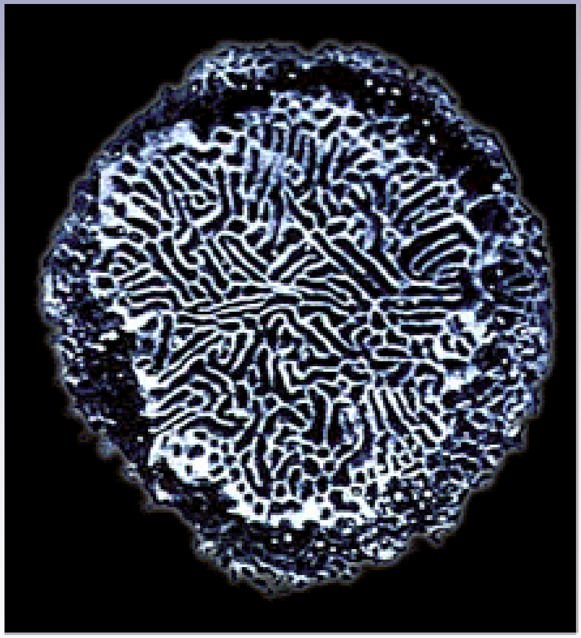
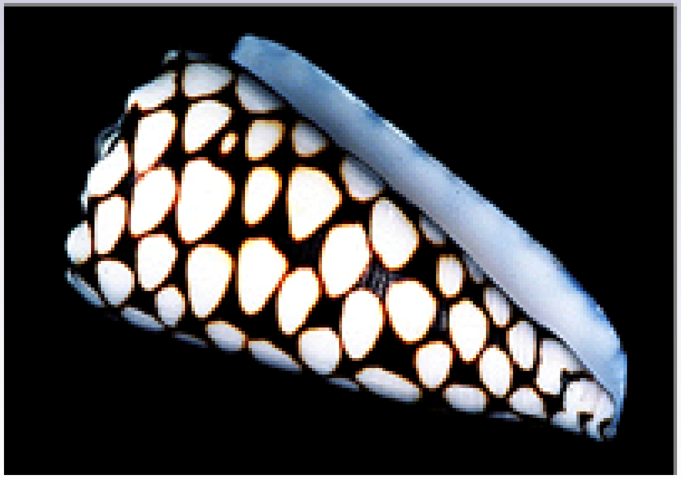
Bird flocks, zebra stripes, honeybee swarms:
Self-organization in biological systems



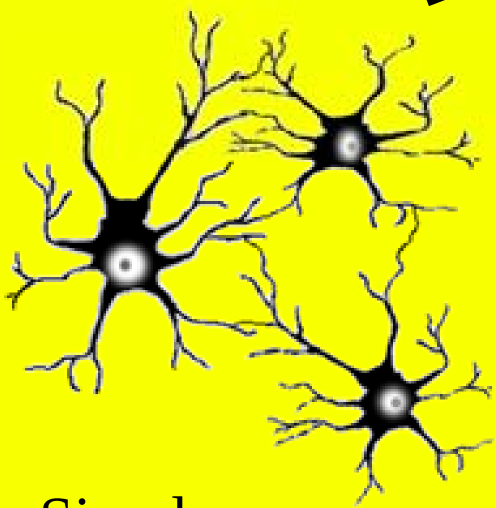


Scott Camazine

April 2004

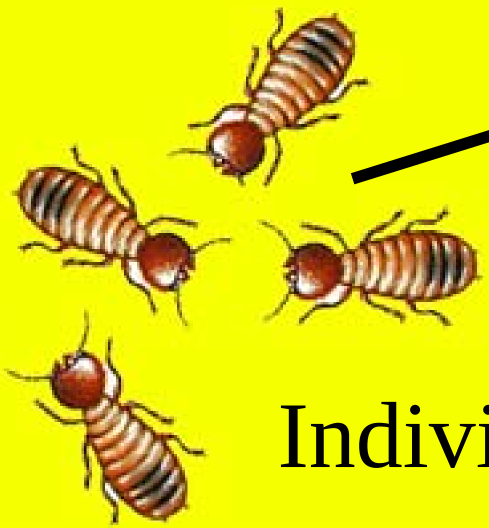
What are the mechanisms for integrating biological subunits into a coherently functioning entity?

Thinking brain



Simple neurons

What are the mechanisms for integrating biological subunits into a coherently functioning entity?

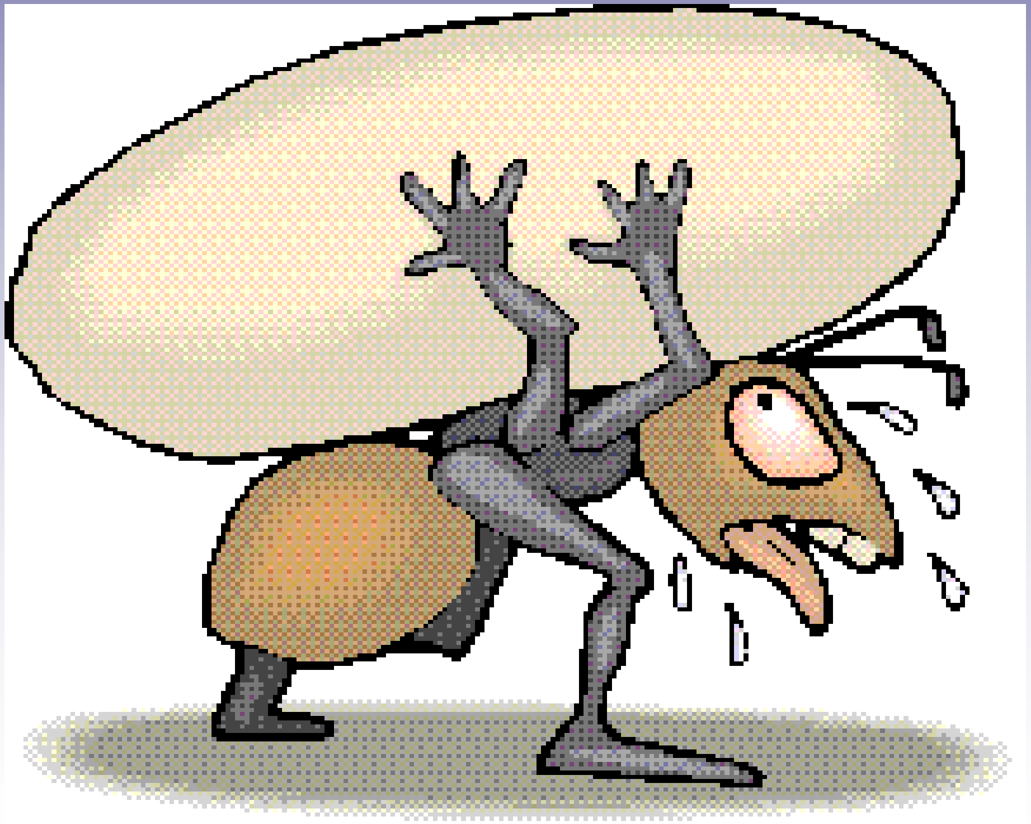


Individuals

Society

Go to the ant, thou sluggard;
consider her ways, and be wise:
Which having no guide, no overseer, or ruler,
Provideth her meat in the summer,
and gathereth her food
in the harvest.

Proverbs VI:6



Outline

- What is self-organization?
- Self-organized patterns in nature
- A more detailed view of social insect nest architecture
- Mechanisms of pattern formation
  - From simple rules to complex structures?
  - Self-organization
- Self-organization and evolution

What is self-organization?

Self-organization is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system.

Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern

What is self-organization?

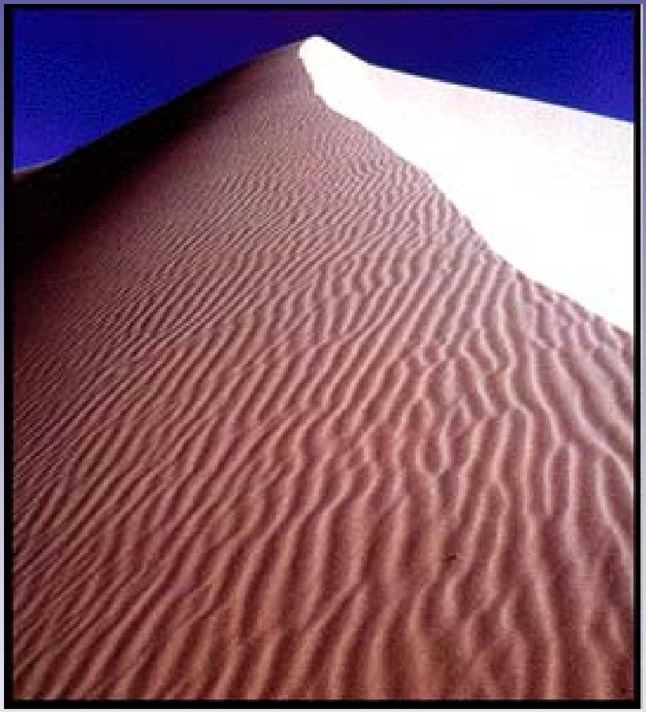
In other words, the pattern is an emergent property of the system, rather than a property imposed on the system by an external influence

Self-Organized Patterns in Nature

Non-Living Systems

Belousov-Zhabotinsky reaction

Bénard convection cells



Sand dune ripples

Self-Organized Patterns in Nature

Non-Living Systems

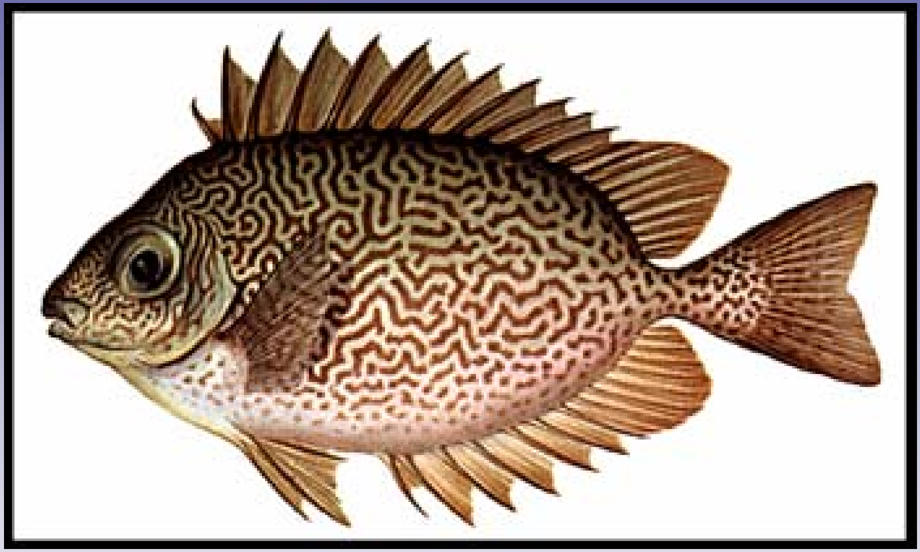
Paint wrinkles

Mud cracks

Self-Organized Patterns in Nature

Living Systems

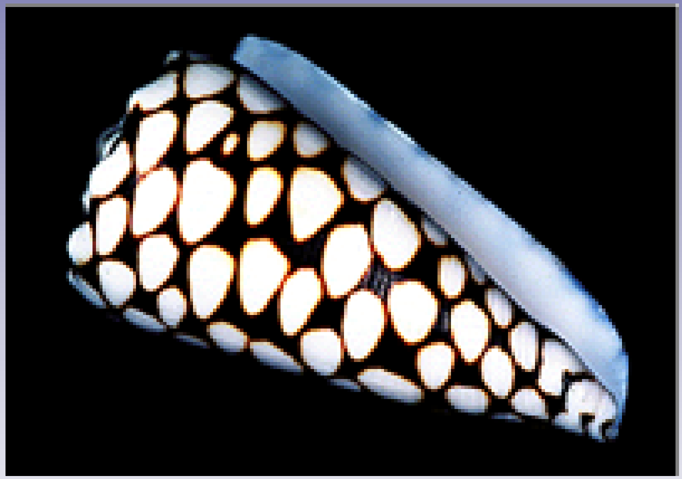
Giraffe coat



Vermiculated rabbitfish

Self-Organized Patterns in Nature

Living Systems

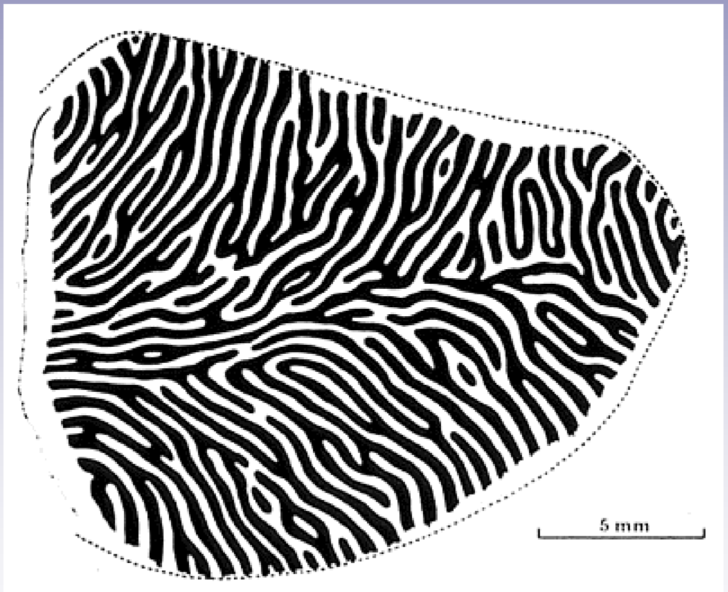


Cone shells

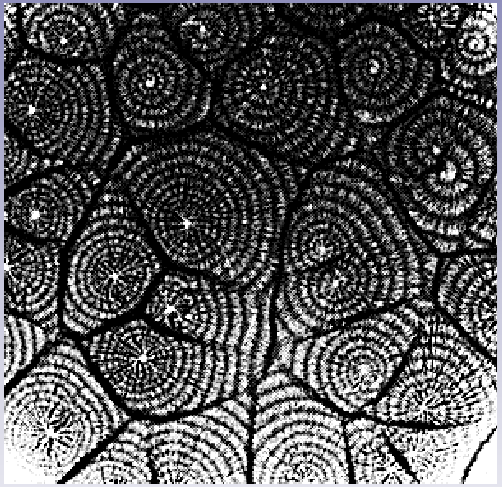
Zebra

Self-Organized Patterns in Nature

Living Systems



Ocular dominance stripes (cat brain)



Slime mold *Dictyostelium*

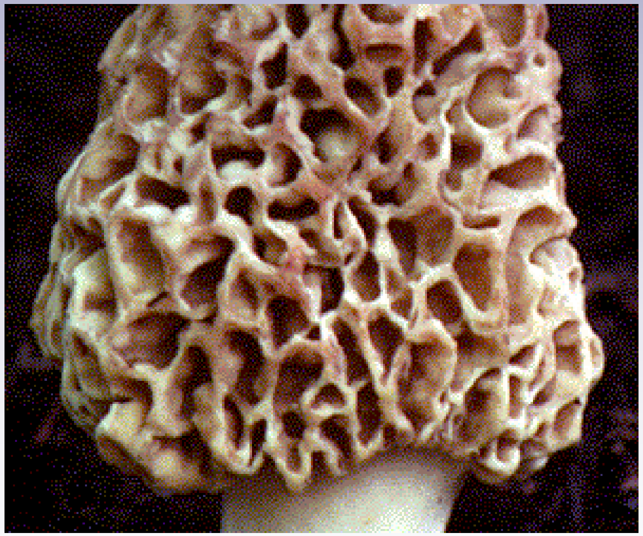
Checkerspot butterfly

Self-Organized Patterns in Nature

Living Systems

Cabbage

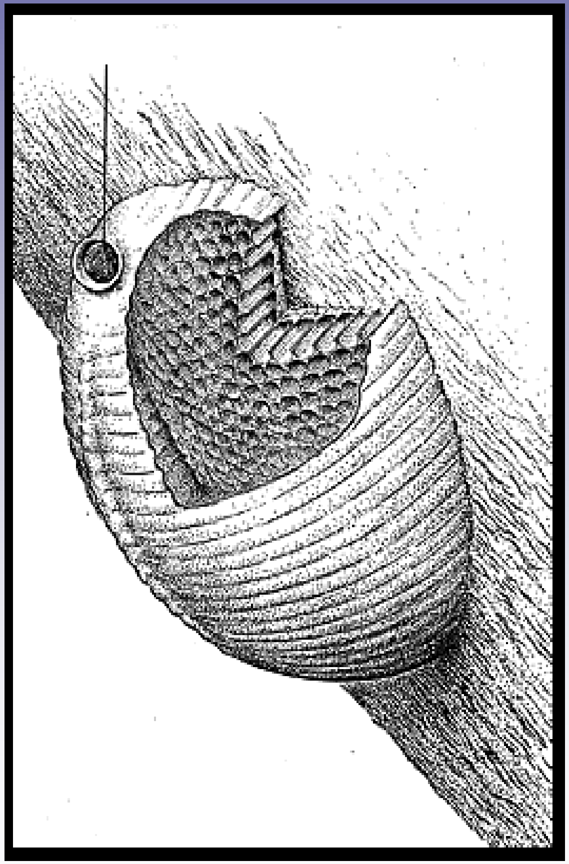
Forsythia pollen grain



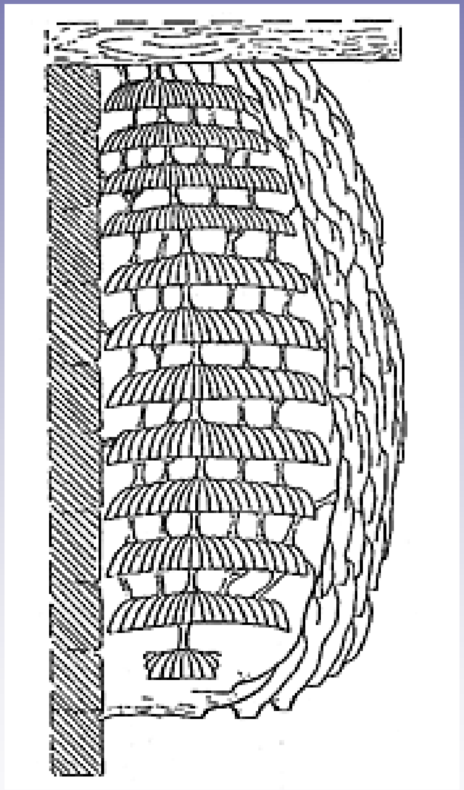
Morel mushroom

Self-Organized Patterns in Nature

Social insect architecture (wasp nests)



Synoeca surinama

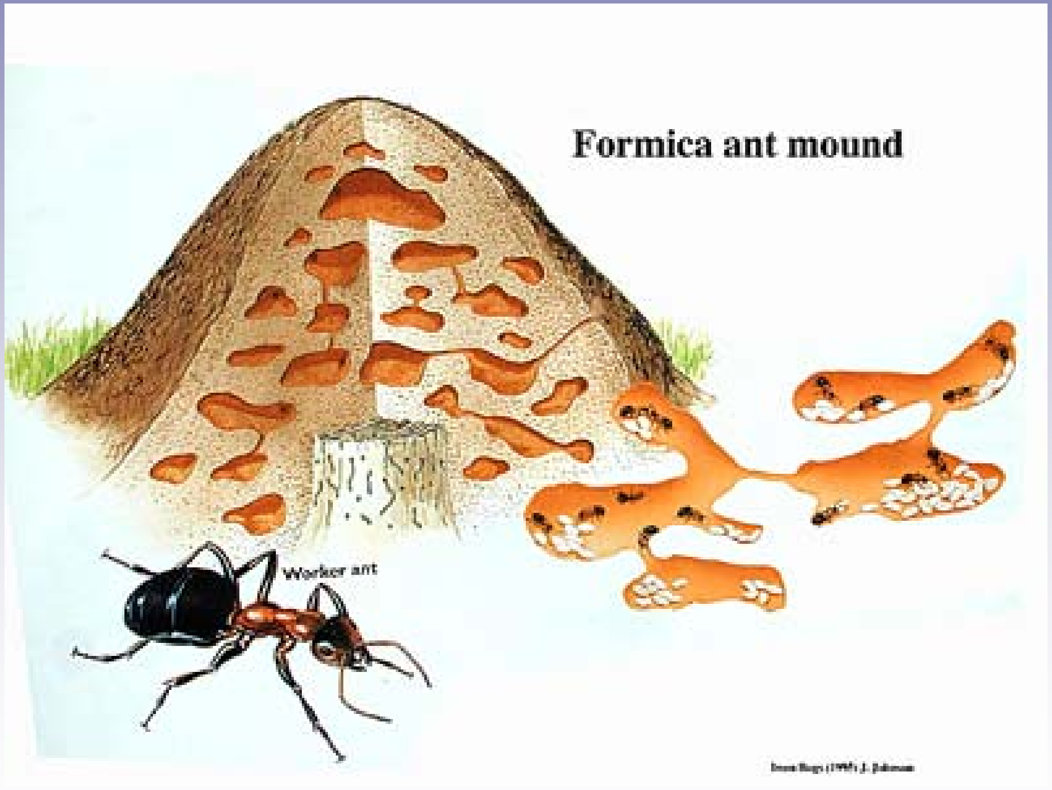


Vespa crabro

Chartergus chartarius

Self-Organized Patterns in Nature

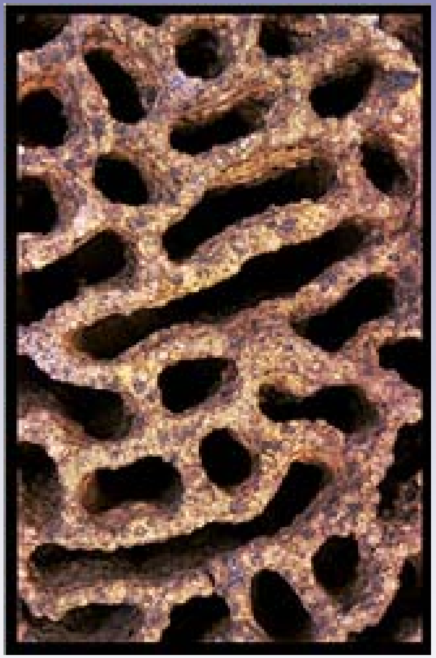
Social insect architecture (ant nests)



Lasius fuliginosus

Self-Organized Patterns in Nature

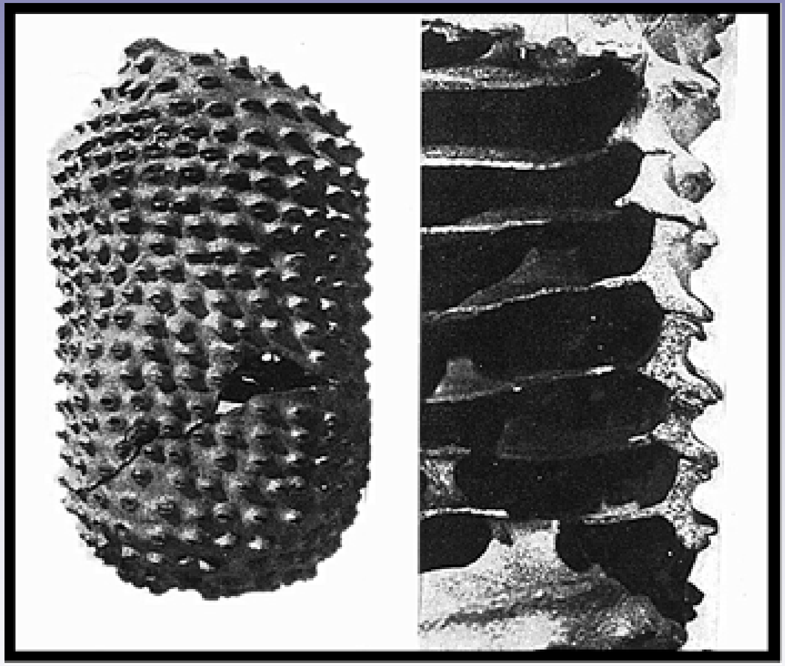
Social insect architecture
(termite nests)



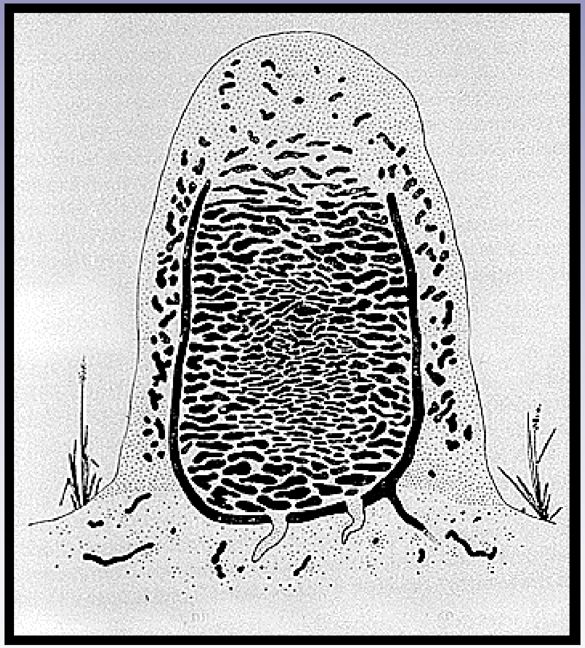
Macrotermes

Self-Organized Patterns in Nature

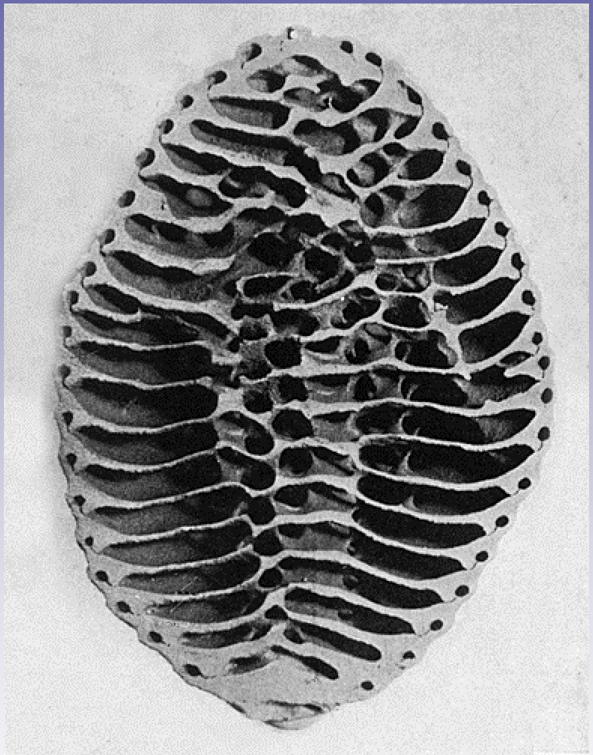
Social insect architecture (termite nests)



Apicotermes gurgulifex



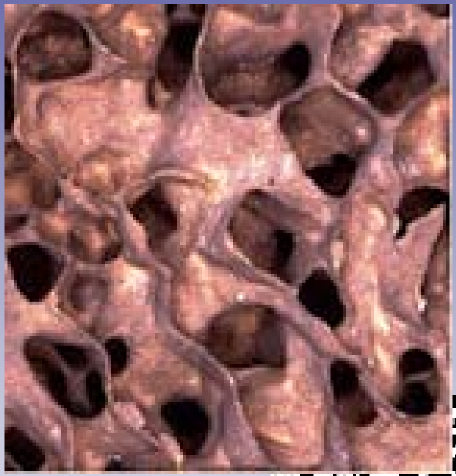
Cornitermes cumulans

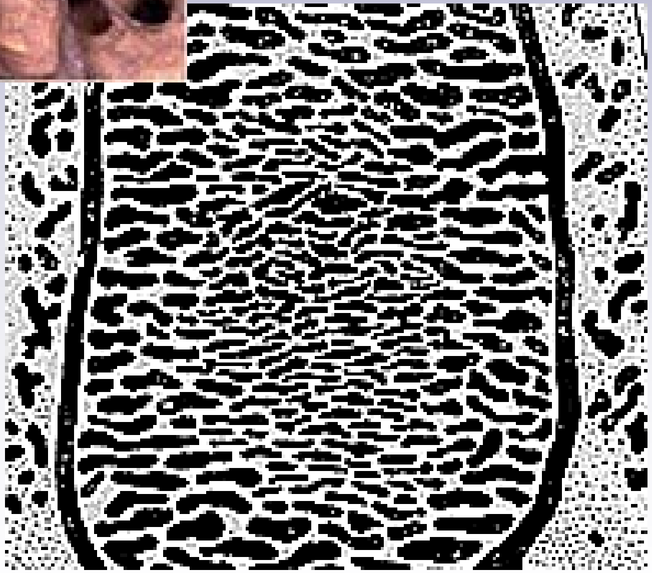


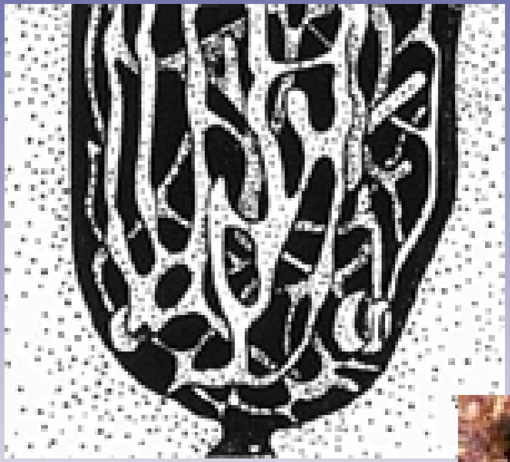
Apicotermes arquieri

Architectural Features Shared by Social Insect Nests

Internal porous structures







Among the termites, we reach a pinnacle of nest complexity

Pillars
Chimneys
Vanes
Royal chamber
Fungus gardens
Air shafts
Cellar

<u>Adaptive design</u>:

- Temperature control
- Humidity control
- Gas exchange
- Protection
  - predators
  - environment
- Conservation of material

Common architectural themes:

•Porous structures

Mottled, spongy patterns of spaces among building material

•Surface structures

Ripples, cracks, pillars, evaginations

•“Positive” and “negative” space (substance and voids)

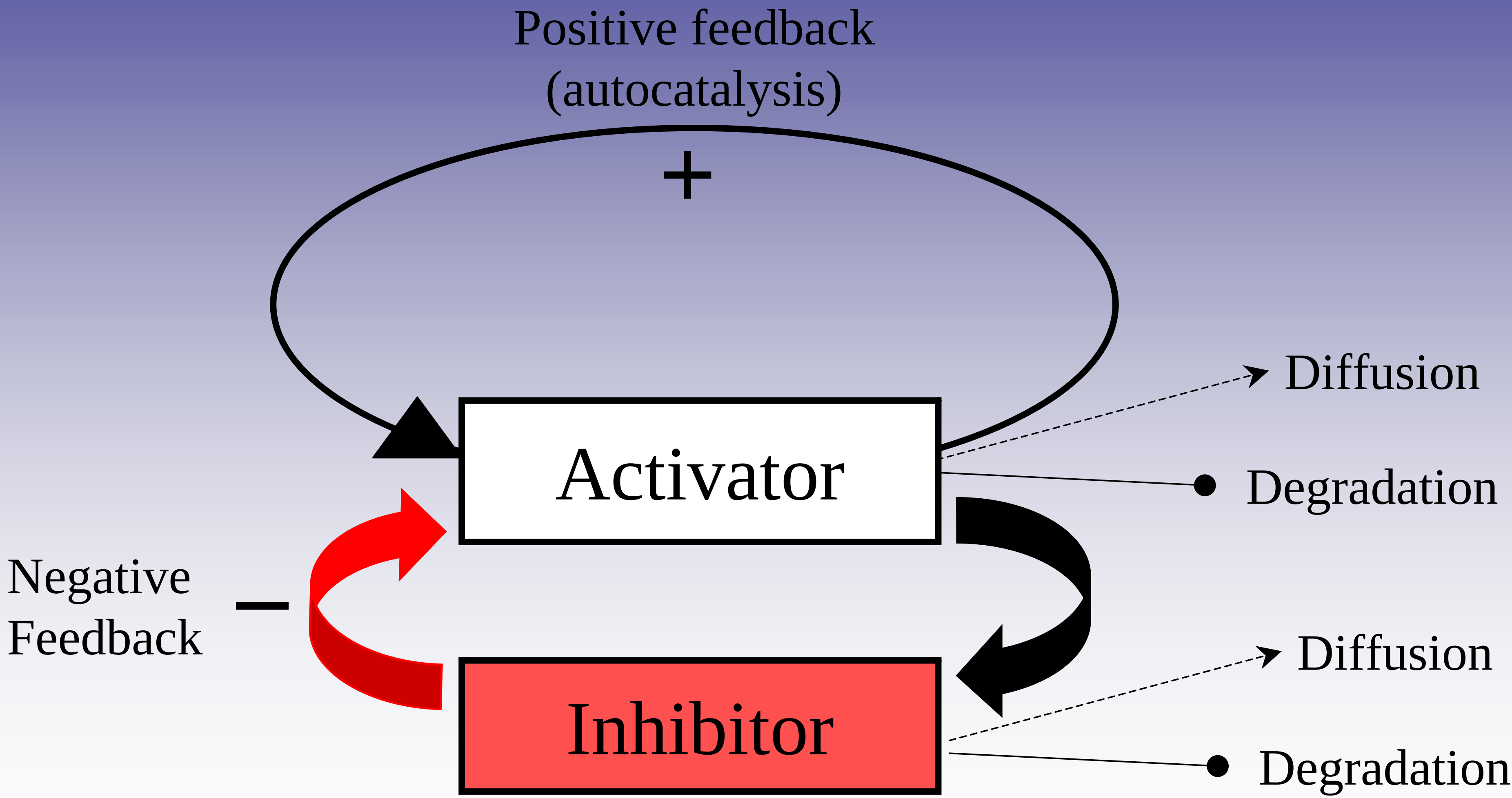
•“Competition” for building material or space

How do insects build these structures?

Proposition:
Social insects have evolved simple behavioral rules for generating these complex architectures.

One such set of simple rules is based upon an activation-inhibition mechanism.

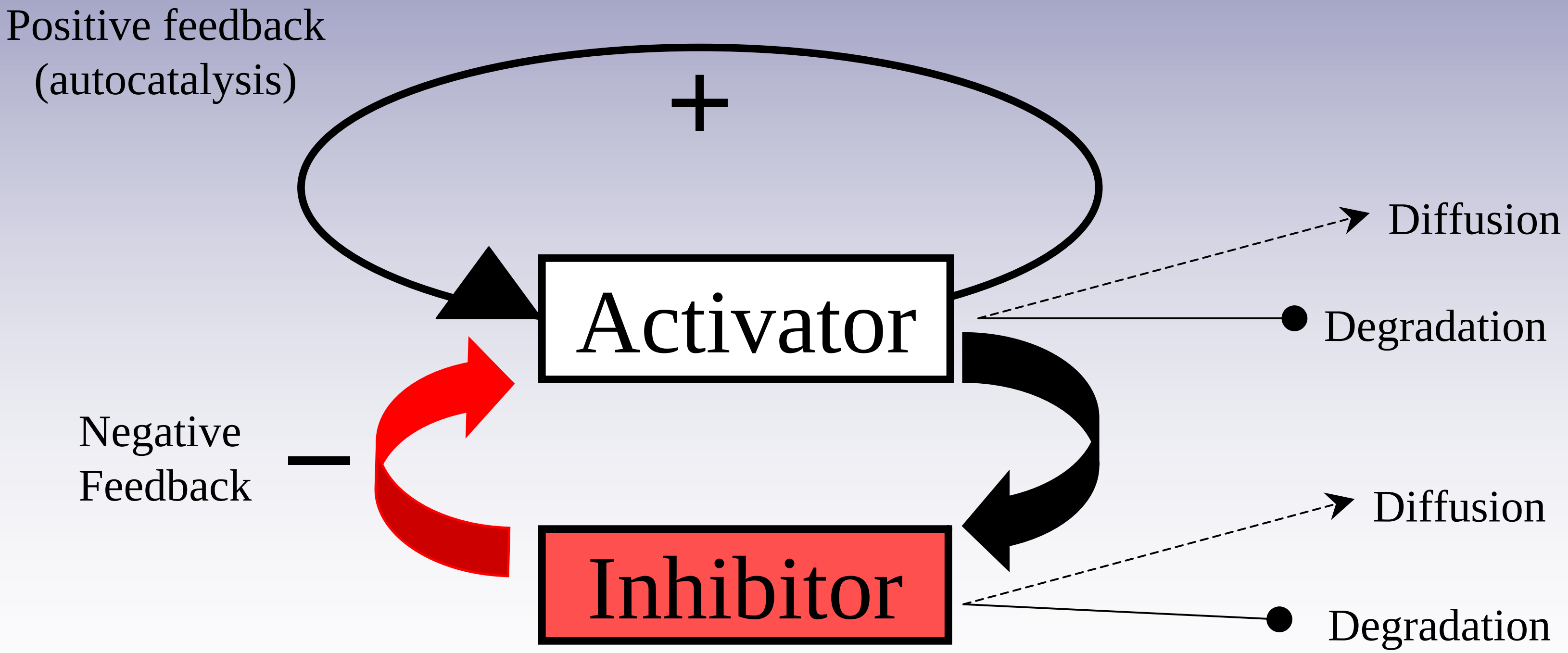
Activation-inhibition mechanisms



Activation-inhibition mechanisms

What happens?

The activator autocatalyzes its own production, and also activates the inhibitor. The inhibitor disrupts the autocatalytic process. Meanwhile, the two substances diffuse through the system at different rates, with the inhibitor migrating faster. The result: local activation and long-range inhibition



Activation-inhibition mechanisms and self-organization

The relationship between activation-inhibition mechanisms and self-organization

They share a common mechanism

Starting point: a homogeneous substrate (lacking pattern)

Positive feedback (local activation or attraction)

Negative feedback (long-range inhibition, depletion, decay)

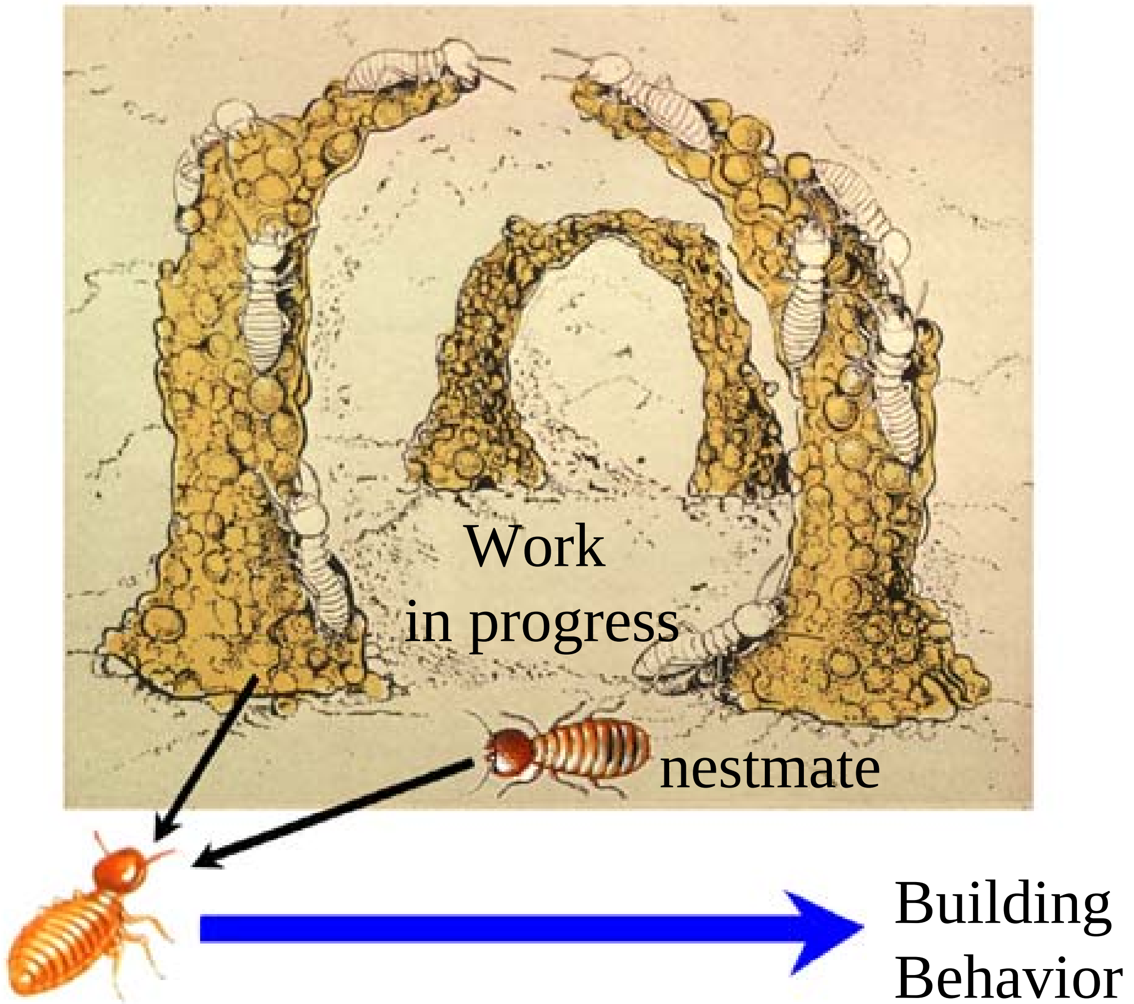
What can self-organization achieve?

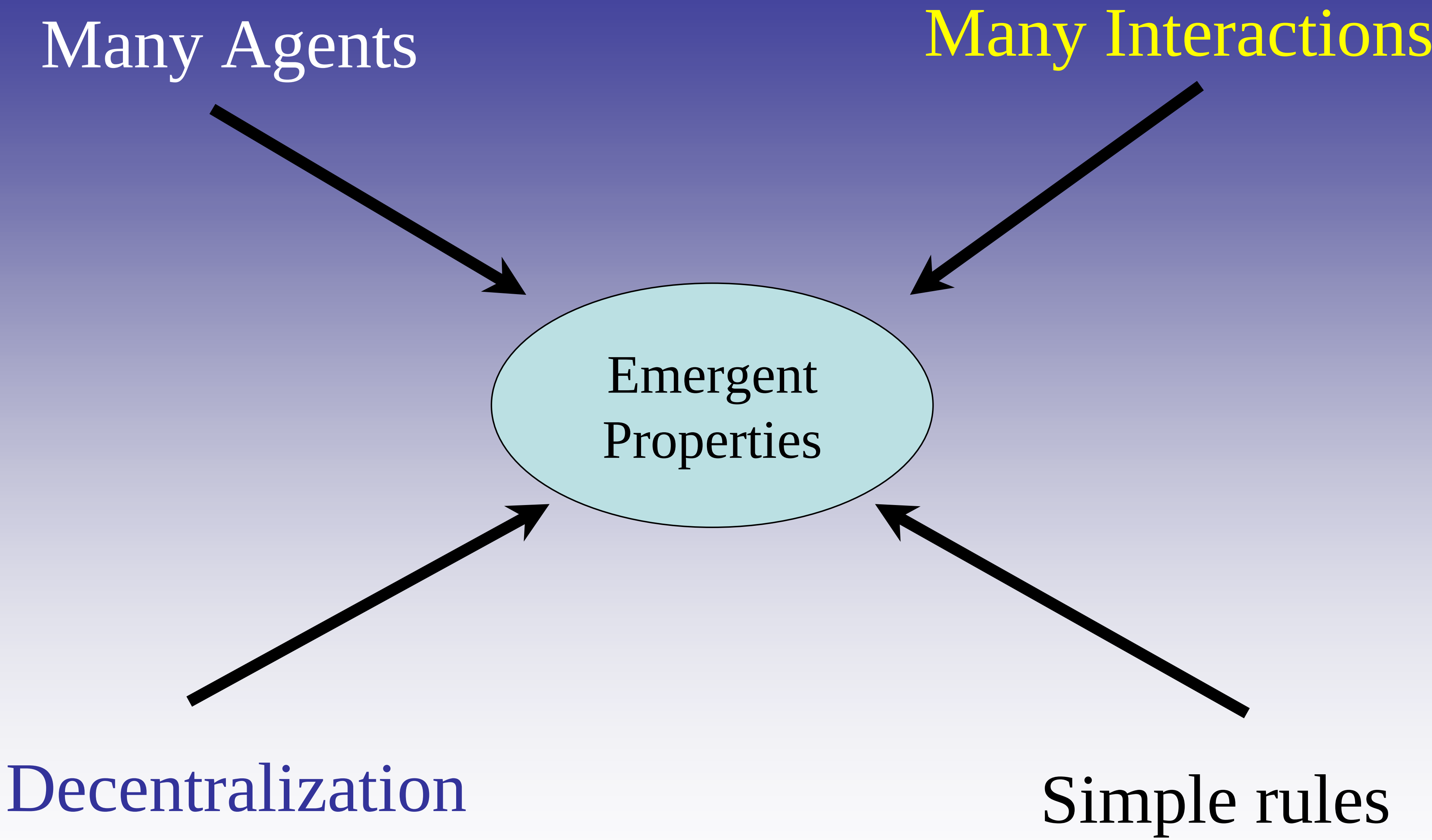
In the case of the termite mound, I suggest the following type of scenario:

Starting with a homogeneous, flat landscape, the random movements of the termites, and their dropping and picking up behavior leads to tiny surface irregularities which become the site of rising pillars. Once a pillar has emerged, this structure acts as a source of heterogeneity that modifies the actions of individual builders. The activity, in turn, create new stimuli that trigger new building actions. Complexity unfolds progressively; increasingly diverse stimuli result from previous building activities, and facilitate the construction of ever more complex structures.

This <u>PLUS</u> a lot of handwaving might give you a termite mound!

As in other activation-inhibition systems, the behavioral rules governing the construction of social insect architectures are based upon local cues rather than a global overview.




Many Agents
Many Interactions
Emergent
Properties
Decentralization
Simple rules

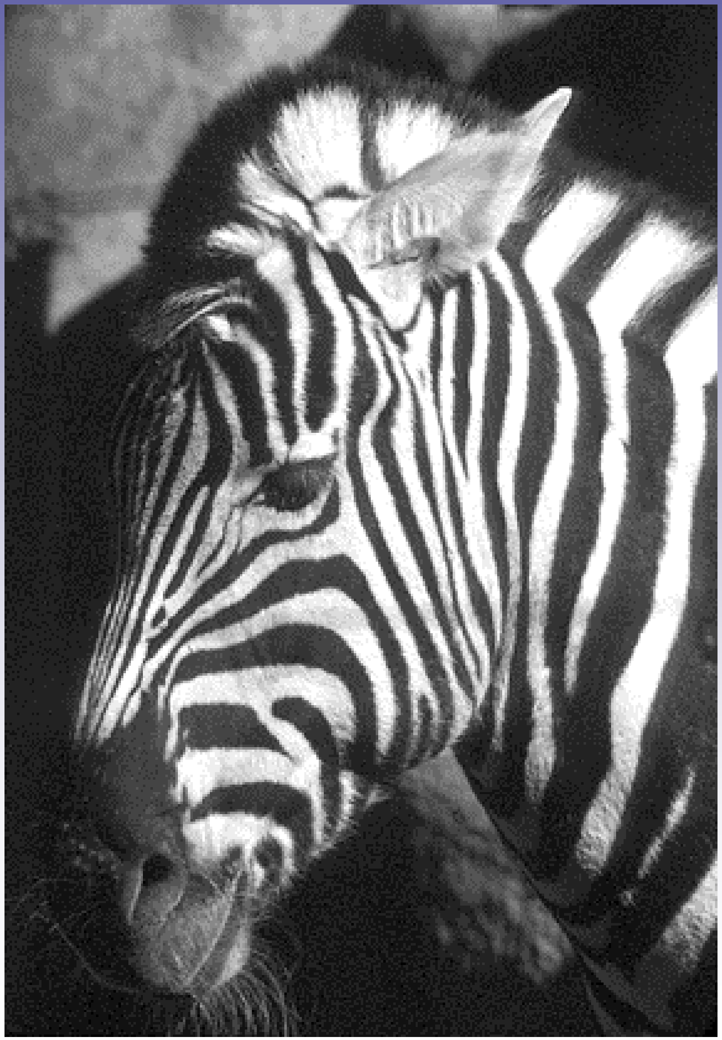
Distinguishing Features of Complex, Self-Organizing Systems

- Large numbers of units (agents)
- Large numbers of interactions
- Simple rules of interaction
- Decentralized organization
- Emergent properties

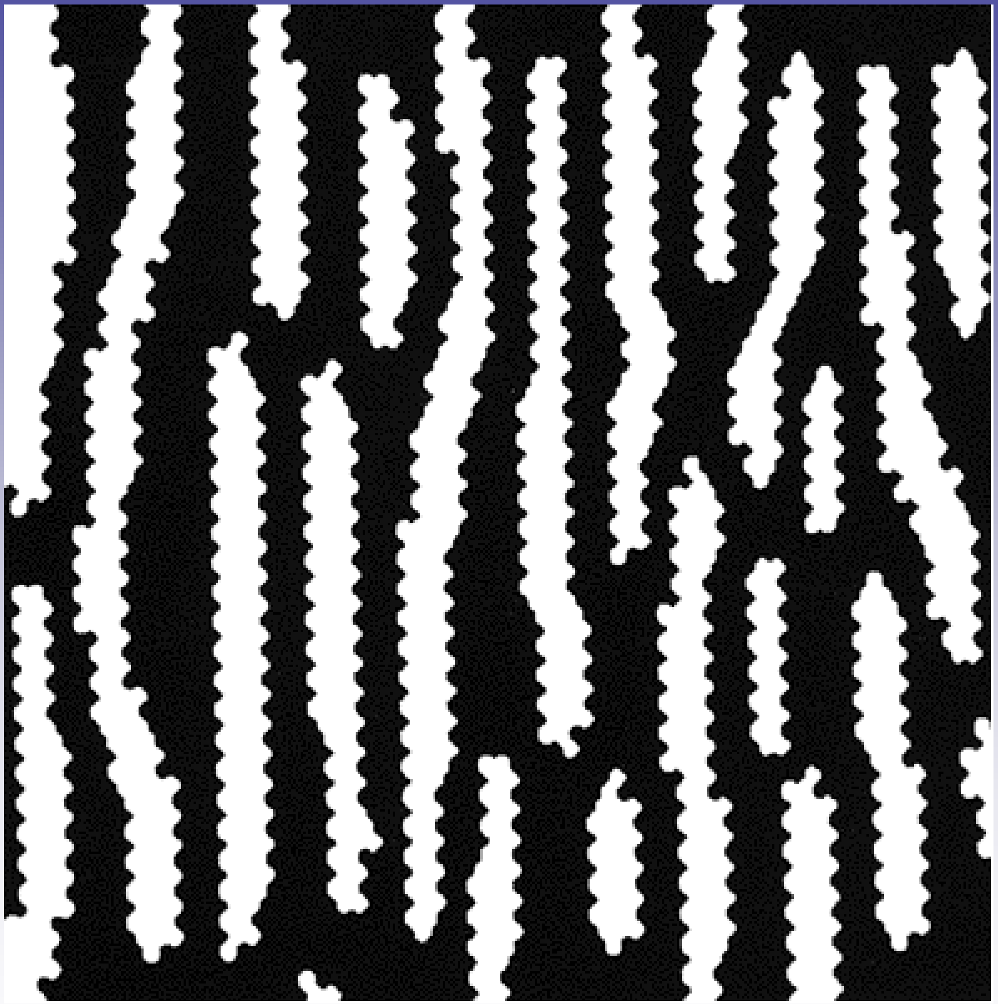
The modeling is relatively easy.

Unraveling the biological mechanisms is extremely difficult

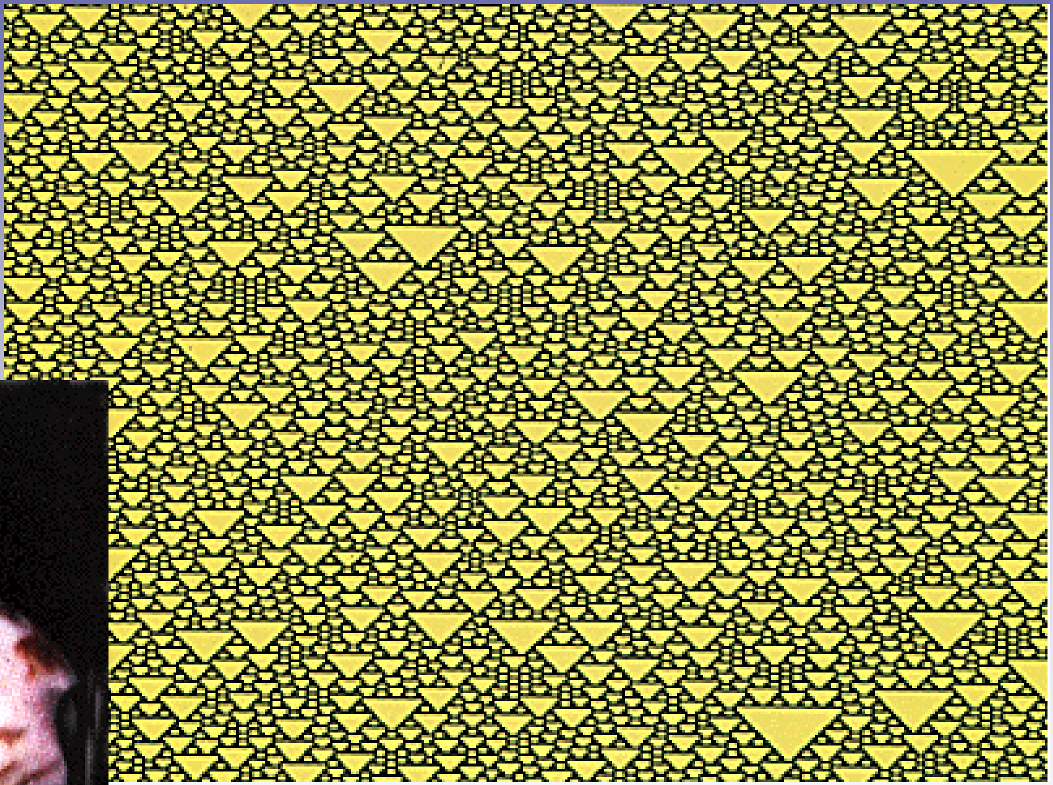
Cellular automaton simulation



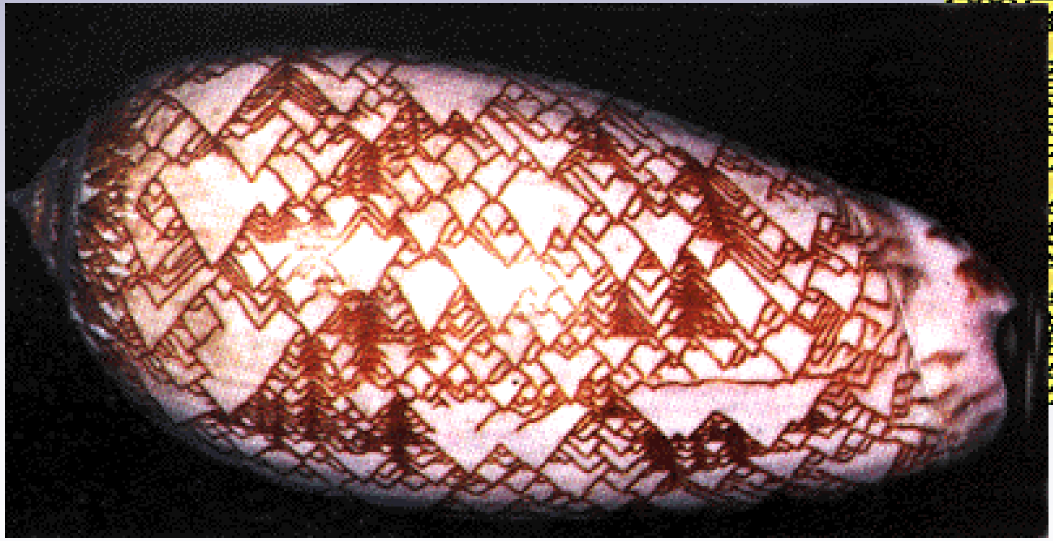
Zebra



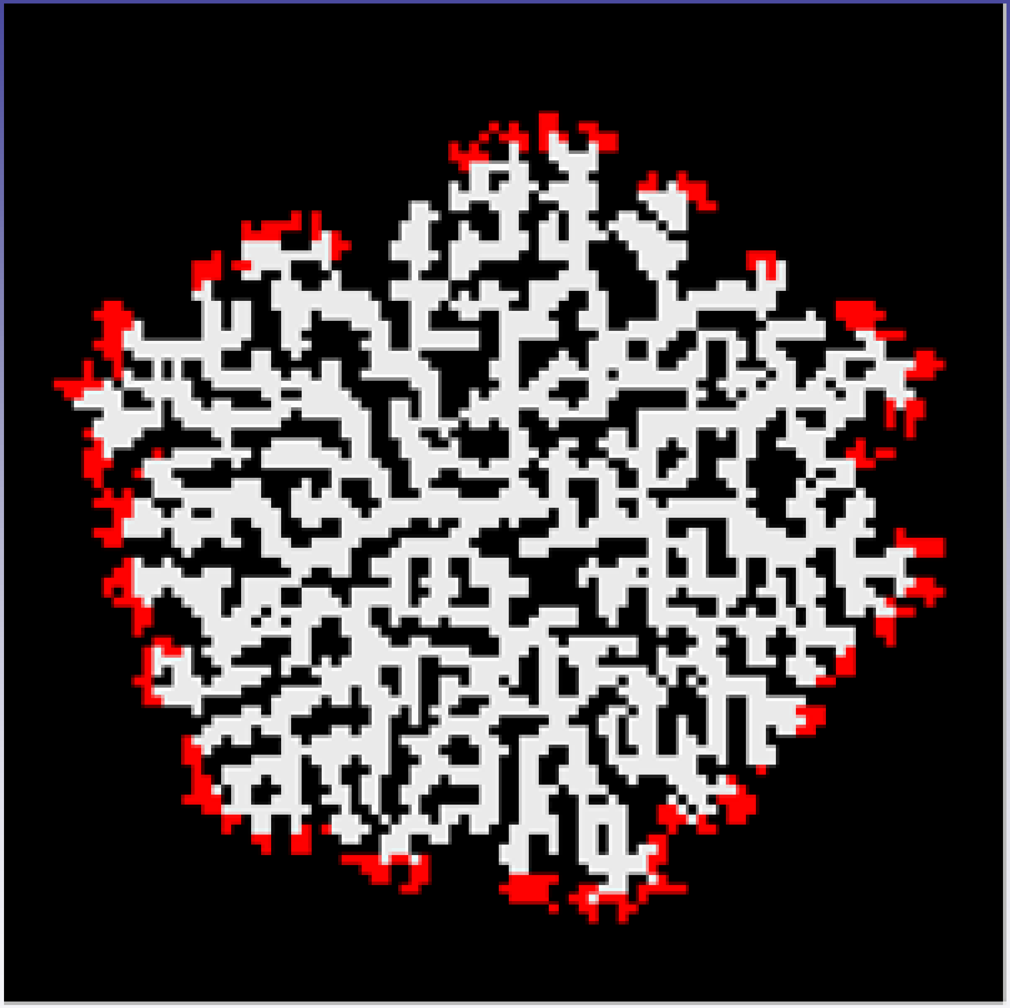
Cellular automaton simulation



Cone shell



Lichen on rock



Cellular automata model of contagion and growth

Adaptive advantages of self-organized systems

Robustness

Error tolerance

Self-repair

Ease of implementation

Simple agents.

Why is all of this important?

Many biological systems have evolved decentralized solutions to their vital challenges.

Through self-organization, evolution has stumbled upon a wide range of extremely efficient, relatively simple solutions for solving very complex problems.

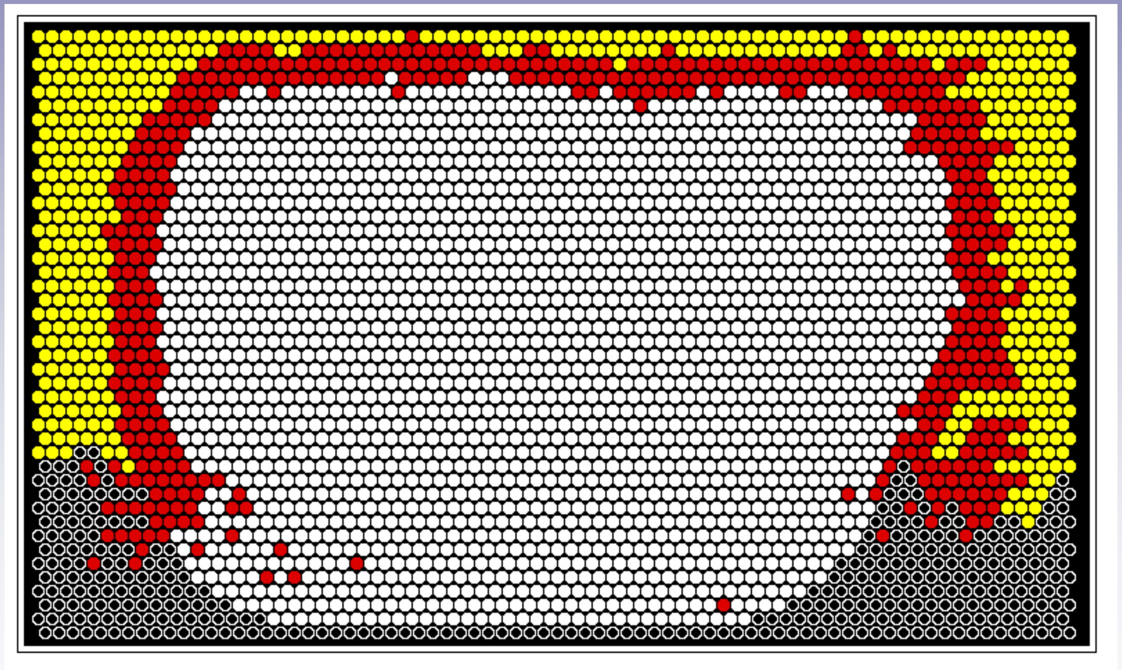
Why has evolution “chosen” these types of solutions?

Biological Constraints

One of the mysteries of biology is how the enormous amount of morphogenic, physiological and behavioral complexity of living organisms can be achieved with the limited amount of genetic information available within the genome.

Self-organization is one solution to this problem

Comb Pattern in Honey Bees
How do the bees do it?



Comb with typical concentric pattern

How do the bees create the pattern?
Behaviorally-Encoded Scenario

Bee Behavioral Rules

Put the honey on the outside

Put the pollen in the rim between the eggs and honey

Lay eggs in the center

Feed the brood

Some details to deal with:

Where is the outside? It changes over time

Where is the rim? It also changes over time

When there is no pollen, should the bees maintain an empty rim?

How do the bees create the pattern?
Self-Organized Scenario

<u>Bee Behavioral Rules</u>

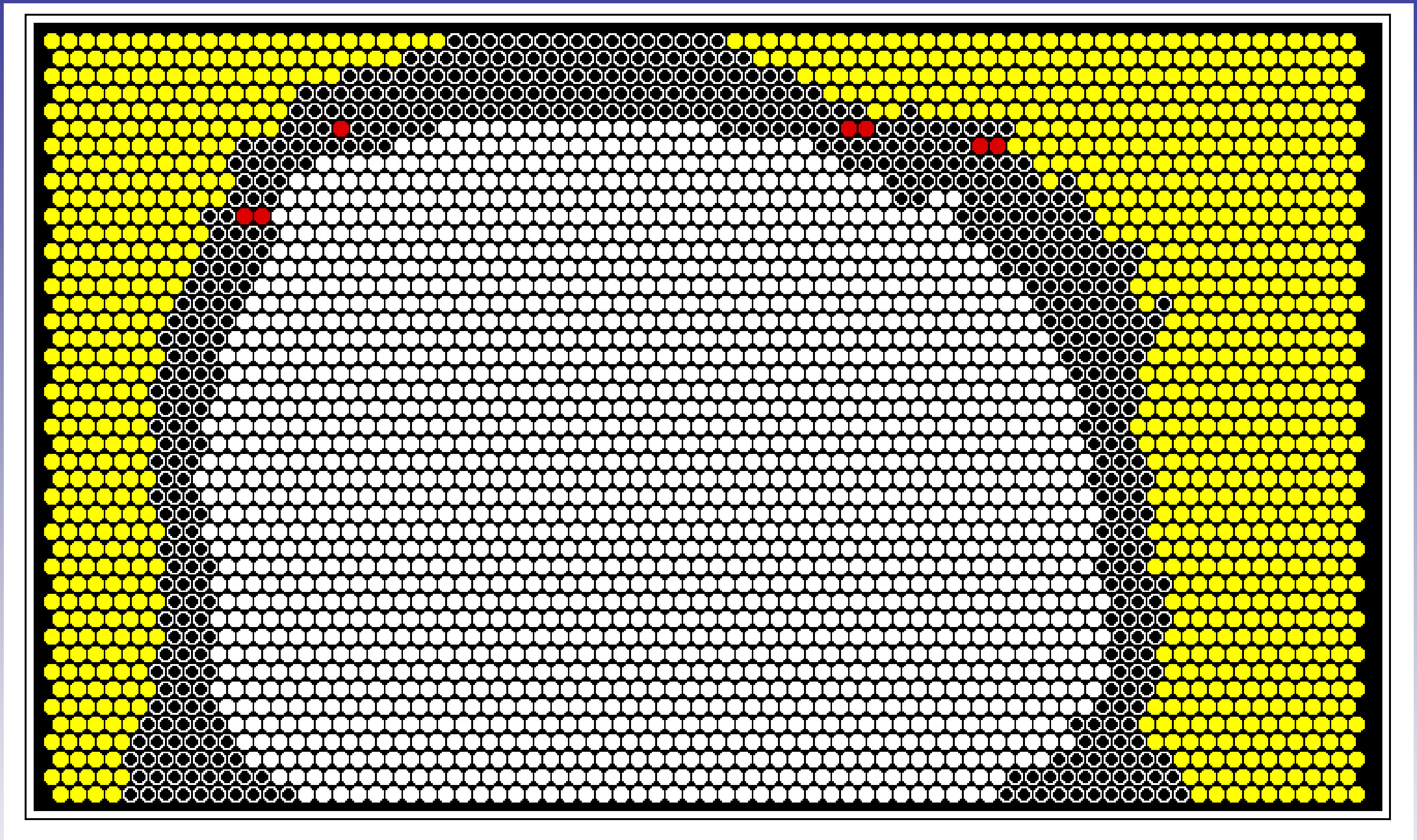
- Put the honey anywhere
- Put the pollen anywhere
- Start somewhere and lay eggs near one another
- Collect lots of honey
- When there is pollen, collect lots of pollen
- Be sure to feed the brood

<u>Environmental Constraints</u>

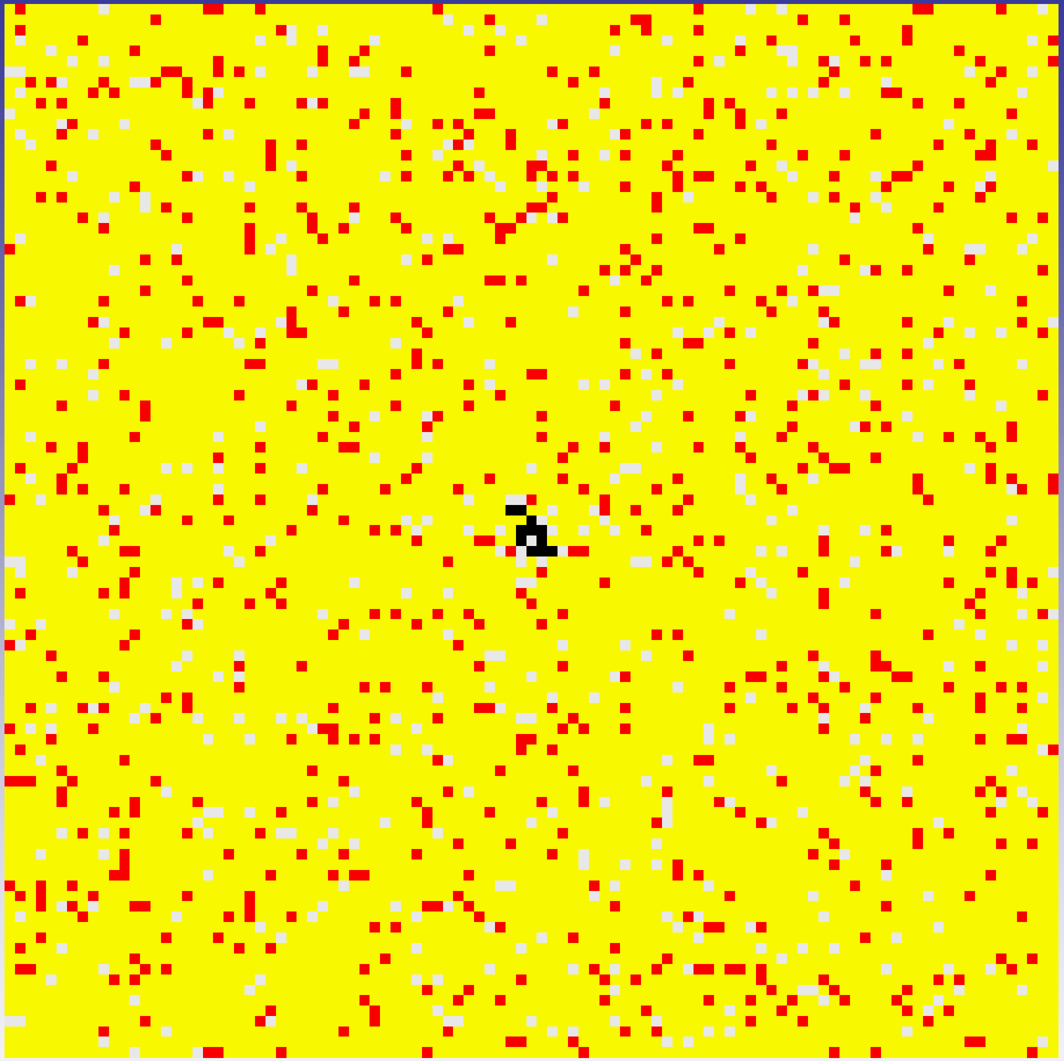
- Pollen and honey availability varies thru season

<u>"Automatic"</u>

- Take honey and pollen from wherever it can be found on the comb



Typical concentric pattern in times of pollen dearth



Field observations and simulations help distinguish between hypotheses

References for further reading and exploration

Turtles, Termites and Traffic Jams: Explorations in Massively Parallel Microworlds. Mitchel Resnick 1994.

Complexity: The Emerging Science at the Edge of Order and Chaos. M. Mitchell Waldrop 1992.

The Quark and the Jaguar: Adventures in the Simple and the Complex. Murray Gell-Mann 1994.

The Self-Made Tapestry: Pattern Formation in Nature. Philip Ball 1999.

At Home in the Universe: The Search for the Laws of Self-Organization and Complexity. Stuart Kauffman 1995.

The Origins of Order: Self-Organization and Selection in Evolution. Stuart Kauffman 1993.

Emergence: From Chaos to Order. John H. Holland 1998.

Hidden Order: How Adaptation Builds Complexity. John H. Holland 1995.

Boids. Craig Reynolds. http://www.red3d.com/cwr/boids/

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