# Lecture 2



# How Do They Do It?

- Communication in Red Harvester Ants
- Good source: Deborah Gordon: *Ants at Work* (1999)

(video from *Stanford Report*, April 2003)



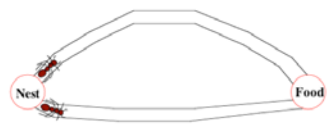
# How do they do it?

- Semiochemically: deposit pheromones
  - 10-20 signs, many signal tasks
  - ants detect pheromone gradients and frequency of encounter
- Follow trails imperfectly
  - ⇒ exploration
- Feedback reinforces successful trails
  - ⇒ biased randomness



## Ant foraging

**Cooperative search by pheromone trails**




slides from EVALife



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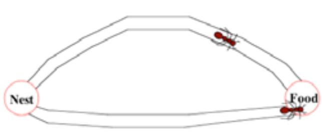


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## Ant foraging

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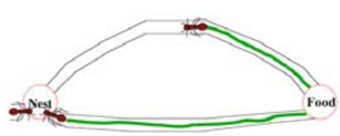


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## Ant foraging

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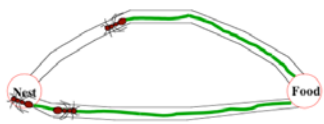


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## Ant foraging

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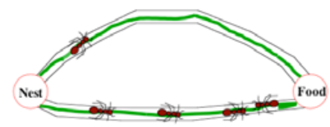


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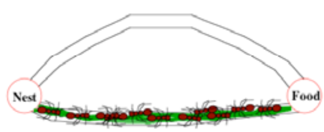
## Ant foraging

**Cooperative search by pheromone trails**

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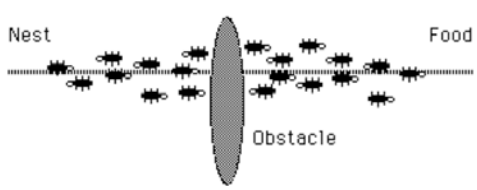
## Adaptive Path Optimization


8/28/07 slides from iridia.ulb.ac.be/~mdorigo 10

## Adaptive Path Optimization

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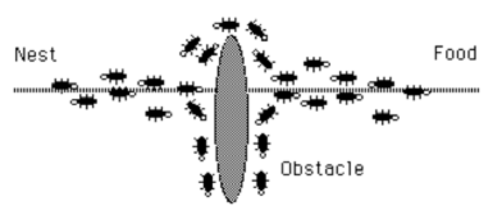
## Adaptive Path Optimization

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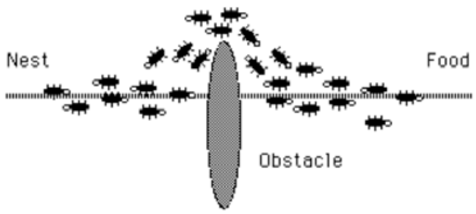
## Adaptive Path Optimization

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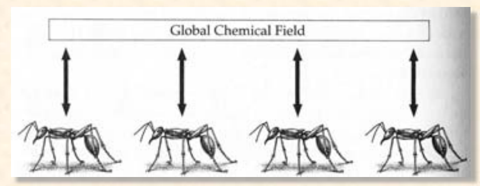
## Circular Causality




- Global pattern emergent from total system
- Individuals respond to local field

8/28/07 fig. from Solé & Goodwin 14

## Stigmergy

- From στιγμός = pricking + ἔργον = work
- The project (work) in the environment is an instigation
- Agent interactions may be:
  - direct
  - indirect (time-delayed through environment)
- Mediates individual and colony levels

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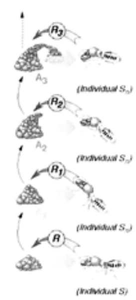
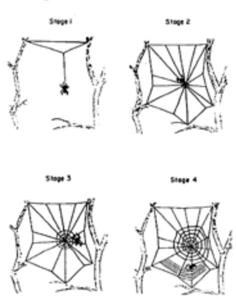
## Stigmergy in termite nest building

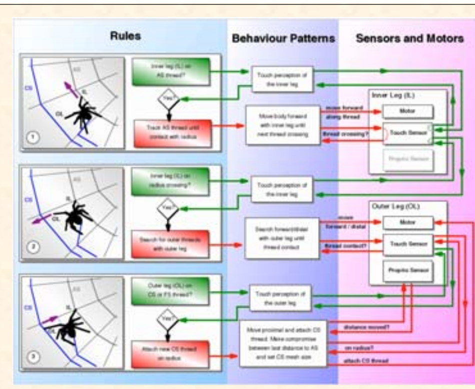


8/28/07 Fig. from EVALife 16

## Stigmergy in spider webs



8/28/07 Fig. from EVALife 17




8/28/07 Fig. from EVALife 18

## Advantages of Stigmergy

- Permits simpler agents
- Decreases direct communication between agents
- Incremental improvement
- Flexible, since when environment changes, agents respond appropriately




## Emergence

- The appearance of *macroscopic* patterns, properties, or behaviors
- that are not simply the "sum" of the *microscopic* properties or behaviors of the components
  - non-linear but not chaotic
- Macroscopic order often described by fewer & different variables than microscopic order
  - e.g. ant trails vs. individual ants
  - *order parameters*



## Self-Organization

- Order may be imposed from outside a system
  - to understand, look at the external source of organization
- In *self-organization*, the order emerges from the system itself
  - must look at interactions within system
- In biological systems, the emergent order often has some adaptive purpose
  - e.g., efficient operation of ant colony



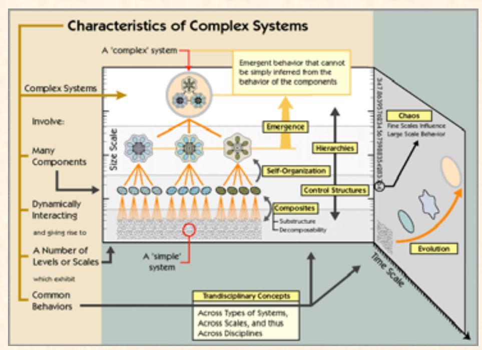



Fig. from NECSI



## Why Are Complex Systems & Self-Organization Important for CS?

- Fundamental to theory & implementation of massively parallel, distributed computation systems
- How can millions of independent computational (or robotic) agents cooperate to process information & achieve goals, in a way that is:
  - efficient
  - self-optimizing
  - adaptive
  - robust in the face of damage or attack



## Some Principles Underlying Emergent Systems

- "More is different"
- "Ignorance is useful"
- "Encourage random encounters"
- "Look for patterns in signals"
- "Pay attention to your neighbor"
  ("Local information leads to global wisdom")

— Johnson, *Emergence*, pp. 77-9.

## Similar Principles of SO

- Ant colonies
- Development of embryo
- Molecular interactions within cell
- Neural networks



## Comparison of Ant Colonies and Neural Networks

| | *Ant Colonies* | *Neural Nets* |
|---|---|---|
| No. of units | high | high |
| Robustness | high | high |
| Connectivity | local | local |
| Memory | short-term | short/long term |
| Connect. stability | weak | high |
| Global patterns | trails | brain waves |
| Complex dynamics | observed | common |

 from Solé & Goodwin: *Signs of Life*, p. 149 

## Self-Organization

- Concept originated in physics and chemistry
  - emergence of macroscopic patterns
  - out of microscopic processes & interactions
- "Self-organization is a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions among its lower-level components." — Bonabeau, Dorigo & Theraulaz, p. 9



## Four Ingredients of Self-Organization

- Activity amplification by positive feedback
- Activity balancing by negative feedback
- Amplification of random fluctuations
- Multiple Interactions

— Bonabeau, Dorigo & Theraulaz, pp. 9-11



## Characteristics of Self-Organized System

- Creation of spatiotemporal structures in initially homogeneous medium
- Multistability
- Bifurcations when parameters are varied

 — Bonabeau, Dorigo & Theraulaz, *Swarm Intelligence*, pp. 12-14 

## Additional Bibliography


1. Solé, Ricard, & Goodwin, Brian. *Signs of Life: How Complexity Pervades Biology*. Basic Books, 2000.
2. Bonabeau, Eric, Dorigo, Marco, & Theraulaz, Guy. *Swarm Intelligence: From Natural to Artificial Systems*. Oxford, 1999.
3. Gordon, Deborah. *Ants at Work: How an Insect Society Is Organized*. Free Press, 1999.
4. Johnson, Steven. *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*. Scribner, 2001. A popular book, but with many good insights.


Part II

# II. Cellular Automata



## Cellular Automata (CAs)

- Invented by von Neumann in 1940s to study reproduction
- He succeeded in constructing a self-reproducing CA
- Have been used as:
  - massively parallel computer architecture
  - model of physical phenomena (Fredkin, Wolfram)
- Currently being investigated as model of quantum computation (QCAs)



## Structure

- Discrete space (lattice) of regular *cells*
  - 1D, 2D, 3D, …
  - rectangular, hexagonal, …
- At each unit of time a cell changes state in response to:
  - its own previous state
  - states of neighbors (within some “radius”)
- All cells obey same state update rule
  - an FSA
- Synchronous updating



## Example: Conway’s Game of Life

- Invented by Conway in late 1960s
- A simple CA capable of universal computation
- Structure:
  - 2D space
  - rectangular lattice of cells
  - binary states (alive/dead)
  - neighborhood of 8 surrounding cells (& self)
  - simple population-oriented rule



## State Transition Rule

- Live cell has 2 or 3 live neighbors
  ⇒ stays as is (stasis)
- Live cell has < 2 live neighbors
  ⇒ dies (loneliness)
- Live cell has > 3 live neighbors
  ⇒ dies (overcrowding)
- Empty cell has 3 live neighbors
  ⇒ comes to life (reproduction)



## Demonstration of Life

Run NetLogo Life

or

<www.cs.utk.edu/~mclennan/Classes/420/NetLogo/Life.html>

Go to CBN
Online Experimentation Center

<mitpress.mit.edu/books/FLAOH/cbnhtml/java.html>

## Some Observations About Life

1. Long, chaotic-looking initial transient
   – unless initial density too low or high
2. Intermediate phase
   – isolated islands of complex behavior
   – matrix of static structures & “blinkers”
   – gliders creating long-range interactions
3. Cyclic attractor
   – typically short period

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## From Life to CAs in General

- What gives Life this very rich behavior?
- Is there some simple, general way of characterizing CAs with rich behavior?
- It belongs to Wolfram’s Class IV

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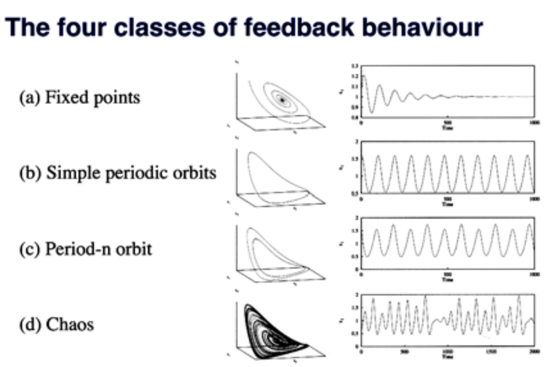


8/28/07 fig. from Flake via EVALife 39

## Wolfram’s Classification

- Class I: evolve to fixed, homogeneous state
  ~ limit point
- Class II: evolve to simple separated periodic structures
  ~ limit cycle
- Class III: yield chaotic aperiodic patterns
  ~ strange attractor (chaotic behavior)
- Class IV: complex patterns of localized structure
  ~ long transients, no analog in dynamical systems

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## Langton’s Investigation

*Under what conditions can we expect a complex dynamics of information to emerge spontaneously and come to dominate the behavior of a CA?*

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## Approach

- Investigate 1D CAs with:
  – random transition rules
  – starting in random initial states
- Systematically vary a simple parameter characterizing the rule
- Evaluate qualitative behavior (Wolfram class)

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## Why a Random Initial State?

- How can we characterize typical behavior of CA?
- Special initial conditions may lead to special (atypical) behavior
- Random initial condition effectively runs CA in parallel on a sample of initial states
- Addresses emergence of order from randomness

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## Assumptions

- Periodic boundary conditions
  - no special place
- Strong quiescence:
  - if all the states in the neighborhood are the same, then the new state will be the same
  - persistence of uniformity
- Spatial isotropy:
  - all rotations of neighborhood state result in same new state
  - no special direction
- Totalistic [not used by Langton]:
  - depend only on sum of states in neighborhood
  - implies spatial isotropy

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## Demonstration of 1D Totalistic CA

Run NetLogo 1D CA General Totalistic

or

<www.cs.utk.edu/~mclennan/Classes/420/NetLogo/CA-1D-General-Totalistic.html>

Go to CBN
Online Experimentation Center

<mitpress.mit.edu/books/FLAOH/cbnhtml/java.html>

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## Langton's Lambda

- Designate one state to be quiescent state
- Let $K$ = number of states
- Let $N = 2r + 1$ = size of neighborhood
- Let $T = K^N$ = number of entries in table
- Let $n_q$ = number mapping to quiescent state
- Then

$$\lambda = \frac{T - n_q}{T}$$

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## Range of Lambda Parameter

- If *all* configurations map to quiescent state: $\lambda = 0$
- If *no* configurations map to quiescent state: $\lambda = 1$
  - If every state is represented *equally*: $\lambda = 1 - 1/K$
  - A sort of measure of "excitability"

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## Example

- States: $K = 5$
- Radius: $r = 1$
- Initial state: random
- Transition function: random (given $\lambda$)

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## Class I (λ = 0.2)


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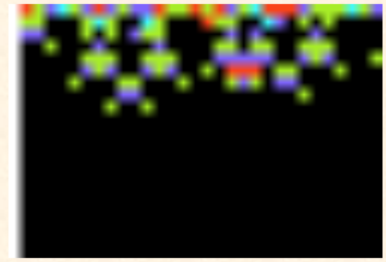
## Class I (λ = 0.2) Closeup



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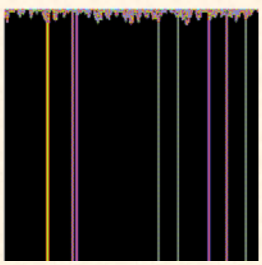
## Class II (λ = 0.4)



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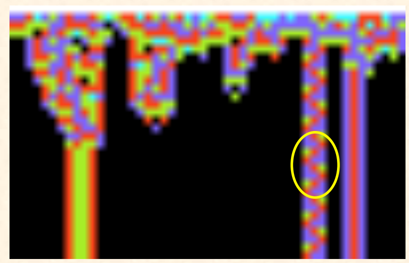
## Class II (λ = 0.4) Closeup



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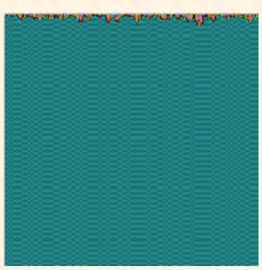
## Class II (λ = 0.31)



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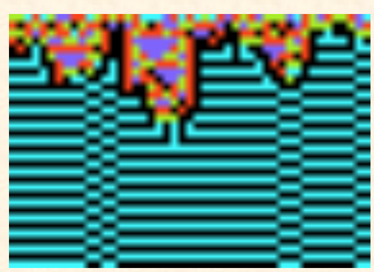
## Class II (λ = 0.31) Closeup



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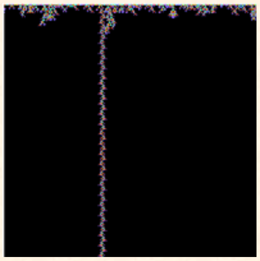
## Class II (λ = 0.37)



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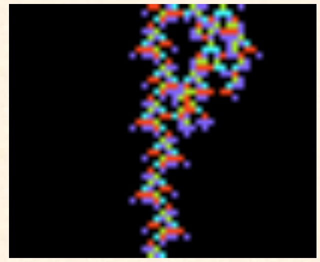
## Class II (λ = 0.37) Closeup



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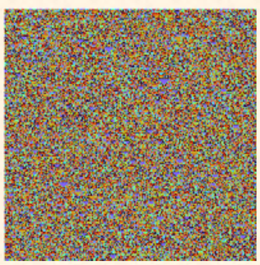
## Class III (λ = 0.5)



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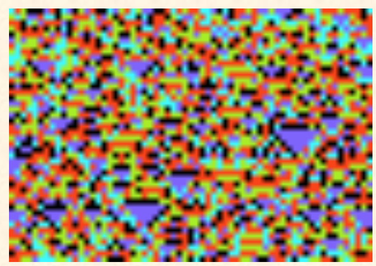
## Class III (λ = 0.5) Closeup



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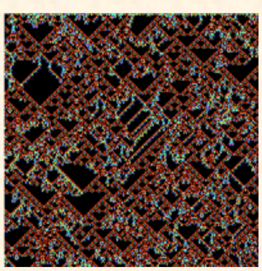
## Class IV (λ = 0.35)



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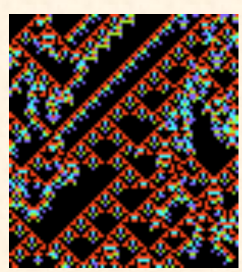
## Class IV (λ = 0.35) Closeup



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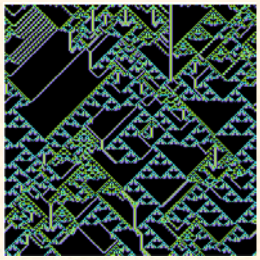
## Class IV ($\lambda = 0.34$)



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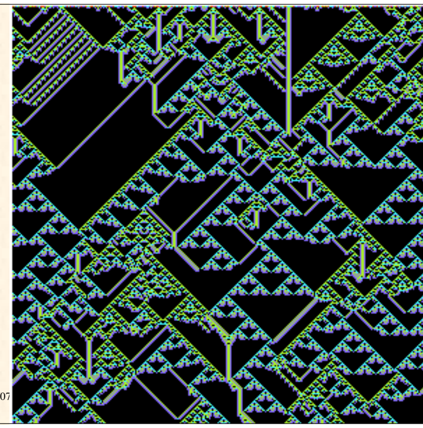

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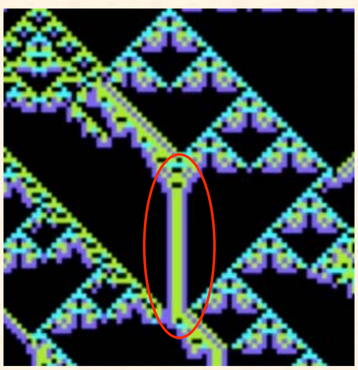

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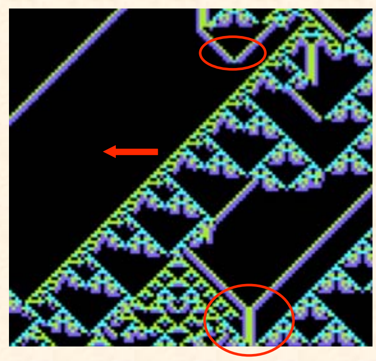

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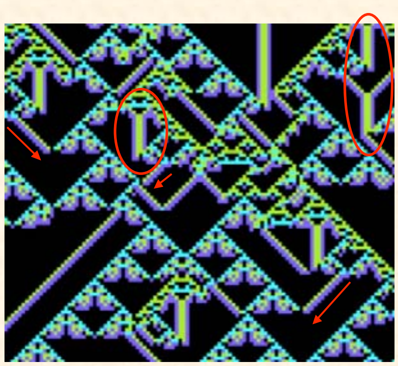

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## Class IV Shows Some of the Characteristics of Computation

- Persistent, but not perpetual storage
- Terminating cyclic activity
- Global transfer of control/information

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## λ of Life

- For Life, $\lambda \approx 0.273$
- which is near the critical region for CAs with:

  $K = 2$

  $N = 9$