - individual recognition
  - etc.

# 2. A Complex Systems Sampler

## b. Pattern formation – *Biological: animal colors*




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

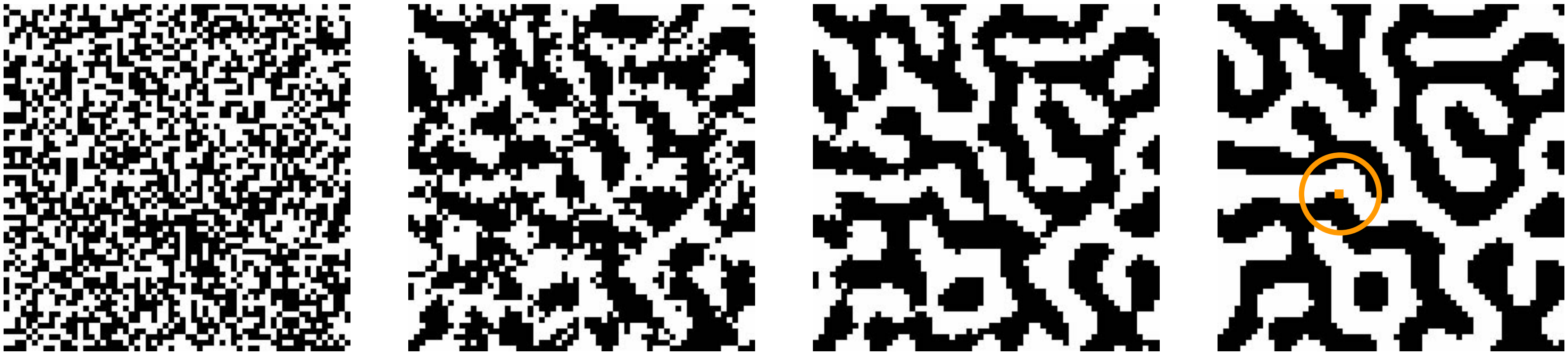
Possible mechanism (schematic)

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

# 2. A Complex Systems Sampler

## b. Pattern formation – *Biological: animal colors*

NetLogo model: /Biology/Fur



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

### Modeling & simulation

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

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

# 2. A Complex Systems Sampler

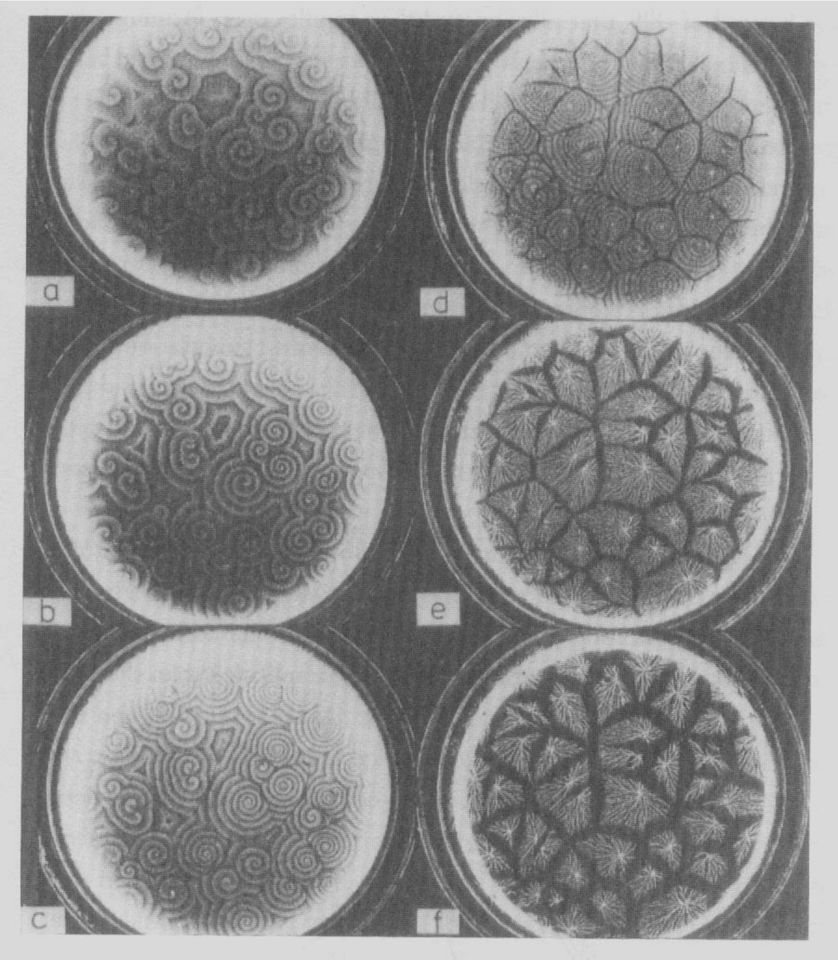
## b. Pattern formation – *Biological: animal colors*

## Concepts collected from this example

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

# 2. A Complex Systems Sampler

## b. Pattern formation – *Biological: slime mold*



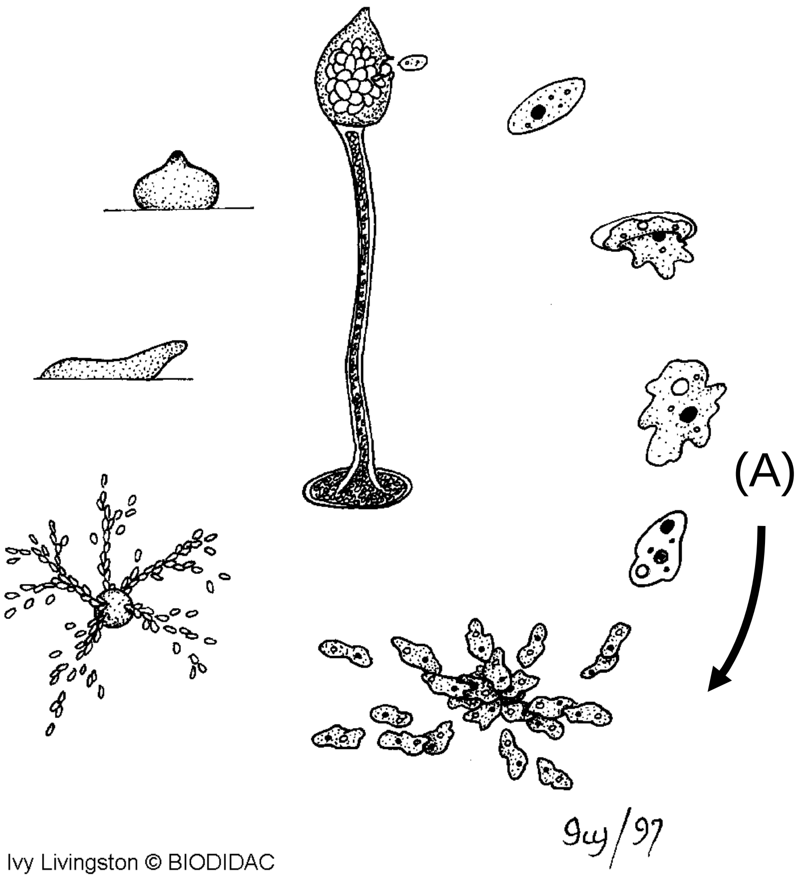

***Synchronization, breakup and aggregation of slime mold amoebae on an agar plate***
*(P. C. Newell; from Brian Goodwin, "How the leopard changed its spots", Princeton U. Press)*

### Phenomenon

- unicellular organisms (amoebae) clump together into multicellular "slugs"
- with enough food, they grow and divide independently
- under starvation, they synchronize (chemical waves), aggregate and differentiate
- aggregation phase shows same concentric wave patterns as BZ reaction
- a famous example of "excitable medium" and self-organization

# 2. A Complex Systems Sampler

## b. Pattern formation – *Biological: slime mold*




***Life cycle of Dictyostelium slime mold***
*(Ivy Livingstone, BIODIDAC, University of Ottawa)*

### Mechanism

- life cycle of slime mold amoebae (Dictyostelium):

  independent amoebae (A)

  → aggregation

  → clump

  → slug

  → growth

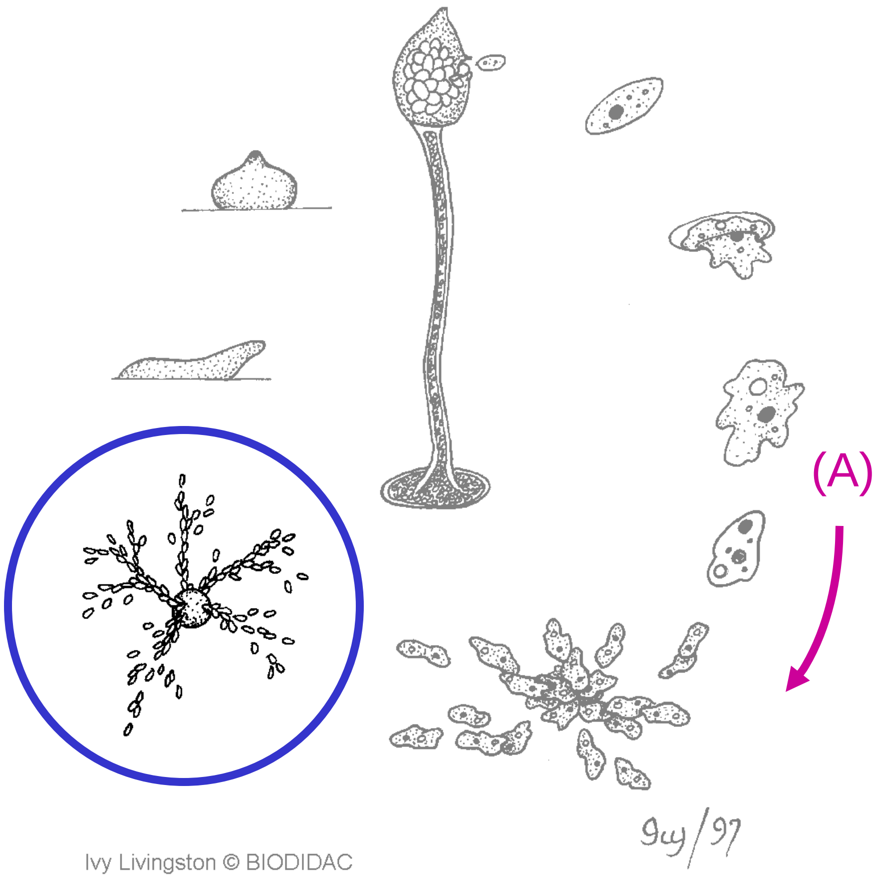
  → body & fruit

  → spore release & germination

  → amoebae (A)

# 2. A Complex Systems Sampler

## b. Pattern formation – *Biological: slime mold*




***Life cycle of Dictyostelium slime mold***
*(Ivy Livingstone, BIODIDAC, University of Ottawa)*

Mechanism

- life cycle of slime mold amoebae (Dictyostelium):

  independent amoebae (A)

  → aggregation
  - stage 1: oscillatory secretion of chemical (cAMP) by each cell
  - stage 2: local coupling of secretion signal, forming spiral waves
  - stage 3: pulsatile motion toward spiral centers

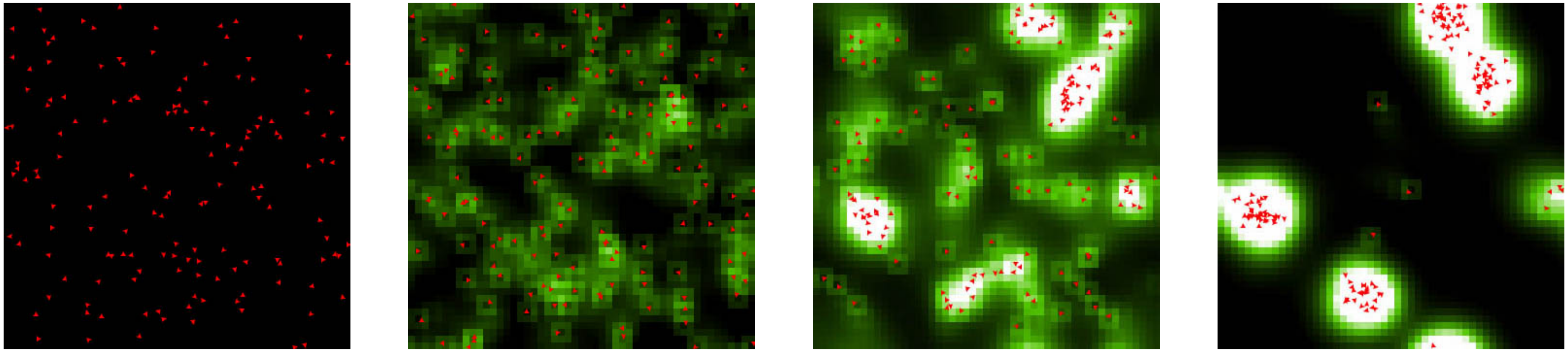
  → clump

  → ...

# 2. A Complex Systems Sampler

## b. Pattern formation – *Biological: slime mold*

NetLogo model: /Biology/Slime



***NetLogo simulation of slime mold aggregation, after Mitchel Resnick***
*(Uri Wilensky, Northwestern University, IL)*

### Modeling & simulation

- for wave formation (stages 1 & 2 of aggregation)

  → *see B-Z reaction model*

- for clumping (stage 3 of aggregation), three simplified rules:
  - each cell (red) secretes a chemical (shades of green)
  - each cell moves towards greater concentration of chemical
  - chemical evaporates

# 2. A Complex Systems Sampler

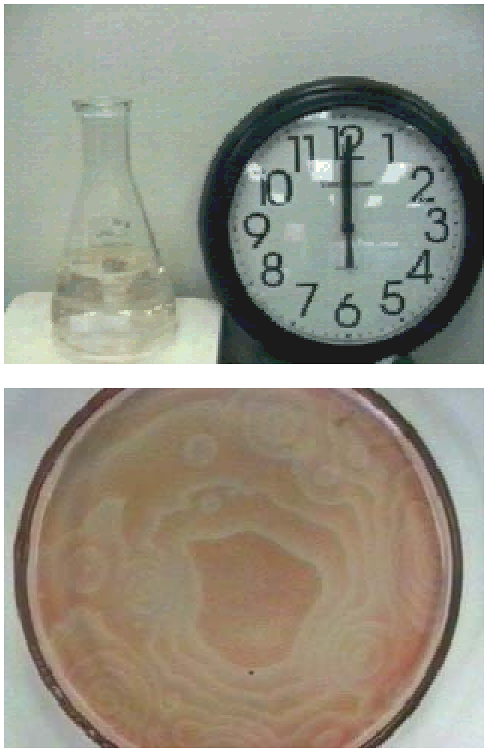
## b. Pattern formation – *Biological: slime mold*

## Concepts collected from this example

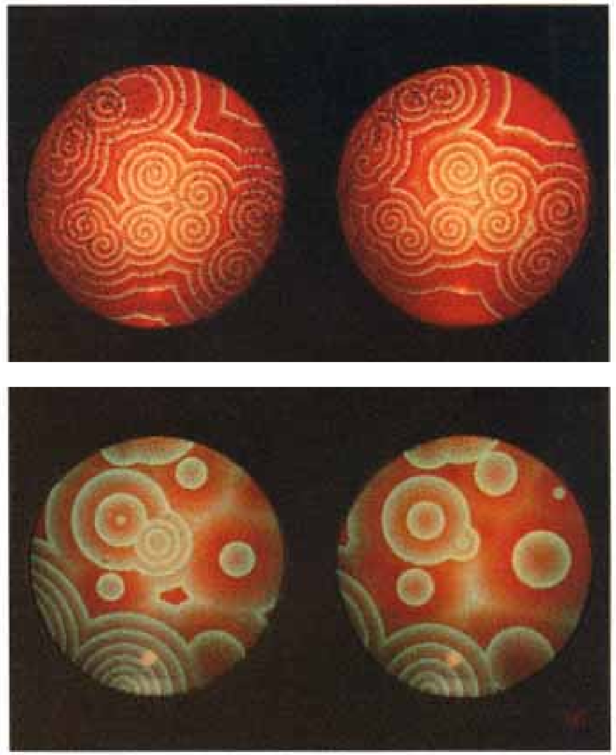
- simple, “blind” individual behavior
- emergence of aggregates
- cluster centers are *not* already differentiated cells (decentralization)
- local interactions (cell $\leftrightarrow$ chemical)
- phase transition (critical mass)

# 2. A Complex Systems Sampler

## b. Pattern formation – *Chemical: BZ reaction*



***The Belousov-Zhabotinsky reaction***
***(a) well-stirred tank; (b) Petri dish***
*(Gabriel Peterson, College of the Redwoods, CA)*



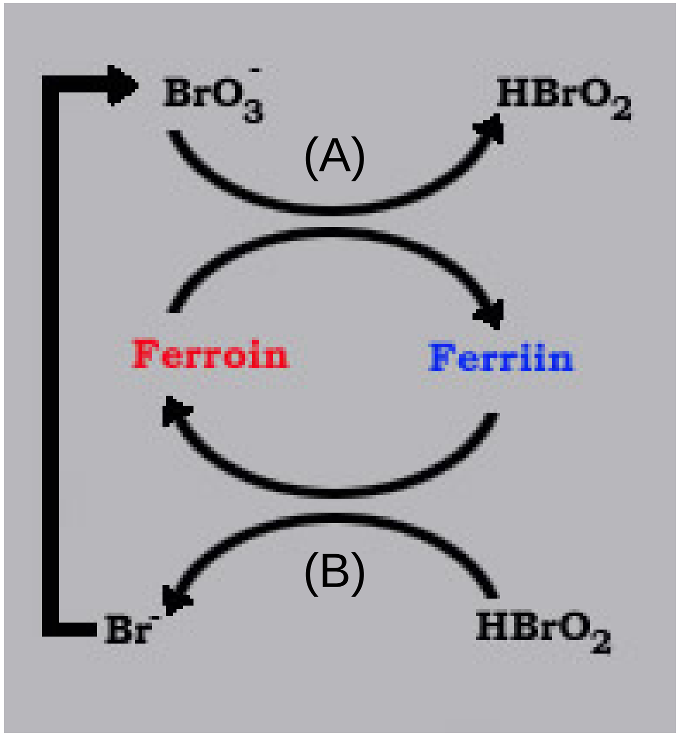
***Spiral and circular traveling waves***
***in the Belousov-Zhabotinsky reaction***
*(Arthur Winfree, University of Arizona)*

### Phenomenon

- Belousov-Zhabotinsky reaction: “chemical clock”
- if well stirred, it oscillates
- if spread on a plate, it creates waves (reaction-diffusion)
- example of an “excitable medium”
- often cited in self-organization

# 2. A Complex Systems Sampler

## b. Pattern formation – *Chemical: BZ reaction*




***Simplified diagram of the Belousov-Zhabotinsky reaction***
*(Gabriel Peterson, College of the Redwoods, CA)*

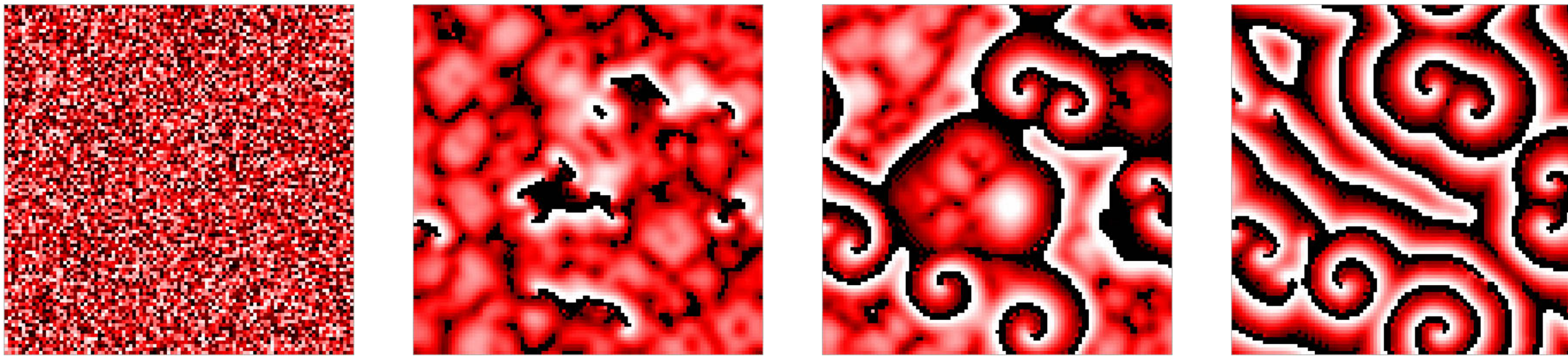
### Mechanism

- in each elementary volume of solution, there is competition between two reaction branches, A and B
- A is faster than B, but B is autocatalytic
- when A runs out of reactants, B takes over and regenerates them
- a color indicator signals the oscillation between A and B through iron ions ($Fe^{2+}$/$Fe^{3+}$)

# 2. A Complex Systems Sampler

## b. Pattern formation – *Chemical: BZ reaction*

NetLogo model: /Chemistry & Physics/Chemical Reactions/B-Z Reaction

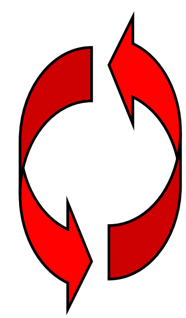


***NetLogo B-Z reaction simulation, after A. K. Dewdney's "hodgepodge machine"***
*(Uri Wilensky, Northwestern University, IL)*

### Modeling & simulation

- abstract, simplified rules
- each cell has 3 states:
  - "healthy" (x = 0, black)
  - "infected" (0 < x < 1, red)
  - "sick" (x = 1, white)

- each cell follows 3 rules that create a cycle:
  - if "healthy, become "infected" as a function of neighbors
  - if "infected", increase infection level as a function of neighbors
  - if "sick", become "healthy"



# 2. A Complex Systems Sampler

## b. Pattern formation – *Chemical: BZ reaction*

## Concepts collected from this example

- simple individual rules (modeling a less simple, but small set of reactions)
- emergence of long-range spatiotemporal correlations
- no impurities; spiral centers are *not* specialized (decentralization)
- local interactions by reaction and diffusion

# Complex Systems Made Simple

1. Introduction

2. A Complex Systems Sampler

   a. Cellular automata
   b. Pattern formation
   c. Swarm intelligence:
      - *Insect colonies: ant trails; termites*
      - *Collective motion: flocking; traffic jams*
      - *Synchronization: fireflies; neurons*
   d. Complex networks
   e. Spatial communities
   f. Structured morphogenesis

3. Commonalities

4. NetLogo Tutorial

# 2. A Complex Systems Sampler

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

***White-footed ants trailing on a wall***
*(J. Warner, University of Florida)*

### Phenomenon

- insect colonies are the epitome of complex systems, self-organization and emergence
- one striking example of collective behavior: spontaneous trail formation by ants, without anyone having a map
- two-way trails appear between nest and food source, brooding area or cemetery
- ants carry various items back and forth on these trails
- the colony performs *collective optimization* of distance and productivity without a leader

# 2. A Complex Systems Sampler

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

***Harvester ant***
*(Deborah Gordon, Stanford University)*

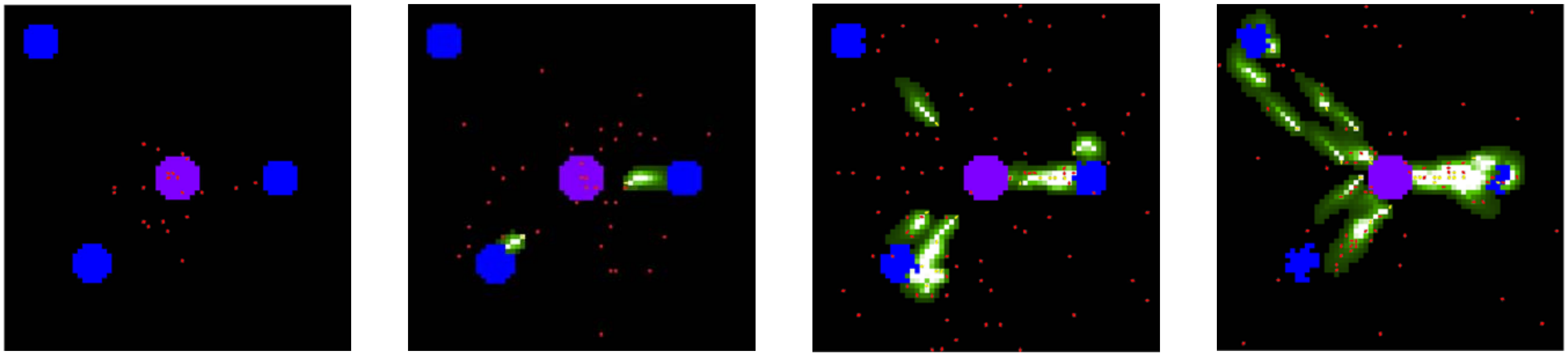
### Basic mechanism

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

# 2. A Complex Systems Sampler

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

NetLogo model: /Biology/Ants



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

### Modeling & simulation

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

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

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

# 2. A Complex Systems Sampler

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

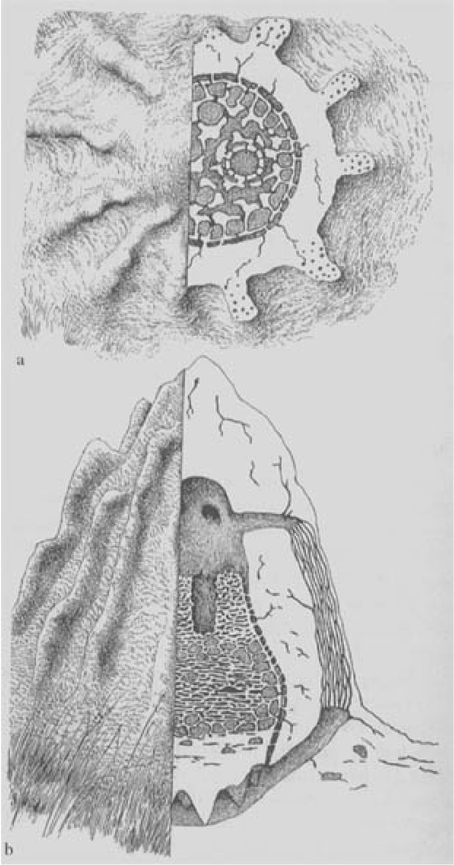
## Concepts collected from this example

- simple individual rules
- emergence of collective computation
- no leader, no map (decentralization)
- amplification of small fluctuations (positive feedback)
- local interactions (ant $\leftrightarrow$ environment)
- phase transition (critical mass = minimal number of ants)

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Insect colonies: termite mounds*

***Termite mound***
*(J. McLaughlin, Penn State University)*



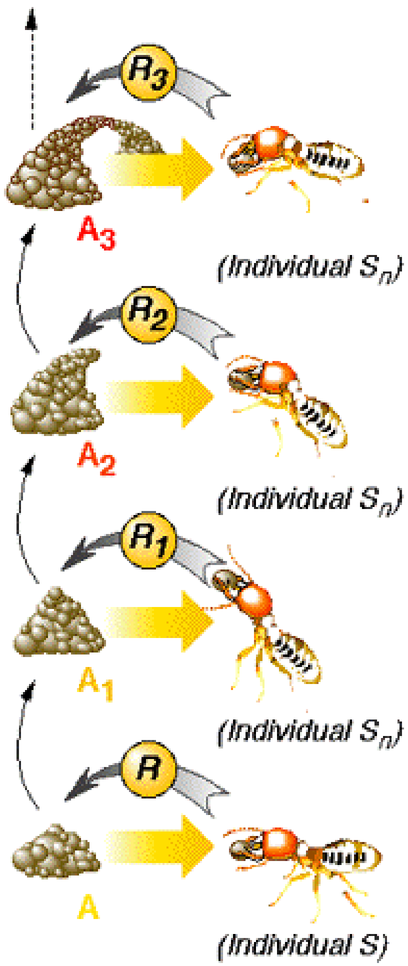
***Inside of a termite mound***
*(Lüscher, 1961)*

### Phenomenon

- another spectacular example of insect self-organization: mound building by termites
- remarkable size and detailed architecture
- essentially made of tiny pellets of soil glued together
- starts with one underground chamber and grows up like a plant

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Insect colonies: termite mounds*




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

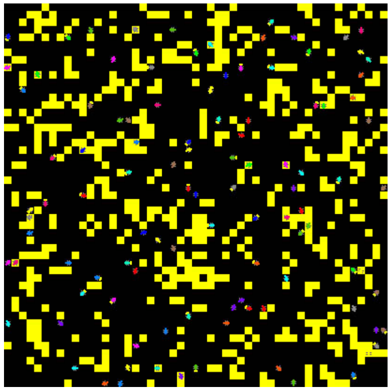
### Mechanism

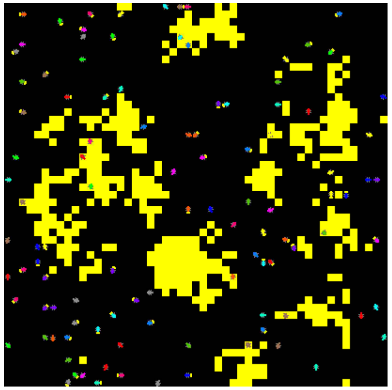
- no plan or central control
- termites interact indirectly, through the environment they are modifying
- "stigmergy" is a set of stimulus-response pairs:
  - pattern A in environment triggers behavior R in termite
  - behavior R changes A into A1
  - pattern A1 triggers behavior R1
  - behavior R1 changes A1 into A2
  - etc.
- for example, a small heap develops into an arch

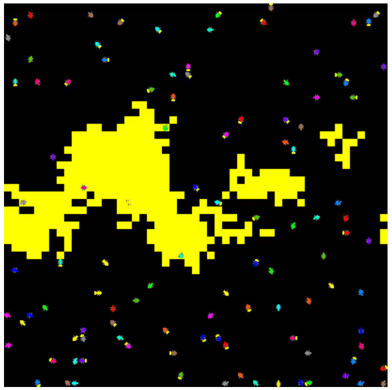
# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Insect colonies: termite mounds*

NetLogo model: /Biology/Termites







***StarLogo termite mound building simulation, after Mitchel Resnick***
*(StarLogo Project, MIT Media Laboratory, MA)*

### Modeling & simulation

- simplified setup:
  - randomly scattered wood chips (or soil pellets)
  - termites moving among the chips

- virtual termite's repertoire:
  - walk around randomly
  - if bump into wood chip, pick it up and move away
  - if carrying wood chip, drop it where other wood chips are

- result: wood chips are stacked in piles of growing size

- explains one aspect of mound formation

# 2. A Complex Systems Sampler

c. Swarm intelligence – *Insect colonies: termite mounds*

## Concepts collected from this example

- simple individual rules
- emergence of macroscopic structure
- no architect, no blueprint
- amplification of small fluctuations (positive feedback)
- local interactions (termite $\leftrightarrow$ environment)

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Collective motion: flocking*

***Giant flock of flamingos***
*(John E. Estes, UC Santa Barbara, CA)*

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

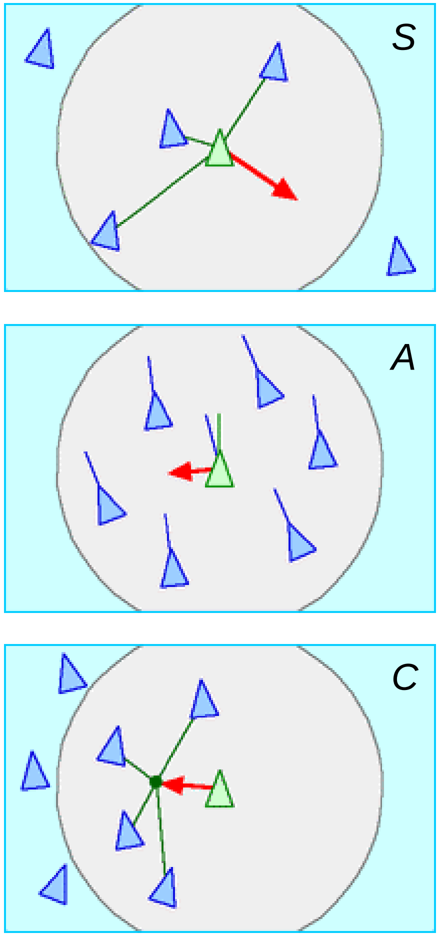
***Bison herd***
*(Center for Bison Studies, Montana State University, Bozeman)*

### Phenomenon

- coordinated collective movement of dozens or thousands of individuals
- adaptive significance:
  - prey groups confuse predators
  - predator groups close in on prey
  - increased aero/hydrodynamic efficiency

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Collective motion: flocking*




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

### Mechanism

- Reynolds' "boids" model
- each individual adjusts its position, orientation and speed according to its nearest neighbors
- steering rules:

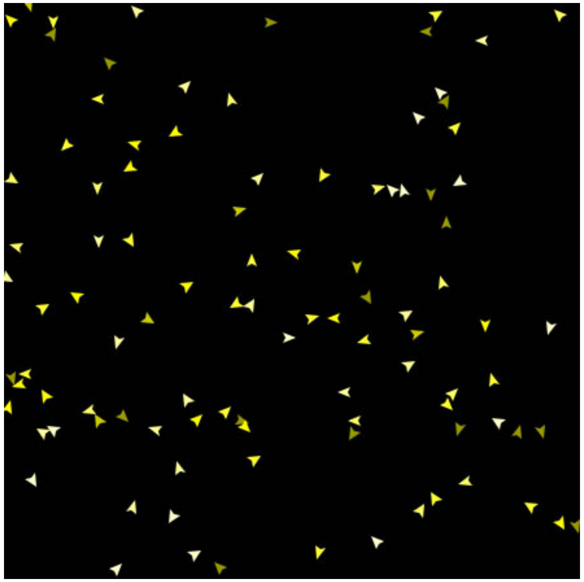
interaction potential {
  - separation: avoid crowding local flockmates
  - cohesion: move toward average position of local flockmates

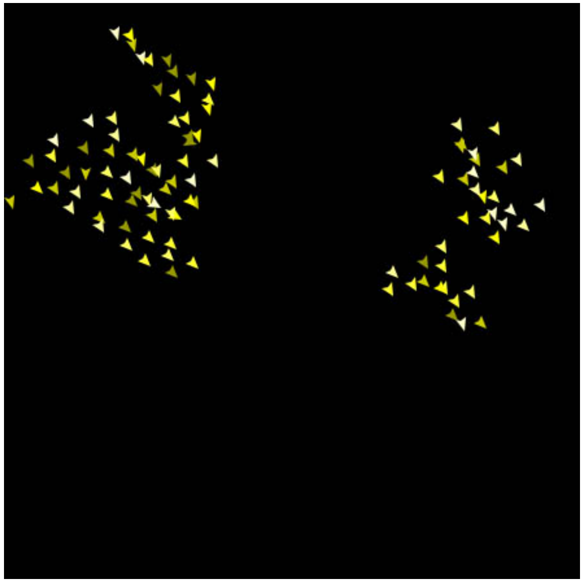
  - alignment: adopt average heading of local flockmates

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Collective motion: flocking*

NetLogo model: /Biology/Flocking





***NetLogo flocking simulation, after Craig Reynolds' "boids" model***
*(Uri Wilensky, Northwestern University, IL)*

Modeling & simulation

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Collective motion: flocking*

## Concepts collected from this example

- simple individual rules
- emergence of coordinated collective motion
- no leader, no external reference point (decentralization)
- local interactions (animal $\leftrightarrow$ animal)
- cooperation

# 2. A Complex Systems Sampler

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

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

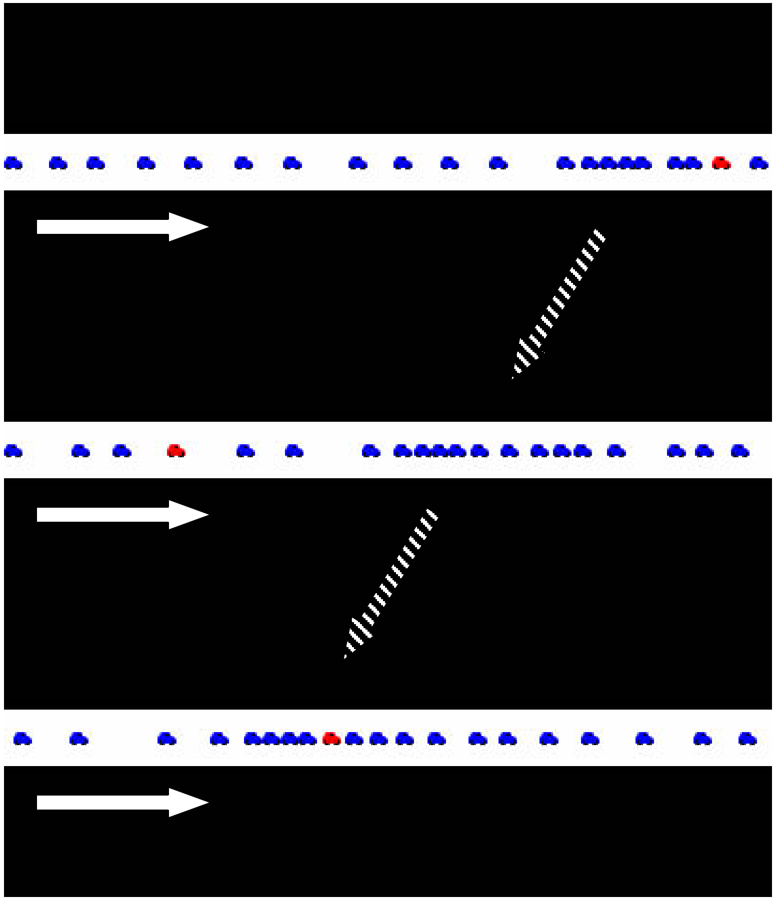
### Phenomenon

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

# 2. A Complex Systems Sampler

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

NetLogo model: /Social Science/Traffic Basic



***NetLogo traffic basic simulation, after Mitchel Resnick***
*(Uri Wilensky, Northwestern University, IL)*

### Modeling & simulation

- each car:
  - slows down if there is another car close ahead
  - speeds up if there is no car close ahead
- traffic nodes move in the direction opposite to cars
- emergence of group behavior qualitatively different from individual behavior

# 2. A Complex Systems Sampler

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

### Concepts collected from this example

- simple individual reactions
- emergence of moving superstructures
- no accident, no light, no police radar (decentralization)
- amplification of small fluctuations (positive feedback)
- local interactions (car $\leftrightarrow$ car)

# 2. A Complex Systems Sampler

## c. Swarm intelligence – Synchronization: fireflies

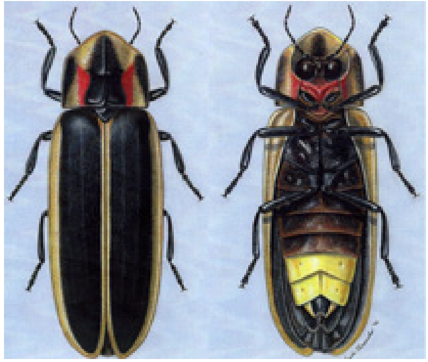
*Fireflies flashing in sync on the river banks of Malaysia*

### Phenomenon

- a swarm of male fireflies (beetles) synchronize their flashes
- starting from random scattered flashing, pockets of sync grow and merge
- adaptive significance:
  - still unclear...
  - cooperative behavior amplifies signal visibility to attract females (share the reward)?
  - cooperative behavior helps blending in and avoiding predators (share the risk)?
  - ... or competition to be the first to flash?
- famous example of synchronization among independently sustained oscillators

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Synchronization: fireflies*



***Say's firefly, in the US***
*(Arwin Provonsha, Purdue Dept of Entomology, IN)*

***Firefly flashing (slow motion)***
*(Biology Department, Tufts University, MA)*

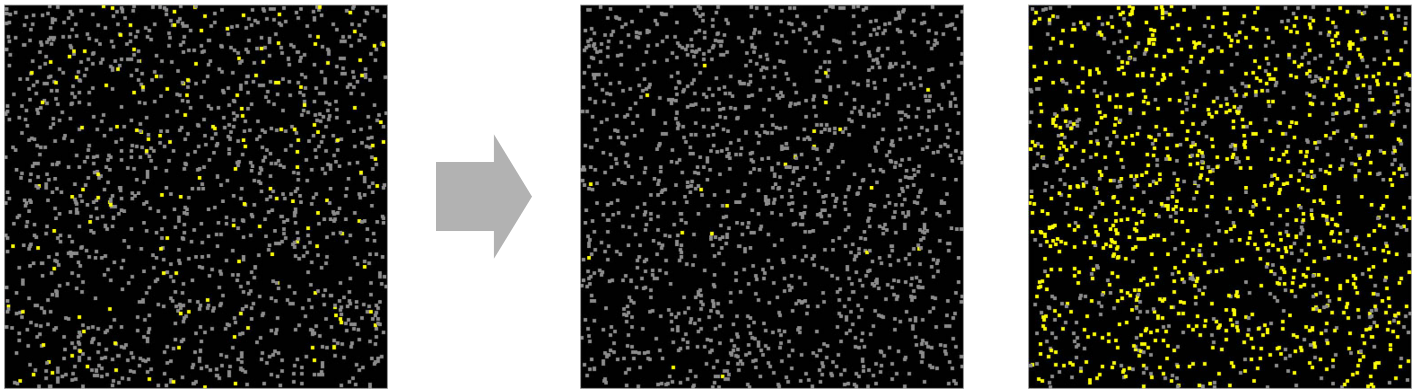
### Mechanism

- light-emitting cells (photocytes) located in the abdomen
- 1. each firefly maintains an internal regular cycle of flashing:
  - physiological mechanism still unclear...
  - pacemaker cluster of neurons controlling the photocytes?
  - autonomous oscillatory metabolism?
  - ... or just the movie in repeat mode? :-)
- 2. each firefly adjusts its flashing cycle to its neighbors:
  - pushing/pulling or resetting phase
  - increasing/decreasing frequency

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Synchronization: fireflies*

NetLogo model: /Biology/Fireflies



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

### Modeling & simulation

- each firefly "cell":
  - hovers around randomly
  - cycles through an internal flashing clock
  - resets its clock upon seeing flashing in the vicinity

- distributed system coordinates itself without a central leader

# 2. A Complex Systems Sampler

c. Swarm intelligence – *Synchronization: fireflies*

## Concepts collected from this example

- simple individual rules
- emergence of collective synchronization
- no conductor, no external pacemaker (decentralization)
- local interactions (insect ↔ insect)
- cooperation

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Synchronization: neurons*

***Medial surface of the brain***
*(Virtual Hospital, University of Iowa)*

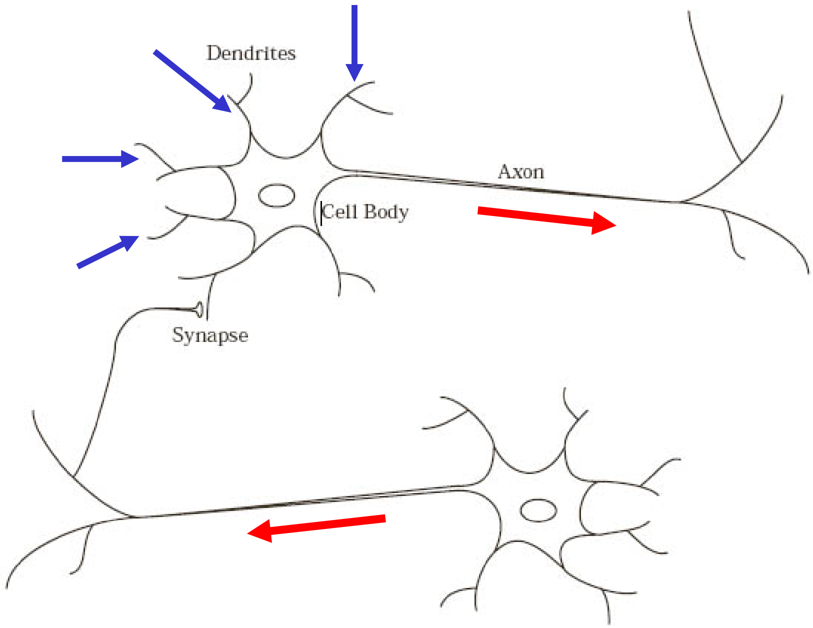
***Pyramidal neurons and interneurons, precentral gyrus***
*(Ramón y Cajal 1900)*

### Phenomenon

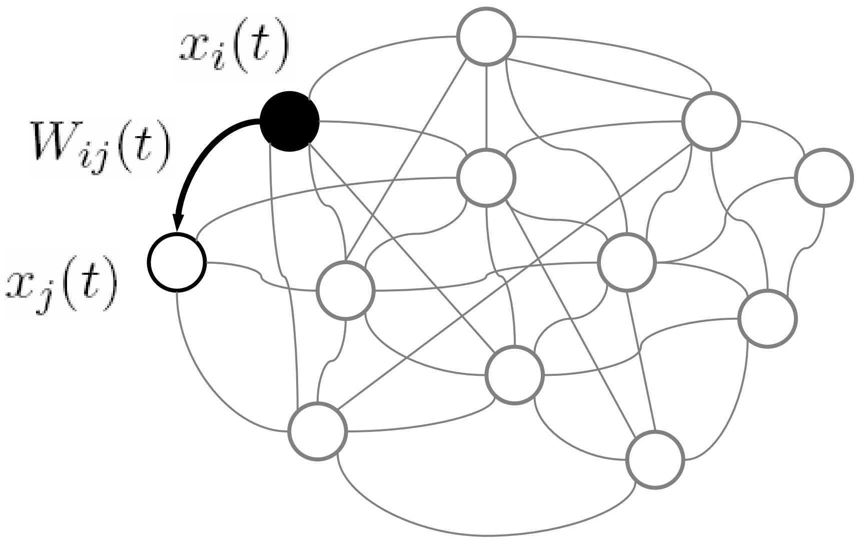
- neurons together form... the brain! (+ peripheral nervous system)
  - perception, cognition, action
  - emotions, consciousness
  - behavior, learning
  - autonomic regulation: organs, glands
- ~$10^{11}$ neurons in humans
- communicate with each other through electrical potentials
- neural activity exhibits specific patterns of *spatial and temporal synchronization* ("temporal code")

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Synchronization: neurons*




***Schematic neurons***
*(adapted from CS 791S "Neural Networks", Dr. George Bebis, UNR)*



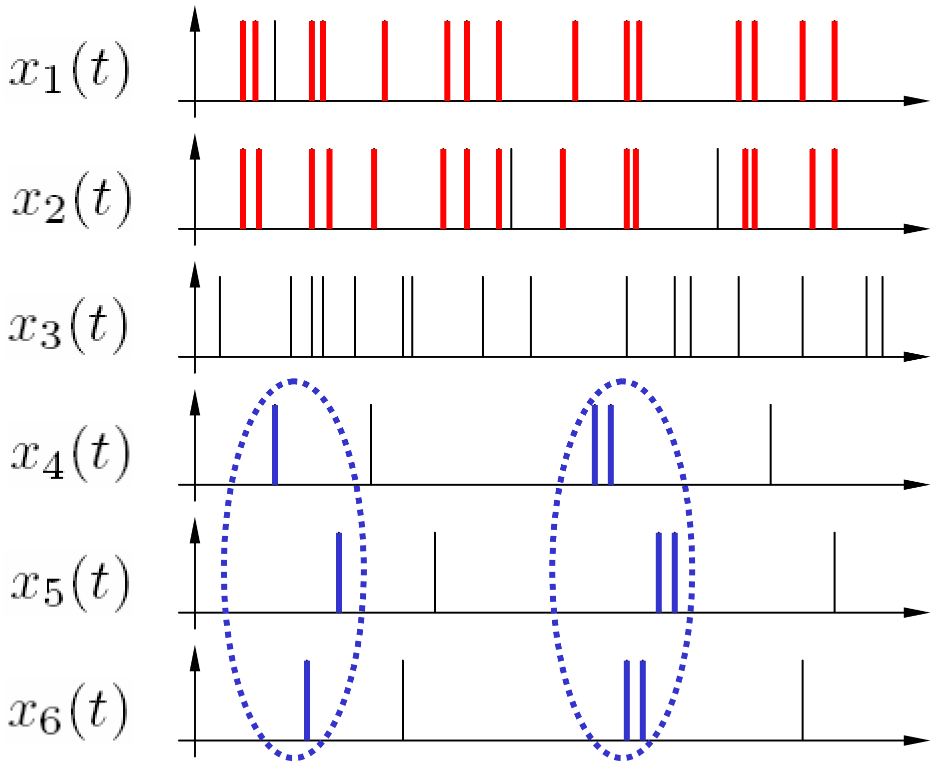

***A binary neural network***

### Mechanism

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

# 2. A Complex Systems Sampler

## c. Swarm intelligence – *Synchronization: neurons*




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

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

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

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

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

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

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

➢ 1 and 2 more in sync than 1 and 3

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

➢ 4, 5 and 6 correlated through delays