Swarm Intelligence:
Distributed Problem Solving Inspired by Collective Behavior of Insects and other Natural Multi-Agent Systems

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Outline

- **What is Swarm Intelligence?**
- Self-organization and Social Insects
  - Self-synchronization
  - Collective building
  - Foraging ants
- Inspiration for problem solving tools
  - Ant Colony Optimization
  - Wasp-inspired Task Allocation
- Conclusion

What is Swarm Intelligence?

- Branch of artificial intelligence that takes problem solving inspiration from natural multi-agent systems
- Largely inspired by mathematical models of the behavior of social insects
- **Key Ideas:**
  - Very simple computational agents
  - Individually "dumb"
  - Indirect communication via changes in environment
  - Positive reinforcement
  - Means of "forgetting"
  - "Intelligence" through collective behavior

Social Insects

- Defining properties of eusociality:
  - Reproductive division of labor
  - Overlapping generations
  - Sterile castes
  - E.g., reproductive queens and sterile workers
- Social Insects
  - Ants
  - Termites
  - Bees[1]
  - Wasps[1]
- Individuals possess little intelligence
- Simplicity of individual behavior
- Collective behavior of colony complex
- How is it governed? By whom?

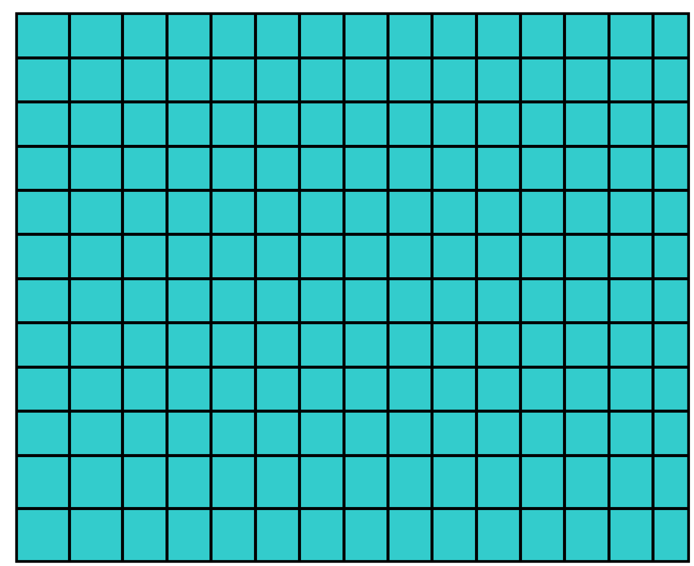
1. Not all species of wasps and bees are social, some are solitary insects.

Self-Organization Governed by Stigmergy

- Stigmergy (term introduced by Grassé):
  - From the Greek stigma (sting) and ergon (work)
  - An environmental stimuli induces a behavioral response
- Term typically used to refer to indirect communication via changes in the environment
- Examples:
  - Ants leave pheromone (chemical) trails… other ants follow these trails
  - Ants carrying dead ants more likely to drop them next to other dead ants (forming cemeteries)

Simulating the Biological Processes

- Mathematics involved usually includes:
  - Probability and Statistics
  - Calculus
  - Discrete math
  - Differential equations and difference equations
- Time typically simulated in discrete intervals
- Grid world used to represent the physical world
- Grid cells have properties:
  - Number of insects that can be located there
  - Quantity of food located there
  - Quantity and type of pheromone (chemical left by insects) located there



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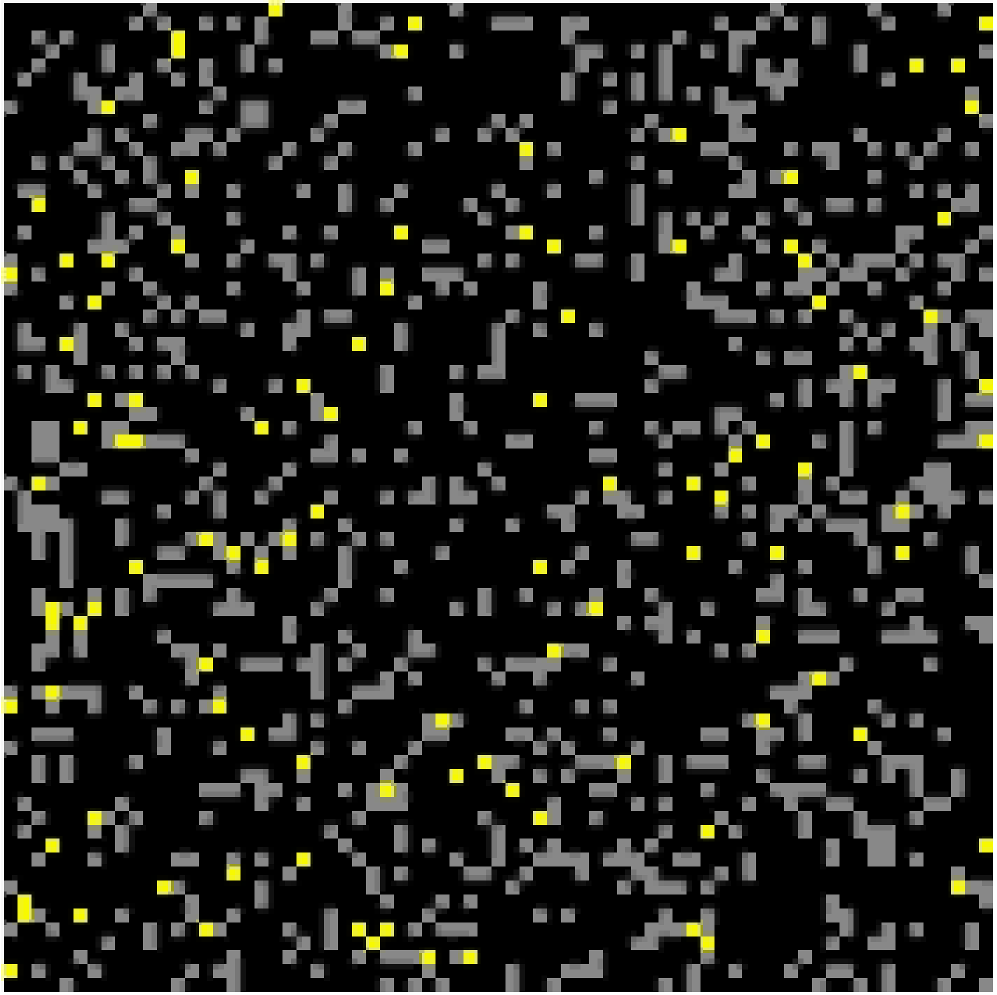
Self-Synchronizing Systems

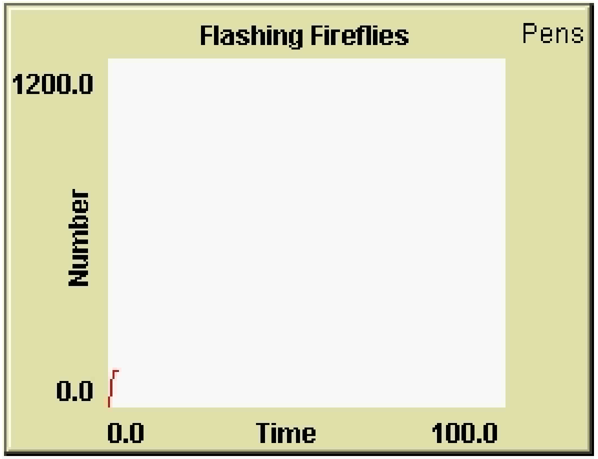
- Cricket chirping
- Horses galloping
- People clapping
- Two pendulum clocks suspended from the same frame
  - Swing at same frequency
  - 180° out of phase
  - According to the Dutch physicist Christiaan Huygens (1665) the inventor of the pendulum clock

Firefly Synchronization

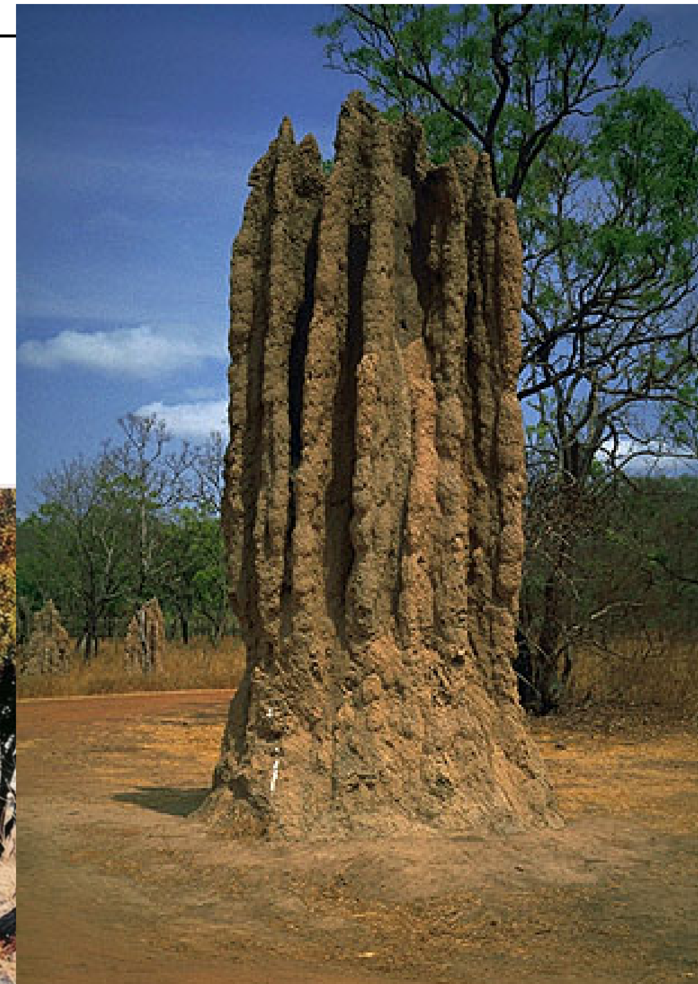
- *Pteroptyx Cribellata*, from Philippines and New Guinea
- Aggregate in large numbers and flash in unison
- Individually each follows its own rhythm
- Flashes by others stimulate individuals to flash sooner
- Effect is cumulative

Fire Flies Simulation





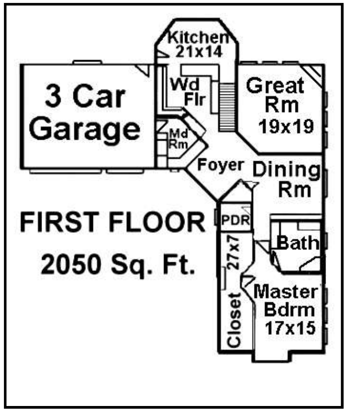
Collective Building by Insects



Termite Nest Building

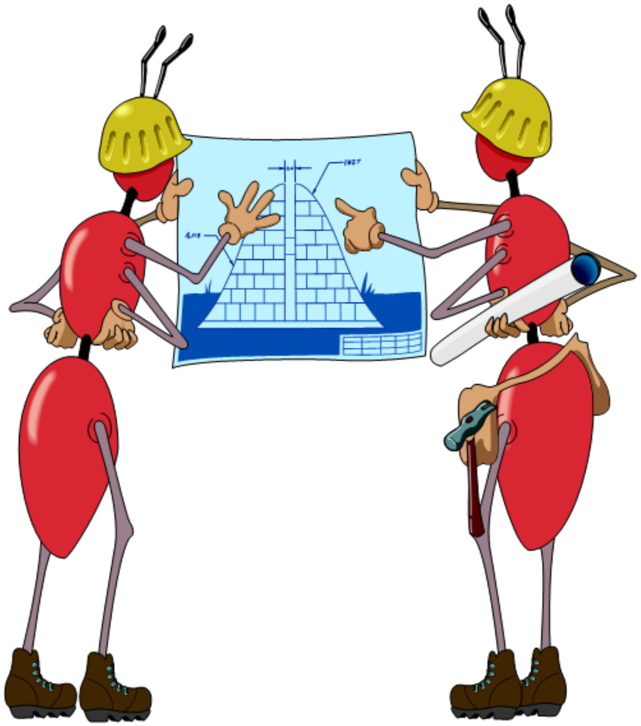
(Kugler et al. 1990)

- Termites construct hills (> 5m high, >10 tons)
  - Multiple floors
  - Intricate networks of passageways
  - Dedicated “climate controlled” chambers to:
    - store food,
    - raise the brood,
    - house the population
- ...and there’s not a supervisor among them!



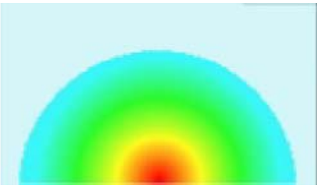
Basic Idea

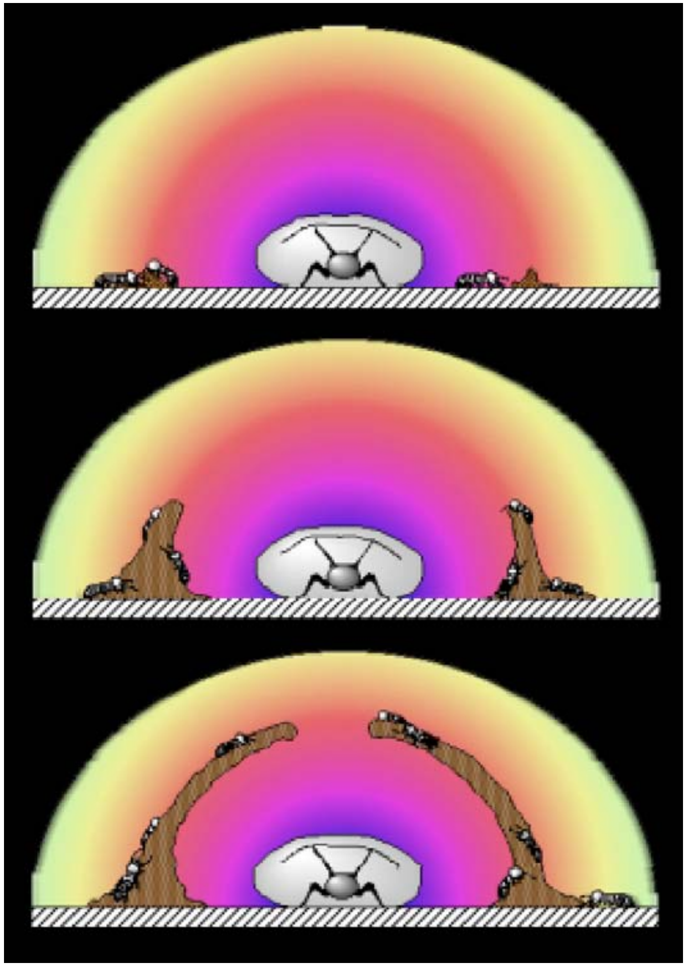
- Completed work is a guide for future work
  - If all builders removed from the site
  - And new population introduced
  - They will continue exactly as original team would



The Queen and Pheromone Diffusion

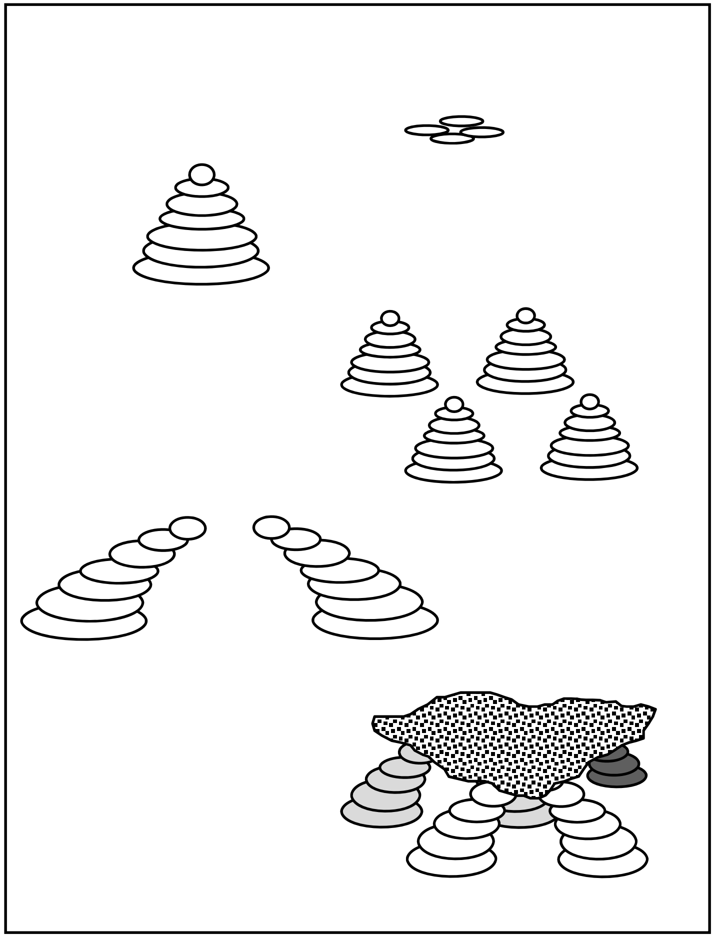
- The queen emits a pheromone that diffuses
- A worker deposits a soil pellet if the concentration of the pheromone is just right
- Wax dummy queen does not stimulate construction





Termite Pillar Construction

- Early deposits attract later ones, yielding concentrations
- Newest (strongest) Pheromones on top lead to columns
- Competition among columns promotes even spacing
- Nearby columns lean toward one another, building arches
- Multiple arches contact to form floors



As a Result

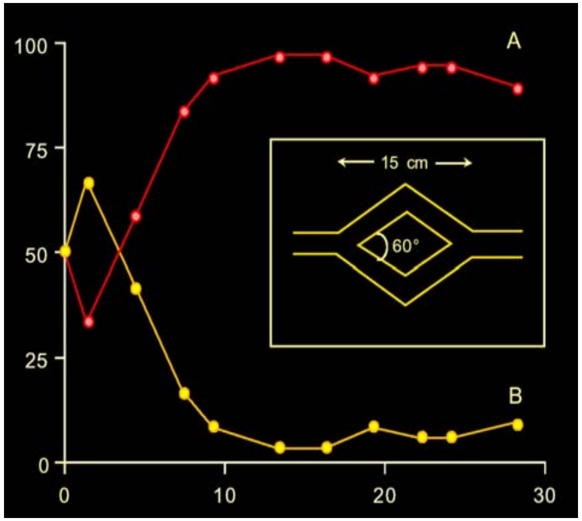
- Termite mounds
- Up to 20' tall
- Up to 6' diameter at base
- Up to 120' below ground
- Exceeds any human structure if measured in body length or weight

Foraging in Army Ants

- Two parts:
  - Pheromone laying
    - While returning with food
  - Pheromone following
    - Always attempt to follow the trail
- Pheromone
  - Evaporates
  - Diffuses
  - Pheromone deposits on trail sum
  - Some lab measurements suggest half-life of 45 min
  - But can persist for months

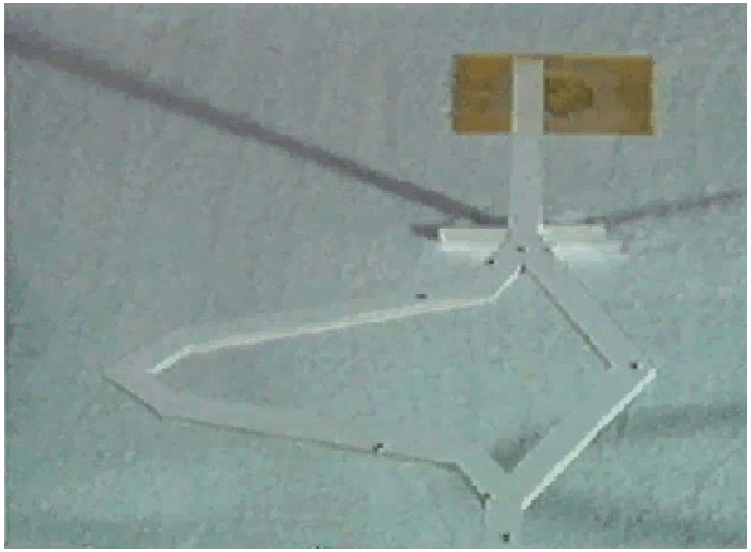
The Double Bridge Experiment

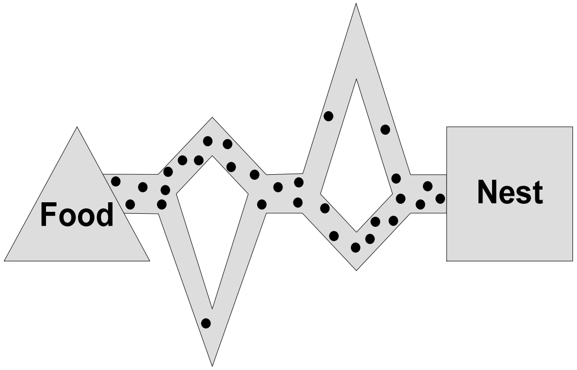
- Initially no pheromone
- Choice of branch is random
- Pheromone left by ants returning from food source
- One branch is eventually chosen by a few more ants
- It becomes more attractive
- Ants increasingly drawn to it
- Colony converges on it
- All (most) ants use that path



Double Bridge Experiment: Unequal Paths

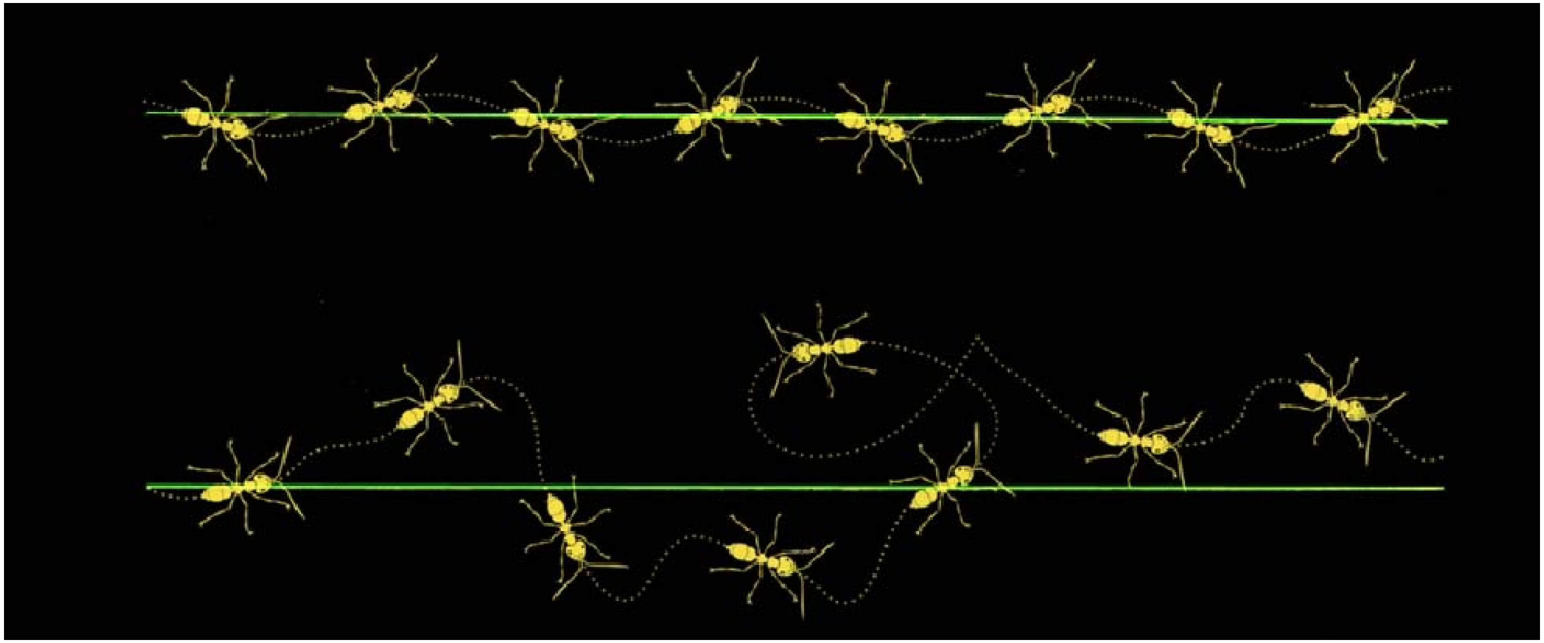
- Ants will return faster over the shorter edge
- Other ants are then more likely to follow shorter edge
- What if that edge is introduced later?





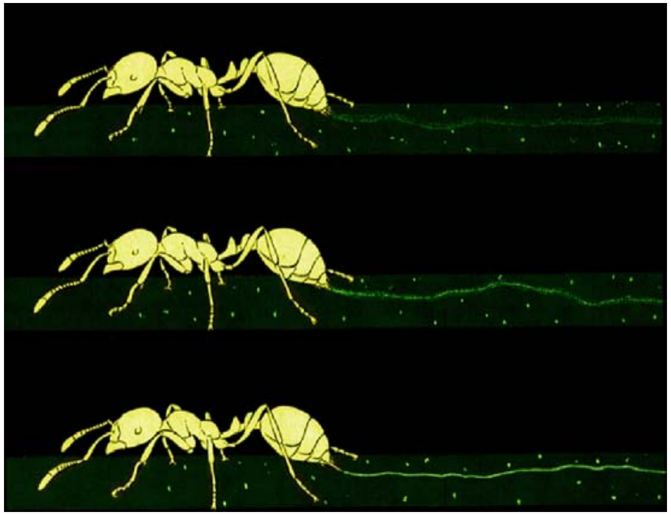
Food Selection

- Chemical trail following is not precise
- Is it a problem?



Food Selection

- Chemical trail following is not precise
- Some ants will lose trail and wander
- They may discover new food sources
- Recruit others via pheromone trail
- Richer food source = more pheromone
- Nearby, rich source can make colony switch

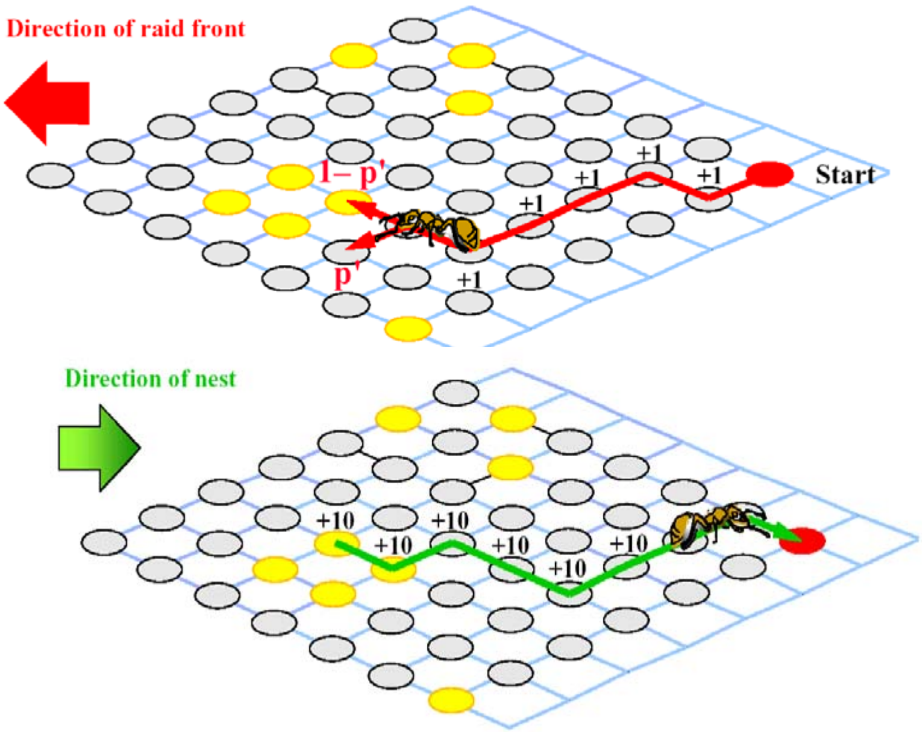


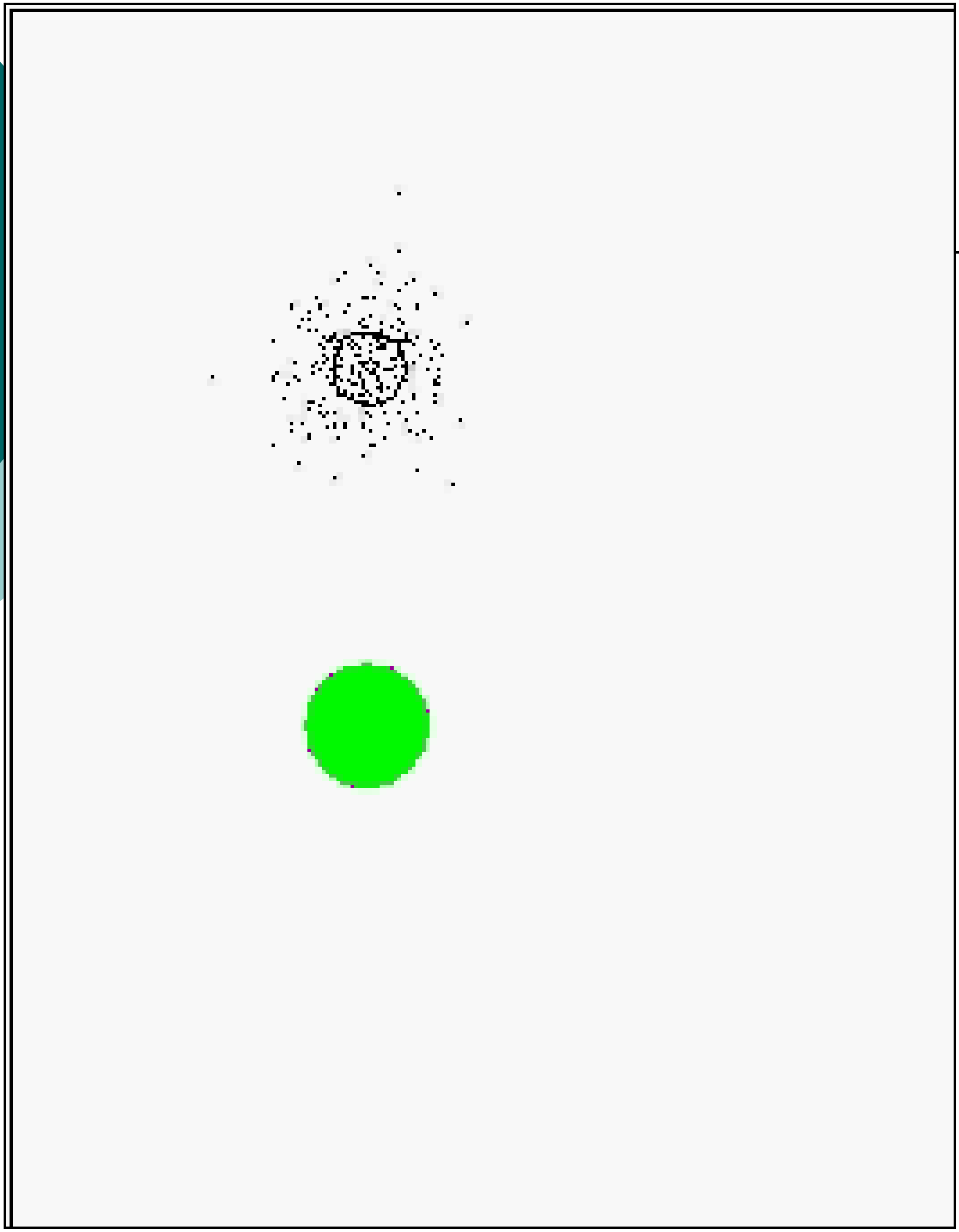
Behavioral Model

- Probabilistic trail following out
- Pheromone laid in both directions
- Evaporation
- Move left with prob.

$$p = \frac{(5+\rho_l)^2}{(5+\rho_l)^2 + (5+\rho_r)^2}$$

- Congestion
  - Move to neighboring cell
  - Wait until space is free, if all cells are congested





Foraging Ants Movie

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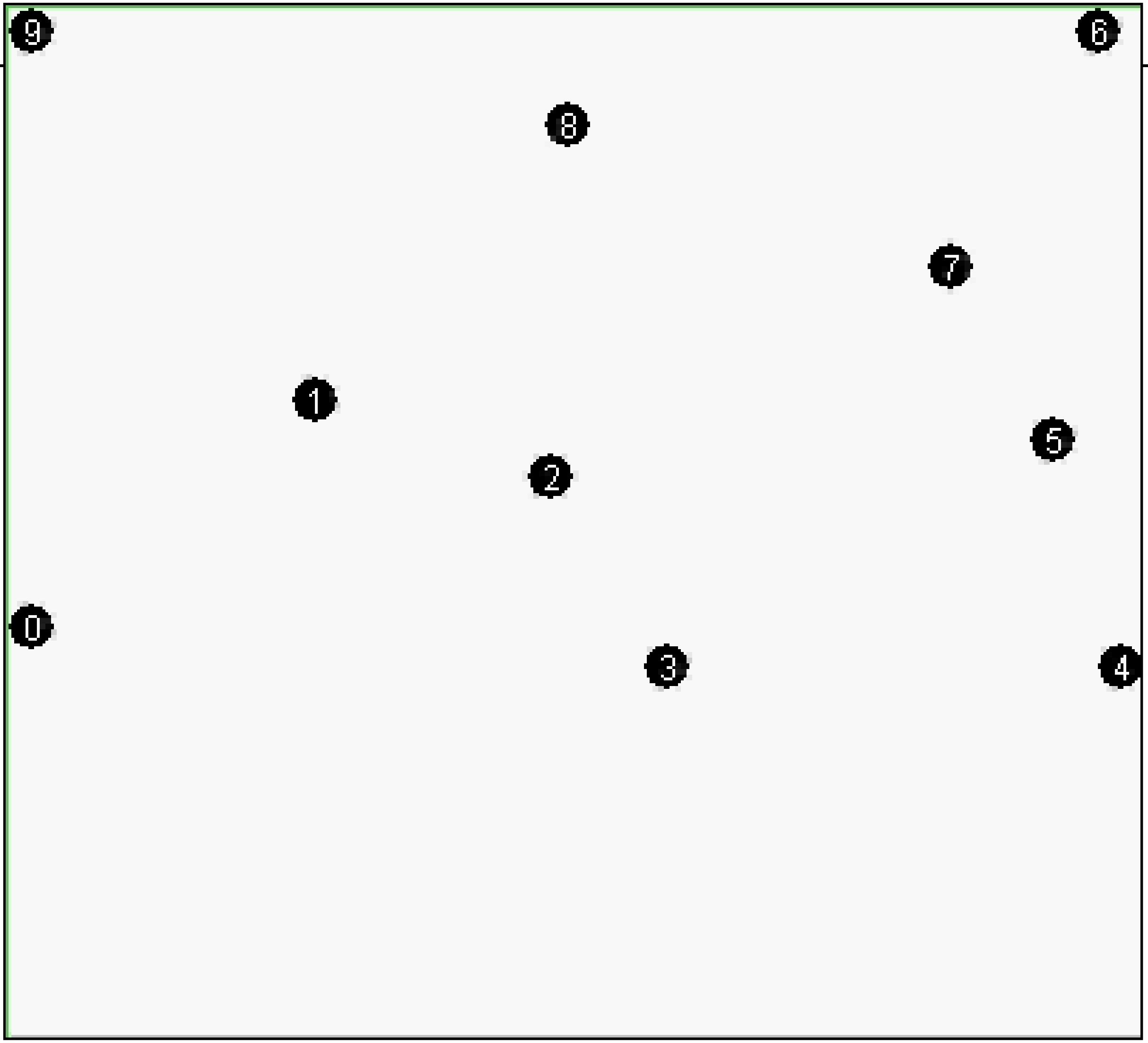
Ant Colony Optimization (ACO)

- First introduced for shortest route problems
  - E.g., the traveling salesperson problem (TSP)
- Key concepts:
  - Population of artificial ants
  - Probabilistically build a solution following artificial pheromone
  - Reinforce pheromone trail according to quality of found solution (positive feedback)
  - Evaporate the pheromone to avoid search stagnation (negative feedback)
  - Time scale – number of runs is also critical.

ACO Example: Traveling Sales Ants



Ant System (AS): The first ACO algorithm

- Transition from city i to j depends on:
  - "Tabu list" – list of visited cities
  - Heuristic, η_{ij}, local desirability to visit city *j* when at city *i* is *(*for TSP η_{ij} = $1/d_{ij}$)
  - Artificial pheromone trail $\tau_{ij}(t)$– represents the learned, desirability of visiting city *j* from city *i*
- Generally, have several "ants" searching the solution space.

Ant System (AS)

- Transition rule is a combination of heuristic and pheromone trail
- Probability of ant k going from city i to j:

$$p_{ij}^{k}(t) = \frac{\left[\tau_{ij}(t)\right]^{\alpha} . \left[\eta_{ij}\right]^{\beta}}{\sum_{\ell \in J_i^k} \left[\tau_{il}(t)\right]^{\alpha} . \left[\eta_{il}\right]^{\beta}}$$

- Alpha and beta are adjustable parameters
  - α= 0 : represents a greedy approach
  - β= 0 : represents rapid selection of tours that may not be optimal.

Ant System (AS)

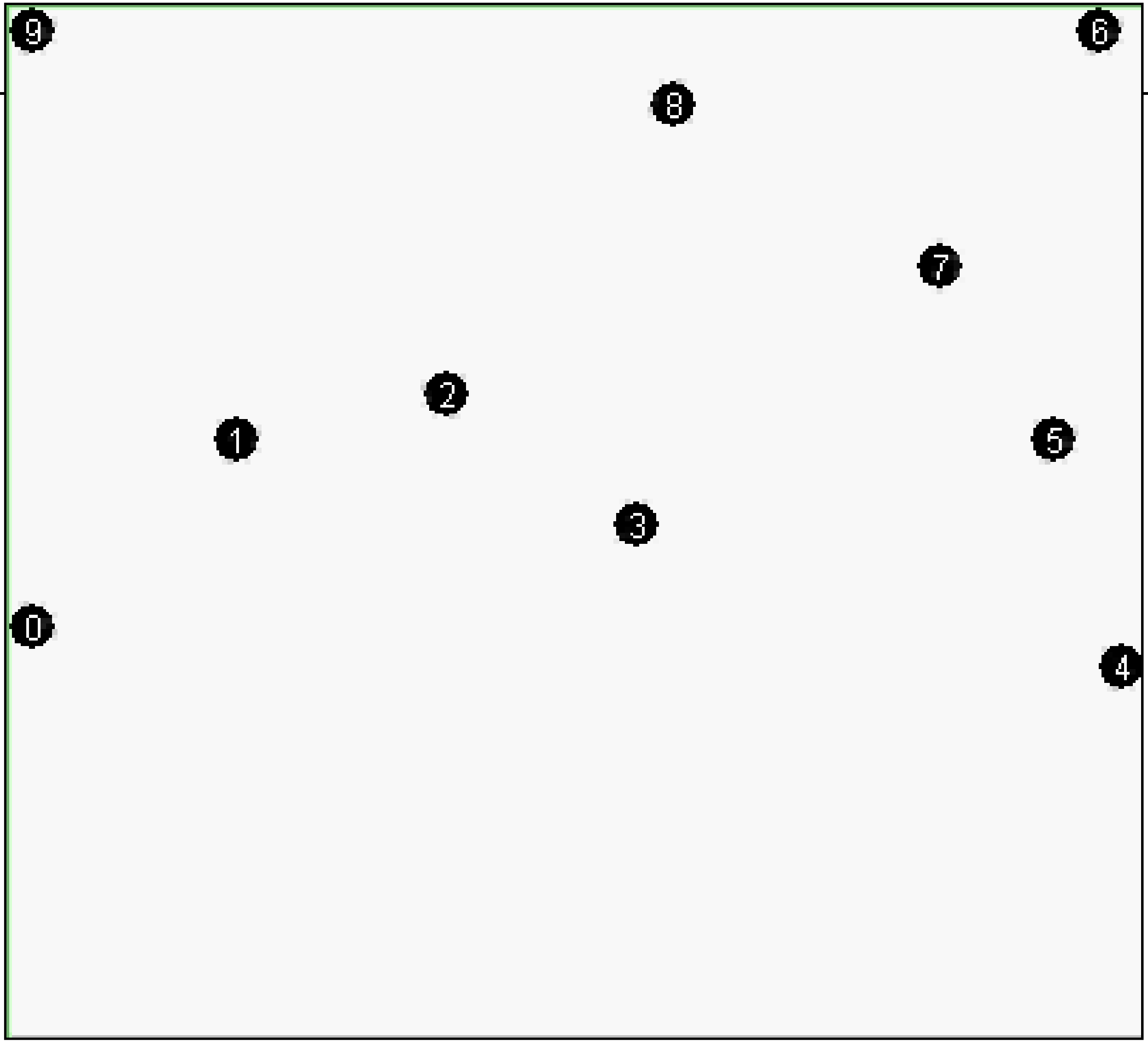
- Pheromone update :

$$\Delta\tau_{ij}^{k} = \begin{cases} Q / L^{k}(t) & \text{if } (i, j) \in T^{k}(t) \\ 0 & \text{otherwise} \end{cases}$$

- T is the tour made at time t by ant k, L is the length, Q is a parameter.
- Pheromone decay:

$$\tau_{ij}(t+1) = (1-\rho).\tau_{ij}(t) + \Delta\tau_{ij}(t)$$

Dynamic ACO Movie



Wasp Task Differentiation
(Theraulaz et al. 1991)

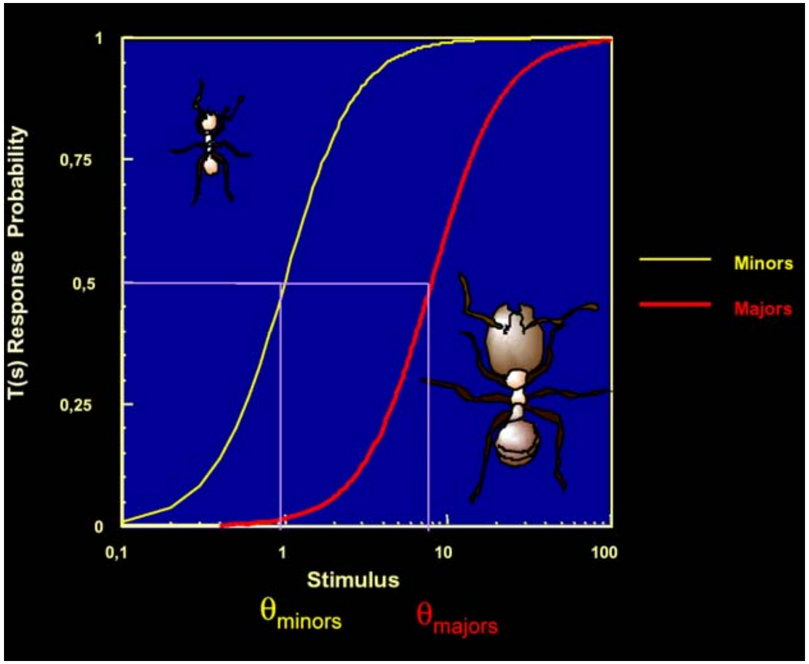
- Wasps in a nest divide into:
  - Foragers who hunt for food,
  - Nurses who care for the brood.
- The relative proportion of Foragers and Nurses varies with the demand
- ...but no wasp explicitly computes the demand.

Division of Labor

- Morphological
  - Inherent physical properties of individuals
- Temporal
  - The time of day, year, age
- Behavioral
  - Specialize/adapt to allocated tasks

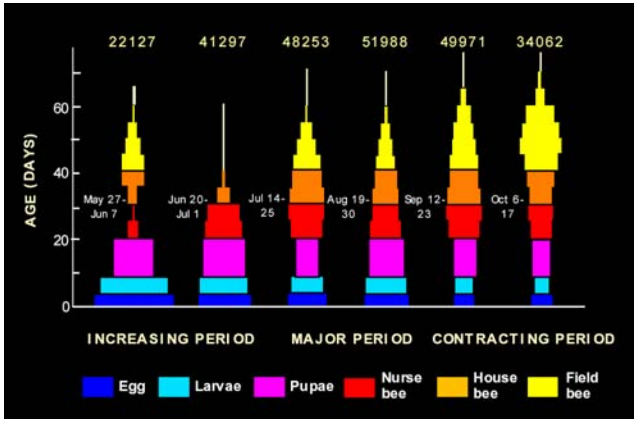
Fixed Threshold model

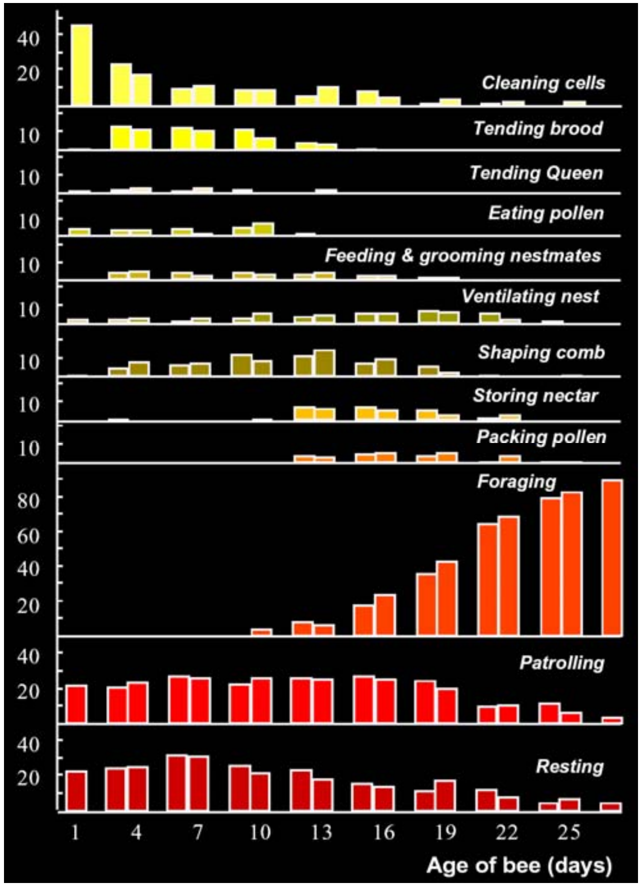
- Each task produces a stimulus
- Each ant has a “response” threshold
- If it is exceeded, the ant starts performing the task
- Just like a dirty coffee pot in the office
- Can be tied to ant morphology



Time Based Thresholds

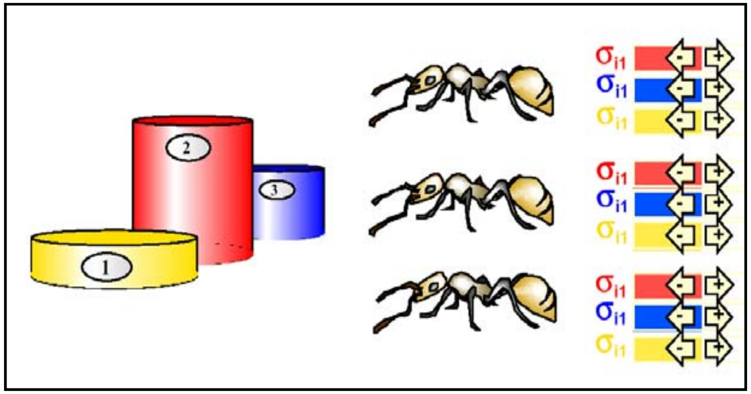
- Older bees/ants forage more
- Thresholds can change
  - Age of bee
  - Time of day
  - Time of year

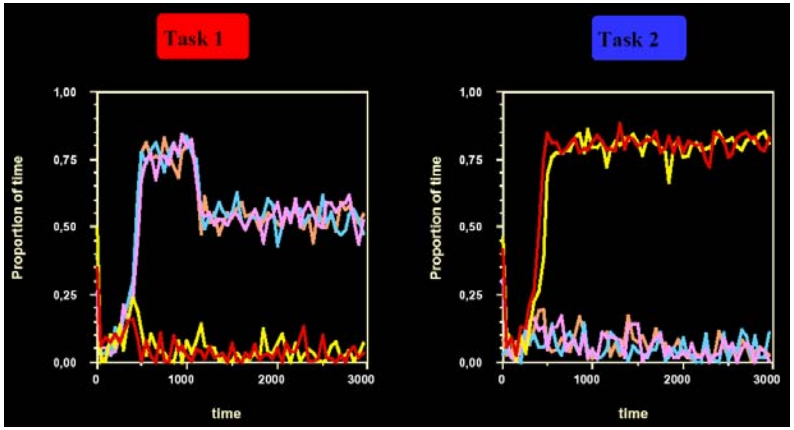




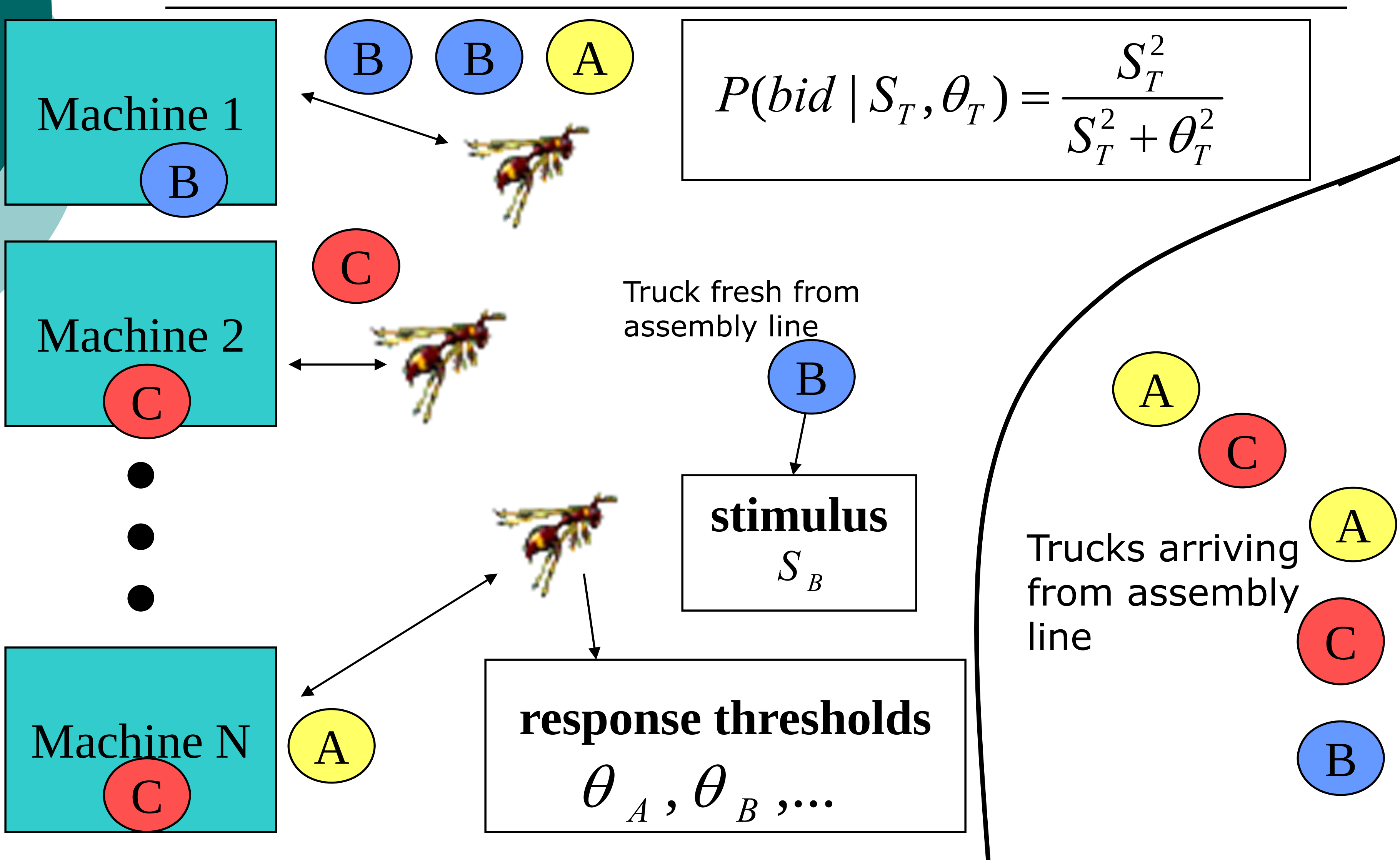
Adjustable Thresholds

- Polist Wasps
  - Small colonies
  - No differences
  - Capable of performing any task
- As wasp works on a task:
  - Associated threshold is lowered
  - All others are raised
- Promotes specialization but keeps it flexible





Wasp Task Allocation for Vehicle Paint Booth Scheduling



Response Threshold Updates

- While painting (or switching to) color *j*

$$\theta_{w,j} = \theta_{w,j} - \delta_1$$

- While painting (or switching to) color other than *j*

$$\theta_{w,j} = \theta_{w,j} + \delta_2$$

- While idle for all colors *j*

$$\theta_{w,j} = \theta_{w,j} - \delta_3$$

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Much to learn from the natural world

- Social insects coordinate to solve complex problems with very simple coordination methods and minimal communication.
- What can we learn from nature?
- Biologists in their studies have produced mathematical models:
  - To simulate the biological systems
  - To test their hypotheses about the biology

Much to learn from the natural world

- Biotracking Project
- Group at Georgia Tech
- Lead: Tucker Balch
- Focusing on:
  - Automatically tracking biological entities in video
  - Automatically identifying behavioral patterns
  - What can we learn that can be applied to robotic systems?

Much to learn from the natural world

- Computer scientists have taken inspiration in developing problem solving systems
- Ant Colony Optimization has been applied to:
  - TSP
  - Scheduling
  - Network routing
  - Graph coloring
  - Many many other combinatorial optimization problems
- Many other swarm-inspired tools:
  - Particle Swarm Optimization
  - Resource allocation inspired by wasps
  - Multi-robot coordination inspired by ants, wasps, bees, etc
  - Many many others

EXTRA SLIDES FOLLOW

Ant Colony System (ACS)

- Modifications to AS with new transition rule:

$$j = \begin{cases} \max_{u \in J_k^i} \left\{ \left[\tau_{ij}(t) \right] . \left[\eta_{iu} \right]^{\beta} \right\}, if\ q \le q_o \\ j' \in J_k^i, if\ q > q_o \end{cases}$$

  - j' is a city randomly selected according to the probabilistic rule of the Ant System
  - q_o is a parameter between 0 and 1
  - This helps ACS to improvise on the best solutions

Ant Colony System (ACS)

- Pheromone update rule (new):

$$\tau_{ij}(t) = (1-\rho)\cdot\tau_{ij}(t) + \rho\cdot\Delta\tau_{ij}(t)$$

  - Only applied to the best ant.
- The change in the pheromone:

$$\Delta\tau_{ij} = \frac{1}{L}$$

  - (i,j) edges of the best tour
  - ρ parameter governs pheromone decay
  - L length of the best tour
- Local update rule
  - L_{nn} length of the nearest neighbor tour

$$\tau_{ij}(t) = (1-\rho)\cdot\tau_{ij}(t) + \frac{\rho}{n\cdot L_{nn}}$$

Ant Colony System (ACS)

- Other methods for improvement
  - Use a local search method in conjunction with ACS-TSP.
  - Elitism, worst tours (pheromone removed), local search enhancement.
- Has been shown to be comparable to the best techniques available