DIVISION OF LABOR AND THE THRESHOLD MODEL

Mauro Birattari

DOL IN HUMAN SOCIETIES

Advantages:

- Reduction of switching costs
- Specialization

Disadvantages:

- Physical/mental stress
- Alienation

DOL IN INSECT SOCIETIES

- Temporal polyethism: age castae
- Worker polyethism: morphologial castae
- Individual variability: behavioural castae

RESILIENCY FROM PLASTICITY:

DoL is rarely rigid

Key feature of DoL in insect societies.

Resilience is what makes DoL in insects so interesting for us

- Food availability, predation, climatic and environmental conditions affect DoL

- Re-allocating individuals to tasks is one of the main way used by insect colonies to react to contingencies

WILSON'S EXPERIMENT

Wilson, 1984

Pheidole genus exhibits morphological polyethism:

- Minors — most of day-to-day tasks
- Majors (a.k.a. soldier) — defense, seed milling...

Majors exhibit elasticity: can take most of minor's tasks
if ratio of minors is too low - this makes plasticity possible

Wilson has artificially modified the ratio of minors in the colony

RESPONSE THRESHOLDS

Bonabeau et al., 1996

Simple model to explain Wilson's observations:

- Each task has an associated stimulus
- Each individual has a response threshold to each task
- An individual engages in a task if stimulus exceeds its threshold

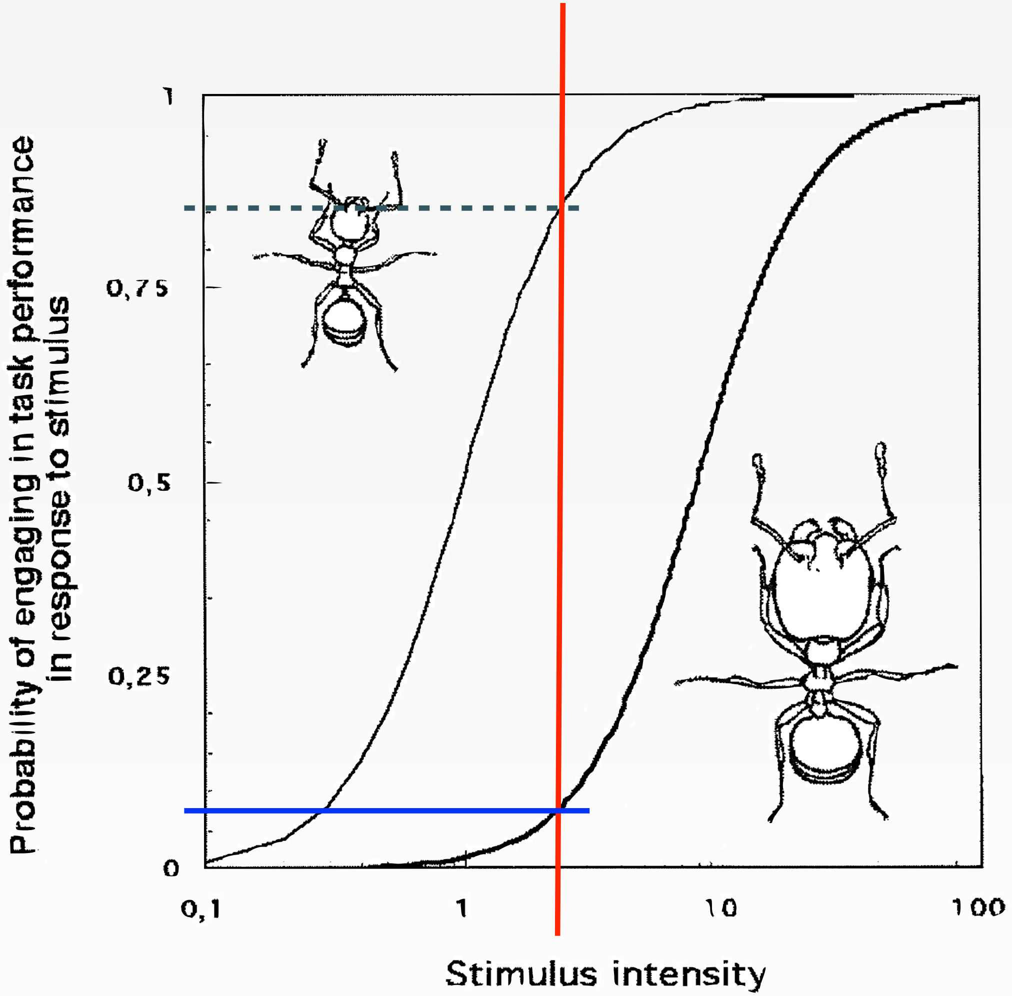
STIGMERGY IN DOL

Actions of an individual modify the stimulatory field of nestmates and, as a consequence, their activity

Example: Larval feeding

- Larval feeding. Larvae demand being fed by emitting pheromone
- When pheromone exceeds a threshold caretakers feed them
- This reduces larval demand and decreases pheromone level
- Some caretakers move to different activities
- When larvae are hungry again, they will resume emitting pheromone...

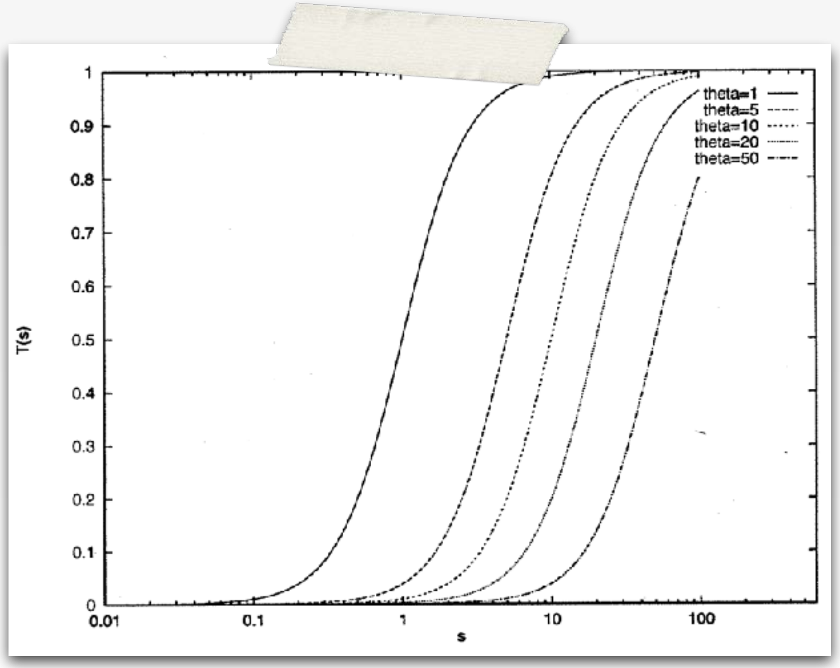
ON WILSON'S...



Majors have a higher response threshold than minors for day-to-day tasks

A SIMPLE THRESHOLD MODEL

$$T_\theta(s) = \frac{s^n}{s^n + \theta^n}$$



n=2, different theta

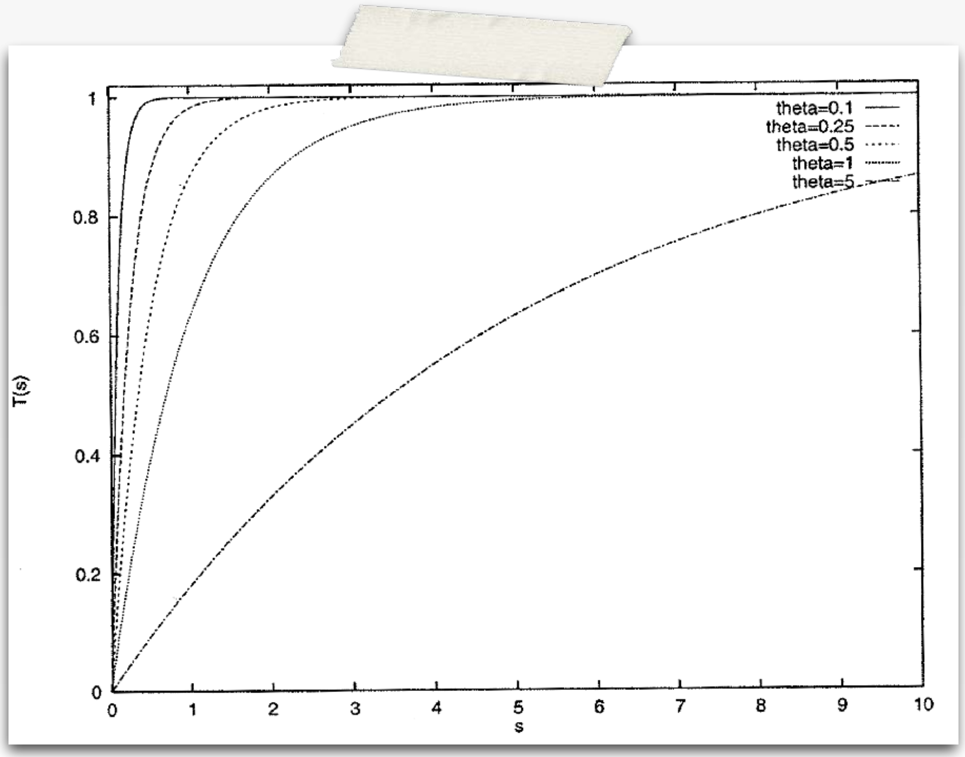
s: stimulus associated to a task

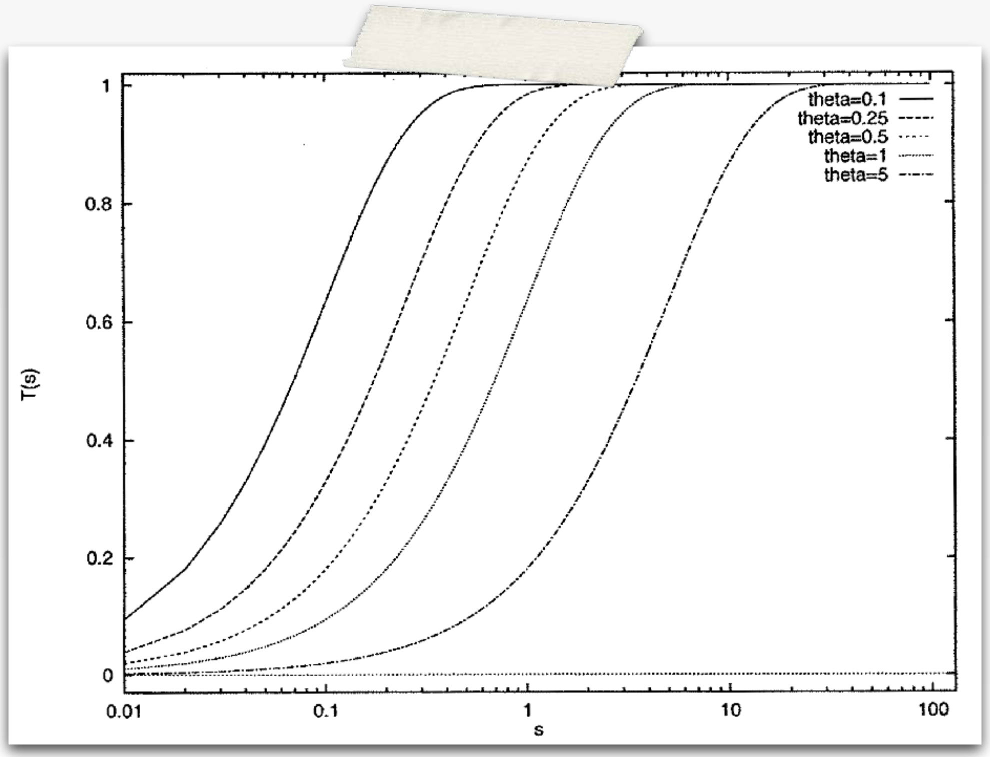
θ: threshold

T: probability of engaging in task

ANOTHER MODEL

$$T_\theta(s) = 1 - e^{-s/\theta}$$





(same plot, but in logarithmic scale)

IN THE FOLLOWING WE FOCUS ON THE SIMPLE THRESHOLD MODEL:

$$T_\theta(s) = \frac{s^n}{s^n + \theta^n}$$

MODEL OF WILSON'S

Bonabeau et al., 1996

- Probability of engaging in task, per time unit:

$$P(X_i = 0 \to X_i = 1) = T_{\theta_i}(s) = \frac{s^2}{s^2 + \theta_i^2}$$

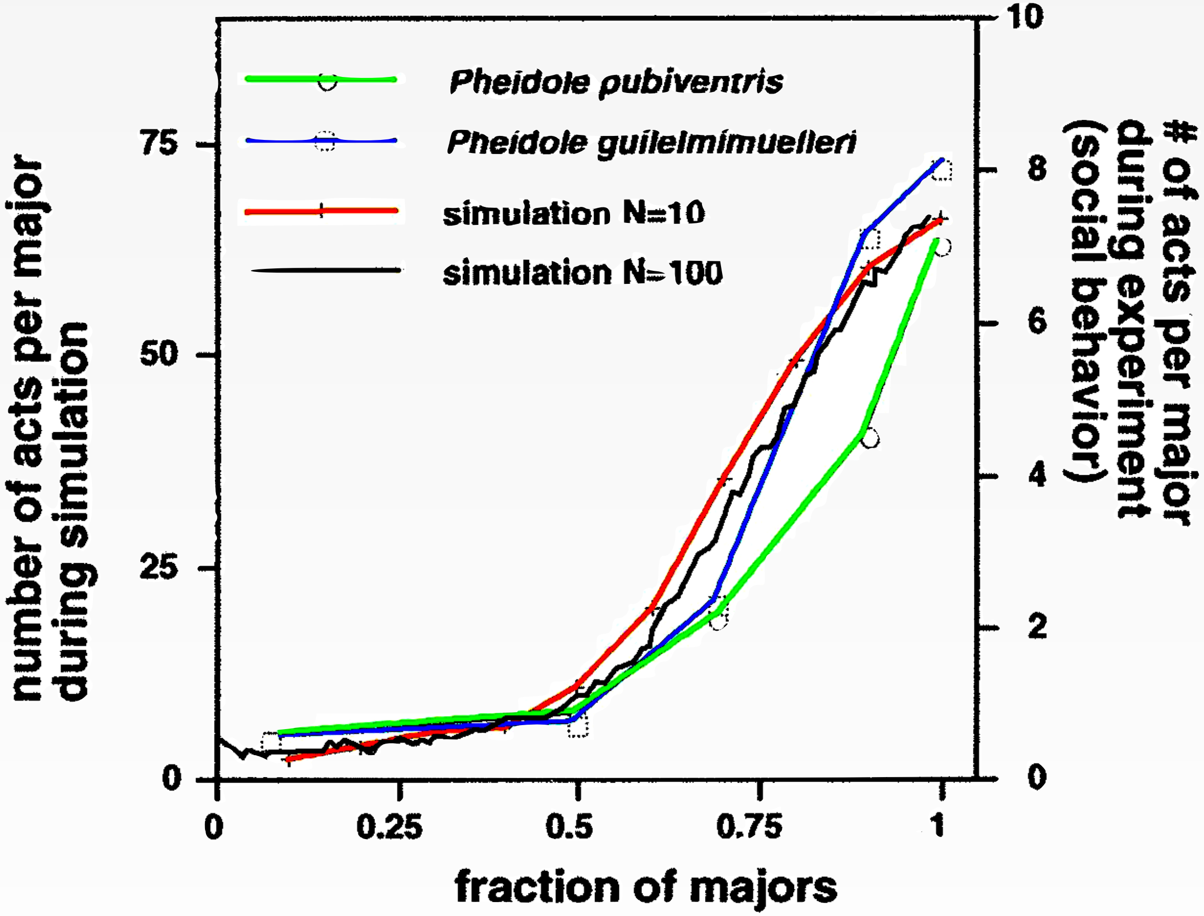
- Probability of quitting task, per time unit:

$$P(X_i = 1 \to X_i = 0) = p$$

- Dynamics of the stimulus:

$$s(t+1) = s(t) + \delta - \alpha \frac{N_{act}}{N}$$

MONTE CARLO SIMULATION



Close fit of real ants data for <u>*short time scales*</u>

SPECIALIZATION

- Real insects learn: by executing a task over and over, they improve their performance
- The fixed threshold model can be extended by allowing the threshold to vary in time
- Threshold adaptation can lead to specialization out of an initially homogeneous population
- The adaptive threshold model closely match real ants data collected over *long time scales*

GROUP FORAGING

Krieger and Billeter, 1998

- Goal:

  DEMONSTRATE SELF-ORGANIZING TASK ALLOCATION BASED ON FIXED BUT DIFFERENT RESPONSE THRESHOLDS

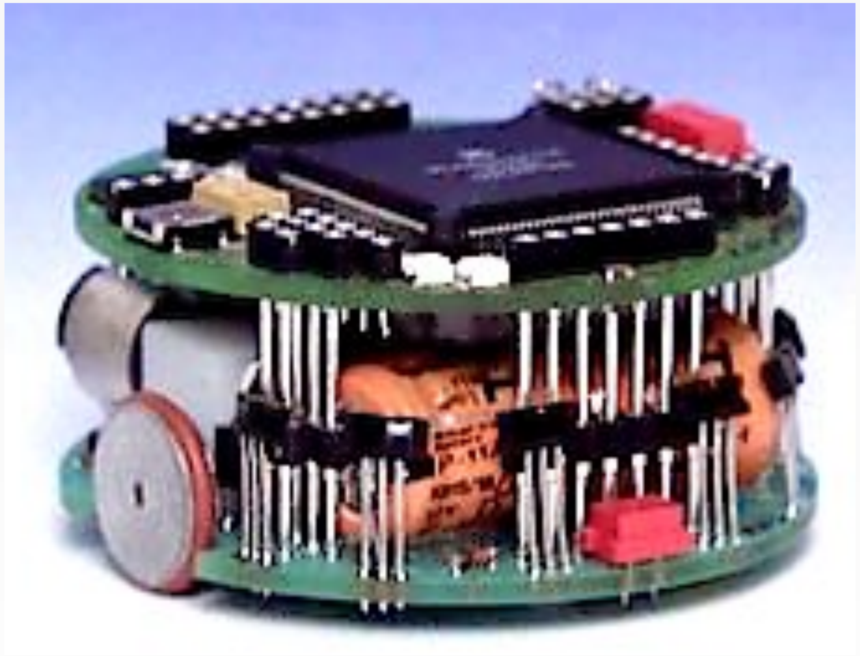
- Robot Mission:

  Collect food (seeds) so that a minimum nest energy level is maintained

Robots communicate stigmergically: The nest energy level is the stigmergic variable

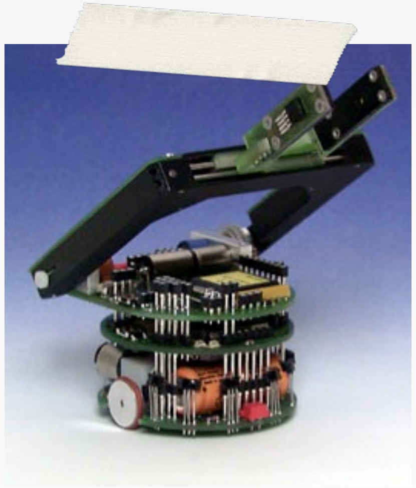
THE KHEPERA ROBOT

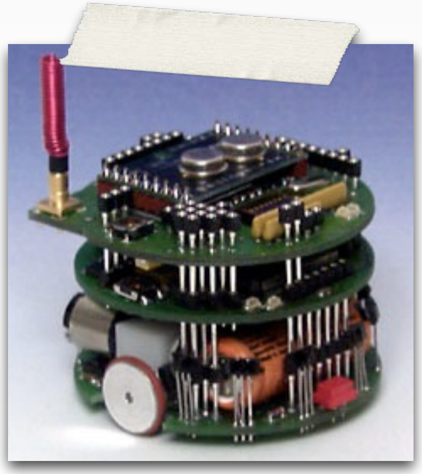
- Basic module (Ø 55 mm)
  - 68331 processor, 256 Kb RAM, 45 min autonomy, 2 DC motors, 8 infrared proximity and light sensors



MODIFICATIONS OF THE KHEPERA

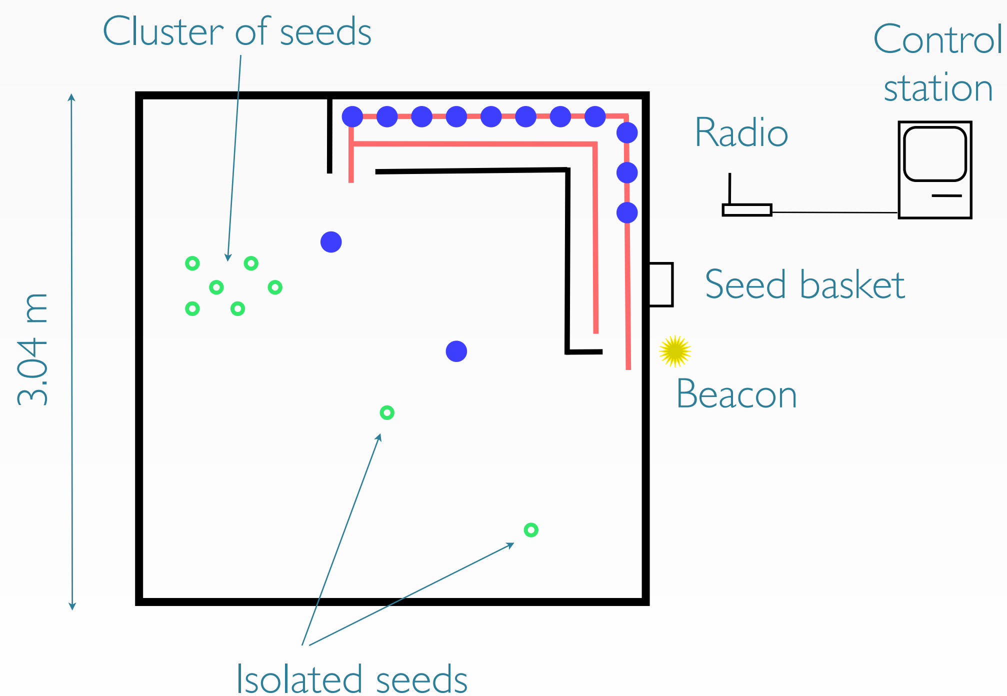
- Modified base: 4 floor contacts for continuos power supply, 3 floor-oriented infrared sensors
- Gripper turret
- Detection module: To distinguish walls, food items, and other robots
- Radio Module: 418 MHz transceiver, RS232 protocol



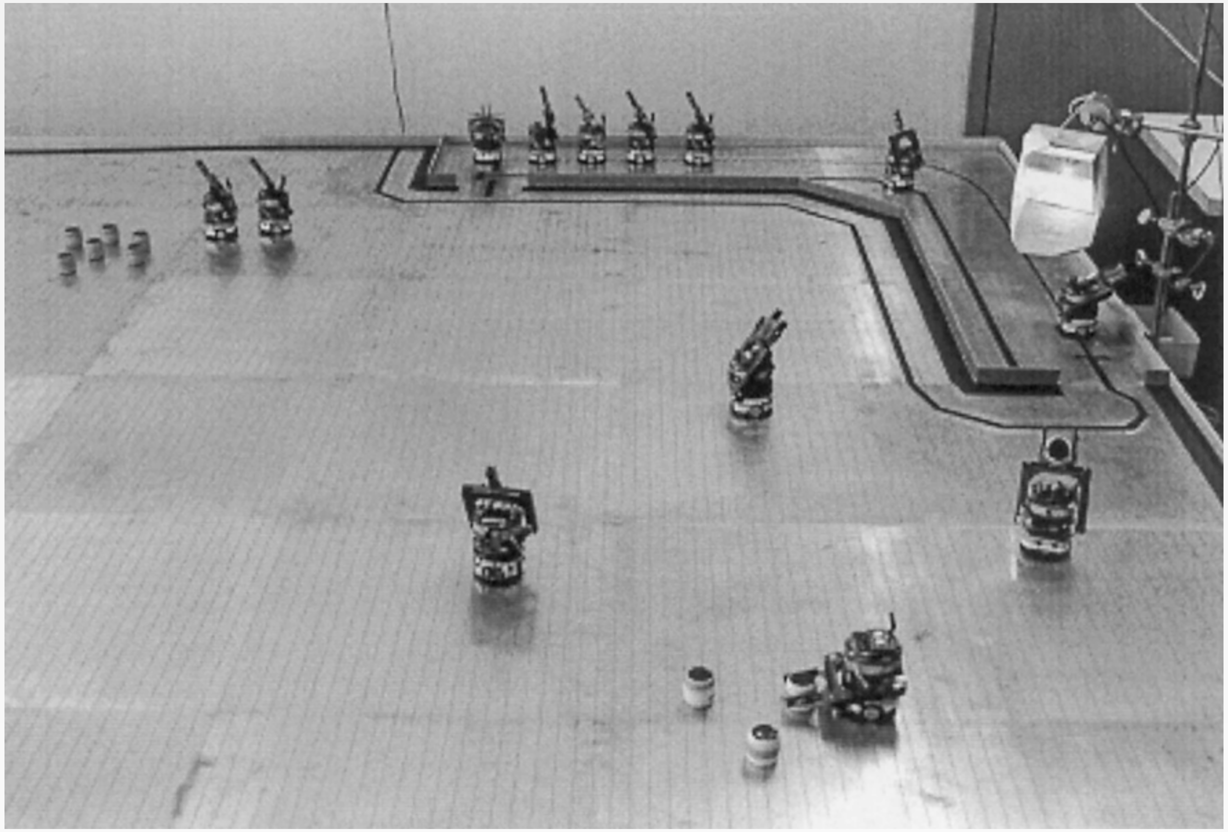


BASIC MISSION CYCLE

- Wait in nest: exchange info on energy level with radio station
- If nest energy level < threshold, then leave nest
- Look for seeds: use either random search or odometry
- Load seed
- Return to nest
- Unload seed

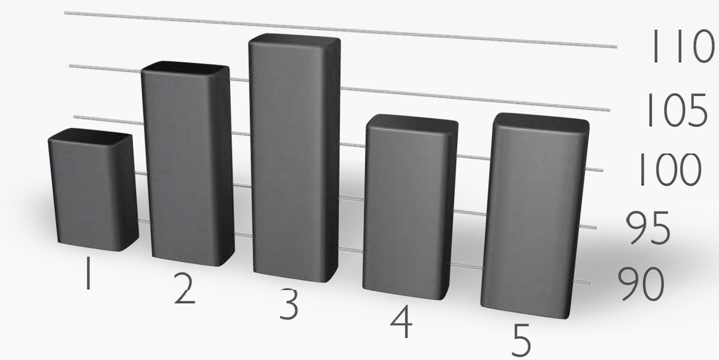


THE EXPERIMENT



Effect of Group Size on Performance

performance=inverse of total energy used



Implications for Applications

- Incremental addition of new robots without need of reprogramming
- Self-adaptation to robot failures
- In case of multiple tasks: self-adaptation to tasks demands

ADAPTIVE POSTMEN ALLOCATION

Bonabeau et al., 1997

- Task:

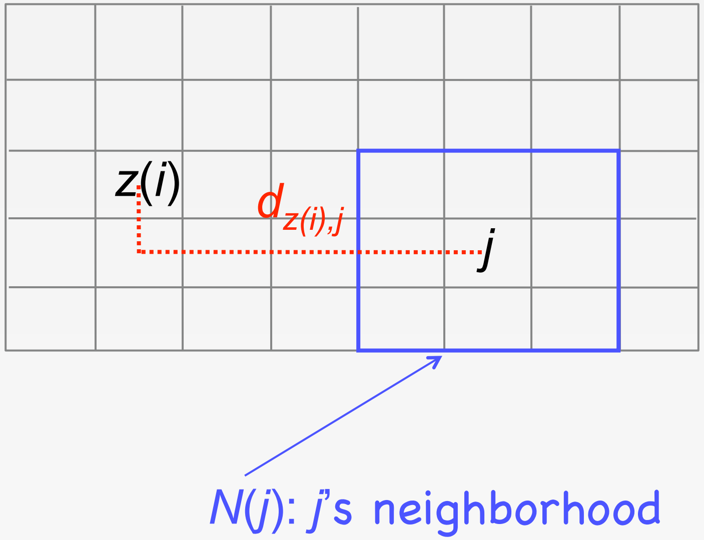
  A GROUP OF MAILMEN PICK UP LETTERS IN A BIG CITY

- Goal:

Allocate mailmen to city zones minimizing a cost function (e.g., the customers waiting time)

Coordination is achieved stigmergically: The level of customers demand is the <u>stigmergic variable</u>

THE PROBLEM



Let the city be divided in a number of zones

$z(i)$: location of mailman i

S_j: demand in zone j

$d_{z(i),j}$: distance between mailman i and zone j

θ_{ij} : threshold of mailman i for zone j

α, β: parameters

$P_{i,j}$: prob. mailman i responds to demand in zone j

$$P_{i,j} = \frac{S_j^2}{S_j^2 + \alpha\theta_{i,j}^2 + \beta d_{z(i),j}}$$

THRESHOLD ADAPTATION

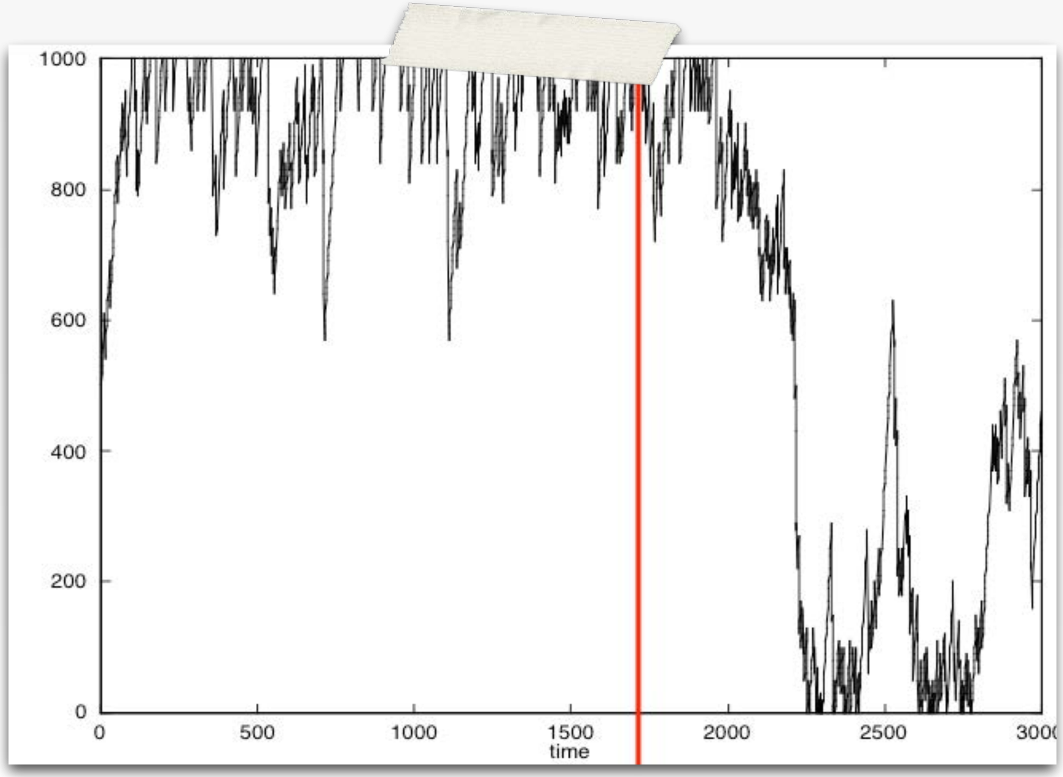
When mailman ***i*** allocates itself to zone ***j***

- He is unavailable for the time needed to reach zone ***j***
- The demand associated to zone ***j*** remain 0
- Agent's thresholds are updated as follows:

$$\begin{aligned}
\theta_{i,j} &\leftarrow \theta_{i,j} - \xi_0 \\
\theta_{i,n} &\leftarrow \theta_{i,n} - \xi_1, \qquad \forall n \in N(j),\ \xi_0 > \xi_1 \\
\theta_{i,k} &\leftarrow \theta_{i,k} + \phi, \qquad \forall k \neq j, k \notin N(j)
\end{aligned}$$

EXPERIMENTAL RESULTS

- The system shows self-adaptation
- Response thresholds adapt to changing conditions



E.g., dynamics of a particular individual's response threshold with respect to the zone from which a specialist is removed

IMPLICATIONS FOR APPLICATIONS

- The example has shown the viability of the approach
- It can be applied to other problems such that:
  - Demand S_j (i.e., the <u>*stigmergic variable*</u>) can be an abstract demand associated to a generic task j
  - θ_{ij} can be the response threshold of agent i relative to task j stimulus
  - $d_{z(i),j}$ can be an abstract distance between i and task j (e.g., it can represent the ability of agent i to perform task j)

DOL AND INTERFERENCE

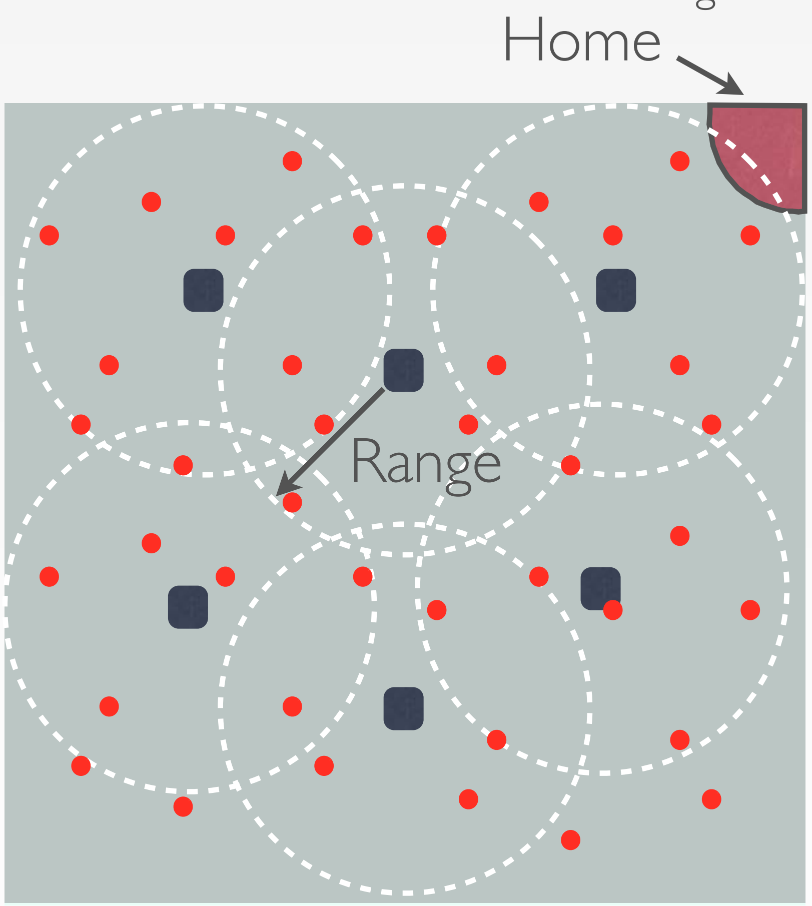
- A possible down side of the swarm intelligence approach is interference among agents
- DoL can be an effective way to reduce interference in a swarm
- Idea: Constraint agents to operate in a specific region

INTERFERENCE IN A SWARM OF FIREFIGHTERS!!!

BUCKET BRIGADE

BUCKET BRIGADE IN ROBOTICS

Østergaard et al., 2001; Shell and Mataric, 2006; Lein and Vaughan, 2008



- Spatio-temporal interference around home
- To reduce interference, robots act in a limited region
- Method relies on even distribution of robots

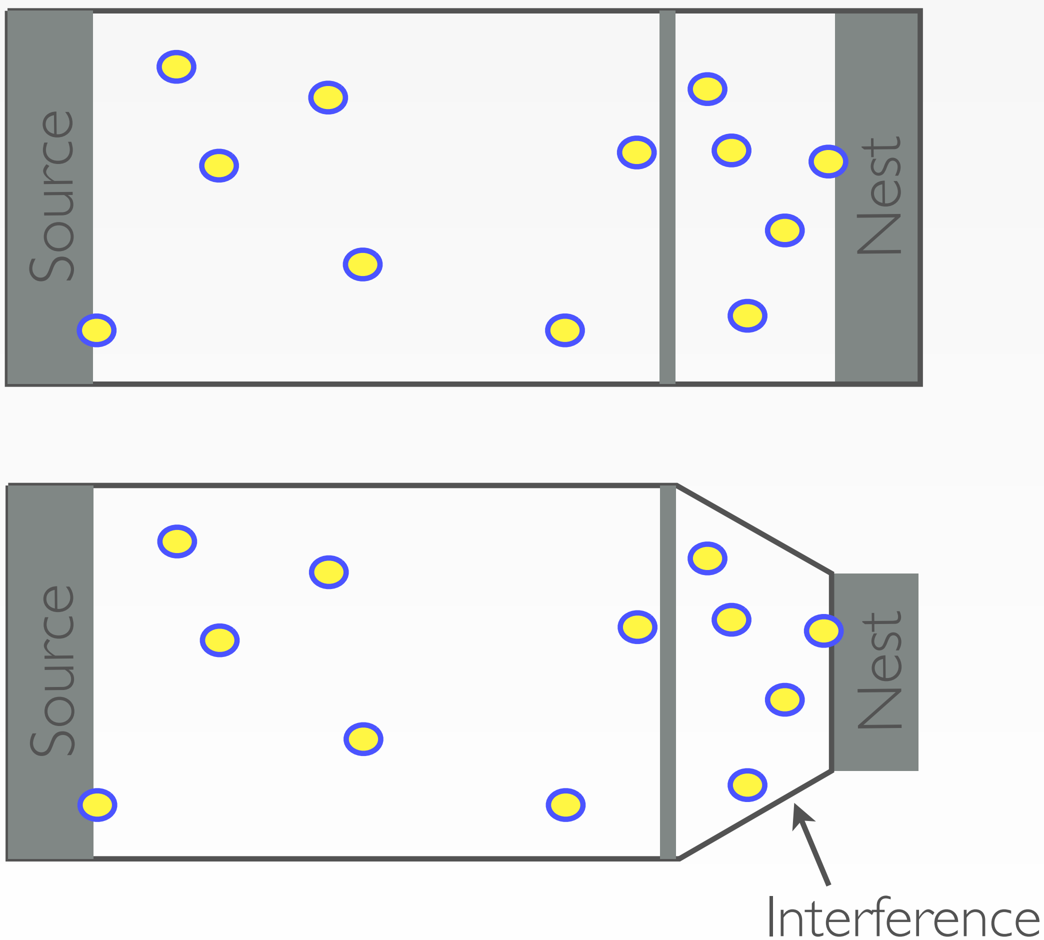
Retrieve objects Unconstrained movement: Robots interfere

Idea: Constrain range of robots Interference is reduced

DOL TO REDUCE INTERFERENCE

Pini et al., 2009

Transport objects from source to nest



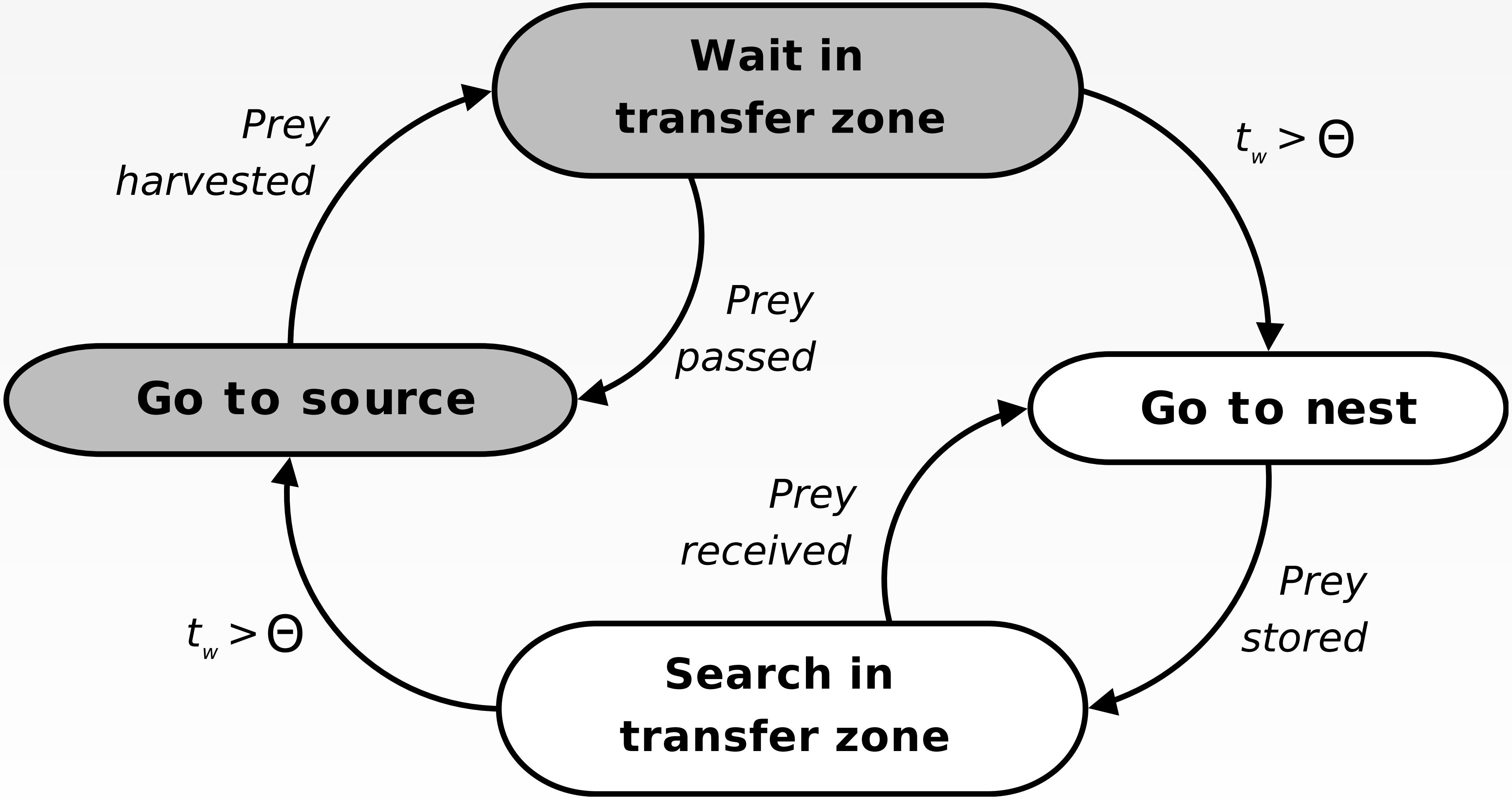
Partition the task in order to avoid interference in the nest area

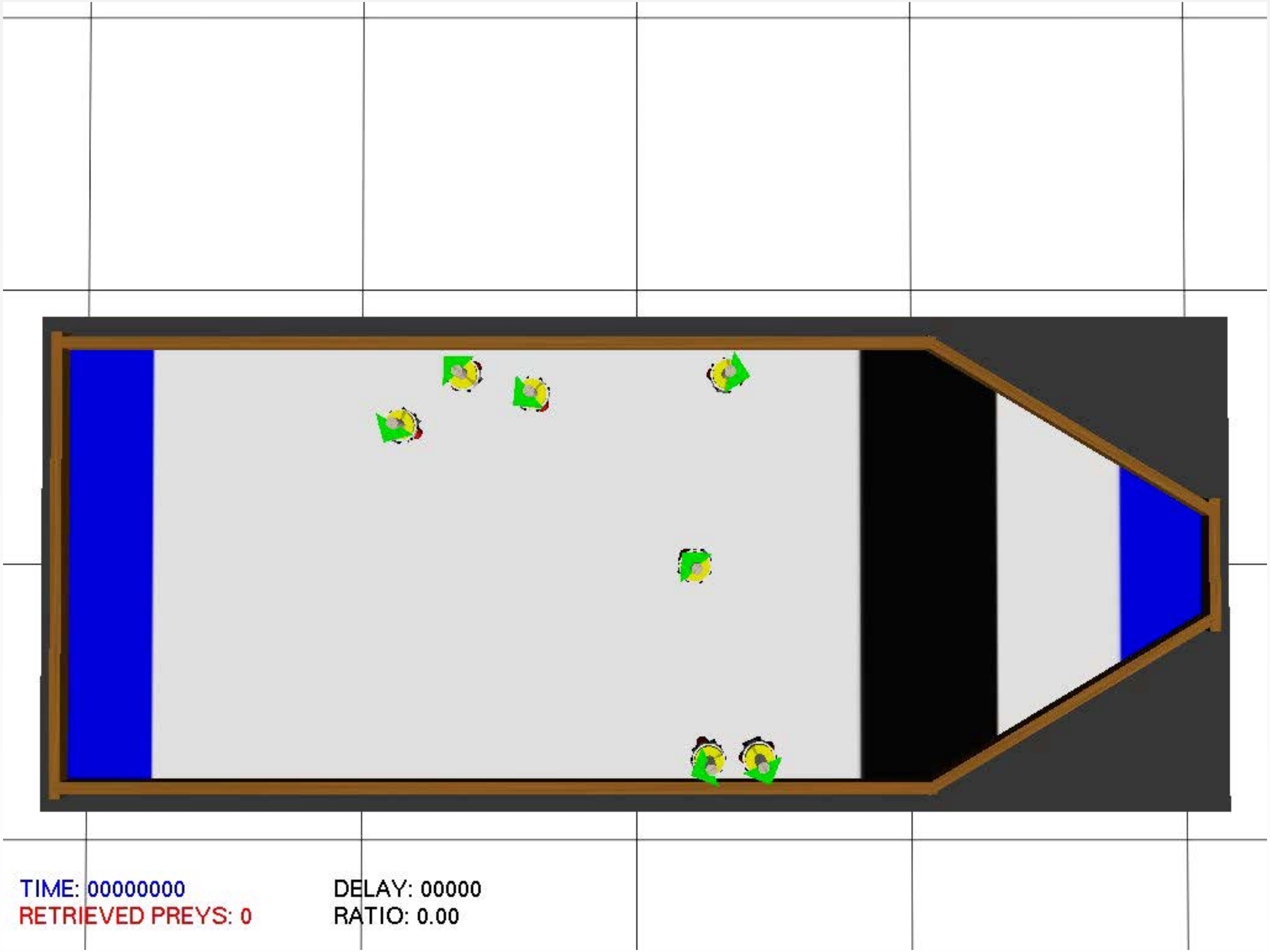
Wait at the exchange area to hand over the item

Task allocation is dynamic: if waiting time is to long, switch to the other task

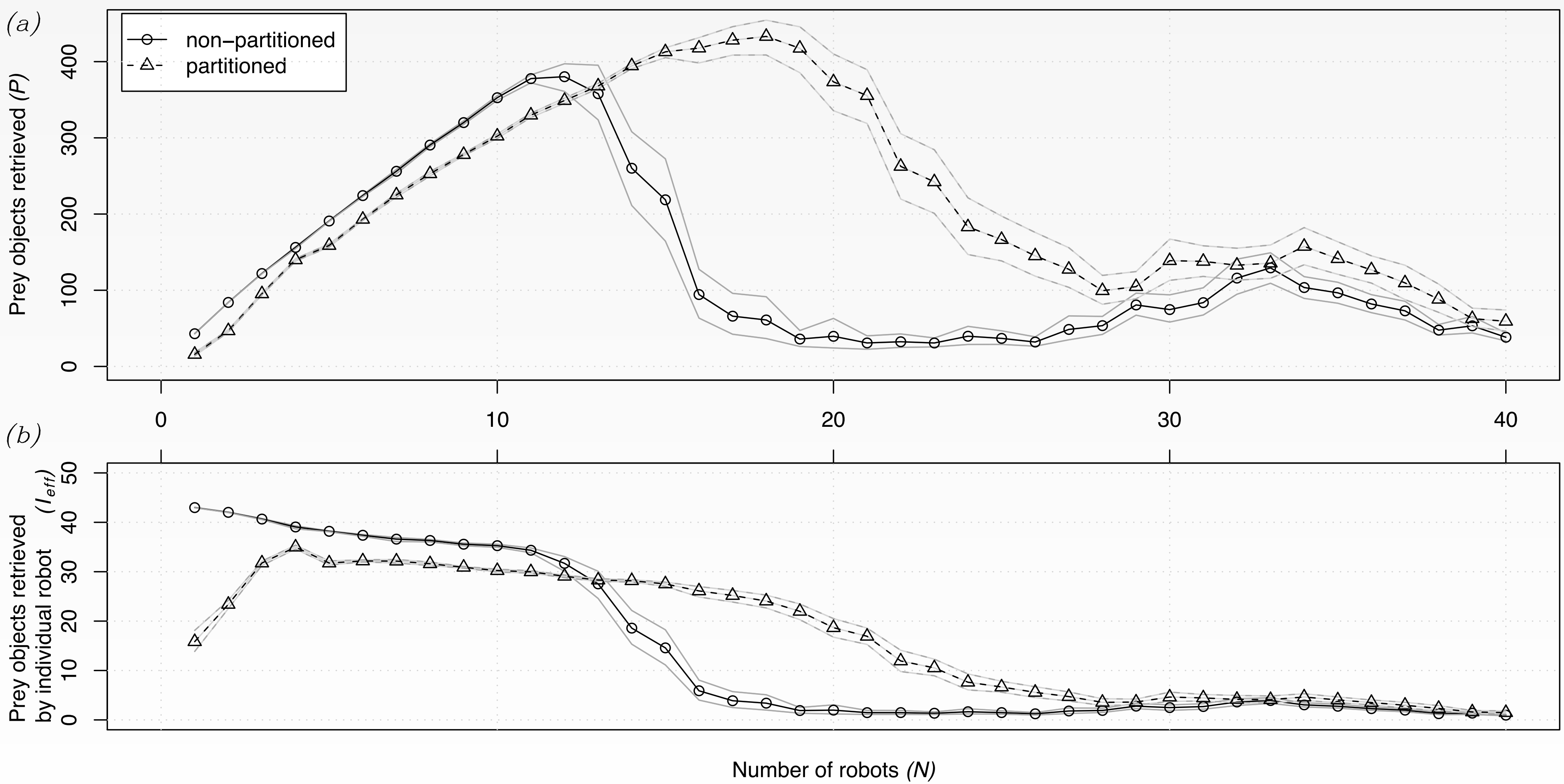
THE CONTROLLER

Pini et al., 2009

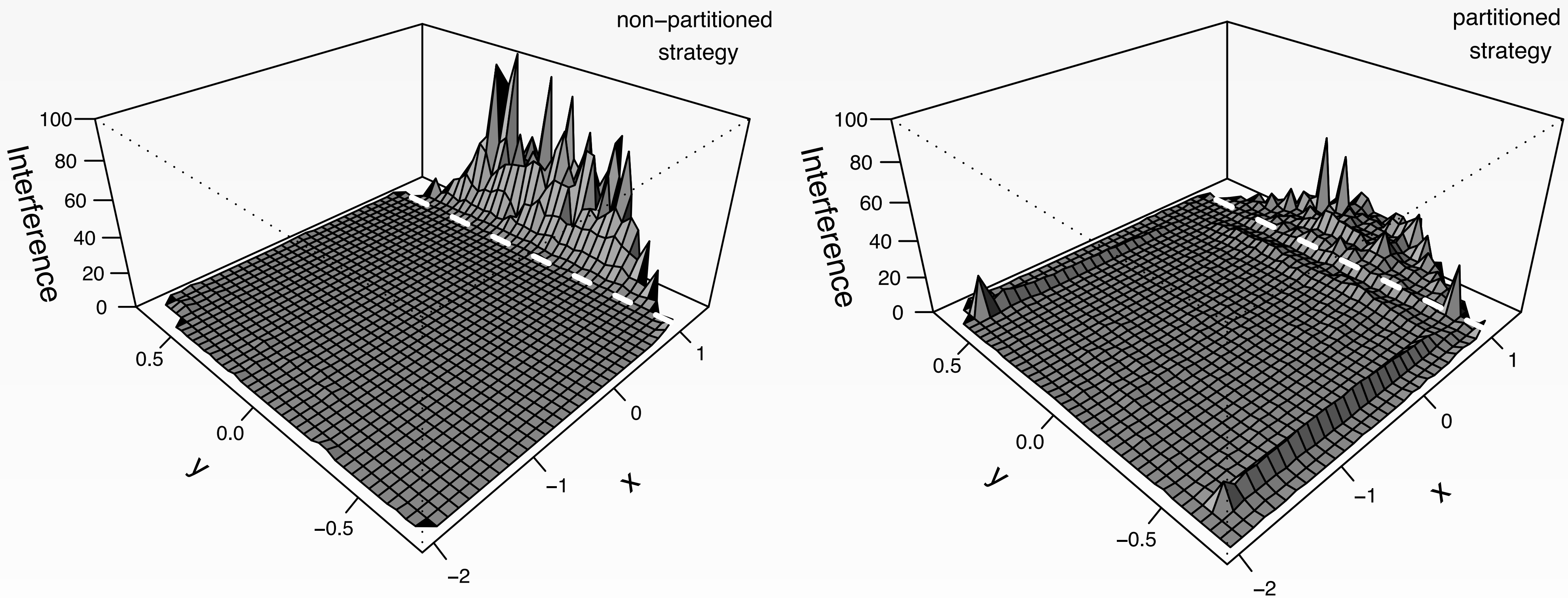



TIME: 00000000
RETRIEVED PREYS: 0
DELAY: 00000
RATIO: 0.00

PERFORMANCE ANALYSIS



INTERFERENCE REDUCTION



SELF-ORGANIZED TASK PARTITIONING IN A ROBOT SWARM

Frison et al., 2010; Pini et al. 2011; Pini et al. 2013

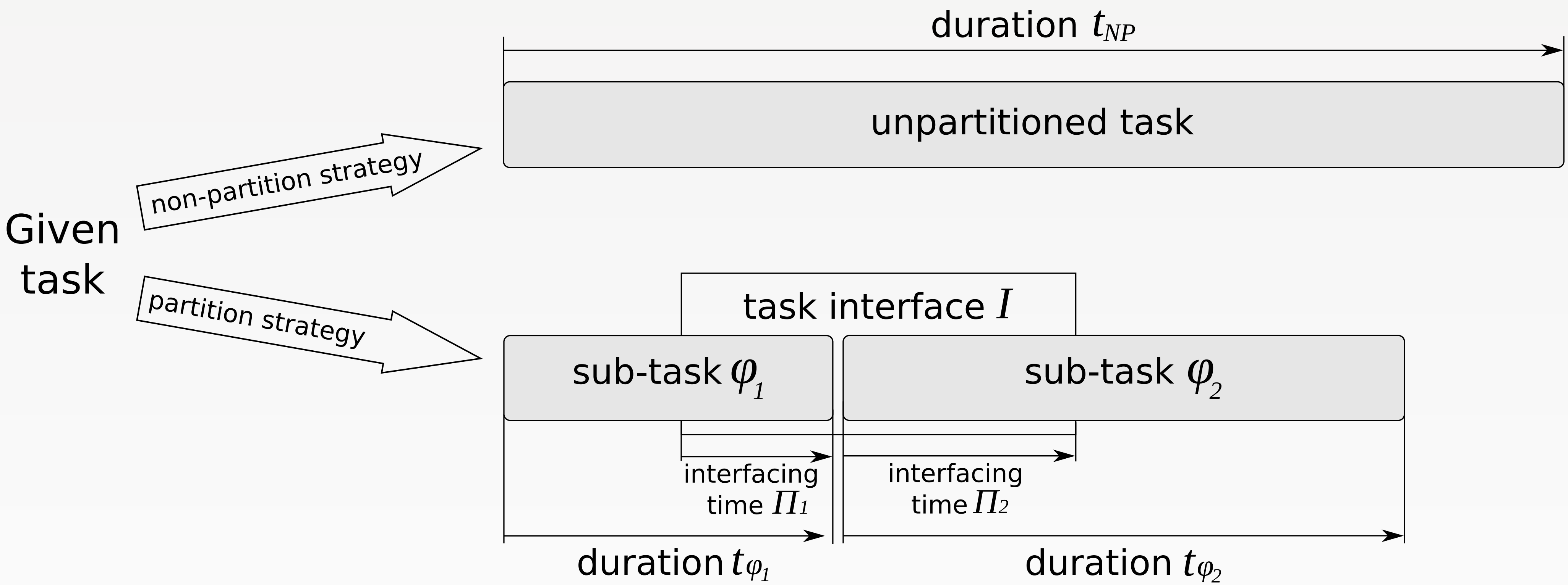
Goal:

Define an adaptive method for partitioning a task into 2 sequential subtasks

In Nature:

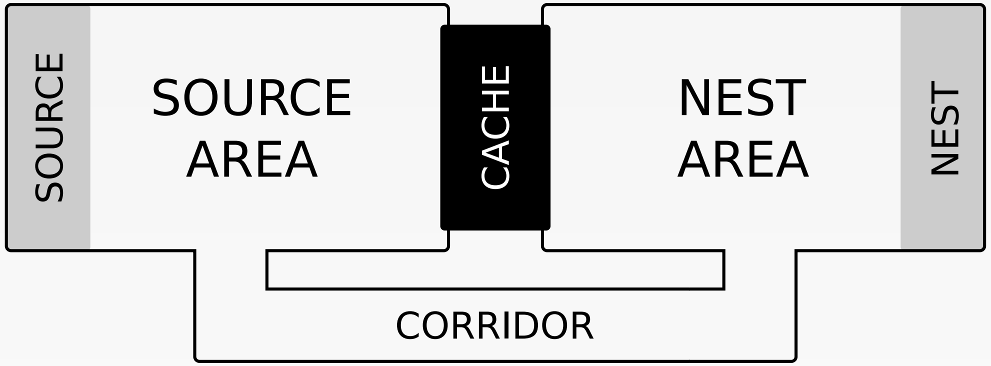
Atta colombica leaf cutting ants

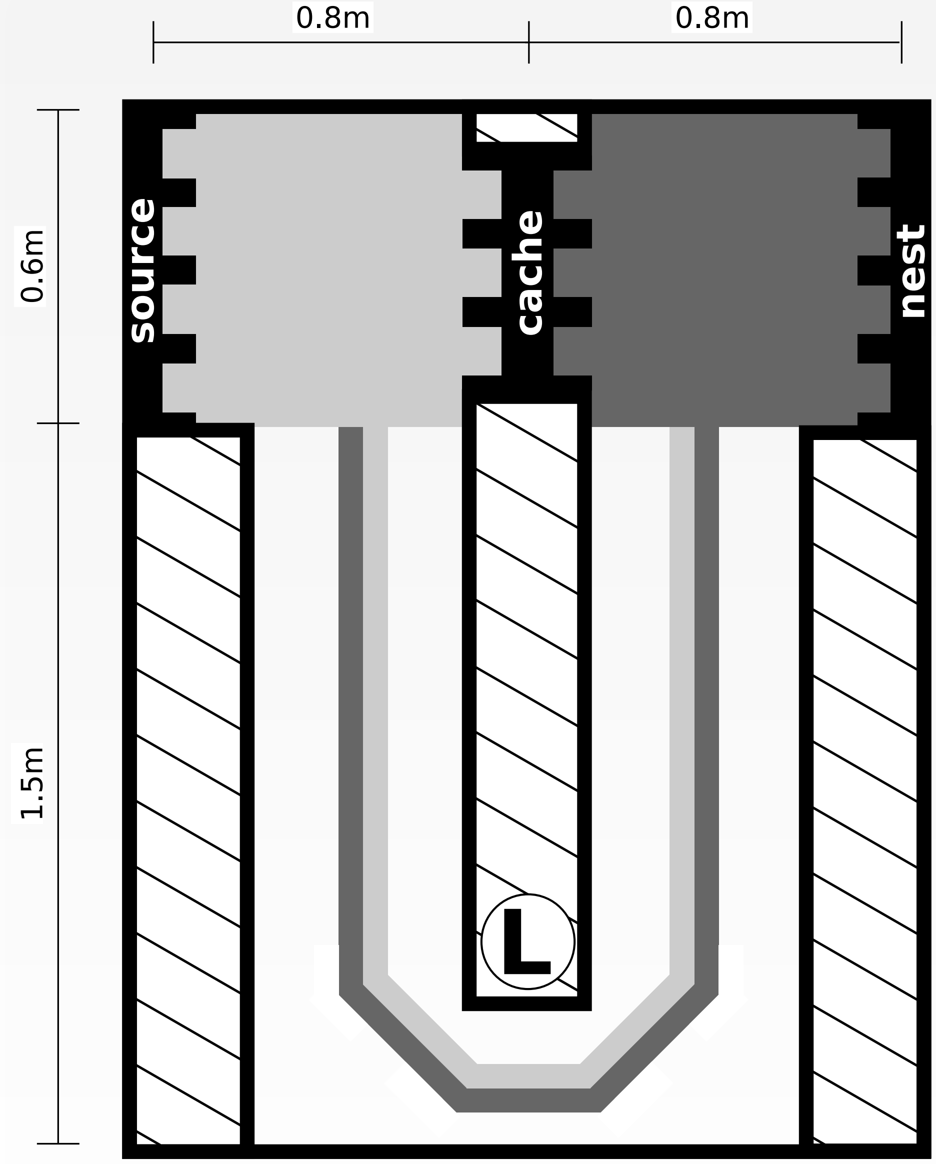
TASK PARTITIONING



EXPERIMENTAL SETUP

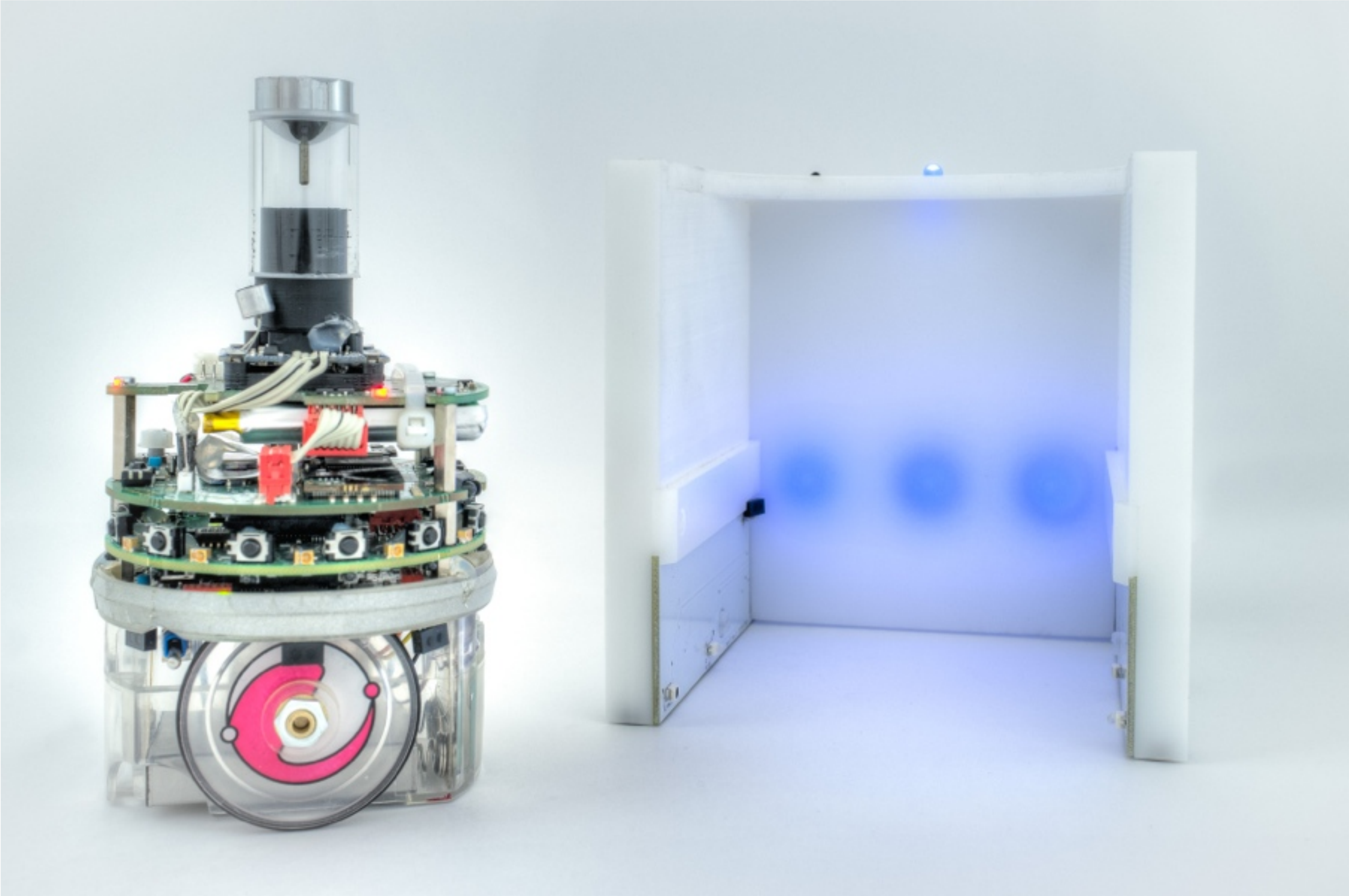
harvest prey from a source,
store them in the nest



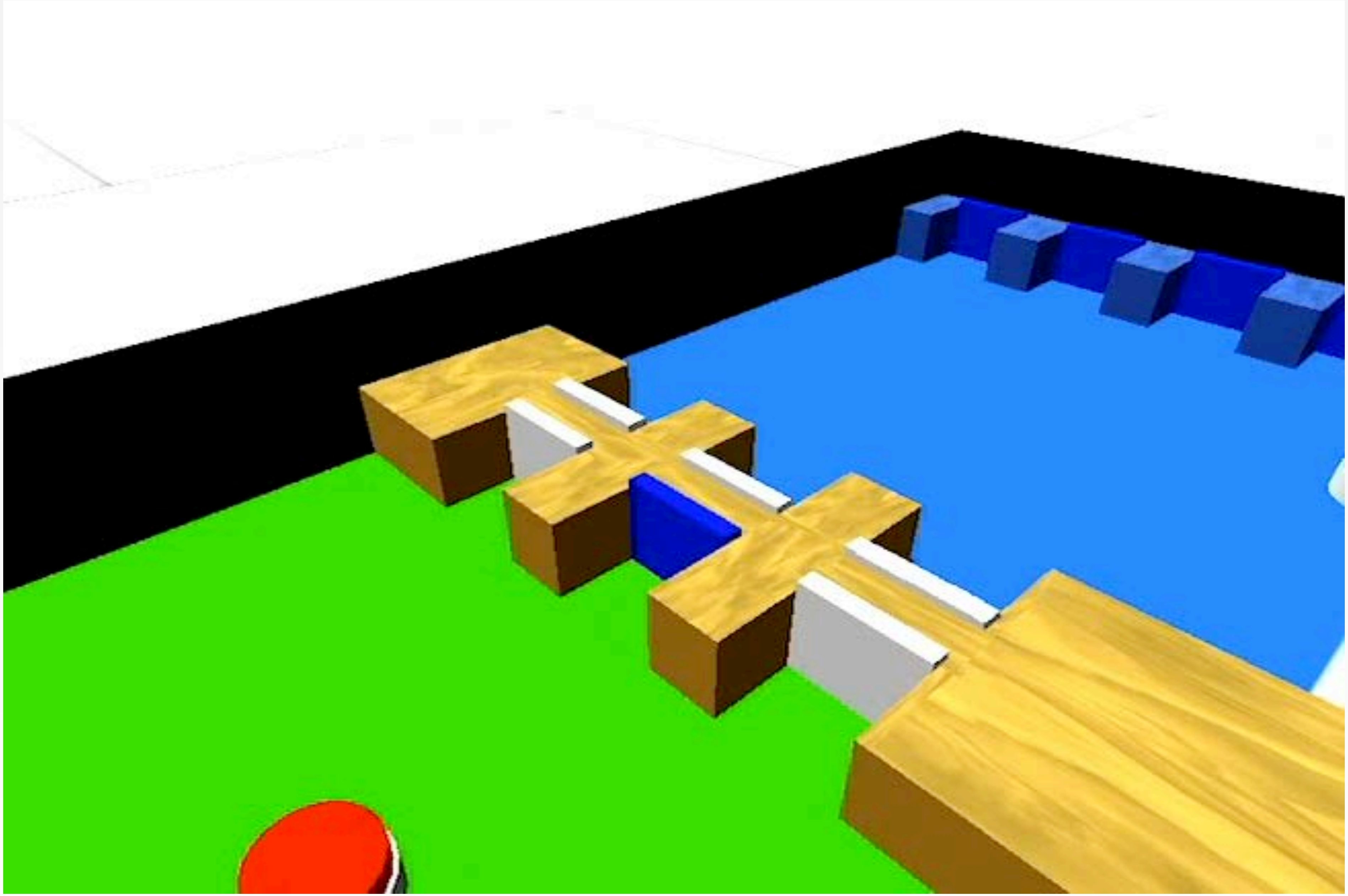


- Task: Source -> Nest
- Sub-Task 1: Source -> Cache
  Sub-task 2: Cache -> Nest

use the cache: partition the task



E-PUCK AND TAM



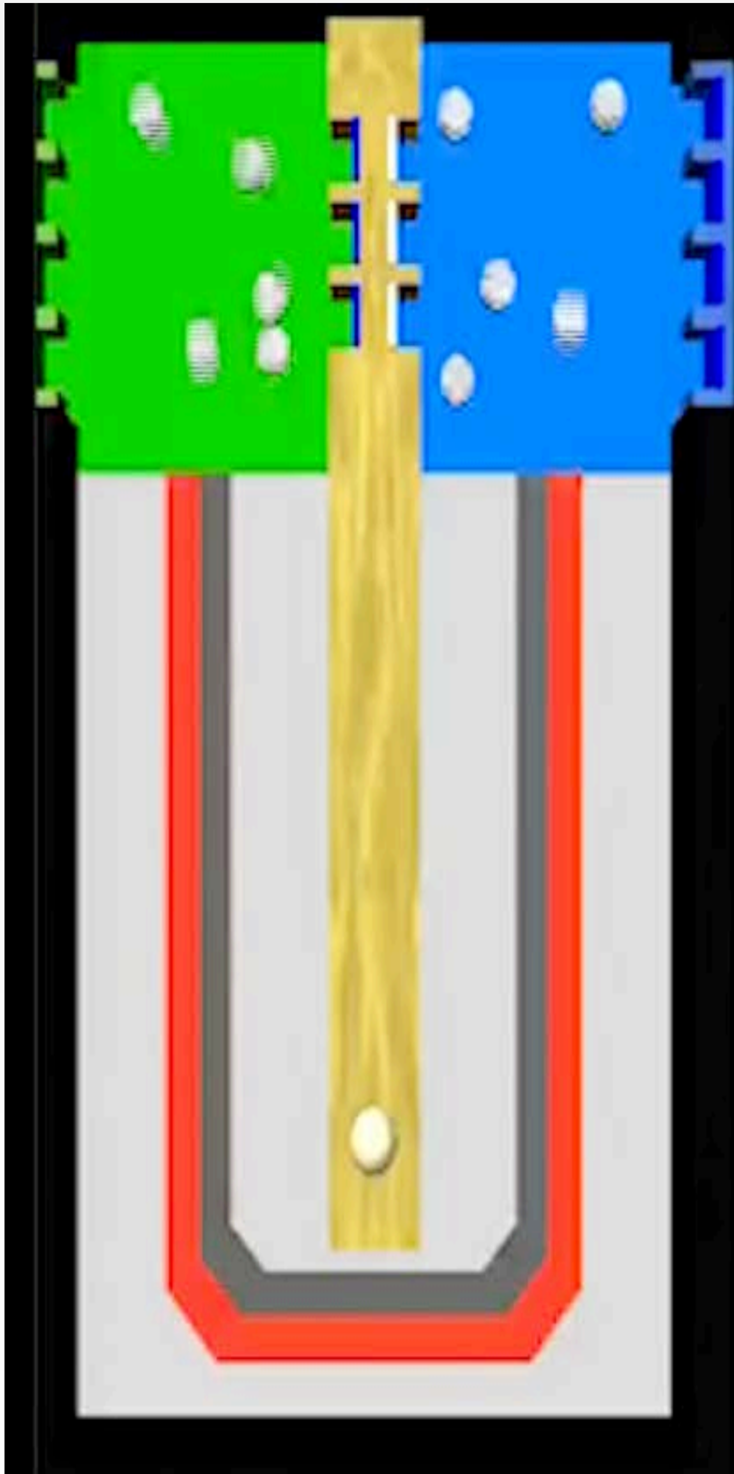
THE TAM

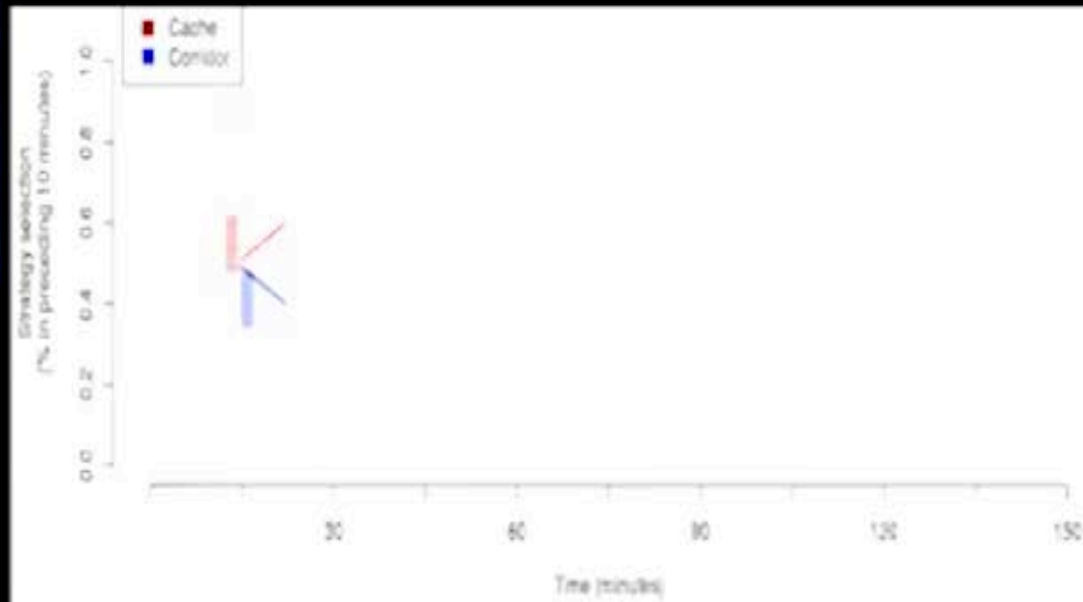
THE METHOD

Probability of partitioning:

$$P_p = \begin{cases} \left[1 + e^{-S\left(\hat{t}_{NP}/\left(\hat{t}_{\varphi_1} + \hat{t}_{\varphi_2}\right) - 1\right)}\right]^{-1}, & \text{if } \hat{t}_{NP} > (\hat{t}_{\varphi_1} + \hat{t}_{\varphi_2}) \\ \left[1 + e^{-S\left(1 - \left(\hat{t}_{\varphi_1} + \hat{t}_{\varphi_2}\right)/\hat{t}_{NP}\right)}\right]^{-1}, & \text{if } \hat{t}_{NP} \leq (\hat{t}_{\varphi_1} + \hat{t}_{\varphi_2}) \end{cases}$$

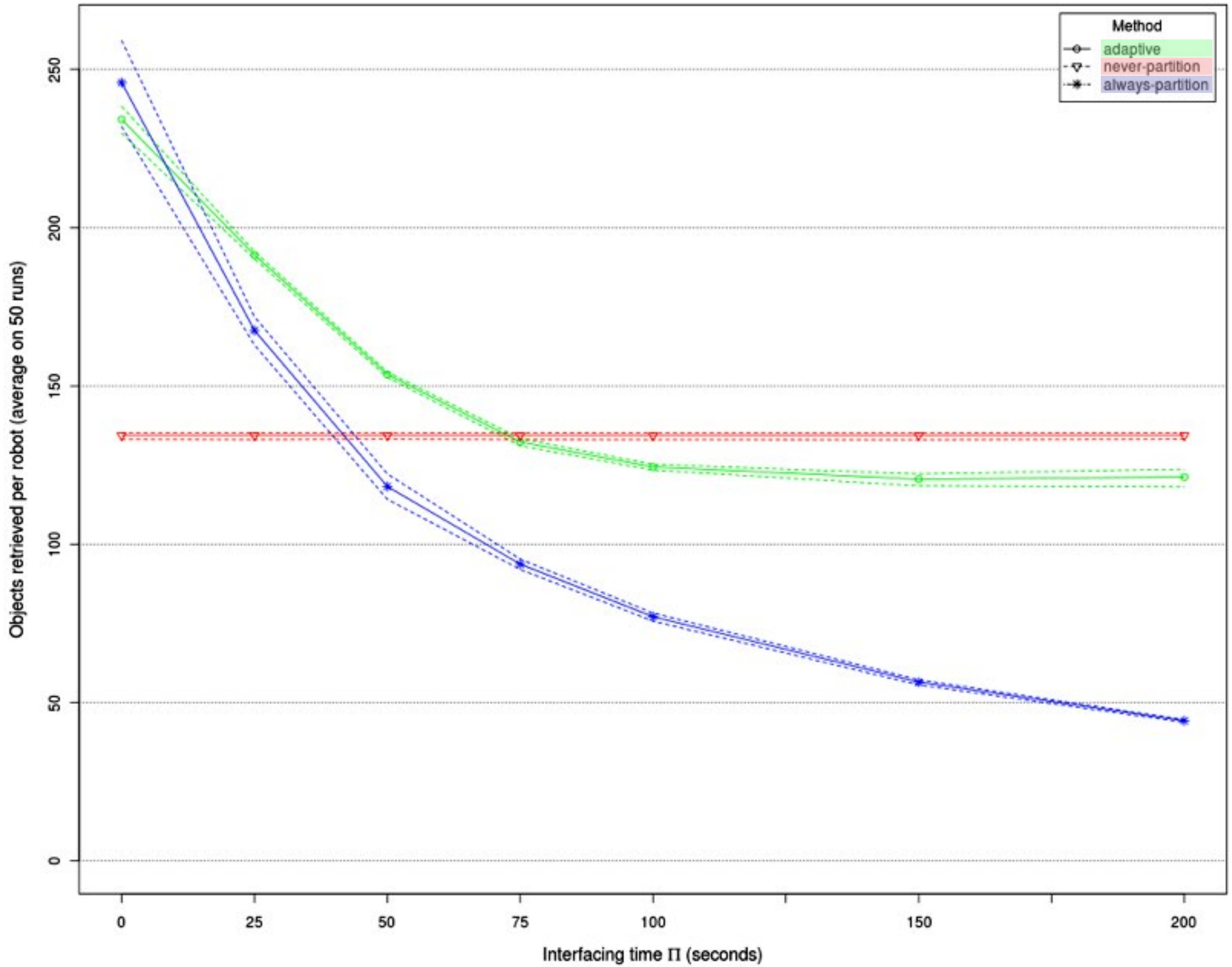
where $\hat{t}_{NP}$, $\hat{t}_{\phi_1}$, and $\hat{t}_{\phi_2}$ are estimates of the time needed to carry out the whole unpartitioned task, subtask 1 and subtask 2, respectively.





The **video** on the left shows the first 150 minutes of an experimental run. The interfacing time *IT* is null, the robots are marked in red when carrying an object. The video is 12.5 times faster than real time.

The **graph** on top plots the percentage of usage of each strategy in time, for the experimental run shown in the video. Each point in the graph refers to the 15 minutes preceding the value reported on the X axis. The red line reports the **percentage of usage of the cache,** the blue line the **percentage of usage of the corridor** (that includes the give up at the cache). The box plot in the background provides a summary of 50 experimental runs, with *IT*=0.


Method
adaptive
never-partition
always-partition
Objects retrieved per robot (average on 50 runs)
0
50
100
150
200
250
0
25
50
75
100
150
200
Interfacing time Π (seconds)

DOL IN SWARM INTELLIGENCE: CONCLUDING STATEMENTS

- Plasticity and adaptability are desired features in applications
- DoL is a characterizing feature in social animals
- Simple threshold models explain DoL
- Specialization can be obtained by varying response thresholds
- DoL can be used to reduce interference