# Introduction to Multi-Agent Programming

## 12. Swarm Intelligence

Flocking, Foraging, Ant Systems, TSP solving

*Alexander Kleiner, Bernhard Nebel*

# Contents

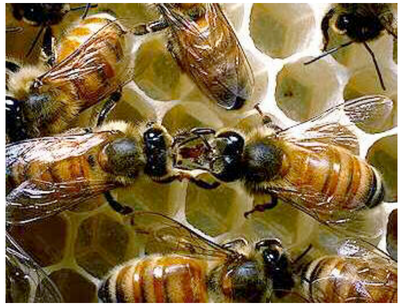
- Introduction
- Swarming & Flocking
- Foraging strategies in ants
- Ant System: Solving TSPs
- *Case-study*: Team coordination of virtual robots
- Summary

# Introduction

- What is swarm intelligence ?
- Swarm intelligence is motivated from insects
  - Colonies of social insects can achieve flexible, intelligent, and complex system level performance from stereotyped, unreliable, unintelligent, and simple elements
  - Insects follow simple rules, use simple local communication (scent trails, sound, touch) with low computational demands
  - Global structure (e.g. nest) reliably *emerges* from the unreliable actions of many
- The modeling of social insects by means of self-Organization can be utilized to motivate the design of methods for distributed problem solving, known as Swarm Intelligent Systems

# Introduction
## Biological Inspiration

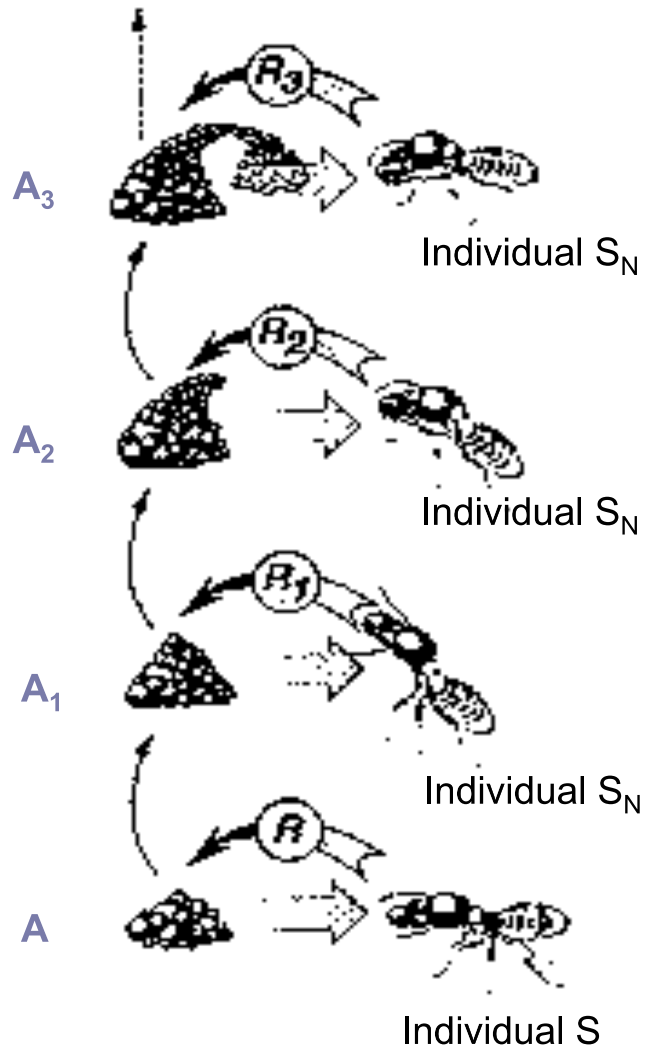
- Bees:
  - Communicate the distance and bearing of food sources by dancing
  - Food sources are exploited according to quality and distance from the hive
- Termites
  - Build large cone-shaped outer walls with ventilation ducts
- Ants
  - Leafcutter ants (*Atta*) cut leaves from plants to grow fungi
  - Weaver ant (*Oecophylla*) workers form chains of their own bodies, allowing them to cross wide gaps and to generate enough force to join leaves together. When the leaves are in place, the ants connect both edges with a continuous thread of silk emitted by a mature larva held by a worker



# Introduction
## Self-organization in social insects

- Relies on four basic ingredients:
  - Positive feedback (amplification)
    - Recruitment to a food source by laying or following a trail (e.g. ant pheromones or bee dance)
  - Negative feedback
    - Counterbalances the positive feedback
    - In form of saturation (limited number of workers), exhaustion (of the food source), or competition (crowding at the food source)
  - Fluctuation
    - Random walks, errors, random task switching
    - Can be seen as "exploration" for finding unexploited food sources
  - Multiple interactions / Stigmergy
    - Direct: antennation, food or liquid exchange, visual contact, chemical contact (the odor of nestmates), …
    - Indirect: Two individuals interact indirectly if one modifies the environment and the other one responds to this modification later in time (Stigmergy)

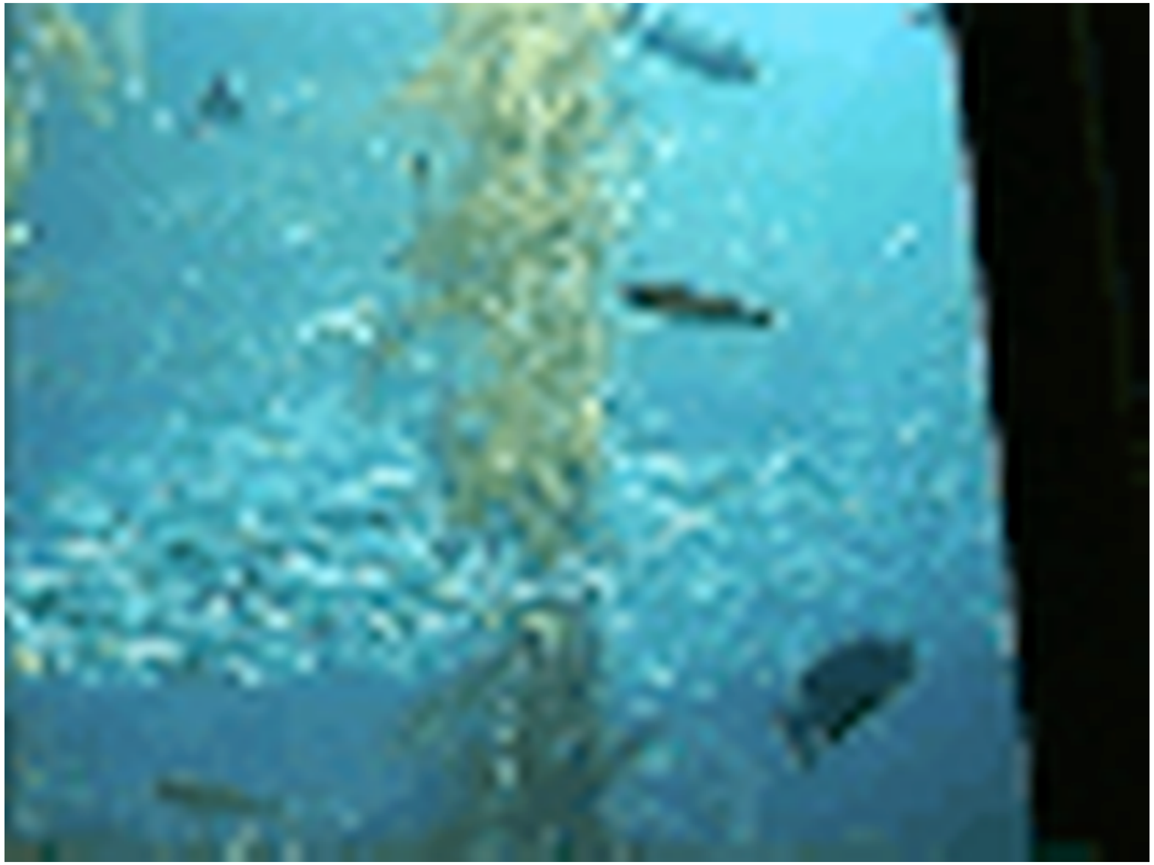
# Stigmergy Example




Pillar construction by termites:

1. Assume the architecture reaches state A that triggers action R from worker S (i.e. drop a soil pellet) transforming the architecture into $A_1$
2. $A_1$ stimulates another response $R_1$ from S or any other worker $S_N$ and so forth.

# Swarming & Flocking
## Real-world example



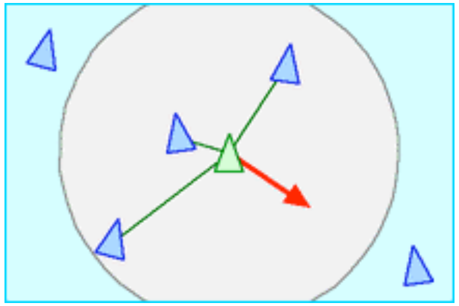
Anchovies

# Swarming & Flocking

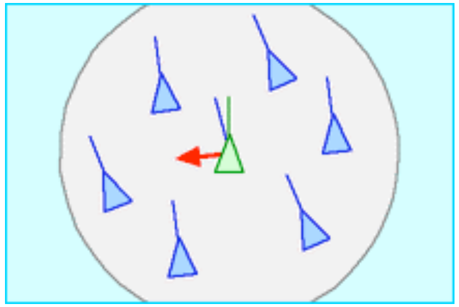
- Aggregation of similar animals that travel into the same direction
- Applications: Movie effects (Lord of the rings, Lion King), Network routing, swarm robotics, computer games
- In the late 80's Craig Reynolds created a simple model of animal motion that he called Boids.
  - **Flock** is a group of objects that exhibit the general class of polarized (aligned), non-colliding, aggregate motion
  - **Boid** is a simulated bird-like object, i.e., it exhibits this type of behavior. It can be a fish, bee, dinosaur, etc.
- The boids model can be implemented by only 3 rules defining a boid's steering behavior

# Boids model
Only 3 simple rules needed

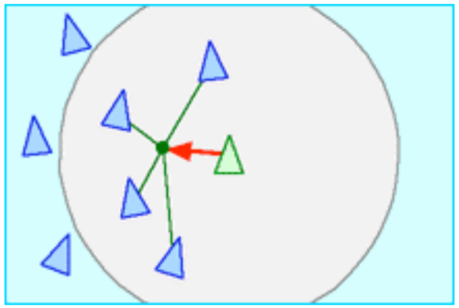
**Separation**: steer to avoid crowding local mates



**Alignment**: steer towards the average heading and speed of local mates



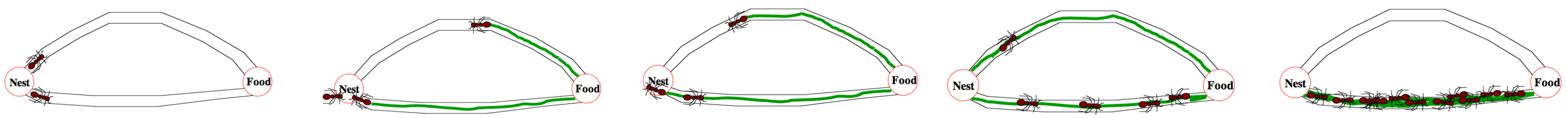
**Cohesion**: steer to move toward the average position of local mates



# Foraging Strategies in Ants

## How ants solve the shortest path problem

- Ants establish indirect communication based on the deposition of pheromone over the path they follow.
  - A single ant moves at random, but when it finds a pheromone trail, there is a high probability to follow the trail.
  - Ants foraging for food deposit pheromones over their routes. When finding a food source, they return to the nest reinforcing their trails.
  - By this, other ants have greater probability to start following such trails and thereby reinforcing it by more pheromones.
  - This process works as a positive feedback loop system because the higher the intensity of the pheromone over a trail, the higher the probability that ants start traveling through it.



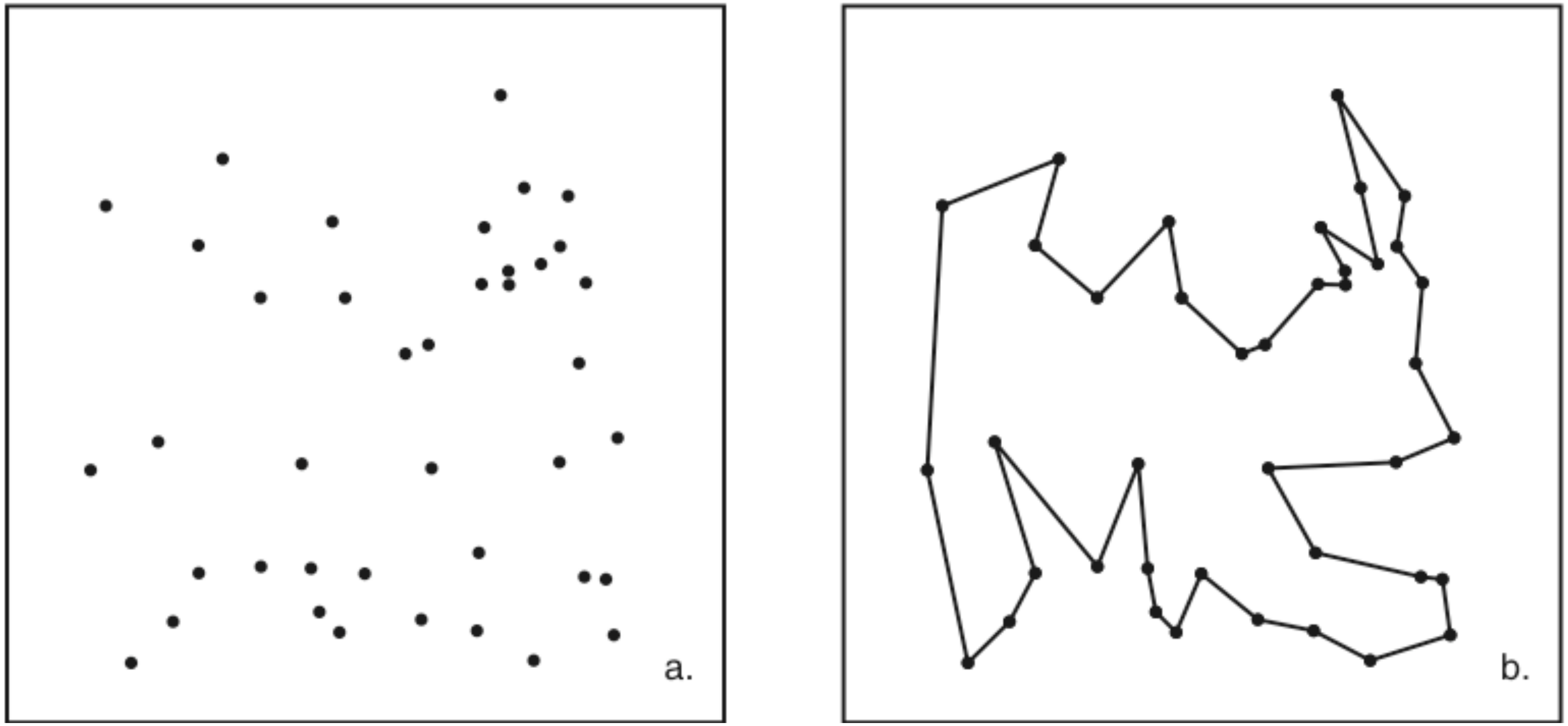

Ants exploring two paths to a food source. The shorter path finally wins due to a higher density of pheromones

# Ant Colony Optimization

## Solving TSPs

- Can be used to solve graph problems such as the Traveling Salesman Problem (TSP)
  - For finding *good* but not necessarily *optimal* solutions!
- Goal: find a closed tour of minimal length connecting *n* given cities, while visiting every city only once
- Ant colony solution concept:
  - Using a positive feedback mechanism based on an analogy with the trail laying/following behavior, to reinforce to keep good solutions
  - Negative feedback by pheromone evaporation

# Traveling Salesman Problem (TSP)




Example 40-node TSP with solution

Note TSPs are NP-Complete problems, i.e. finding solutions with increasing number of cities becomes intractable

# Ant System (1)
Solution to the TSP

- Ants move on the problem graph from one city to another until completing a tour
- Each transition depends on:
  - Whether the city has already been visited (tabu list). We denote the set of cities **not** visited by ant *k* when located at city *i* with $J^k_i$
  - The inverse of the distance $\eta_{ij}=1/d_{ij}$, called visibility. Can be seen as heuristic for choosing city *j* when in city *i*.
  - The amount of virtual pheromone $\tau_{ij}(t)$ on the edge connecting city *i* with city *j*

## Ant System (2)
### Random Transition Rule

- The transition rule, i.e. probability for ant *k* to go to city *j* while building its *kth* tour is given by:

$$p_{ij}^{k}(t) = \frac{[\tau_{ij}(t)]^{\alpha} \cdot [n_{ij}]^{\beta}}{\sum_{l \in J_i^k} [\tau_{il}(t)]^{\alpha} \cdot [n_{il}]^{\beta}} \quad if\ j \in J_i^k \ , else\ 0$$

- Where α and β are parameters controlling the trade-off between trail intensity and visibility

# Ant System (3)

## Trail update

- After completing a tour (episode), each ant *k* lays a quantity of pheromone $\Delta\tau_{ij}(t)$ on each visited edge *(i,j)*
- The quantity depends on the ant's performance during tour $T^k$ at iteration $t$:

$$\Delta\tau_{ij}^{k} = \frac{Q}{L_k(t)} \, if\,(i,j) \in T^k(t), else\; 0$$

- Where $L_k(t)$ is the length, and Q is a parameter which should be set close to the optimal tour length
- Pheromone decay (evaporation): controlled by parameter ρ ,$0 \leq \rho < 1$
- Resulting update rule: $\tau_{ij}(t) \leftarrow (1-\rho) \cdot \tau_{ij}(t) + \Delta\tau_{ij}(t)$

with $\Delta\tau_{ij}(t) = \sum_{k=1}^{m} \Delta\tau_{ij}^{k}(t)$

# Ant System (4)

## Elitist ants

- Idea borrowed from genetic algorithms: always keep the best n solutions in the genetic pool
- An elitist ant is an ant that reinforces the edge belonging to $T^+$ (the best tour found so far) by the quantity $Q/L^+$, where $L^+$ is the length of $T^+$
- During each iteration we add *e* elitist ants to the usual ants
- Hence, the edge belonging to $T^+$ gets an extra reinforcement of $e*Q/L^+$

# Ant System (5)
## Complete algorithm

/* **Initialization** */
**For** every edge $(i, j)$ **do**
  $\tau_{ij}(0) = \tau_0$
**End For**
**For** $k = 1$ to $m$ **do**
  Place ant $k$ on a randomly chosen city
**End For**
**Let** $T^+$ be the shortest tour found from beginning and $L^+$ its length
/* **Main loop** */
**For** $t = 1$ to $t_{\max}$ **do**
  **For** $k = 1$ to $m$ **do**
    Build tour $T^k(t)$ by applying $n - 1$ times the following step:
    Choose the next city $j$ with probability

$$p_{ij}^k(t) = \frac{[\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{l \in J_i^k} [\tau_{il}(t)]^\alpha \cdot [\eta_{il}]^\beta},$$

    where $i$ is the current city
  **End For**
  **For** $k = 1$ to $m$ **do**
    Compute the length $L^k(t)$ of the tour $T^k(t)$ produced by ant $k$
  **End For**
  **If** an improved tour is found **then**
    update $T^+$ and $L^+$
  **End If**

(1)

  **For** every edge $(i, j)$ **do**
    Update pheromone trails by applying the rule:
    $\tau_{ij}(t) \leftarrow (1 - \rho) \cdot \tau_{ij}(t) + \Delta\tau_{ij}(t) + e \cdot \Delta\tau_{ij}^e(t)$ where

$$\Delta\tau_{ij}(t) = \sum_{k=1}^{m} \Delta\tau_{ij}^k(t),$$

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

    and

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

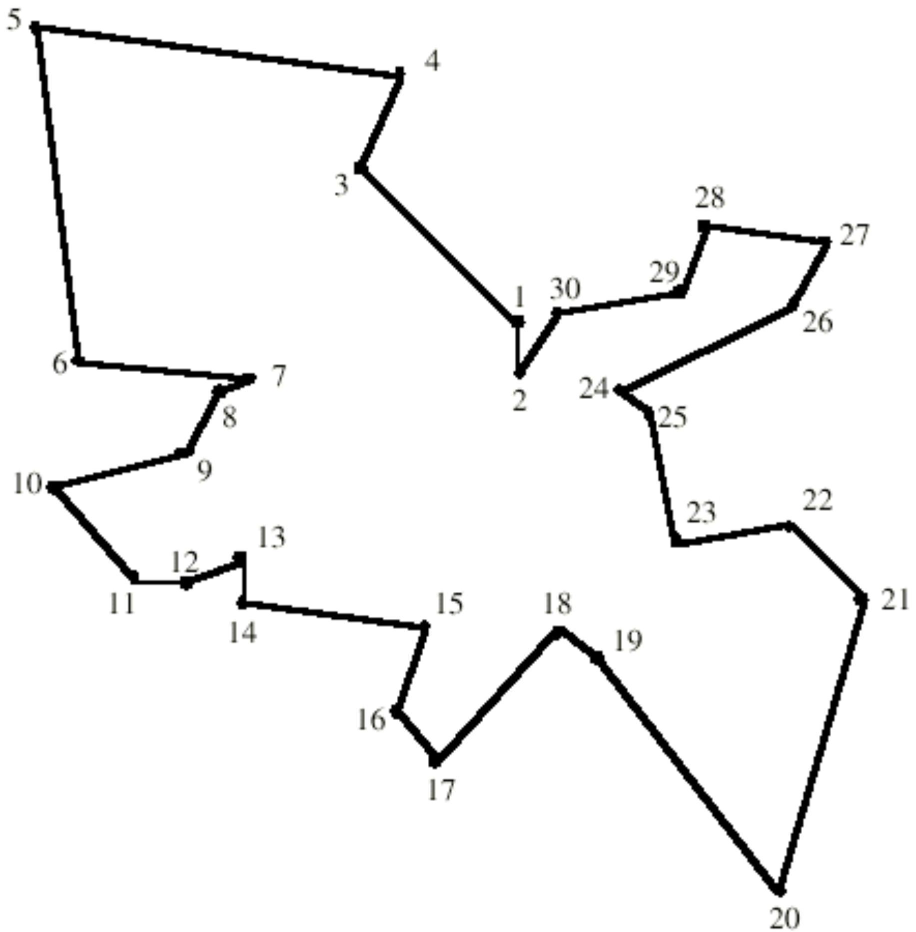
  **End For**
  **For** every edge $(i, j)$ **do**
    $\tau_{ij}(t + 1) = \tau_{ij}(t)$
  **End For**
**End For**
**Print** the shortest tour $T^+$ and its length $L^+$
**Stop**
/* **Values of parameters used in experiments** */
$\alpha = 1, \beta = 5, \rho = 0.5, m = n, Q = 100, \tau_0 = 10^{-6}, e = 5$

(2)

Notes: $t_{max}$ is the number of episodes

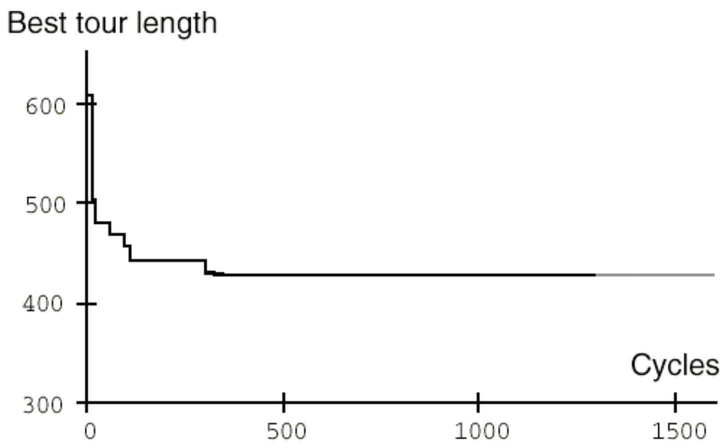
# TSP Solving Examples

## Oliver30 Problem




Episodes: 342
Length : 420

$\alpha = 1$
$\beta = 5$
$\rho = 0.5$



# Case-study: Team coordination of virtual robots

## USARSim: A simulator for emergency response

- Based on the Unreal game engine (UT2004, Epic Games)
- Realistic models for
  - USAR environments, indoor & outdoor
  - Robots, such as Pioneer2 DX, Sony AIBO, …
  - Sensors, such as Laser Range Finder, Color Camera, IMU, Wheel Odometry, RFID
- Agents connect via a TCP/IP interface
- Path loss simulation (e.g. WLAN)
- Research challenges:
  - Autonomous control of large robot teams (up to 12)
  - Multi-robot disaster area mapping
  - Coordination of heterogeneous robots with different manipulation and sensing capabilities

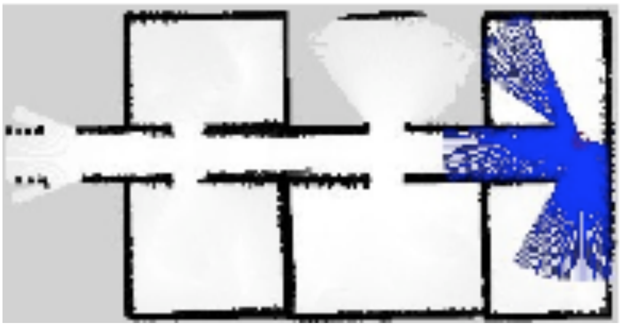
# RFID-based exploration
## Hybrid: local exploration and global planning

- Local exploration (LE):
  - Indirect communication
  - Scales-up with # of robots and environment size
  - Inefficient exploration due to local minima
- Global task assignment and path planning:
  - Based on node graph abstraction of the environment
  - Monitors LE and computes new agent-node assignment If exploration overlap is high
  - Requires communication

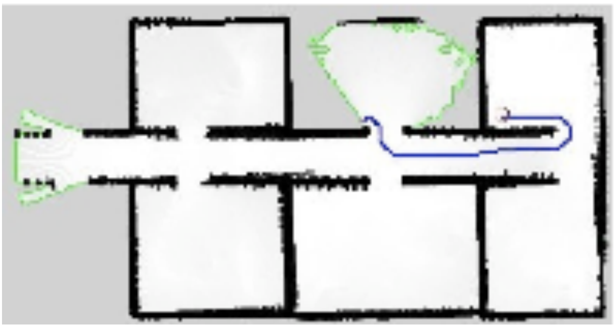
# Local Exploration
## Navigation

- Local trajectory planning:
  - Based on evidence grid, e.g. limited to 4X4 meters
  - Exploration targets taken from extracted frontier Cells
  - Efficient A* planning to selected FP
  - Cost function considering path length and occupancy:

$$c(s_{i+1}) = c(s_i) + d(s_{i+1}, s_i) * (1 + \alpha * occ(s_{i+1}))$$



Occupancy Grid generated from laser scans



Extracted frontier cells and A* plan to selected target

# Local exploration
## Coordination & Frontier Cell Selection

- RFID tag distribution and detection:
  - Deployment of *new* RFIDs with respect to the detected RFID density
  - Detection of nearby RFIDs and consequent update of Local RFID Set (LRS)
  - Programming of RFID memory with visited locations (relative position)
- Coordination:
  - Automatic node deployment w. r. t. a pre-defined density
  - Discretization of node vicinity into equally sized patches
  - Node memory for counting visits of each patch [Svennebring and Koenig, 2004])
- Frontier selection by minimizing the following cost function:

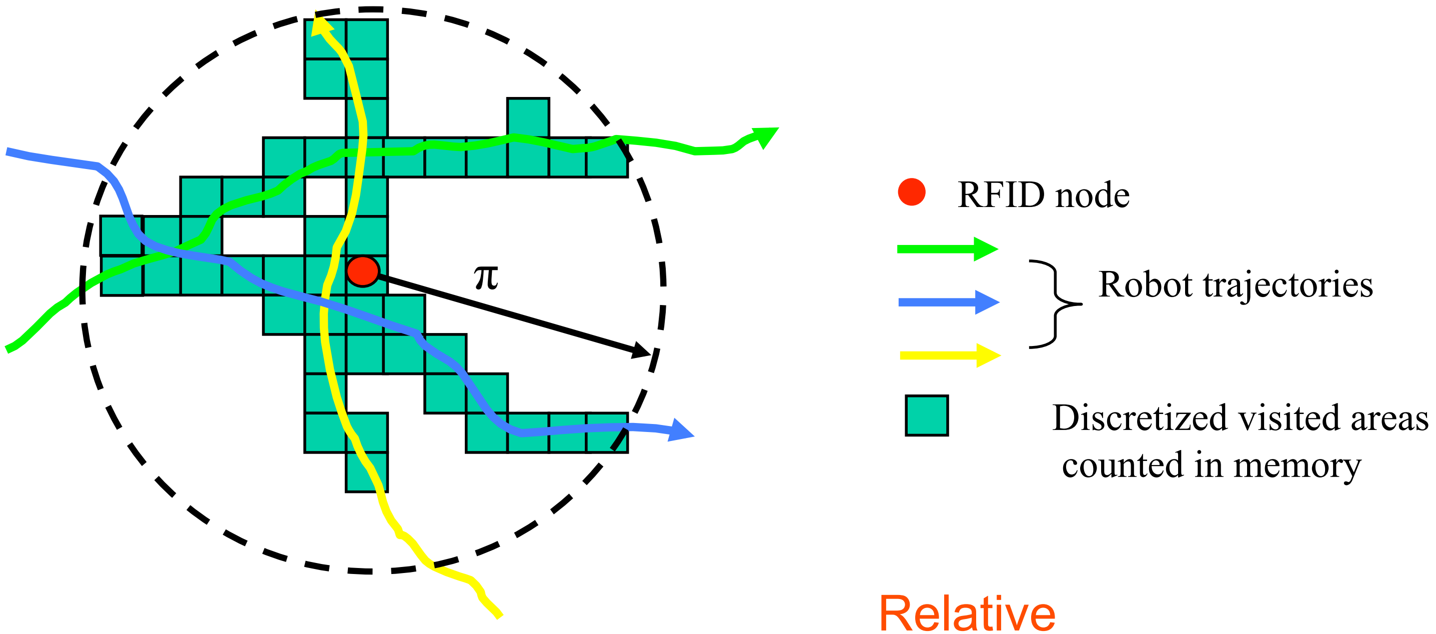
$$F_v\left(l_{f_j}\right) = \sum_{r \in LRS} \sum_{p \in P_r} \frac{count(p)}{d\left(l_{f_j}, p\right)}$$

$l_{fi}$ : frontier cell location,
LRS: set of nodes within range,
Pr: set of patches around node r,
d(.): the Euclidean distance

This models ant pheromones!

# Local exploration cont.

## Discretization of the node's vicinity $\pi$




Relative
addressing!

# Results Local Team Coordination

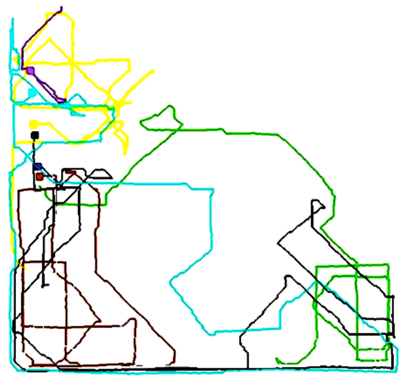
## Virtual rescue scenarios from NIST (RoboCup'06)

| | | RRFreiburg | GROK | IUB | SPQR | STEEL | UVA |
|---|---|---|---|---|---|---|---|
| | Area [m2] | **579** | 27 | 227 | 96 | 134 | 262 |
| **SemiFinal1** | # Robots | 8 | 1 | 6 | 4 | 6 | 6 |
| | Tot. Length | 2503,25 | 39,81 | 257,7 | 143,91 | 190,59 | 365,51 |
| | Area [m2] | **1276** | 82 | 139 | 123 | 139 | 286 |
| **Semifinal 2** | # Robots | 8 | 1 | 6 | 5 | 6 | 7 |
| | Tot. Length | 1991,86 | 79,64 | 152,91 | 124,226 | 271,69 | 401,45 |
| | Area [m2] | **1203** | - | 210 | - | - | - |
| **Final 1** | # Robots | 8 | - | 8 | - | - | - |
| | Tot. Length | 2536,55 | - | 224,667 | - | - | - |
| | Area [m2] | **350** | - | 136 | - | - | - |
| **Final 2** | # Robots | 8 | - | 6 | - | - | - |
| | Tot. Length | 1761,63 | - | 254,681 | - | - | - |

Largest explored area
(by 8 robots)

Final 1 (indoor, 1276m$^2$)

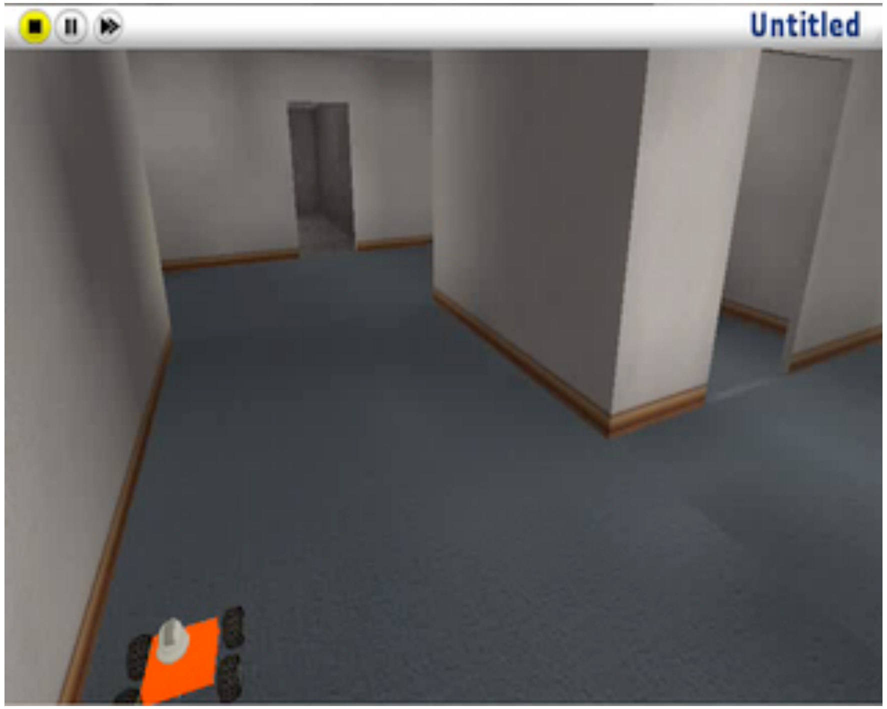
Each color
denotes the path
of a single robot



Final 2 (outdoor. 1203m$^2$)

# Rescue Virtual Competition
## Videos from RoboCup'06

*Semi-Final`06*




*Final`06*

# Summary

- Flocking is a very simple mechanism that has been uses quite successfully in many applications
- The foraging behavior of ants has motivated many solutions to complex problems
  - Although sub-optimal, they are powerful to find fast good solutions
  - Numerous of extensions to the presented approach have been proposed
  - Other problems that have been solved: Task Allocation, Graph Partitioning, Transport problems, …
- RFIDs might be a good choice for simulating pheromones (at least if they are getting cheaper)

# Literature


- Bonabeau E., Dorigo M., and Theraulaz G. **Swarm Intelligence: From Natural to Artificial Systems**, *Oxford University Press*, 1999.
- Reynolds, C. W. (1987) **Flocks, Herds, and Schools: A Distributed Behavioral Model**, in *Computer Graphics*, 21(4) (SIGGRAPH '87 Conference Proceedings) pages 25-34.
- V.A. Ziparo, A. Kleiner, B. Nebel, and D. Nardi, **RFID-Based Exploration for Large Robot Teams**, In *Proc. of the IEEE Int. Conf. on Robotics & Automation (ICRA), 2007*
- Svennebring, J. and Koenig, S. **Building terrain-covering ant robots: A feasibility study**. *Autonomous Robots*, 16(3):313–332, 2004.