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EMERGING TECHNOLOGY CONFERENCE
APRIL 22-25, 2003 • SANTA CLARA, CA

Swarm Intelligence

Eric Bonabeau

icosystem

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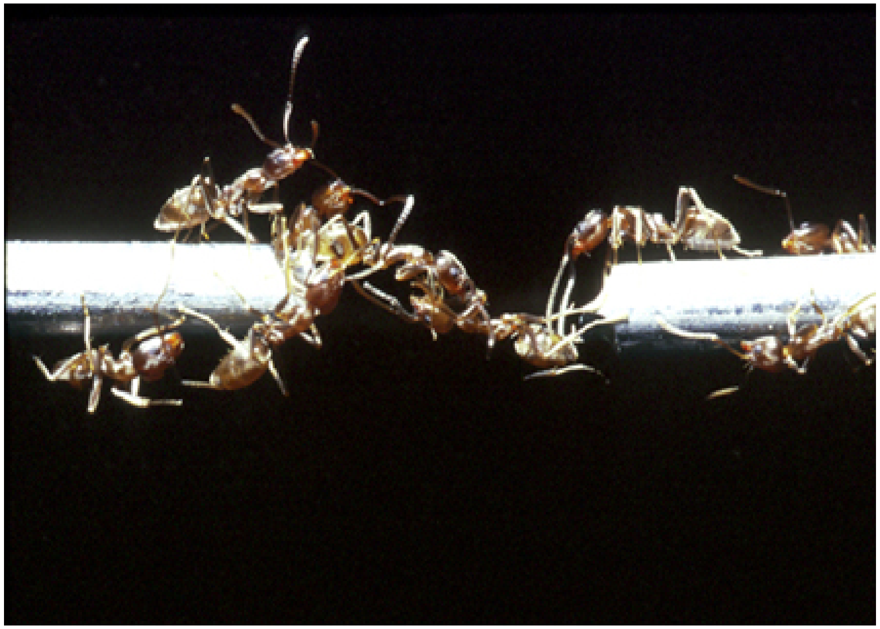
Dumb parts, properly connected into a swarm, yield smart results.

Kevin Kelly

Great, but how do you properly connect the parts??

Social insects do it



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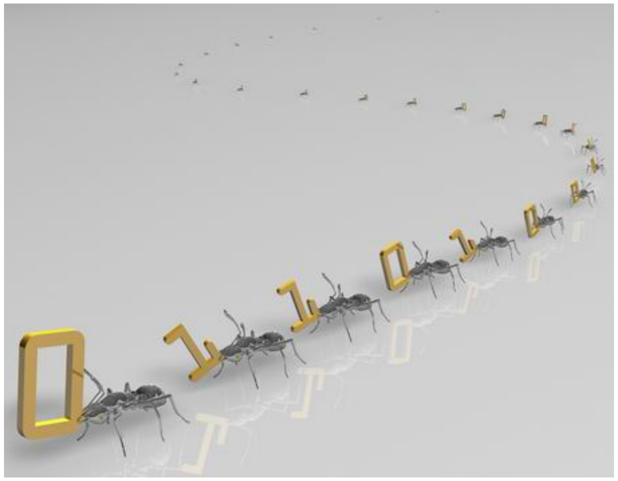
From social insects to… artificial insects!



A social insect colony is...

- ***Flexible***: the colony can respond to internal perturbations and external challenges
- ***Robust***: tasks are completed even if some individuals fail
- ***Decentralized***: there is no central control(ler) in the colony
- ***Self-organized***: paths to solutions are emergent rather than predefined

Swarm Intelligence

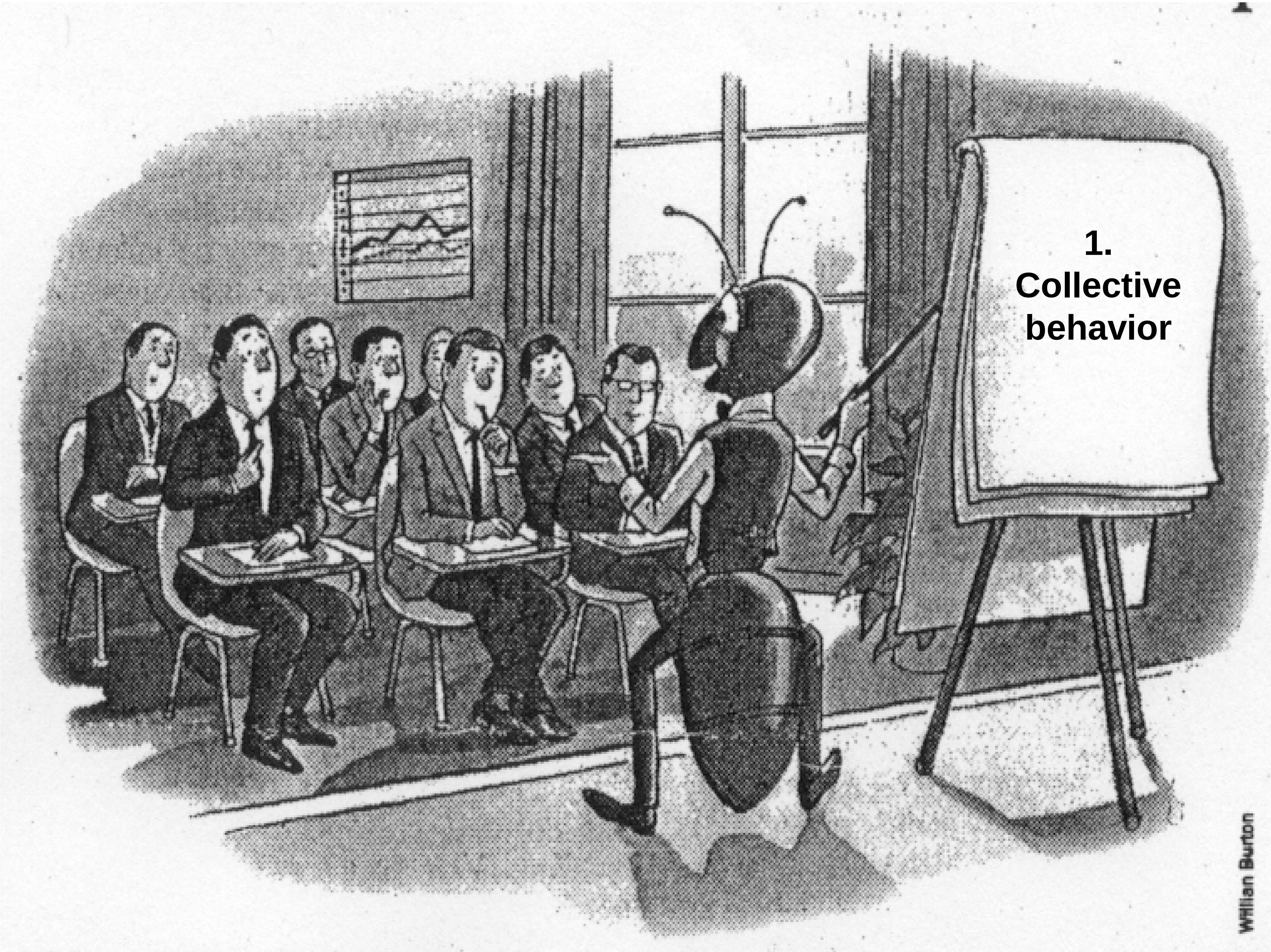
- is a mindset rather than a technology.
- It is a bottom-up approach to controlling and optimizing distributed systems,
- using resilient, decentralized, self-organized techniques,
- initially inspired by how social insects operate –shaped by millions of years of evolution (but does it matter in the end?).

Social insects

How do we shape emergence?

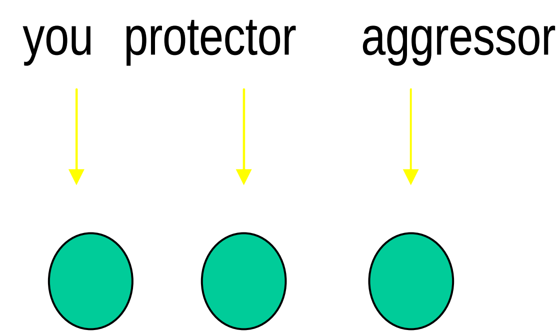
How do we define individual behavior and interactions to produce desired emergent patterns?

How do we fight swarms – organizations that operate on swarm principles?

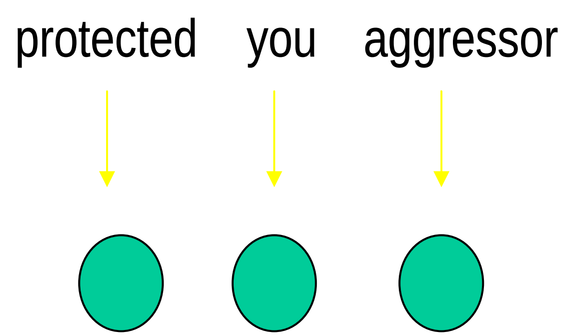

1.
Collective
behavior

Swarm lesson #1: complexity from simple rules

- Network 1: pick a protector and an aggressor, then move so that your protector is always located between you and your aggressor.



- Network 2: pick a protected and an aggressor, then move so as to be always located between your protected and his/her aggressor.



Bad news, good news

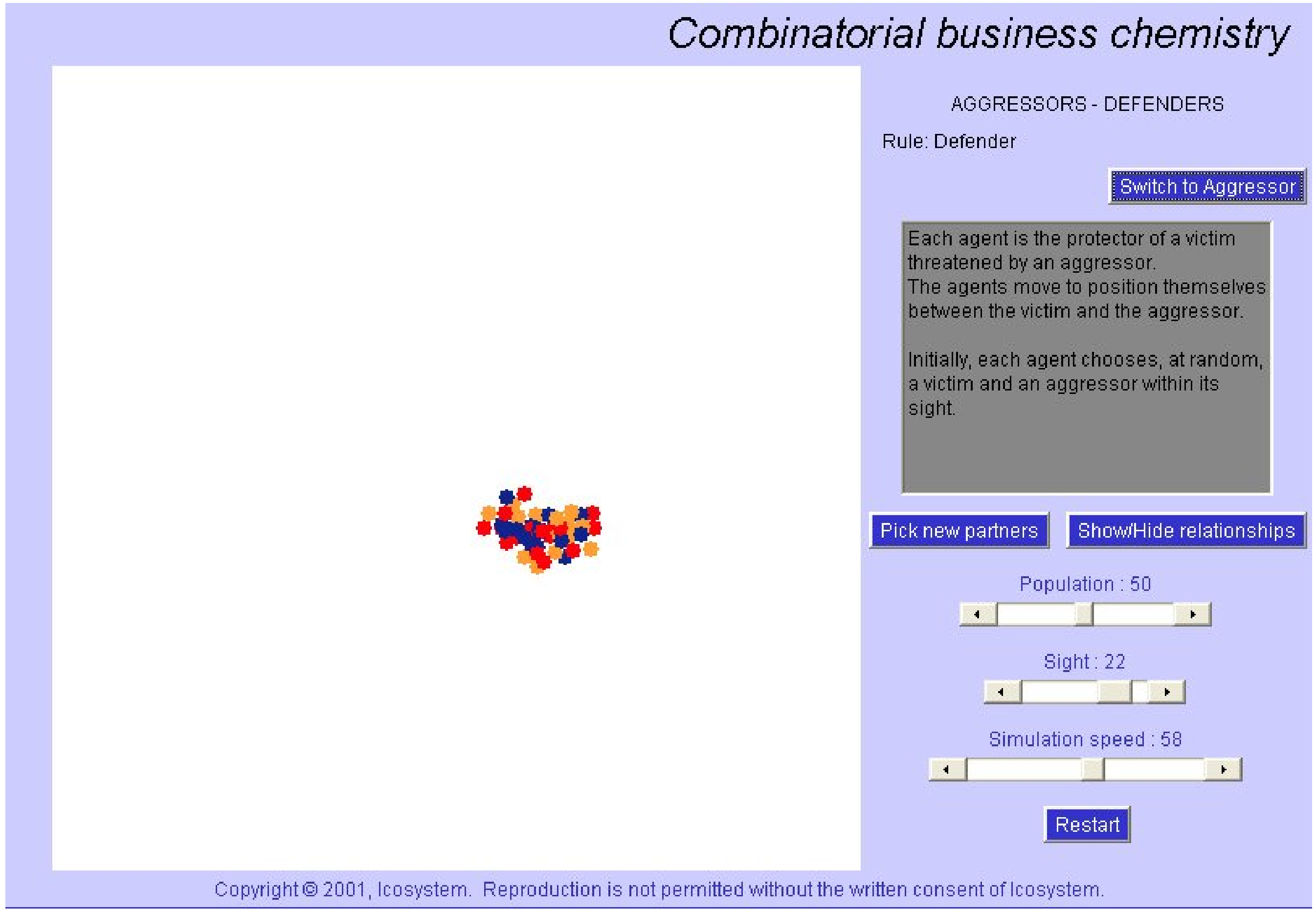
Bad news

- Difficult to predict collective behavior from individual rules.
- Interrogate one of the participants, it won't tell you anything about the function of the group.
- Small changes in rules lead to different group-level behavior.
- Individual behavior looks like noise: how do you detect threats?

Good news

- Possible to efficiently control organization or manipulate groups using simple rules.
- Possible to predict group-level outcome using bottom simulation.

The Icosystem Game



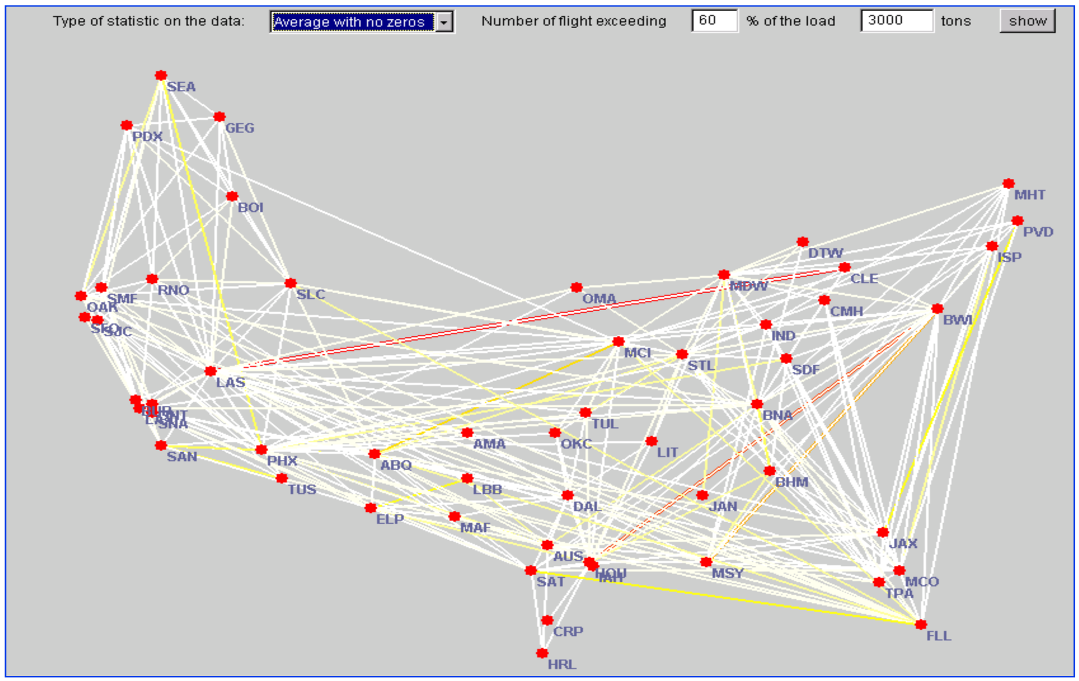
Simple rules and bottom up modeling at Southwest Airlines

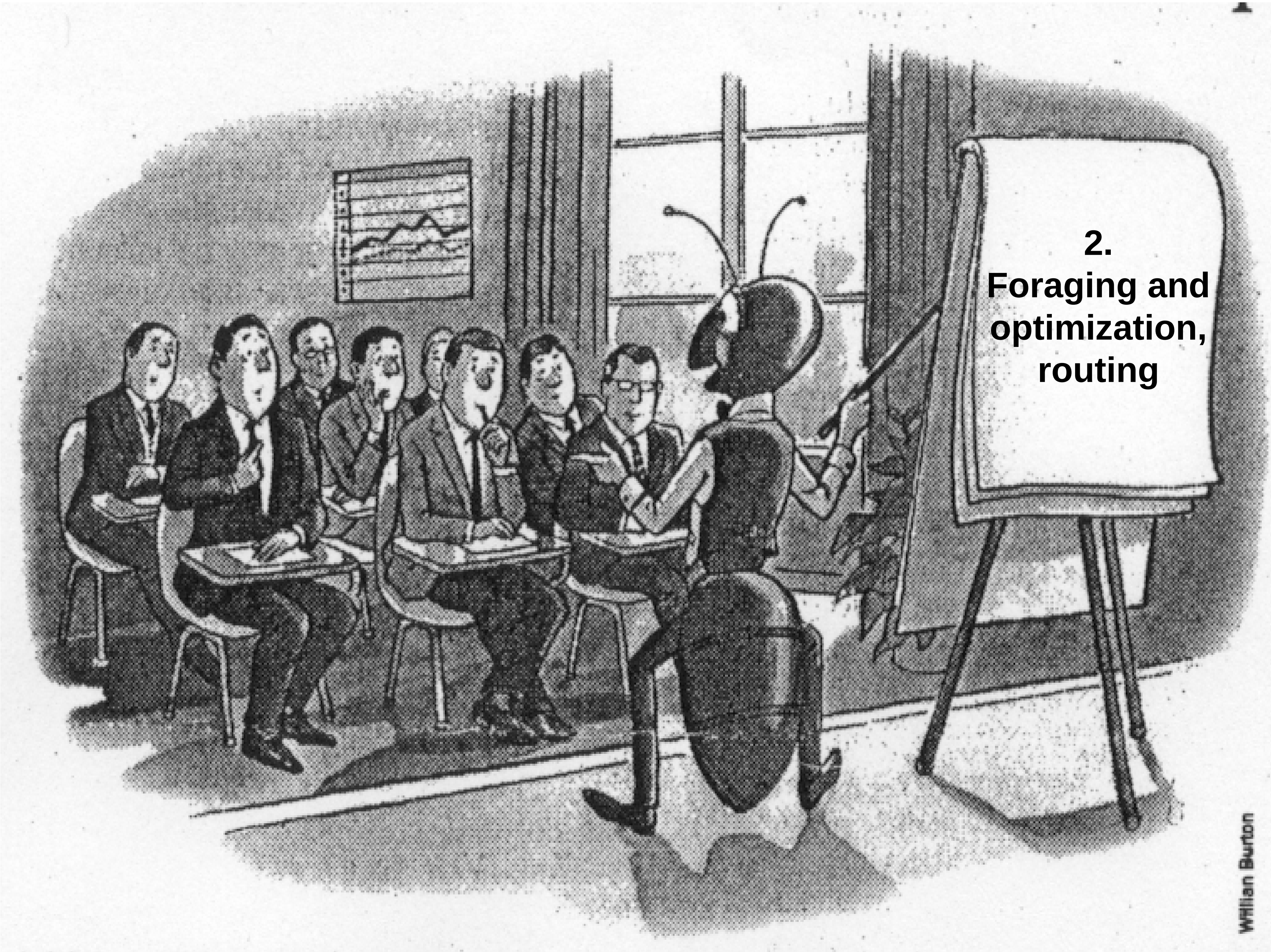
Problem

- Optimize cargo routing
- Use simple rules

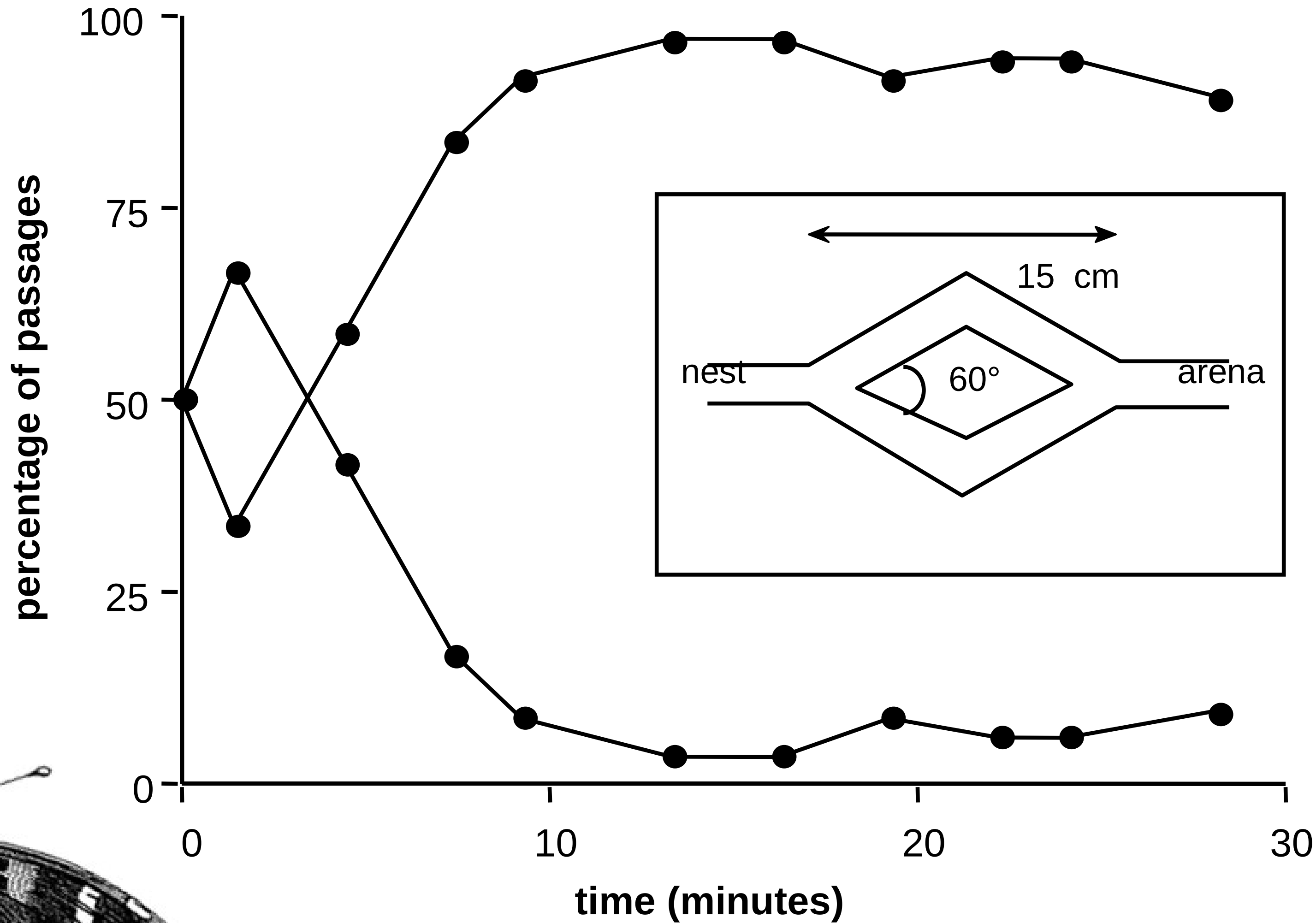
Results

- 71% improvement
- At least $10m/yr




2.
Foraging and optimization, routing
Willian Burton

Double-bridge experiment



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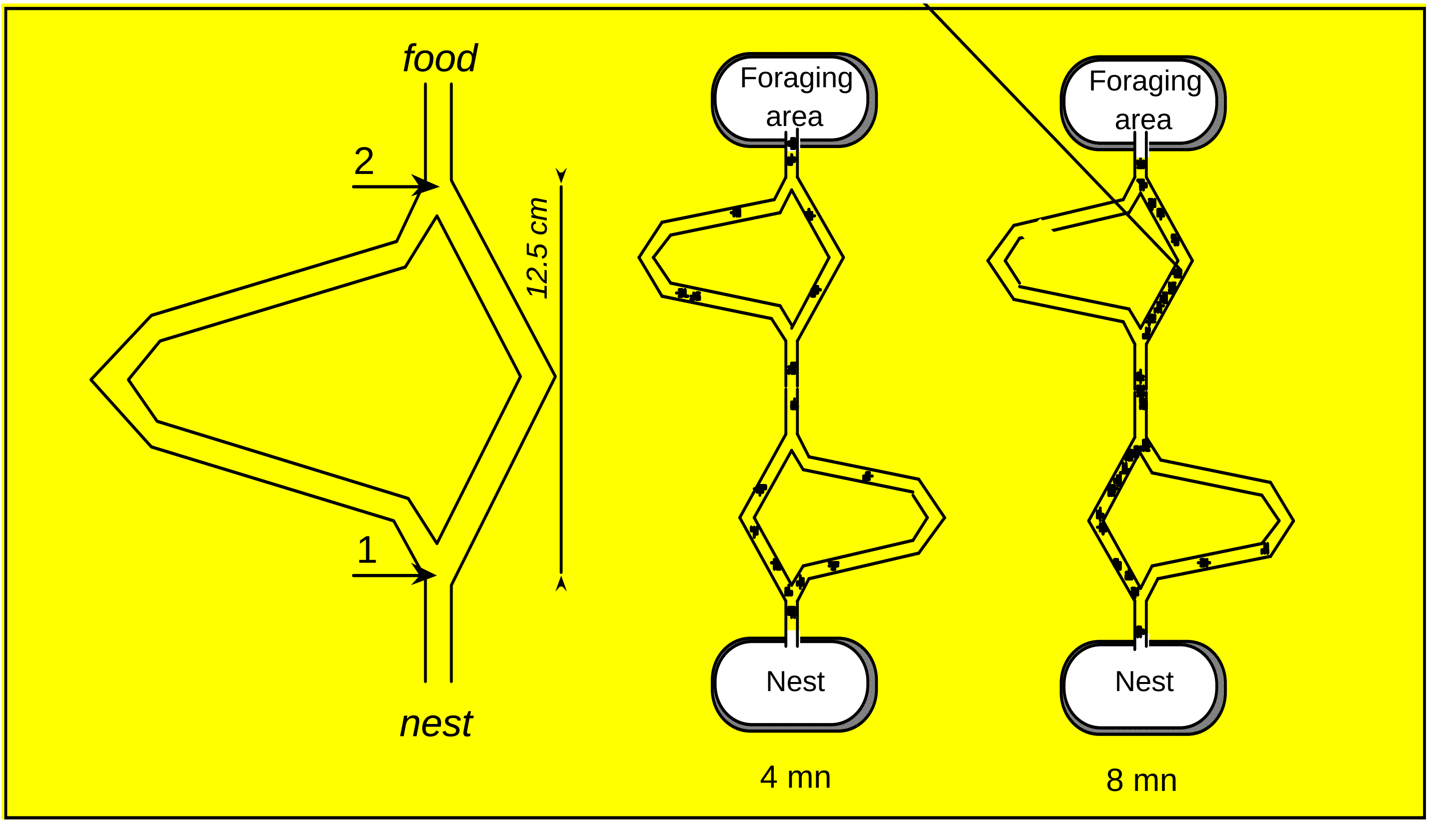
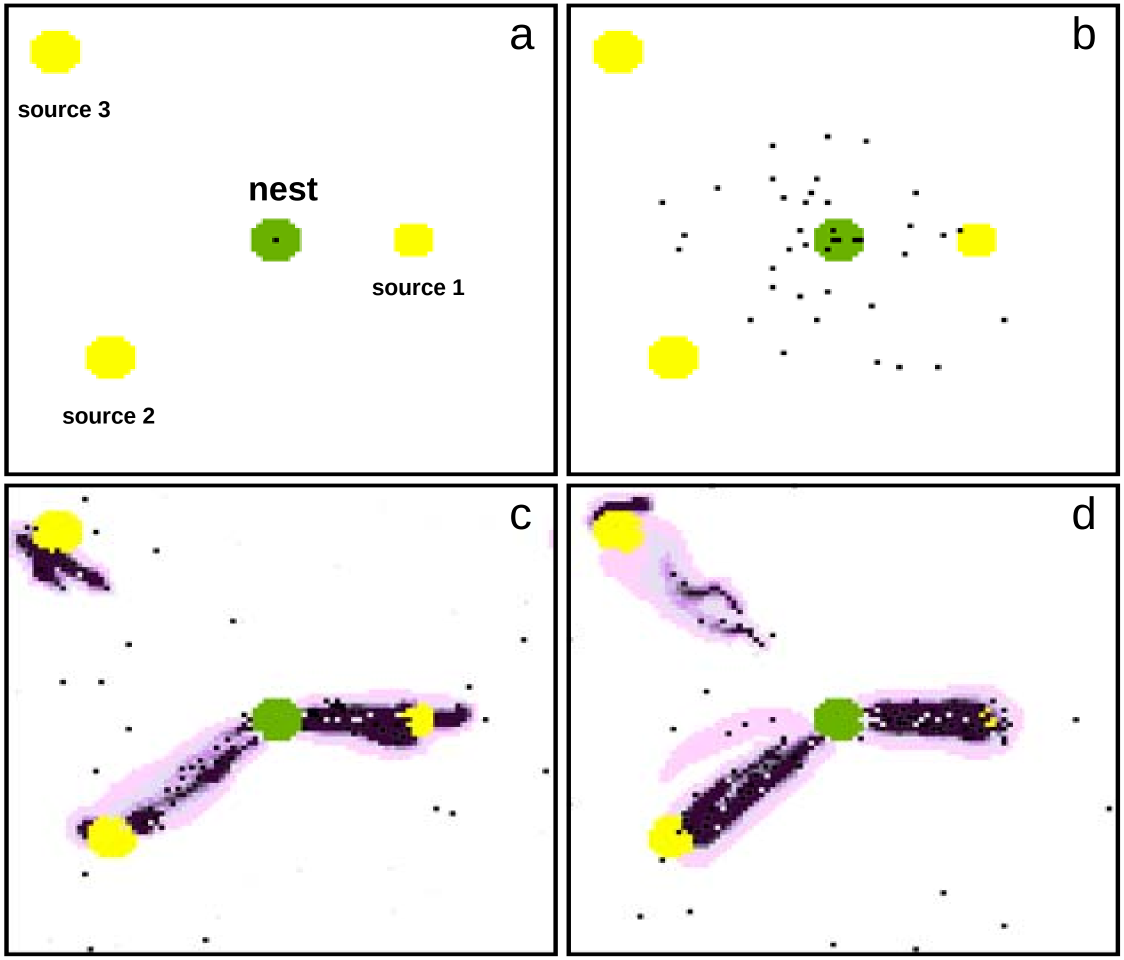
Simple (but not robust) optimization



Ants collectively select the shortest path to the food source.

Robustness via evaporation



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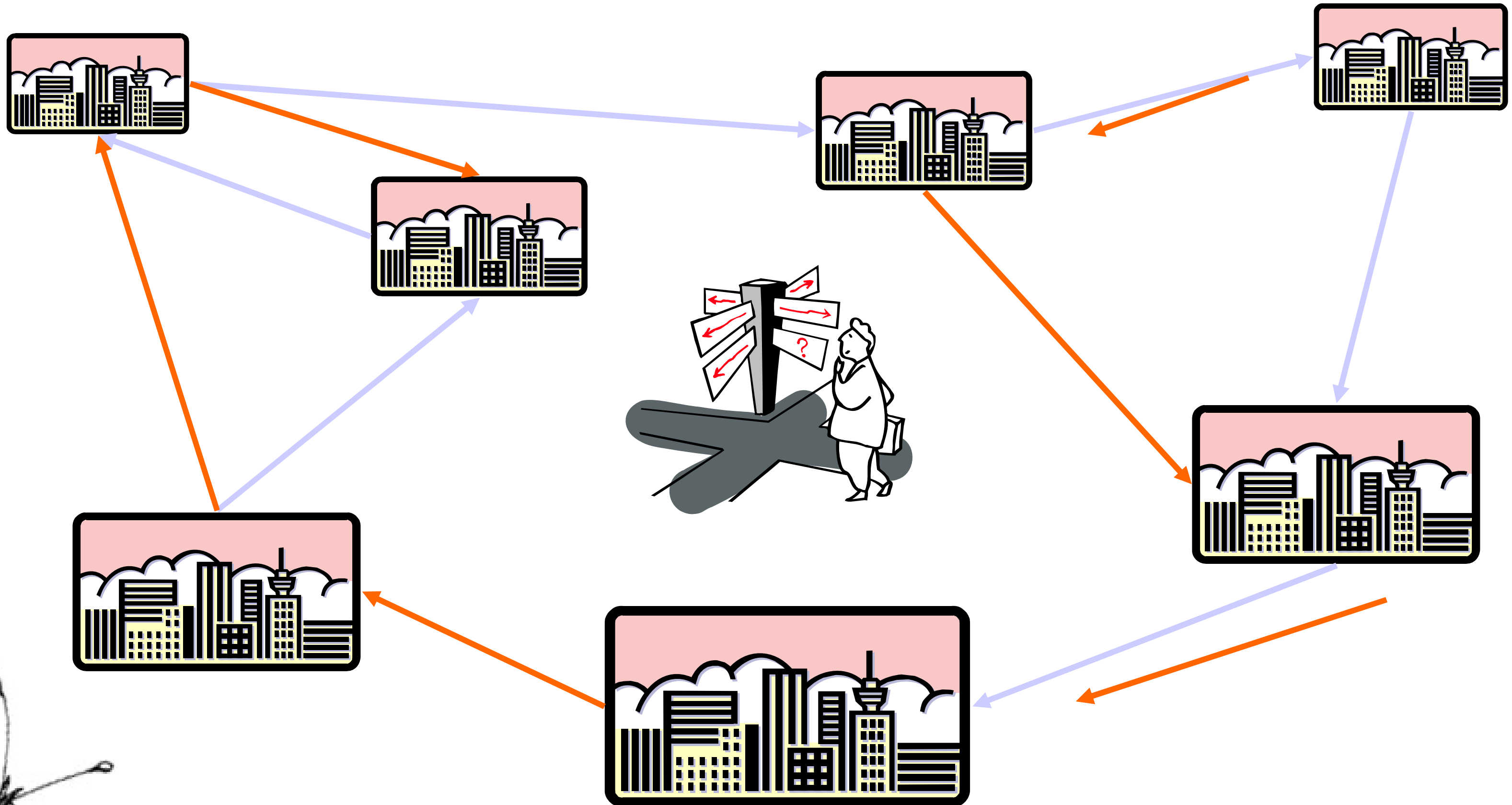
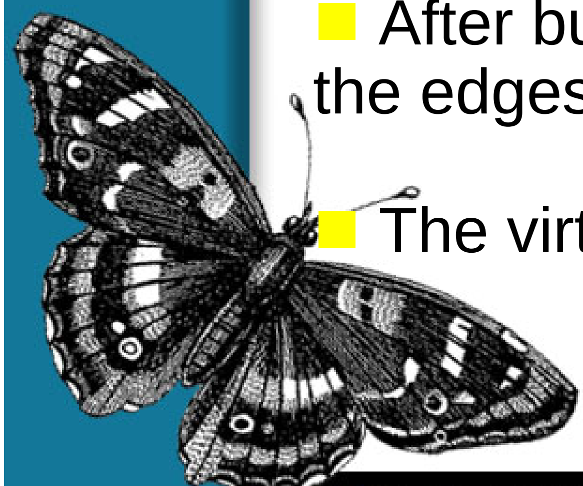
The Traveling Salesman (TSP)



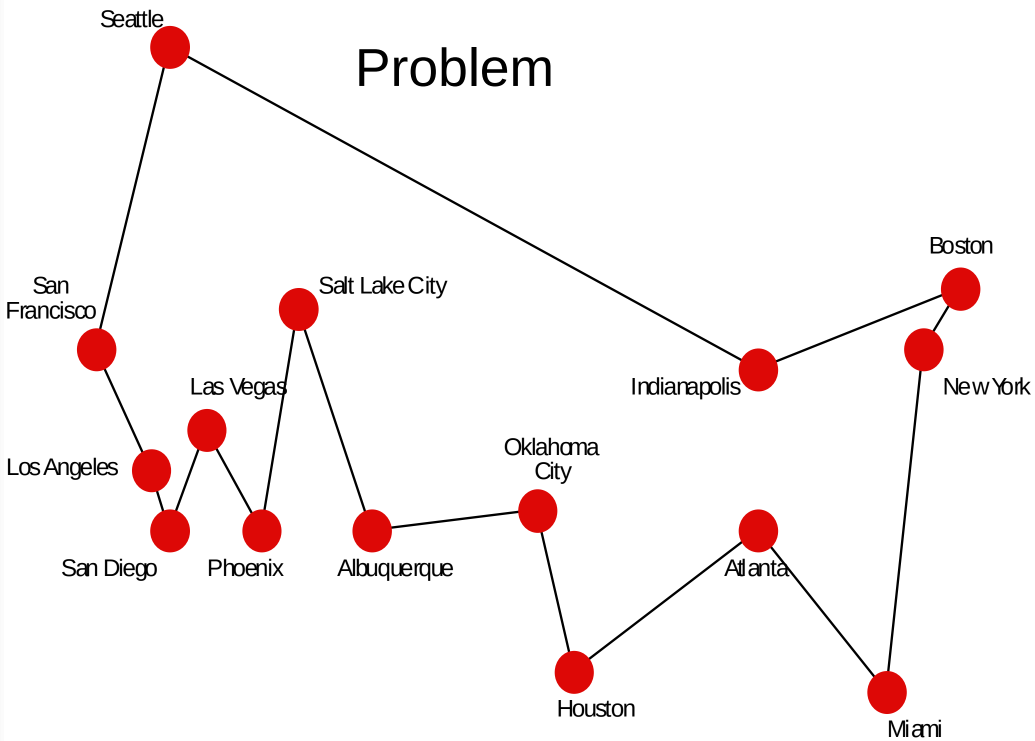
Traveling sales-ants

- d_{ij}= distance between i and city j
- τ_{ij}= virtual pheromone on link (i,j)
- m agents, each building a tour
- At each step of a tour, the probability to go from city i to city j is proportional to $(\tau_{ij})^a(d_{ij})^{-b}$
- After building a tour of length L, each agent reinforces the edges is has used by an amount proportional to 1/L
- The virtual pheromone evaporates: $\tau \longrightarrow (1-\rho)\,\tau$

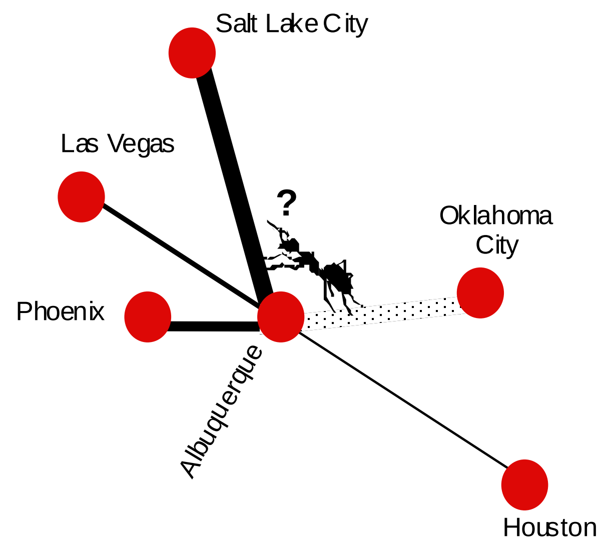


Concretely

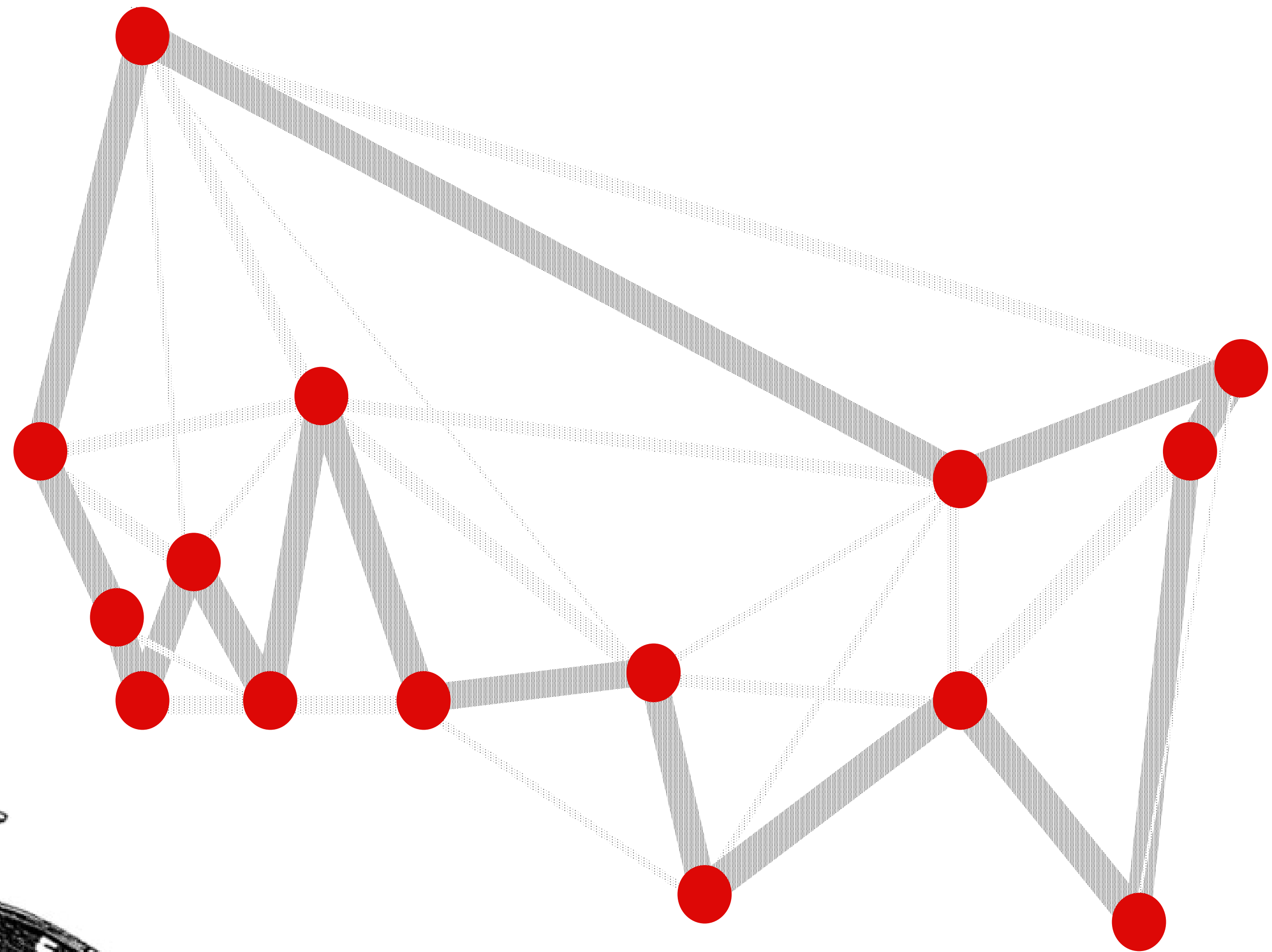
Problem



The ant algorithm



More than just one solution



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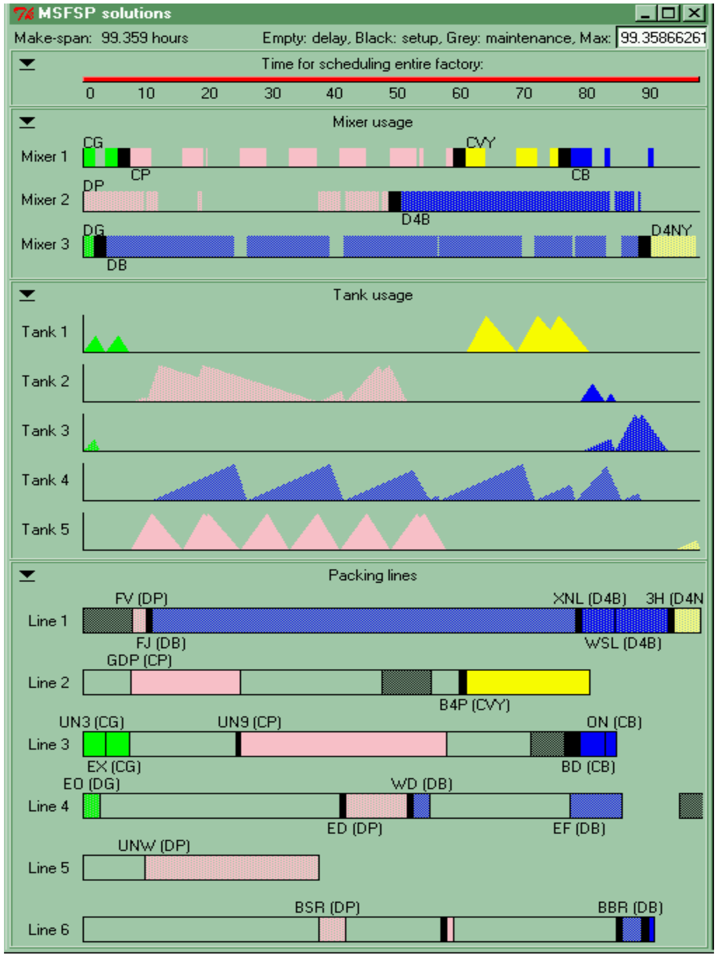
Dynamic factory scheduling

Problem

- Production scheduling
- Dynamic problem with tough constraints

Results

- Always finds a solution
- Better than best solution on market
- Order of magnitude faster!
- Copes with glitches and perturbations



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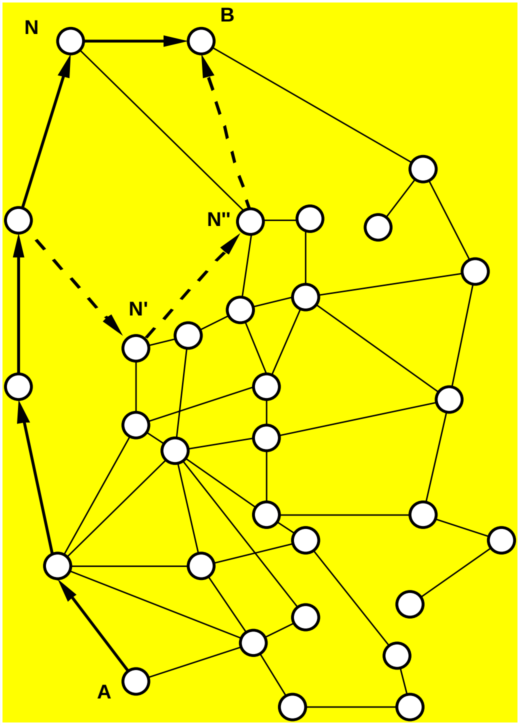
Routing in communications networks



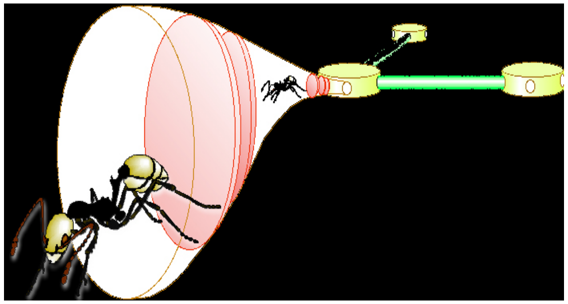
- Simple agents are launched in the network. Each agent goes from a source to a destination node.

- An agent updates routing tables on its way to its destination, *viewing its source as a destination*.

    "If you are going toward my source node, then hop to the node I am just coming from. Or don't."

- Agent influence decreases with age.

- Agents are artificially delayed at congested nodes.



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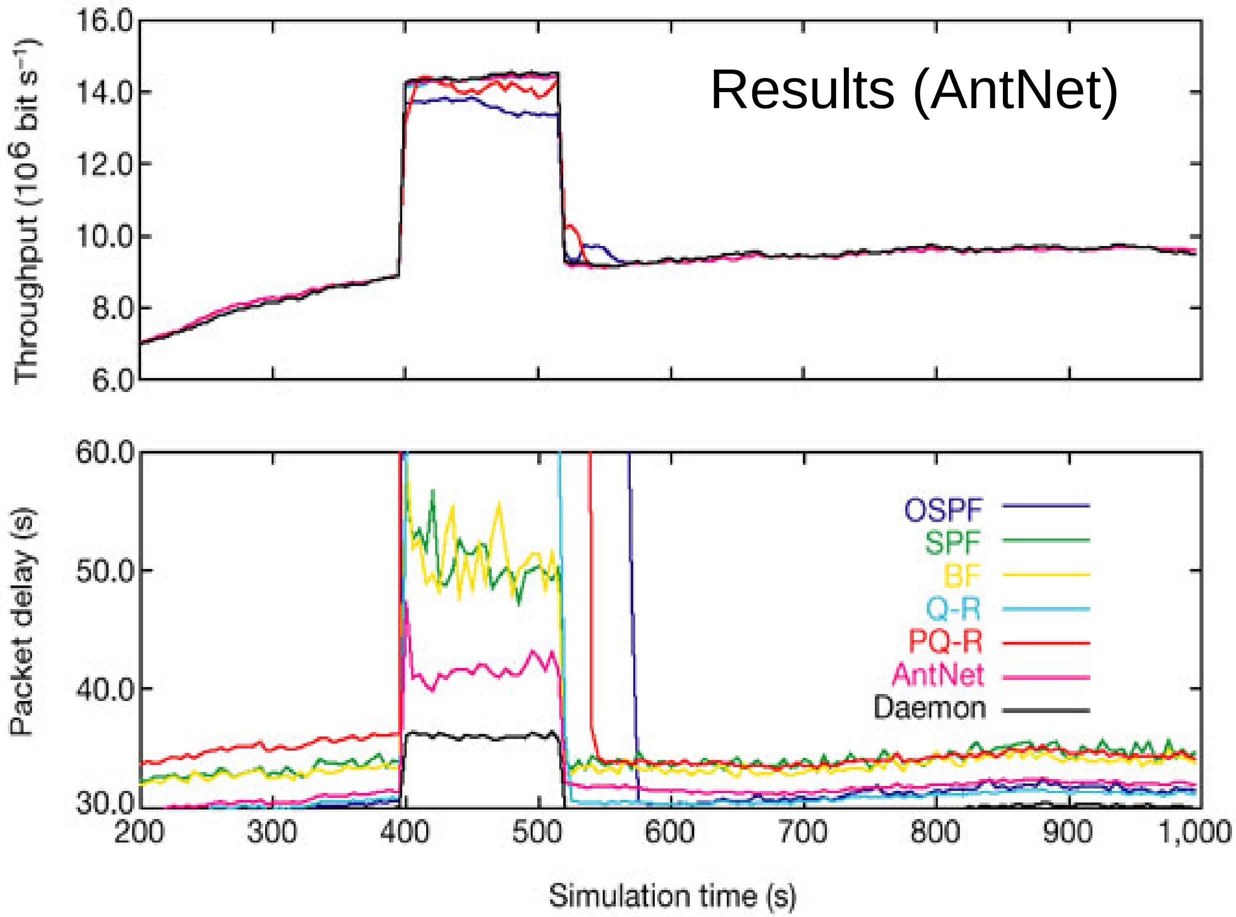
Routing in communications networks

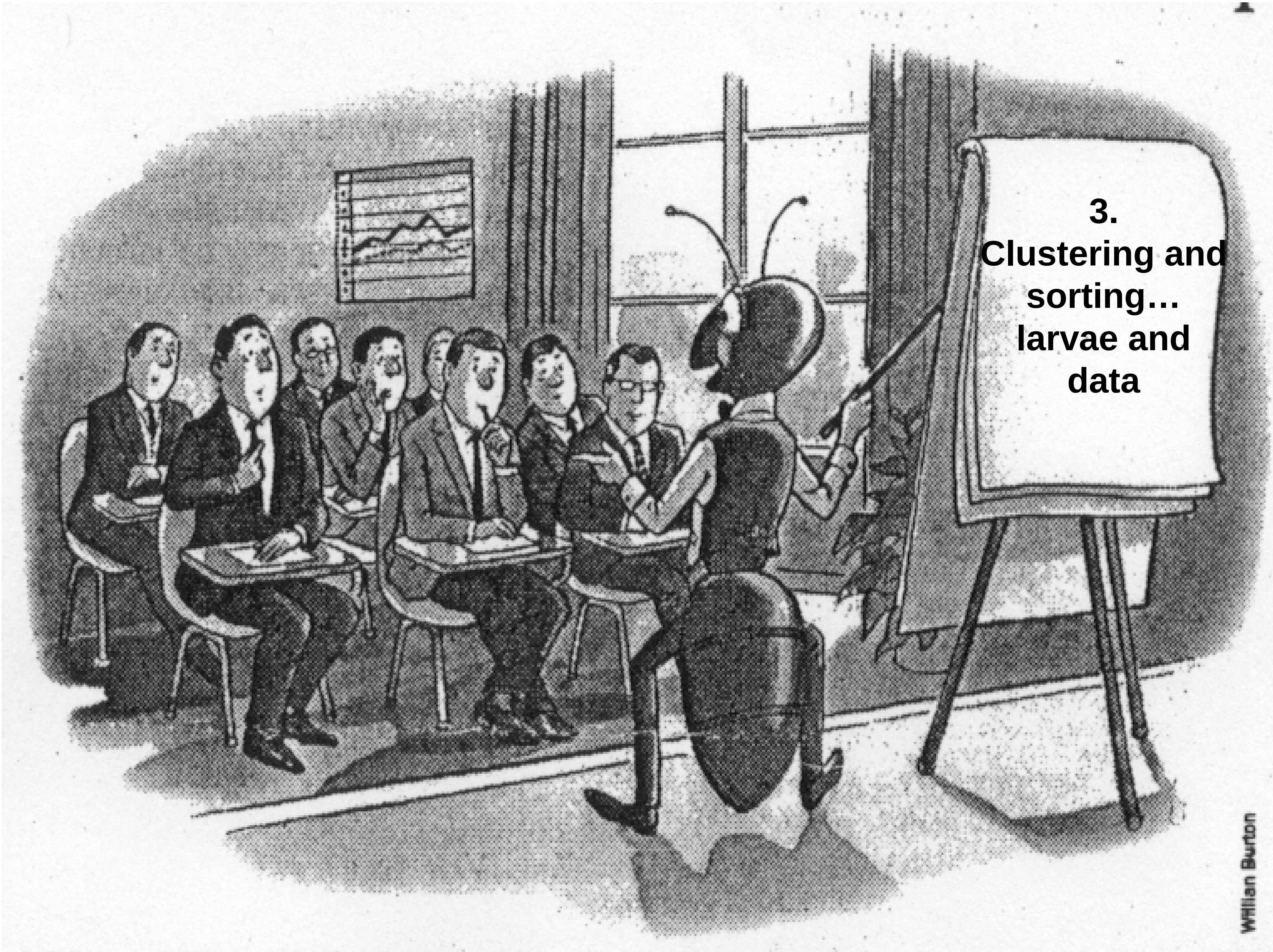


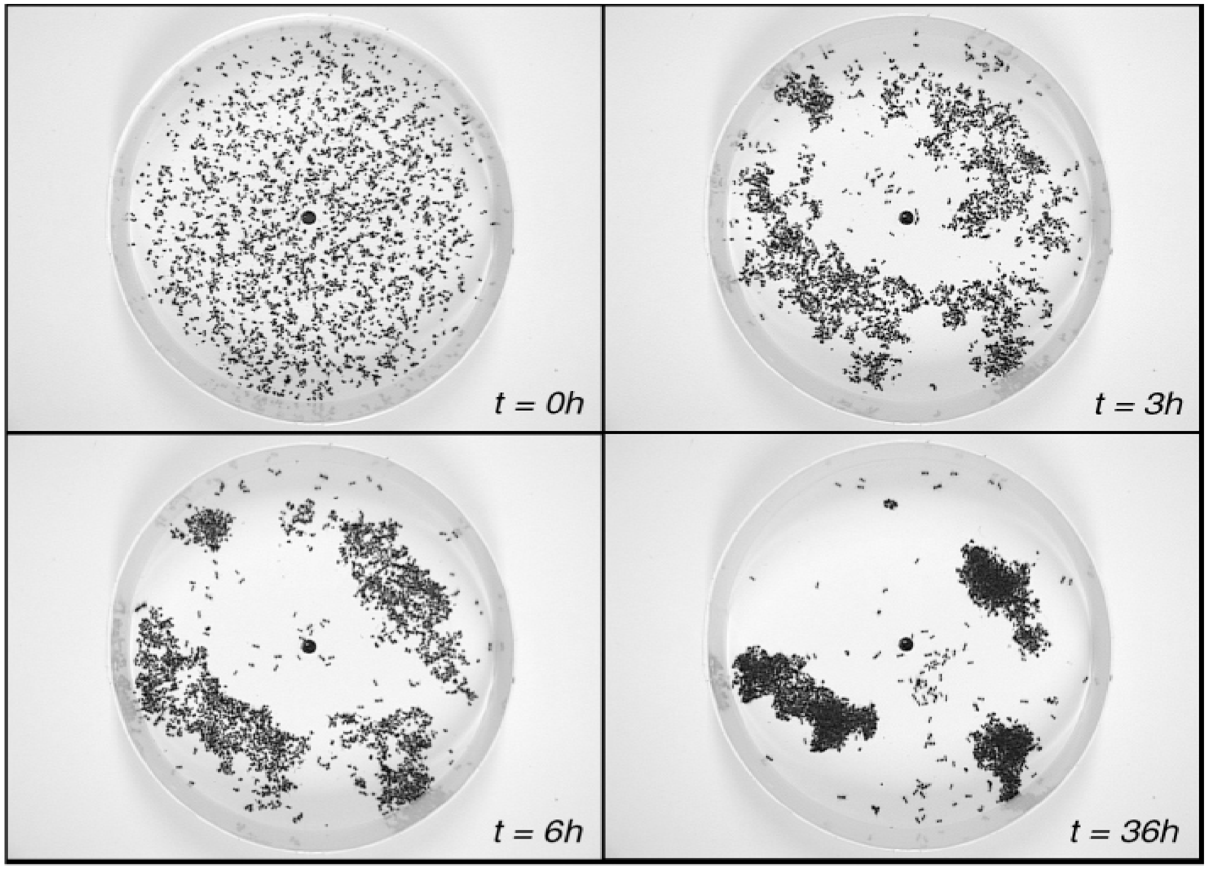
Hot spot superim-posed to Poisson traffic.

Moving average over 10s.

Existing successful commercial applications

- Unilever plant scheduling
- Pina Petroli truck routing
- Air Liquide supply chain optimization and control
- British Telecom, France Telecom, MCI routing in communications networks


3.
Clustering and sorting…
larvae and data

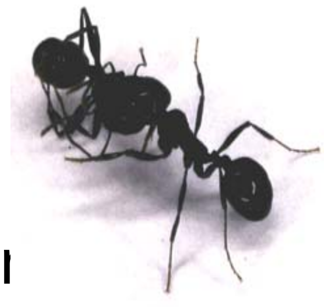

t = 0h
t = 3h
t = 6h
t = 36h

Clustering model

- An isolated item is more likely to be picked up by an unladen agent:

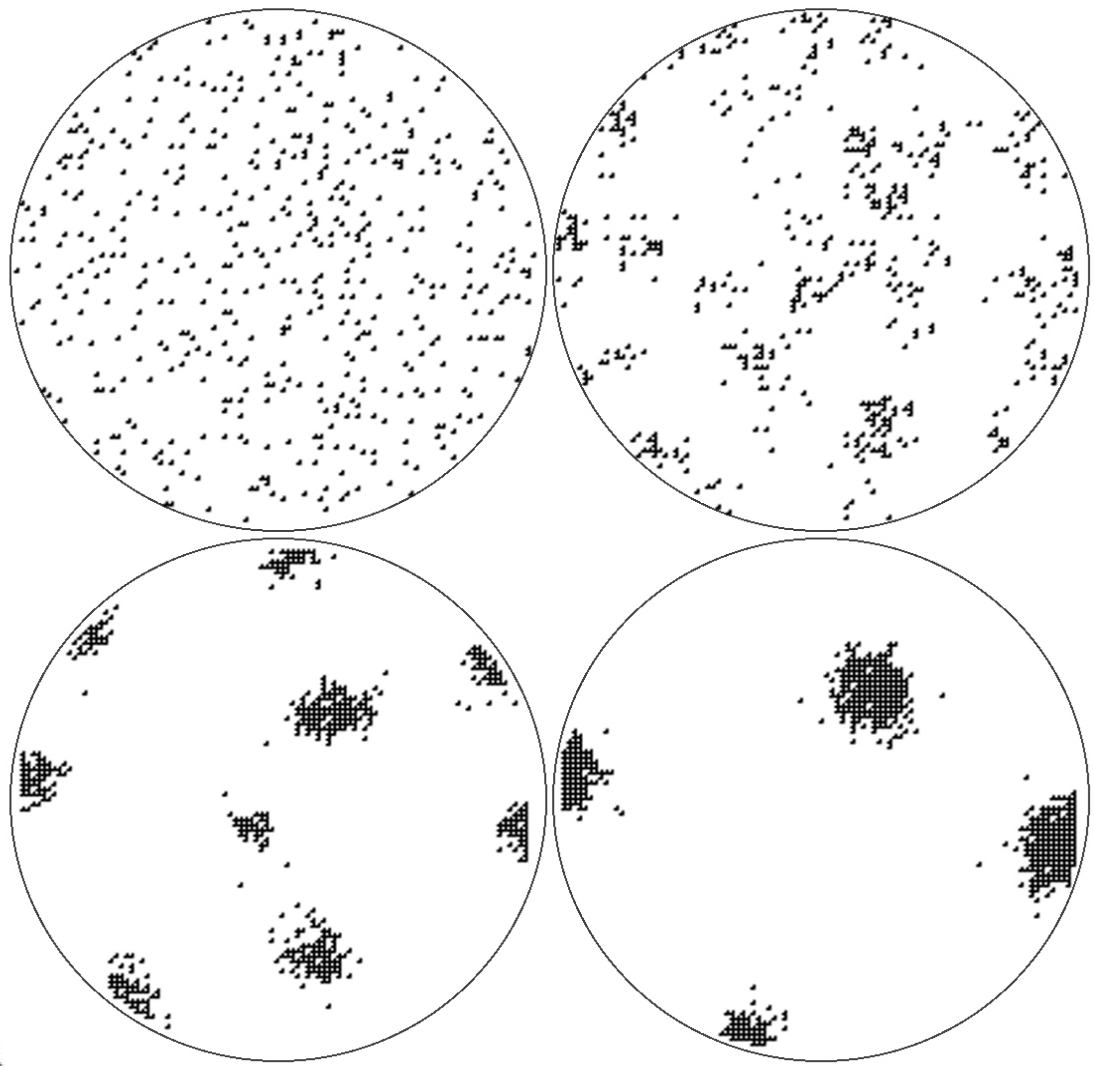
$$P_p=[k_1/(k_1+f)]^2$$

where f=density of items in neighborhood

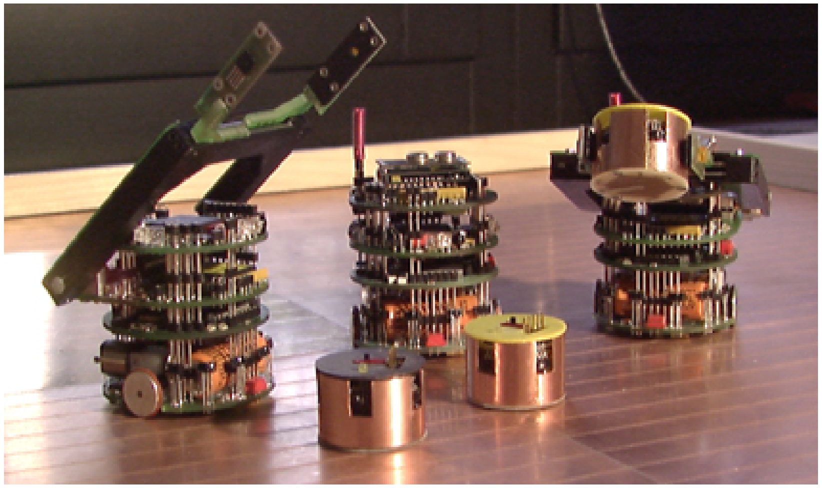


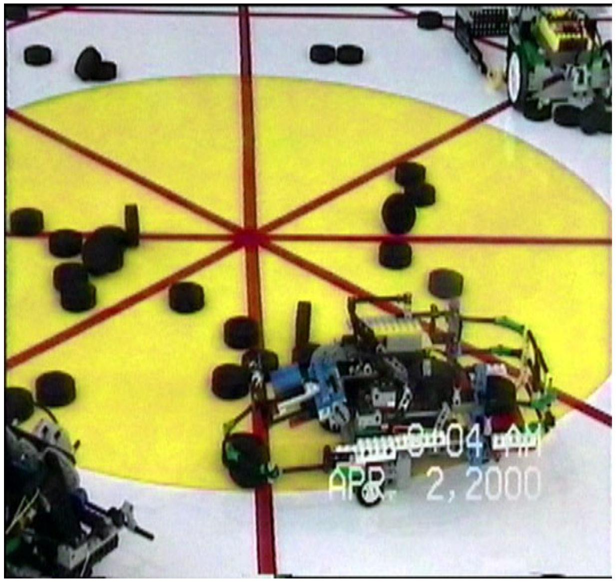
- A laden agent is more likely to drop an ite to other items:

$$P_d=[f/(k_2+f)]^2$$



Clustering robots





From clustering to sorting…

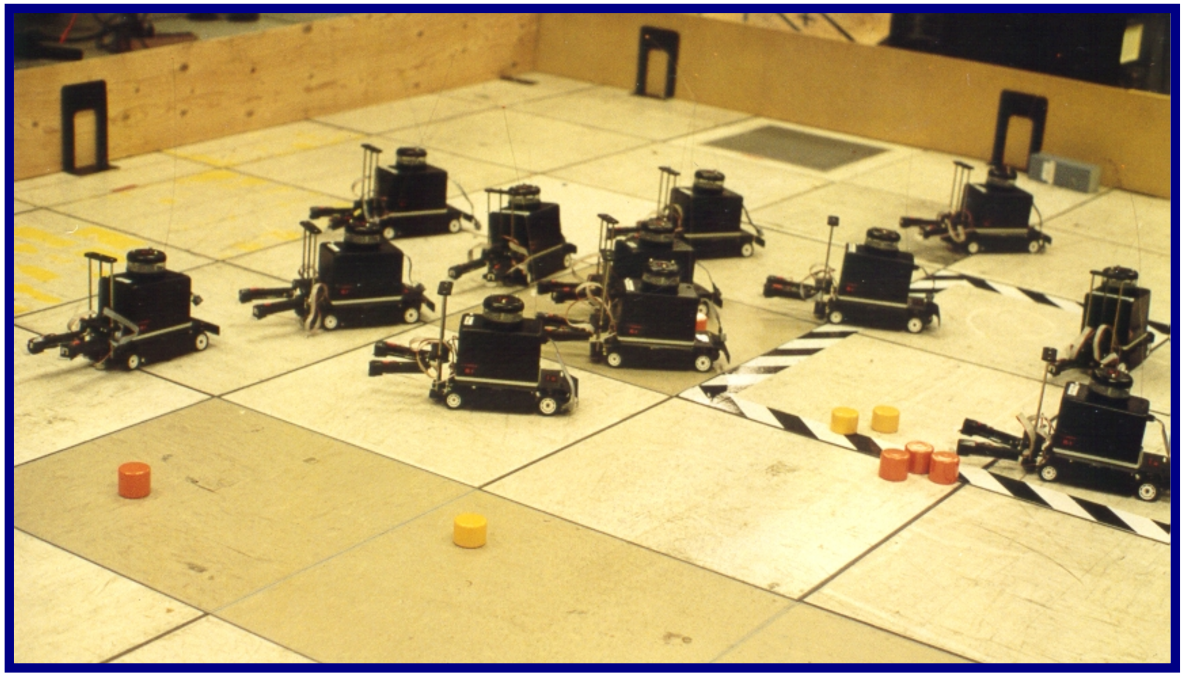
- The same principle can be applied to sort items of several types (i=1,...,n).

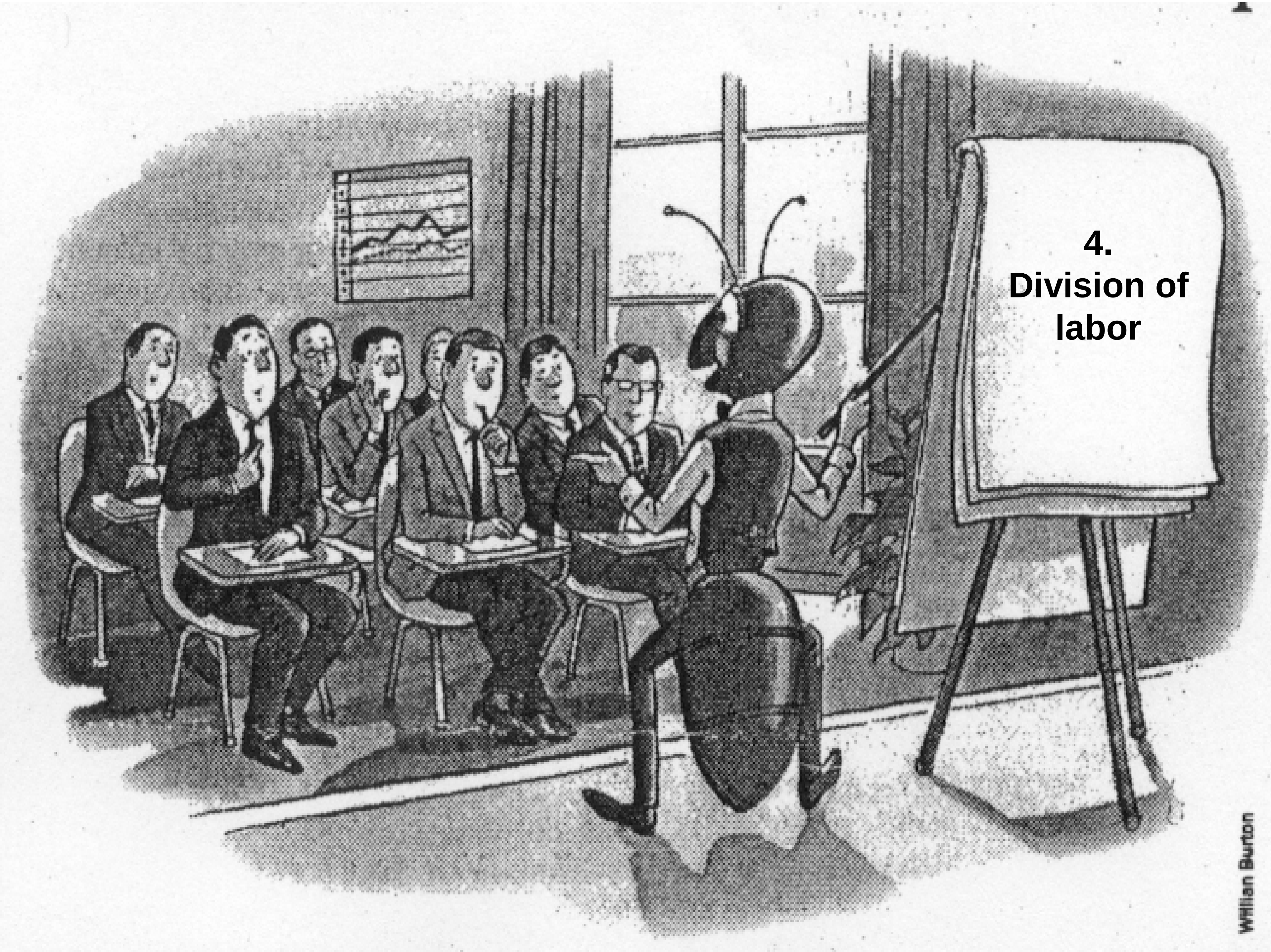
- f is replaced by f_i, the fraction of type i items in the agent's neighborhood:

$$P_p(i)=[k_1/(k_1+f_i)]^2$$

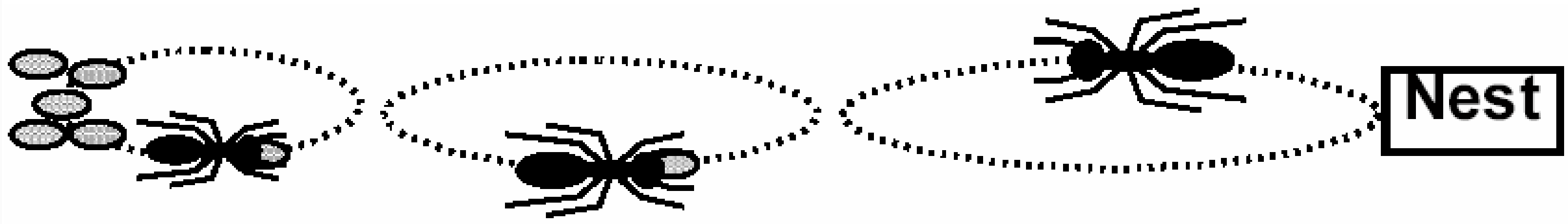
$$P_d(i)=[f/(k_2+f_i)]^2$$

Sorting robots



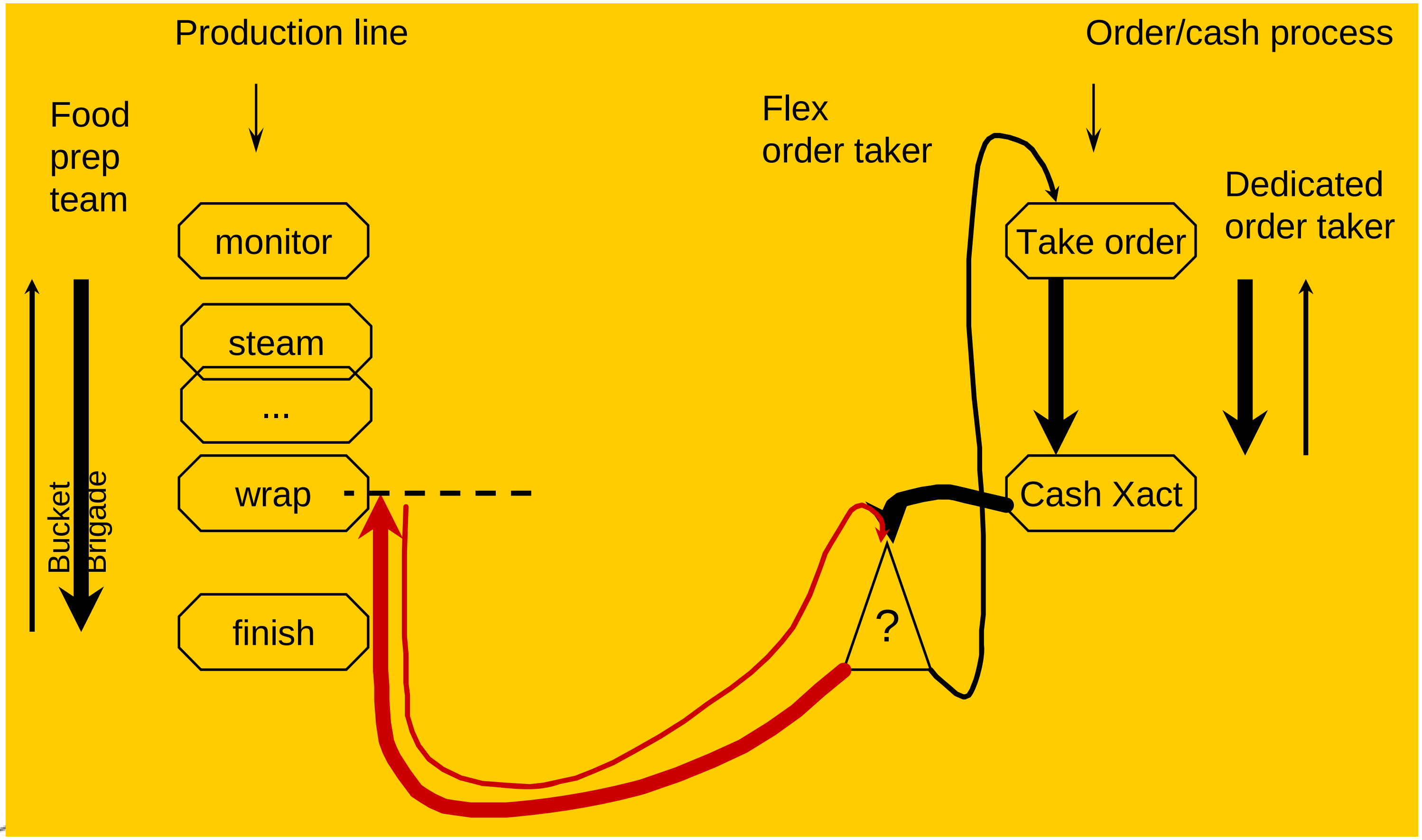

4.
Division of
labor

Bucket brigades in harvester ants



- *Messor barbarus* ants in southern Spain retrieve seeds from a source in a bucket brigade of up to six workers.
- The first and smallest ant collects a seed from a source and starts to carry it along a trail towards the nest until it meets a larger worker.
- This larger worker takes the seed from the ant and continues to transport the seed towards the nest while the smaller ant turns and walks back towards the seed source. And so on.

Bucket brigades at Taco Bell



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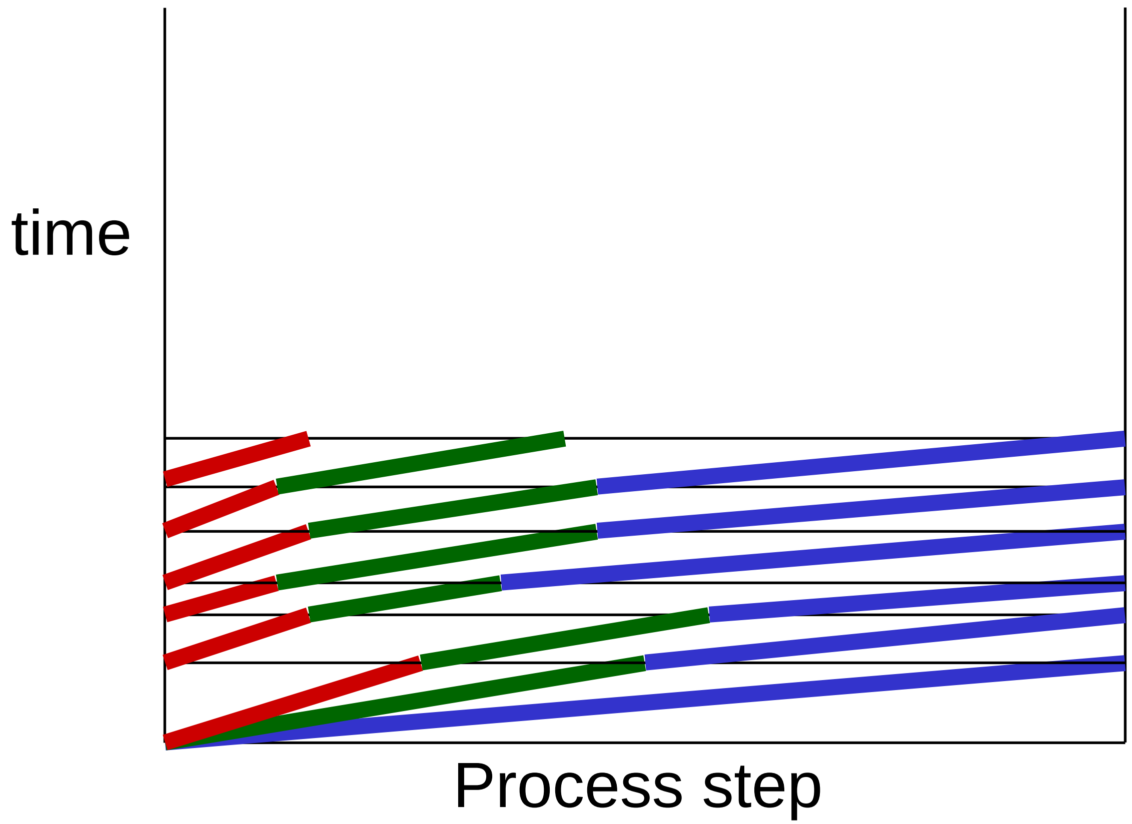
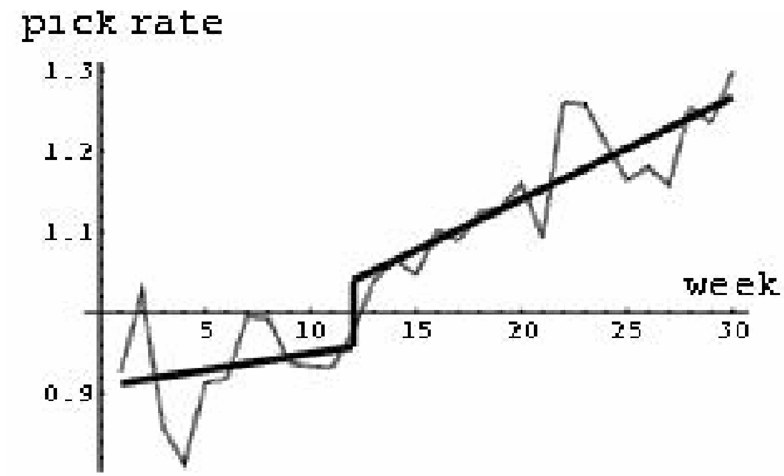
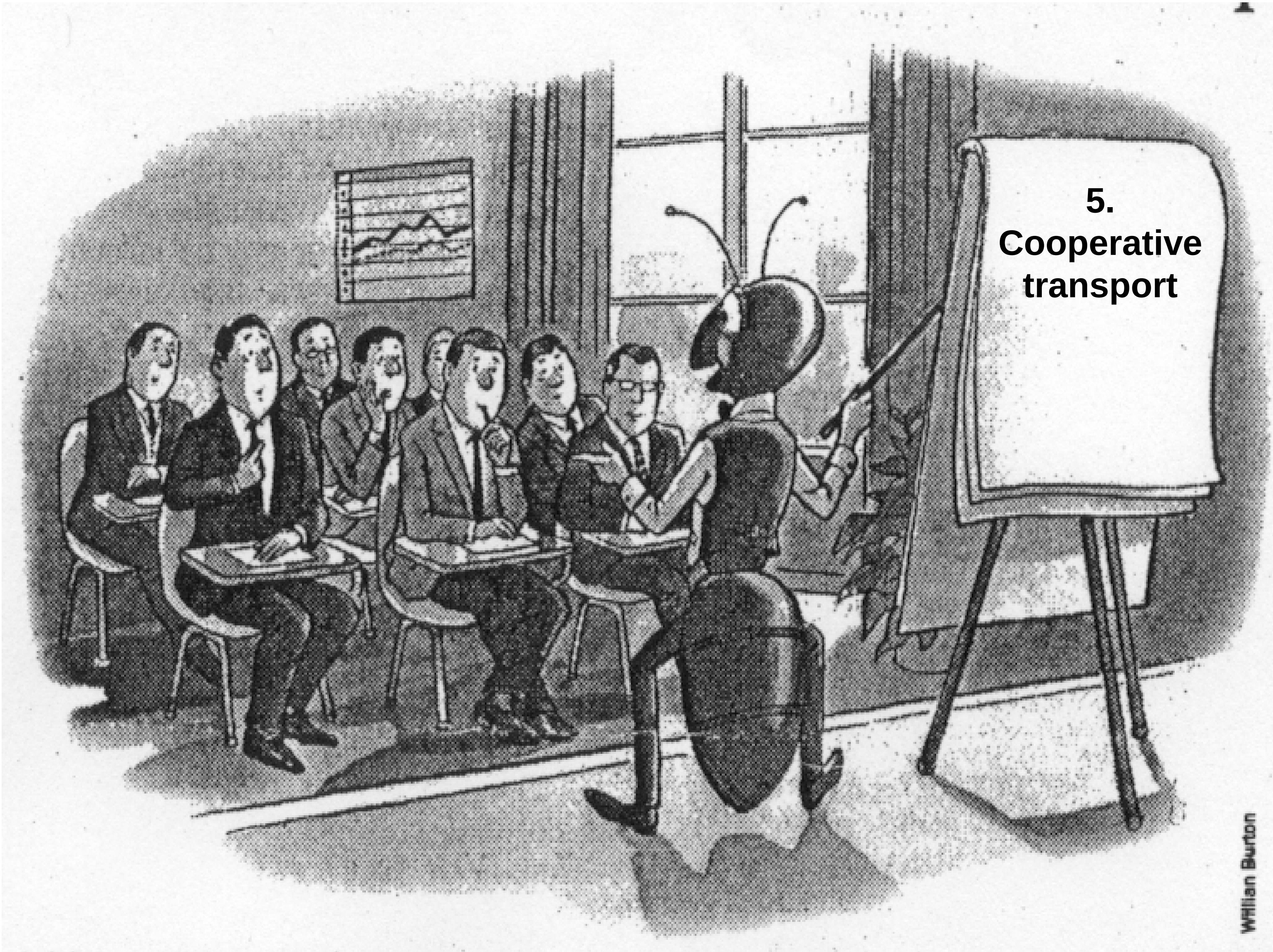

time
Process step

Optimal work-sharing emerges spontaneously



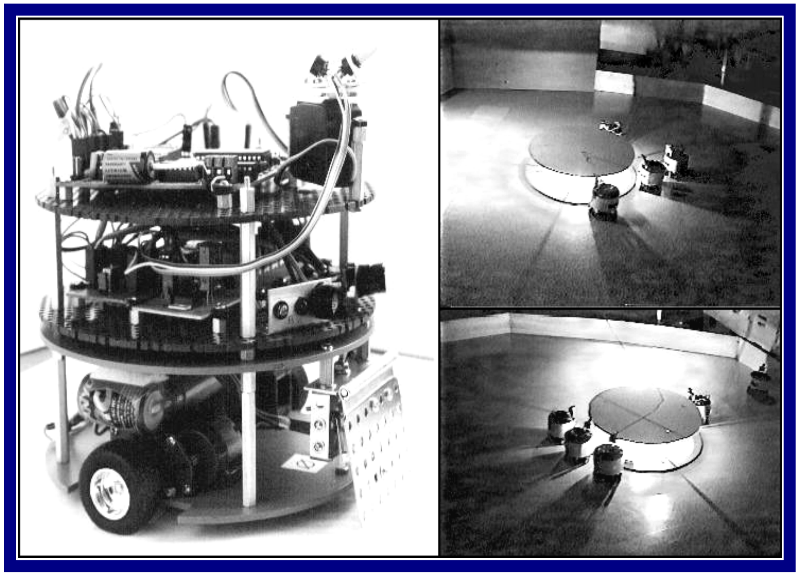
Average pick rates as fraction of work standard both before, and after, switching from zone picking to bucket brigades (in week 12) at the national distribution center of *Revco Drugstores* (now *CVS*). Achieved 34% increase in throughput among order-pickers after converting to bucket brigades.


5.
Cooperative
transport
William Burton

Cooperative transport

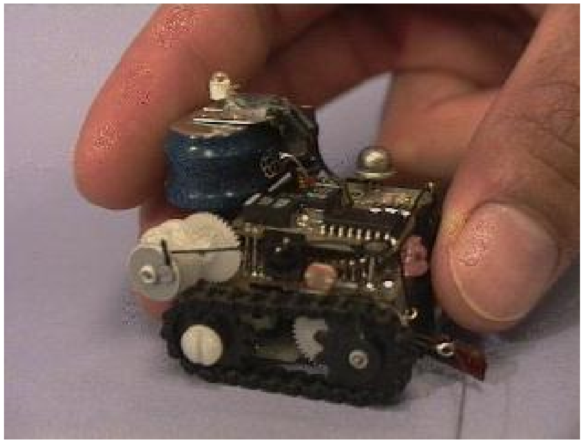
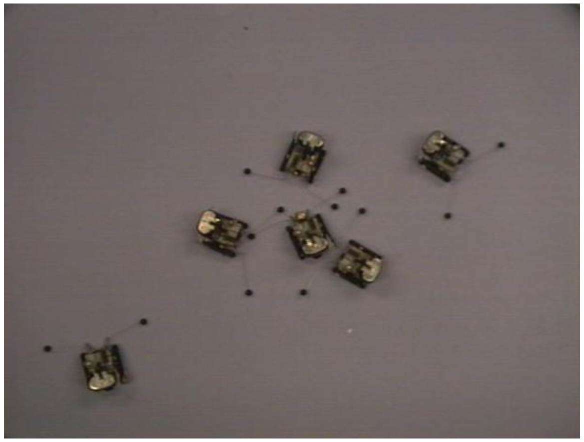
When a single ant cannot retrieve large prey or food items, nestmates are recruited to help. During an initial period of up to several minutes, the ants change position and alignment around the item without making progress, until eventually the item can be moved toward the nest.

Cooperative transport

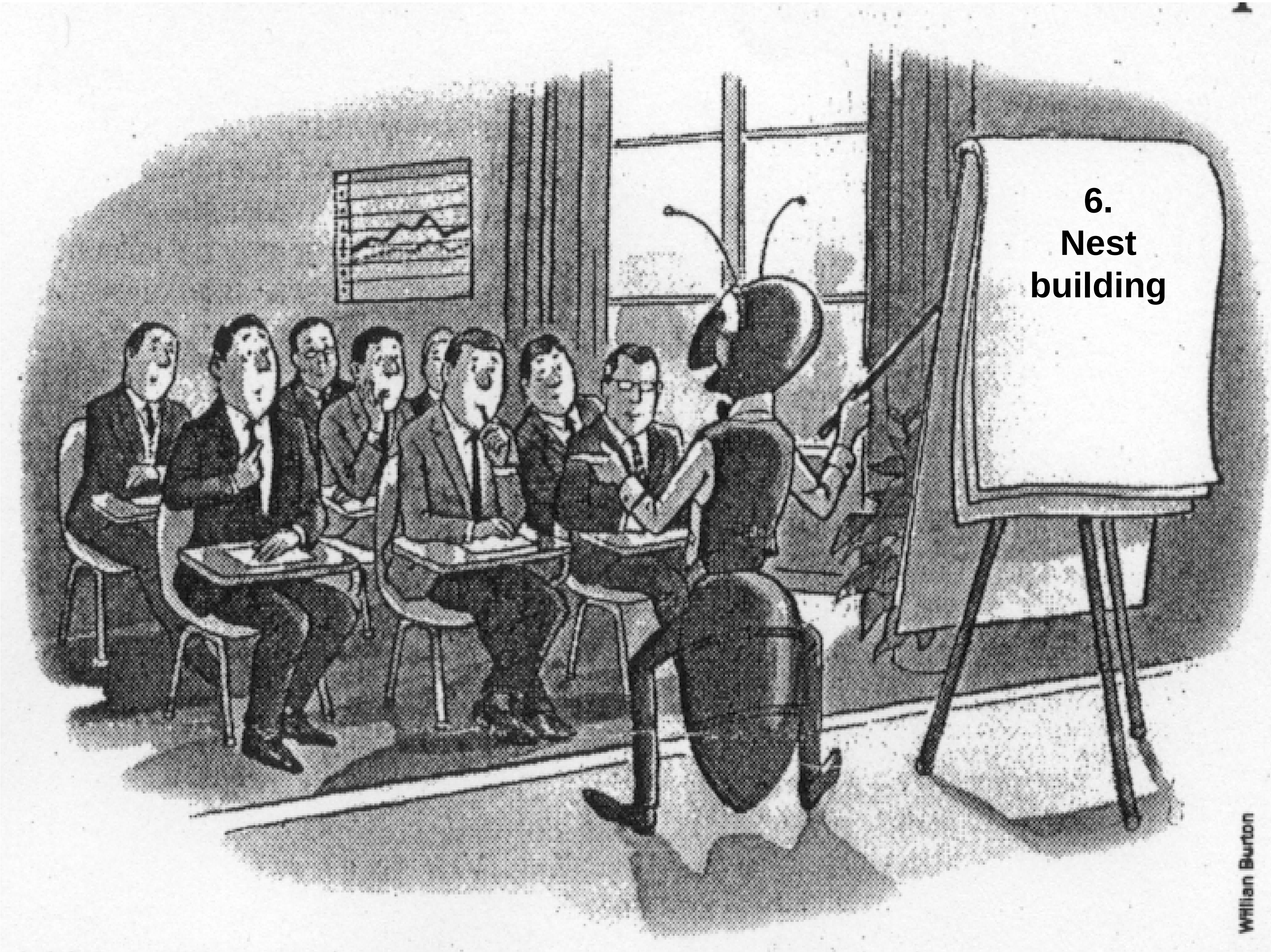


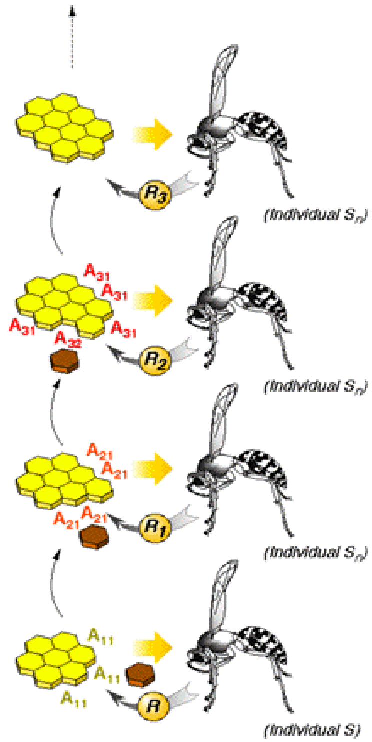
- Scientists have reproduced emergent coordination with a swarm of very simple robots. Videotaped experiments at http://www.cs.ualberta.ca/~kube/.
- Not the most efficient way of pushing a box. But, because of robots' simplicity, promising in the perspective of miniaturization and low-cost robotics.

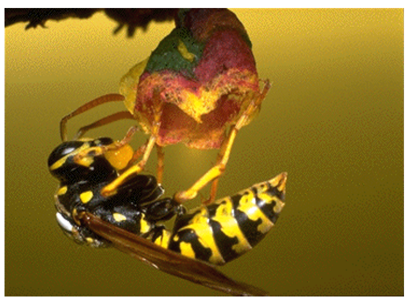
Robots

- **Collective task completion**
- **No need for overly complex algorithms**
- **Adaptable to changing environment**

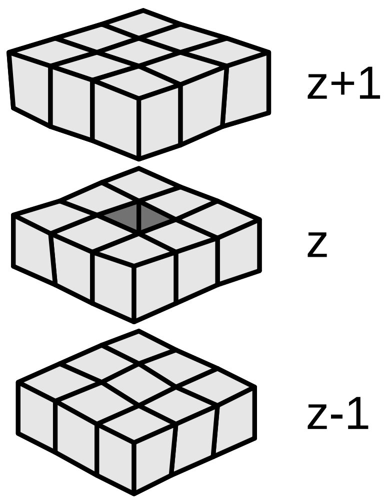

6.
Nest
building
William Burton





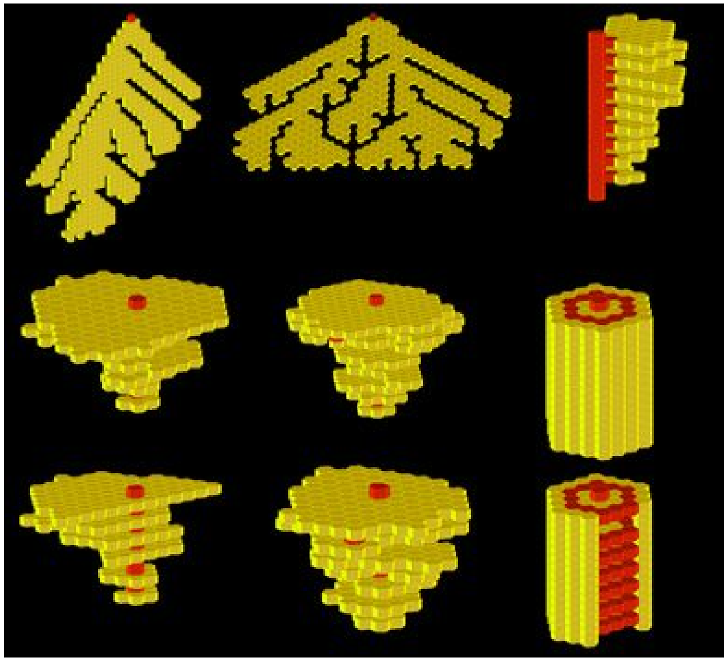
From a model of wasp nest building to self-assembly

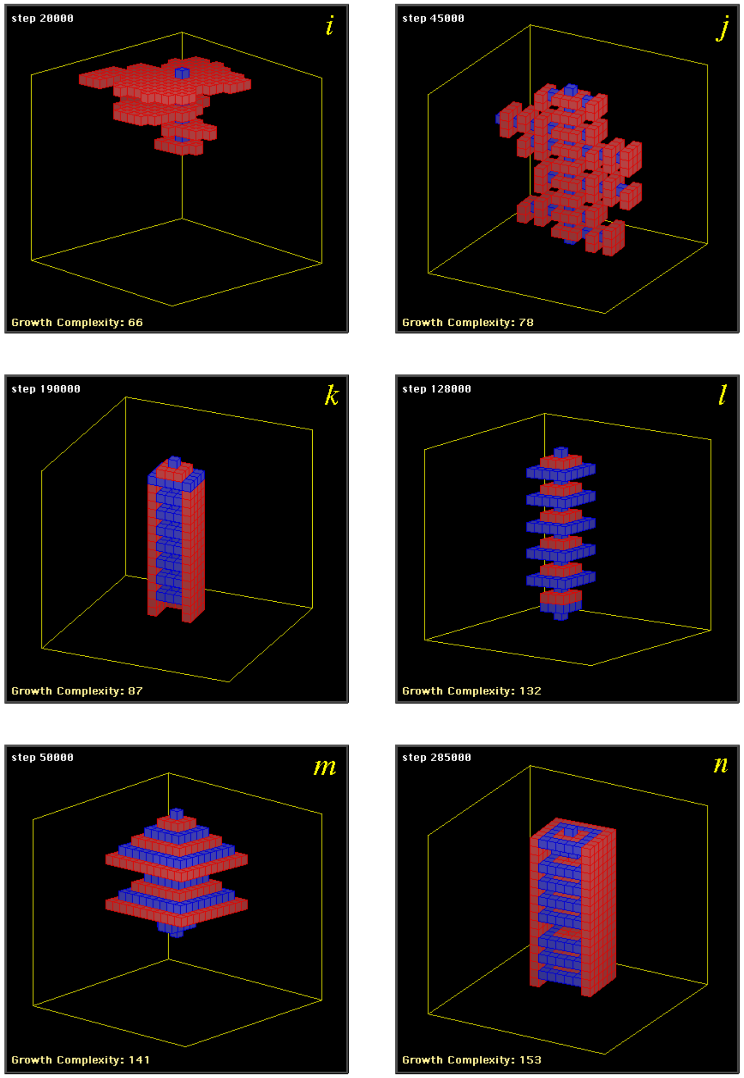
Building model

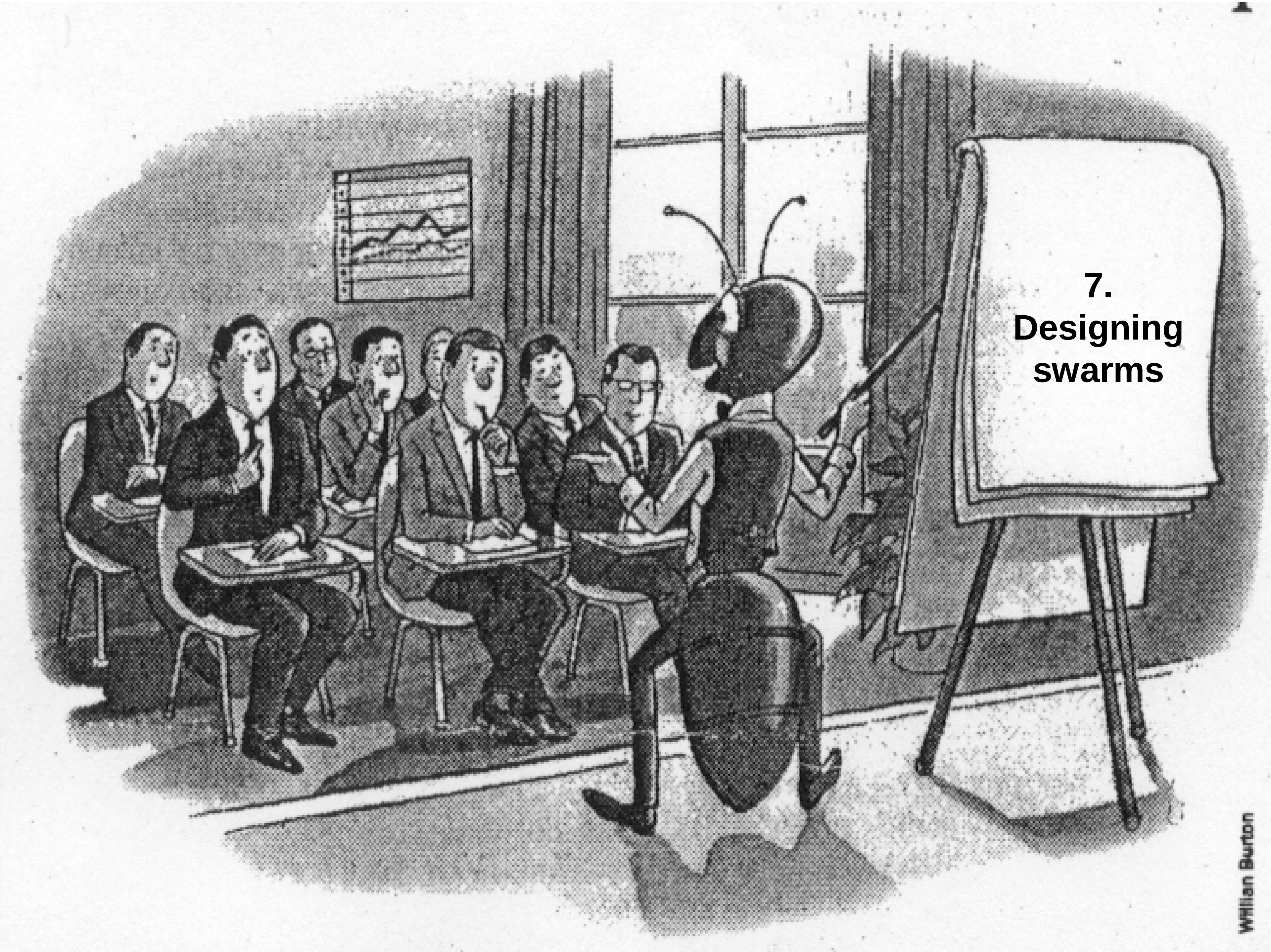


- Agents move randomly on a 3D grid of sites.
- An agent deposits a brick every time it finds a stimulating configuration.
- Rule table contains all such configurations. A rule table defines an algorithm.
- Rule space is very large.

Engineered emergent patterns






7.
Designing
swarms

Simple rules are not always good

Circular mill in army ants: a circle of ants continuously following each other round and round in circles until death (Schneirla). Beebe (1921) observed a mill in Guyana that measured 1200 feet in circumference with a circuit time for each ant of about 2½ hours. The mill persisted for two days, with ever increasing numbers of dead bodies littering the route, but eventually a few workers straggled from the trail thus breaking the cycle, and the raid marched off into the forest.

How do we shape emergence?

How do we define individual behavior and interactions to produce desired emergent patterns?

Simulation of nest building

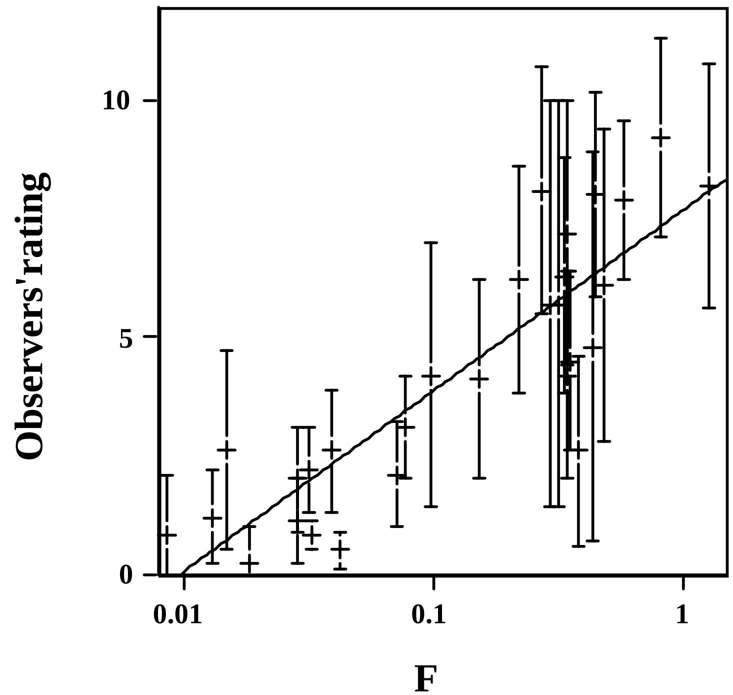
- Most algorithms generate structureless shapes.
- But some produce "structured" architectures.
- Structured architectures:

  - Usually modular
  - Most complex patterns have large modules
  - Produced by specific algorithms
  - Convergence to similar shape in all runs
  - Compact
  - Take time to generate

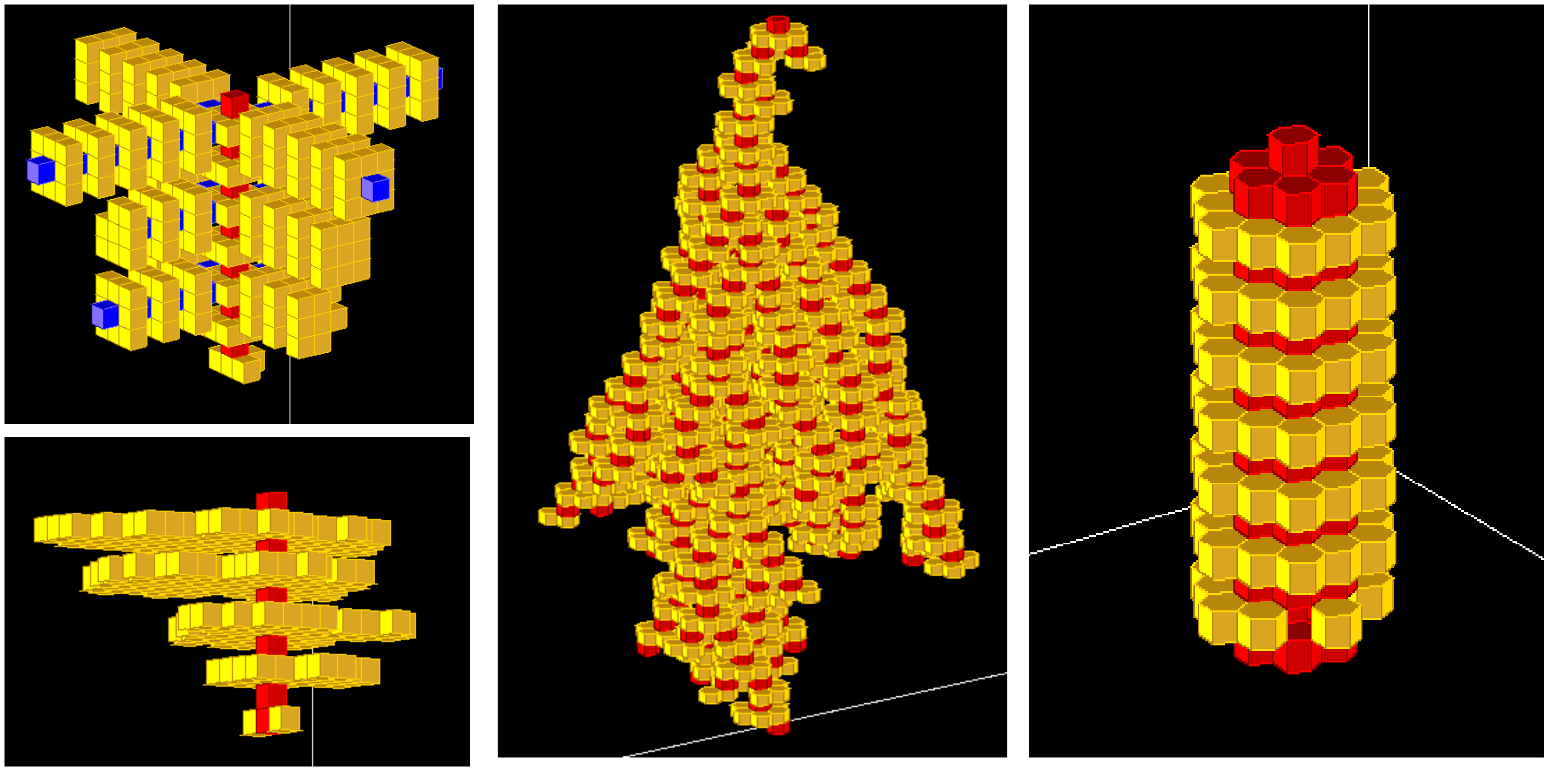
Genetic algorithm to explore rule space

Some of the characteristics of "structured" architectures can be formalized (graph associated with the building process) and quantified.

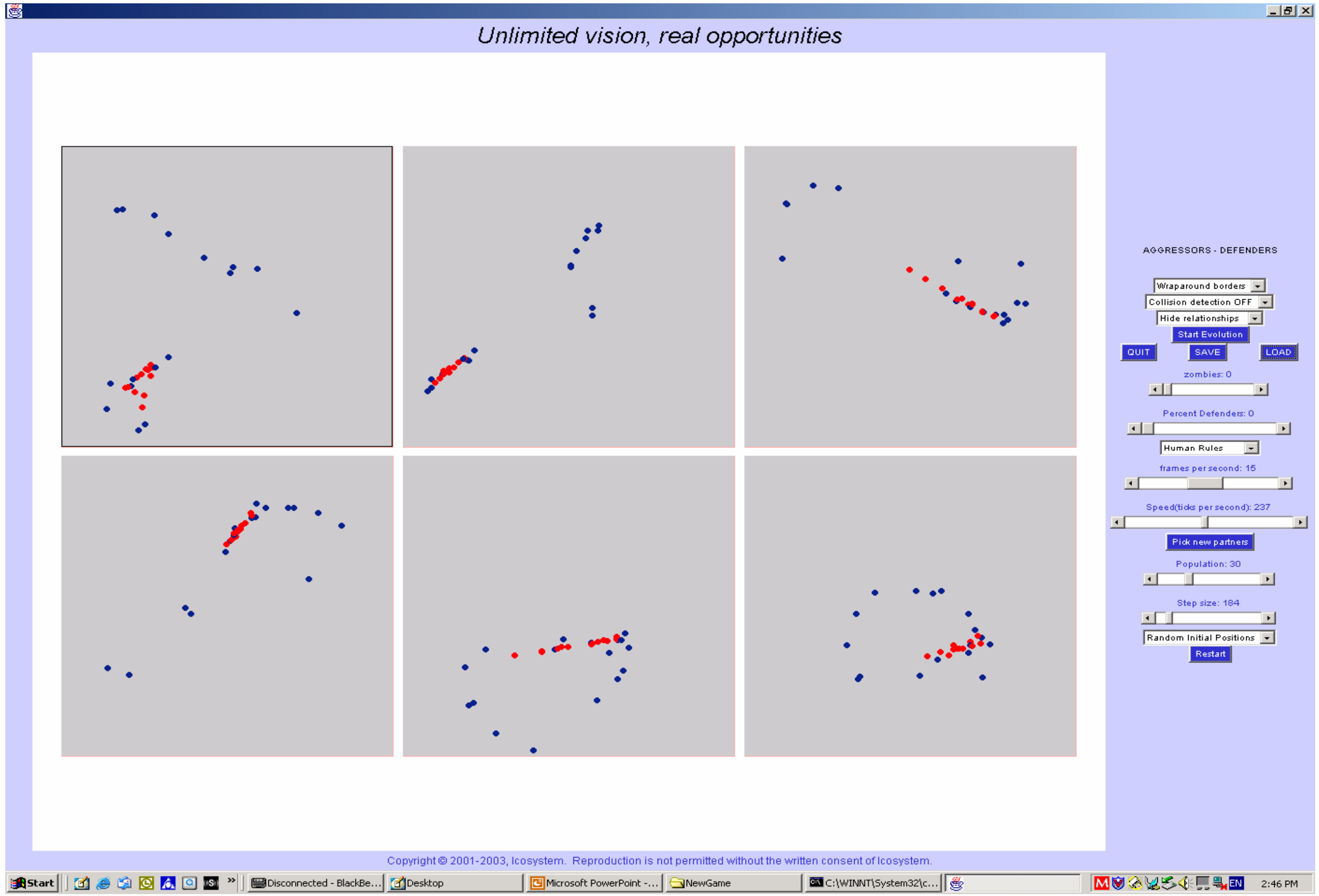
Quantification is useful to define a fitness function. Heuristic fitness correlates well with observers' notion of structure. A GA has been run with this fitness.



Emergent patterns from evolutionary design



Emergent behavior by design



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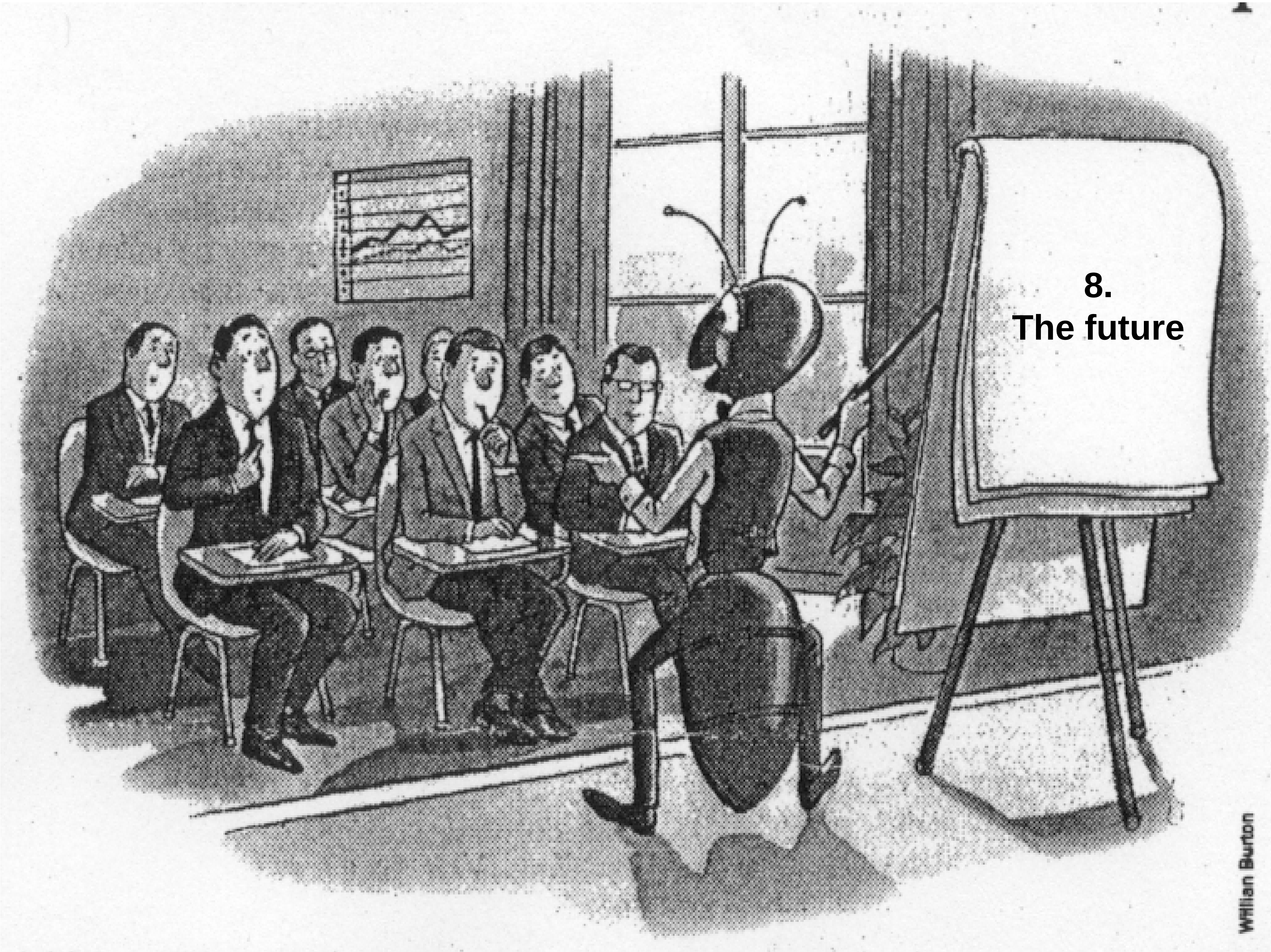
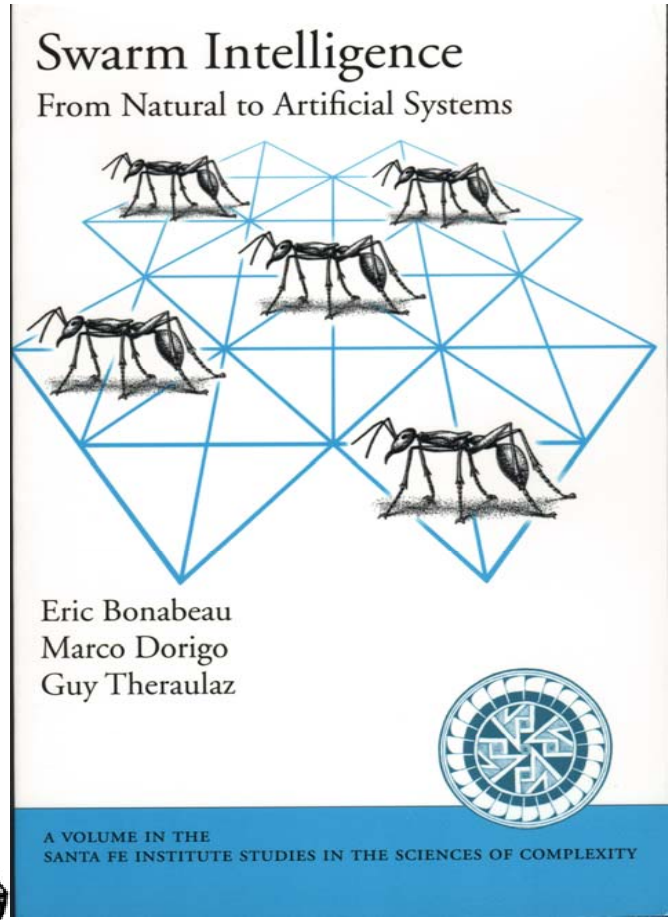
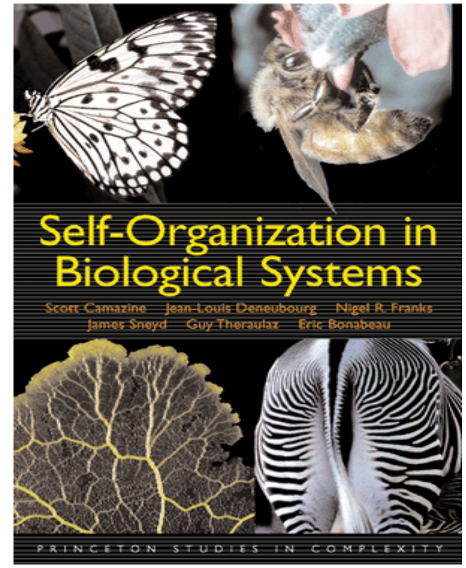

8.
The future

Swarm Intelligence…

is obviously becoming popular





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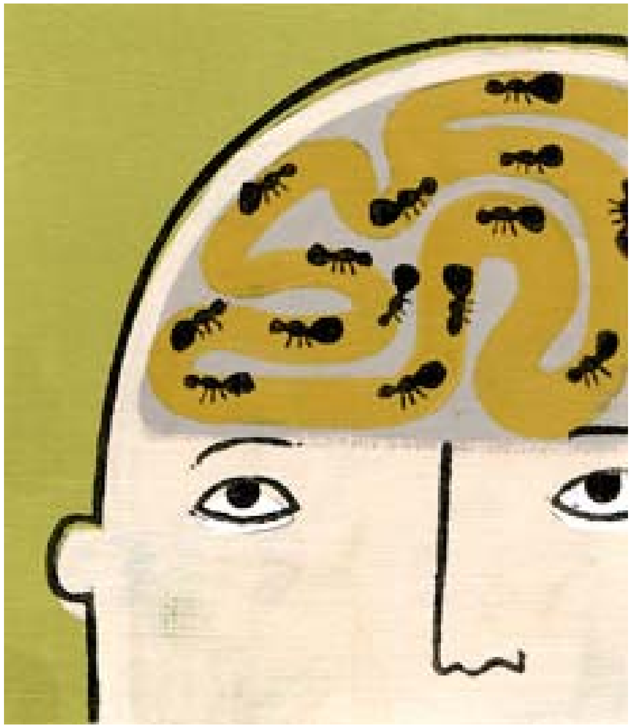
What's really important



The decentralized mindset

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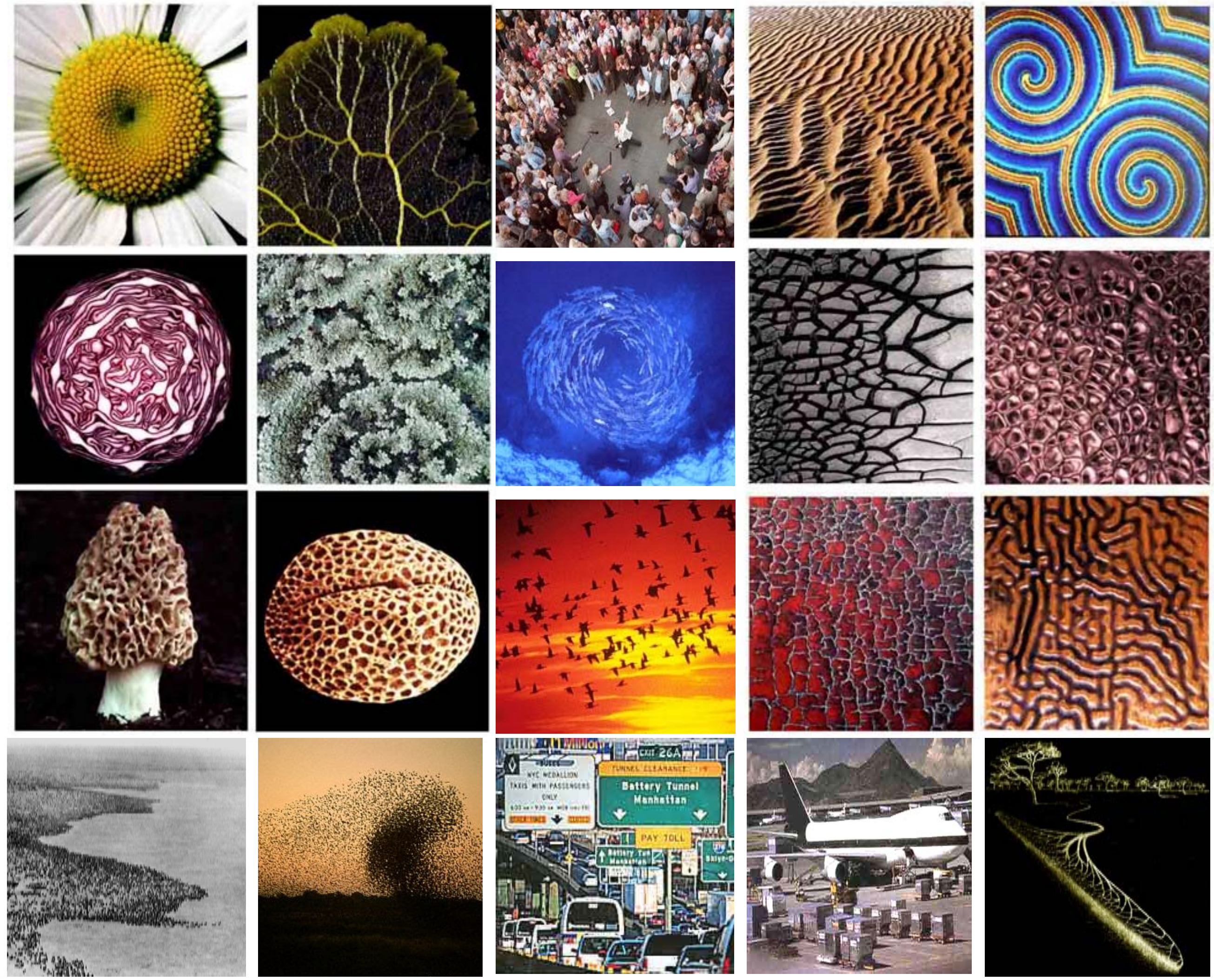
What's really important



Carl Anderson, Scott Camazine (http://www.scottcamazine.com/personal/research/index.htm)

Coming soon

- More distributed optimization/control applications (scheduling, resource allocation, routing)
- Self-healing, self-organizing comm networks
- Swarm robotics will move beyond mapping
- Self-aggregating devices
- Self-organized satellite deployment and maintenance (NSF/NASA/EPRI)
- Controlling swarms of UAVs, UGVs, UUVs
- Swarm “urban combat model”
- Swarm-based sensor networks, smart dust
- More!

Articles

- Swarm Intelligence, Scientific American, March 2000
- Swarm intelligence, Harvard Business Review, May 2001
- Predicting the Unpredictable, Harvard Business Review, March 2002
- Real-world applications of agent-based models of human systems, Proc. Nat. Acad. Sci. USA, 2002

Contact me at eric@icosystem.com

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