

# Introduction to Mobile Robotics

## **Multi-Robot Exploration**

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# Motivation

Whenever teams of mobile robots are used, the question arises, how to control them in order to optimize the performance of the whole team.

- Exploration
- Path planning
- Action planning ...

# Exploration: The Problem

## Given:

- **Unknown environment**
- **Team of robots**

## Task:

- **Coordinate the robots to efficiently learn a complete map of the environment**

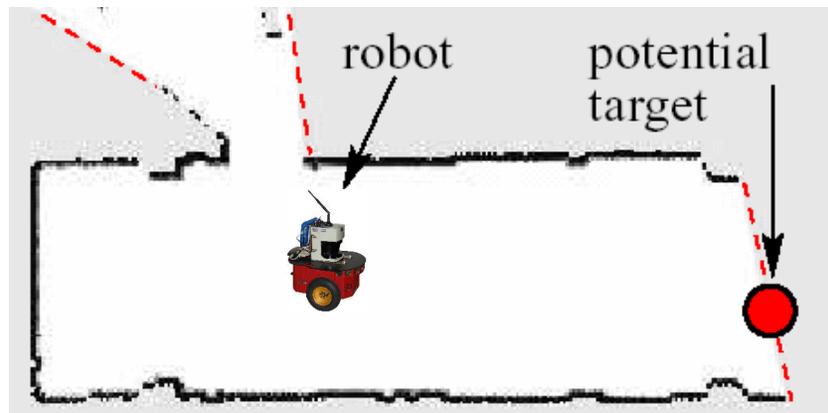
## Complexity:

- **NP-hard for single robots in known, graph-like environments**
- **Exponential in the number of robots**



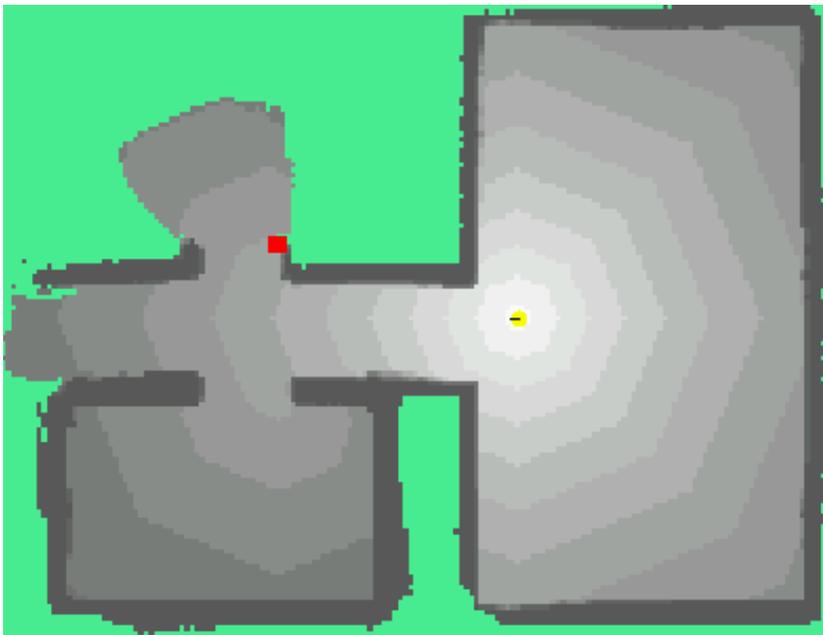
# What is a Frontier?

- A frontier-cell is a free-space cell that has an unknown cell as its direct neighbor
- A frontier is a collection of connected frontier cells
- The set of frontiers are reasonable potential target locations for exploration missions



# Example

**Robot 1:**



**Robot 2:**



# Levels of Coordination

- No exchange of information
- Implicit coordination: Sharing a joint map  
[Yamauchi et.al, 98]
  - Communication of the individual maps and poses
  - Central mapping system
- Explicit coordination: Determine better target locations to distribute the robots
  - Central planner for target point assignment

# Idea

1. Choose target locations at the frontier to the unexplored area by trading off the expected information gain and travel costs.
2. Reduce utility of target locations whenever they are expected to be covered by another robot.
3. Use on-line mapping and localization to compute joint map.

# The Coordination Algorithm (informal)

- 1. Determine the frontier cells.**
- 2. Compute for each robot the cost for reaching each frontier cell.**
- 3. Choose the robot with the optimal overall evaluation and assign the corresponding target point to it.**
- 4. Reduce the utility of the frontier cells visible from that target point.**
- 5. If there is one robot left go to 3.**

# The Coordination Algorithm

1. Determine the set of frontier cells
2. Compute for each robot  $i$  the cost  $V_{x,y}^i$  for reaching each frontier cell
3. Set the utility  $U_{x,y}$  of all frontier cells to 1
4. While there is one robot left without a target point

- (a) Determine a robot  $i$  and a frontier cell  $\langle x, y \rangle$  which satisfy

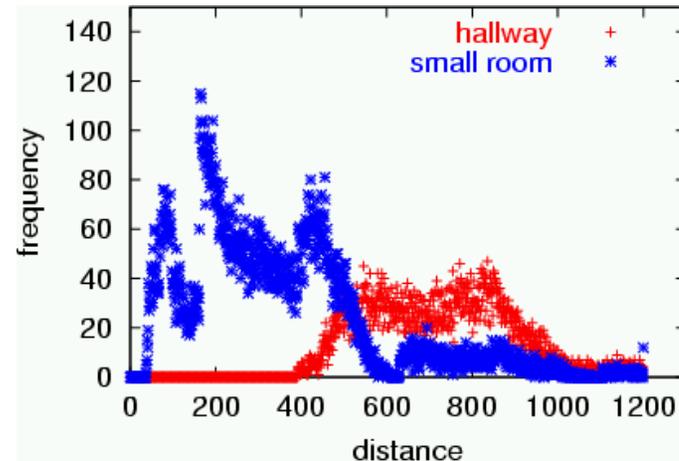
$$(i, \langle x, y \rangle) = \operatorname{argmax}_{(i', \langle x', y' \rangle)} U_{x', y'} - V_{x', y'}^{i'}$$

- (b) Reduce the utility of each target point  $\langle x', y' \rangle$  in the visibility area according to

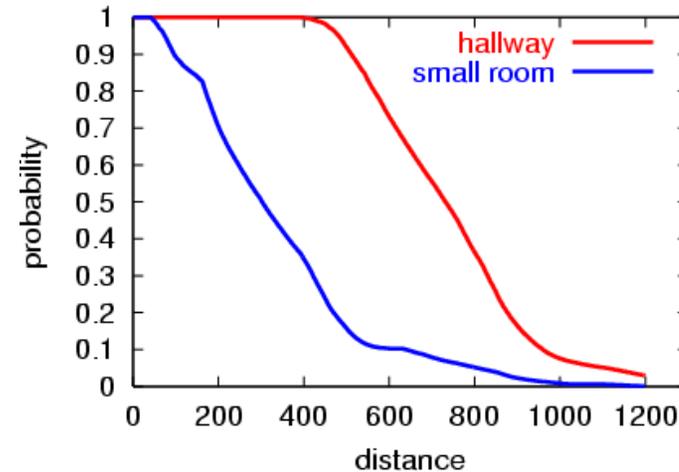
$$U_{x', y'} \leftarrow U_{x', y'} \cdot (1 - P(\| \langle x, y \rangle - \langle x', y' \rangle \|))$$

# Estimating the Visible Area

**Distances measured during exploration:**

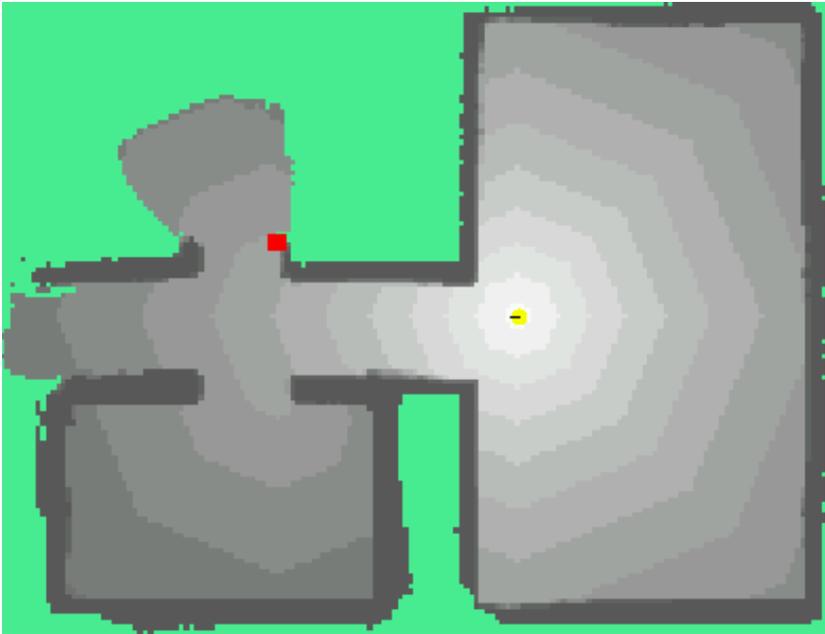


**Resulting probability of measuring at least distance  $d$ :**



# Application Example

**First robot:**



**Second robot:**

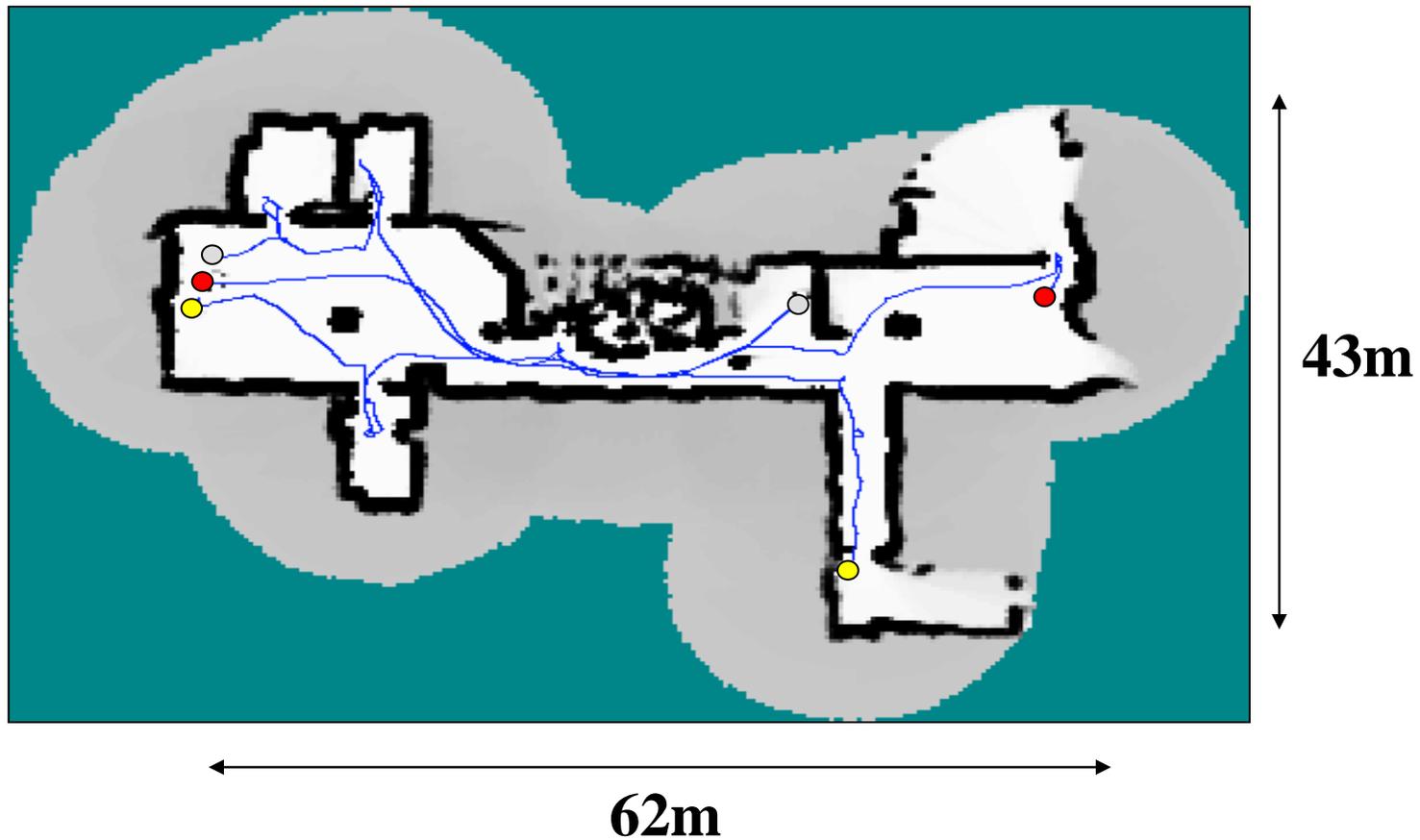


# Multi-Robot Exploration and Mapping of Large Environments

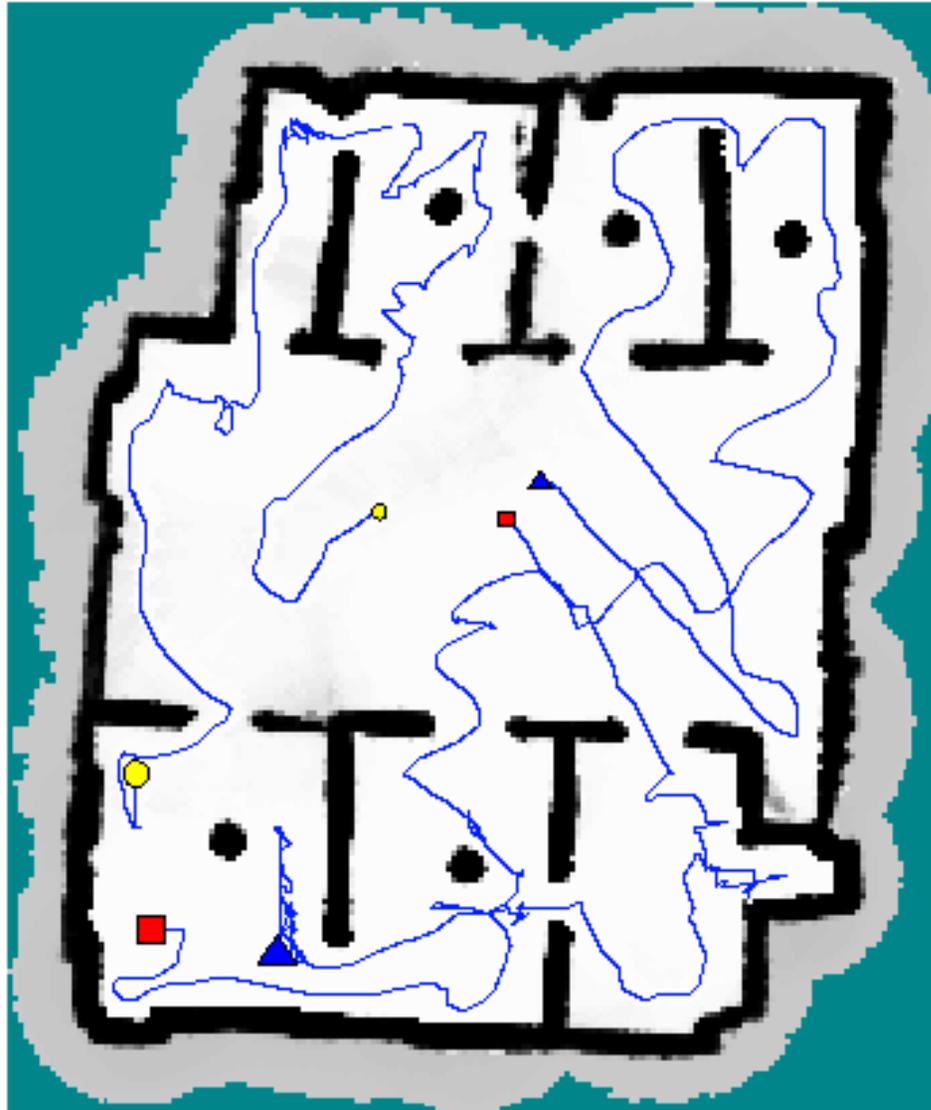
Multi-Robot Mapping  
and Exploration

Carnegie Mellon  
October 1999

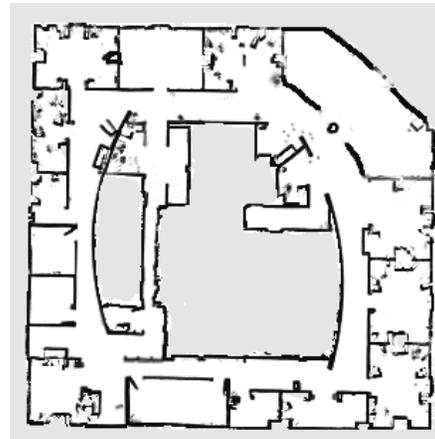
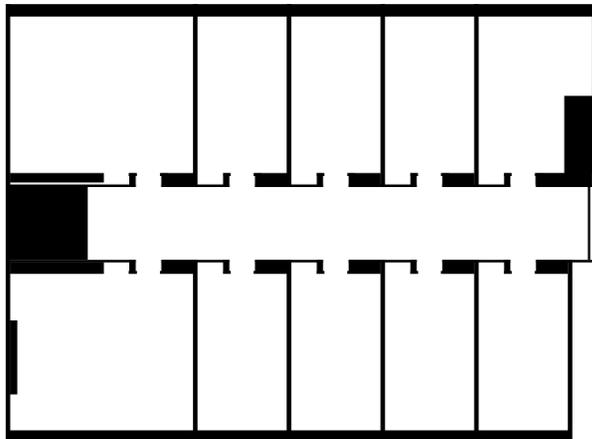
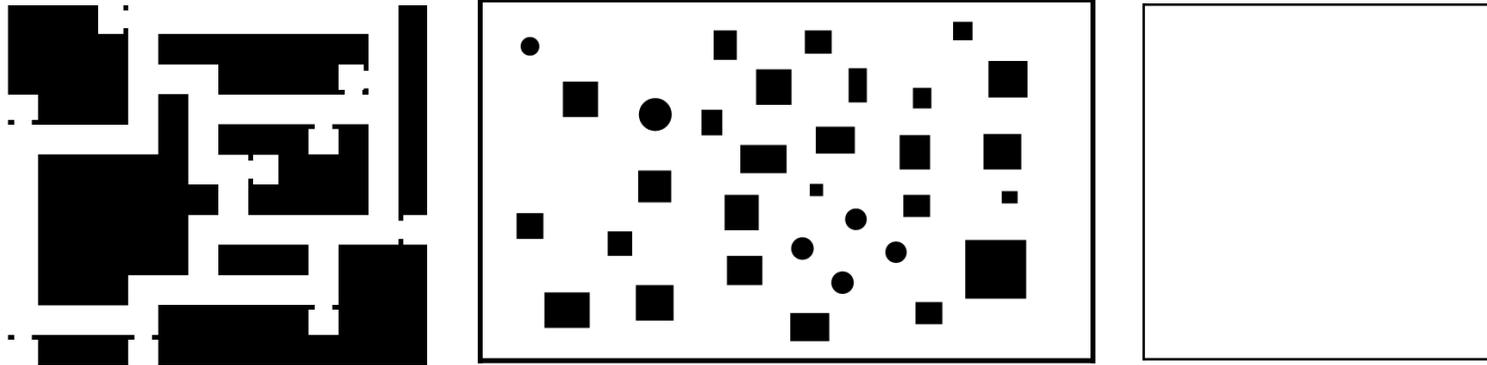
## Resulting Map (constructed in 8 minutes!)



# Another Application

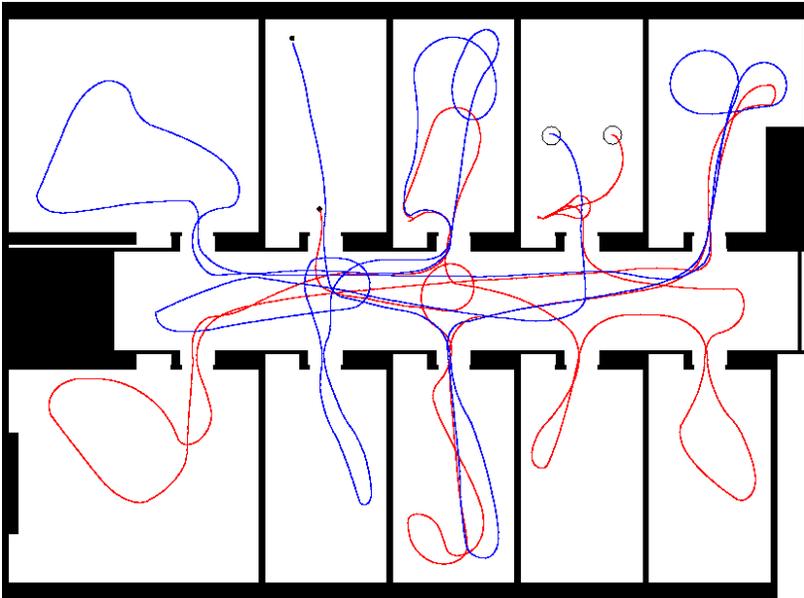


# Maps Considered

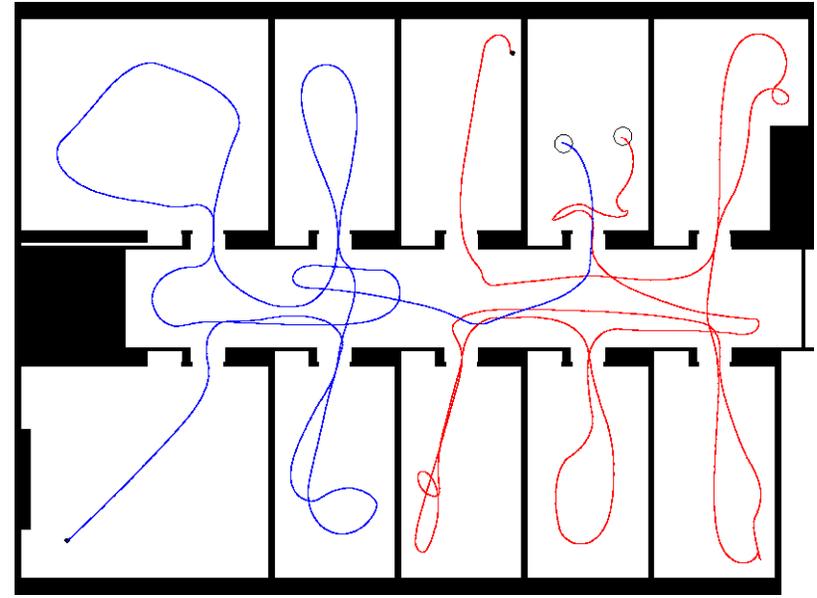


# Typical Trajectories

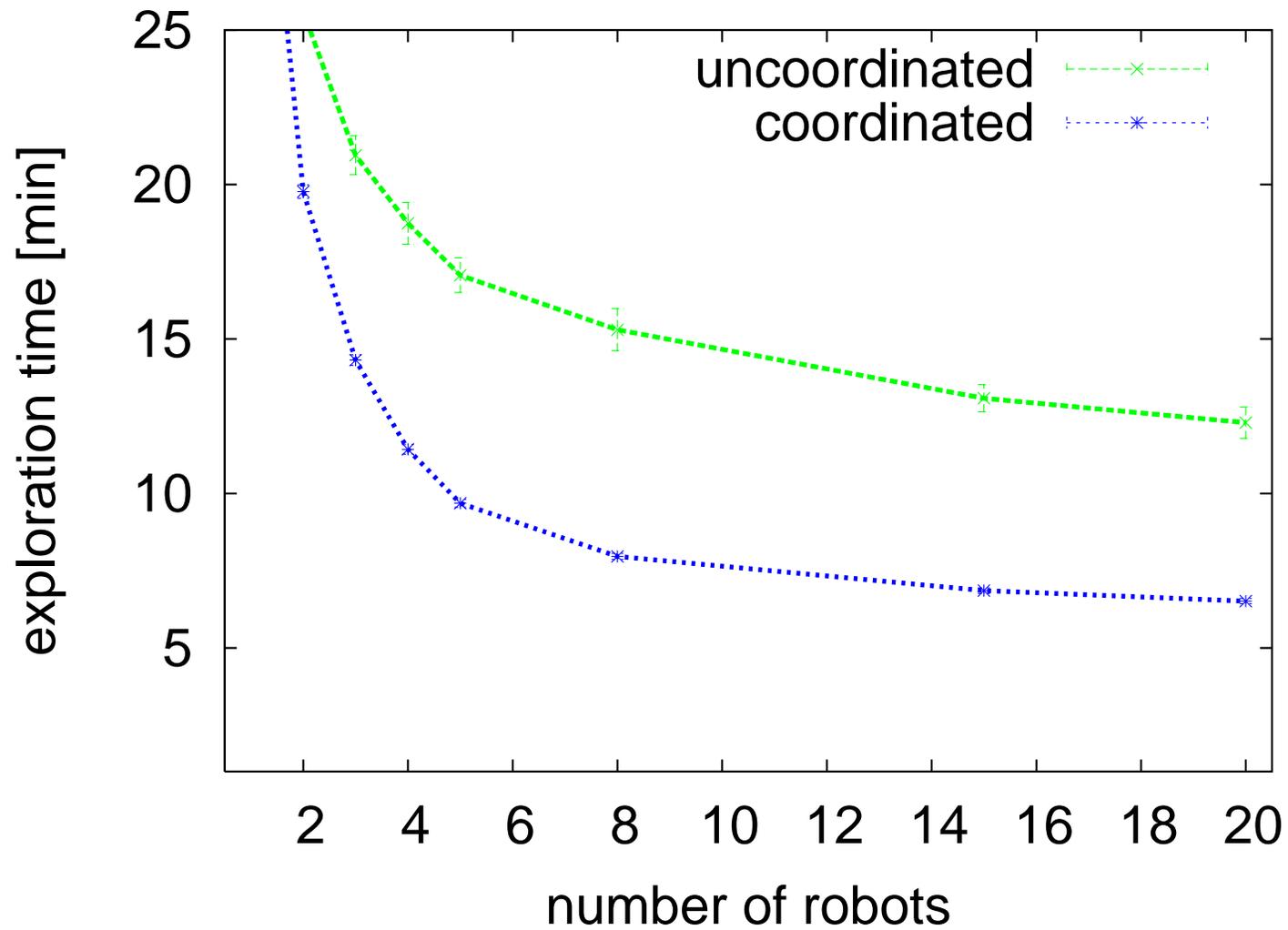
**Implicit coordination:**



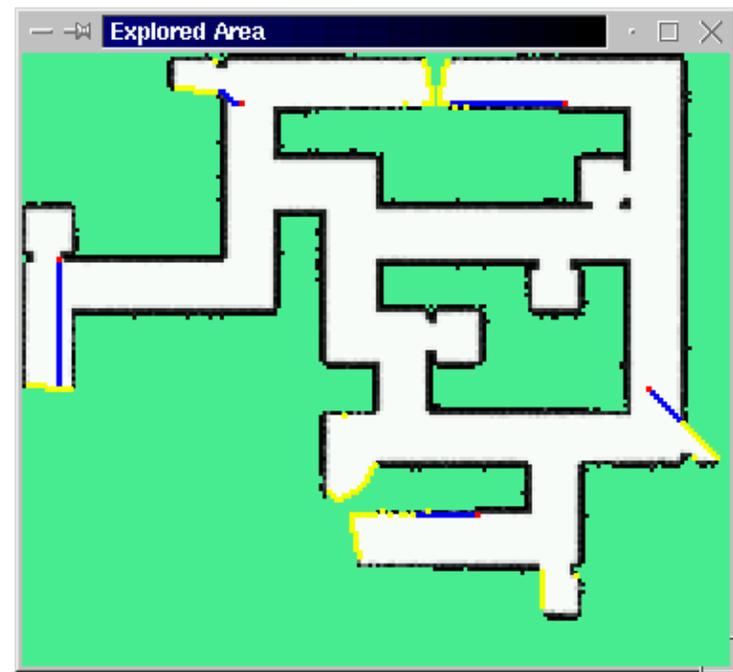
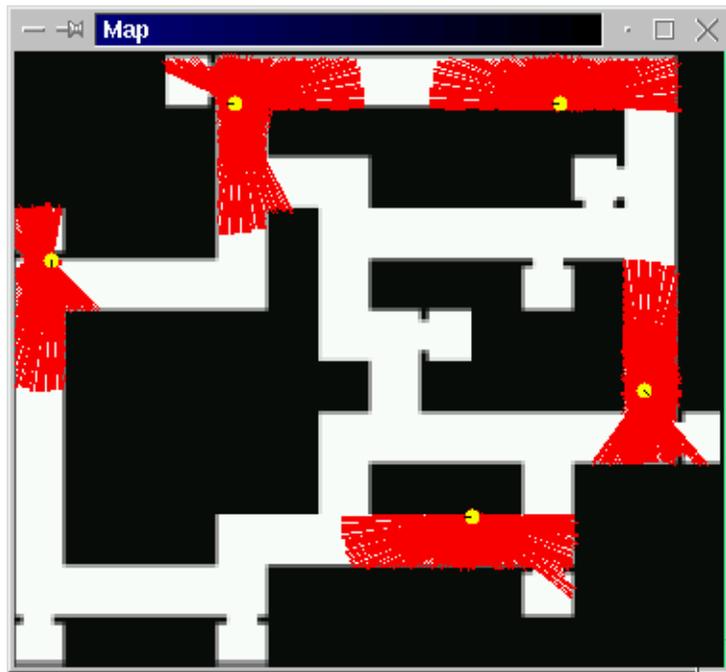
**Explicit coordination:**



# Exploration Time

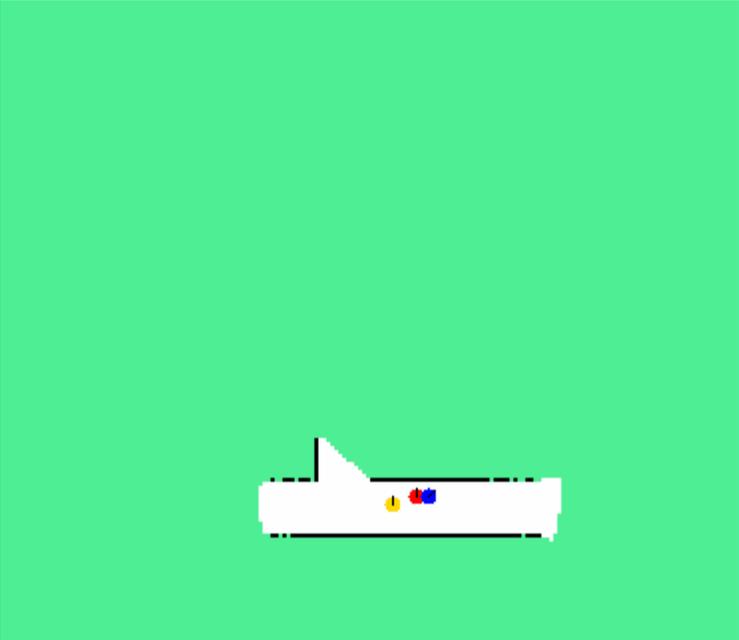


# The Simulation Tool

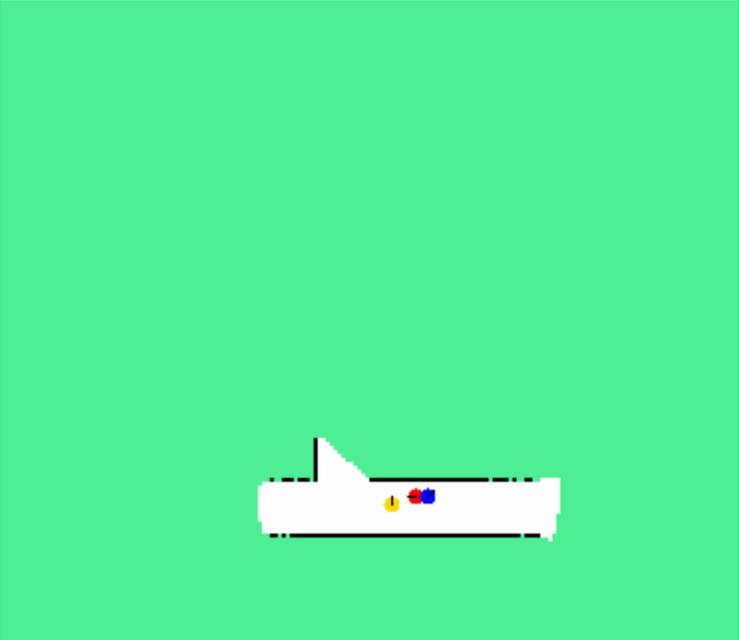


# Example

**Implicitly coordinated:**

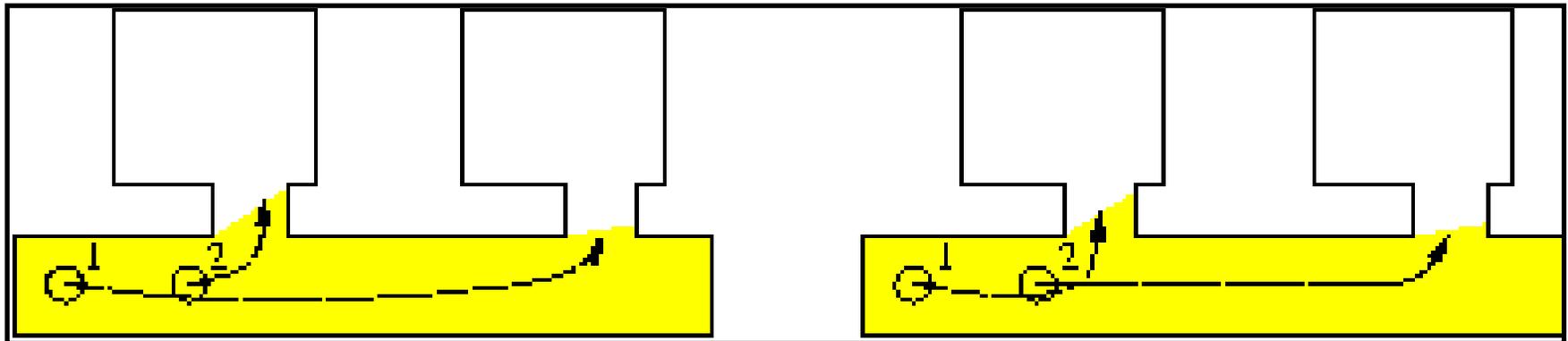


**Explicitly coordinated:**



# Optimizing Assignments

- The current system performs a greedy assignment of robots to target locations



- What if we optimize the assignment?

# Optimizing Assignment Algorithm

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**Algorithm 2** Goal selection determining the best assignment over all permutations.

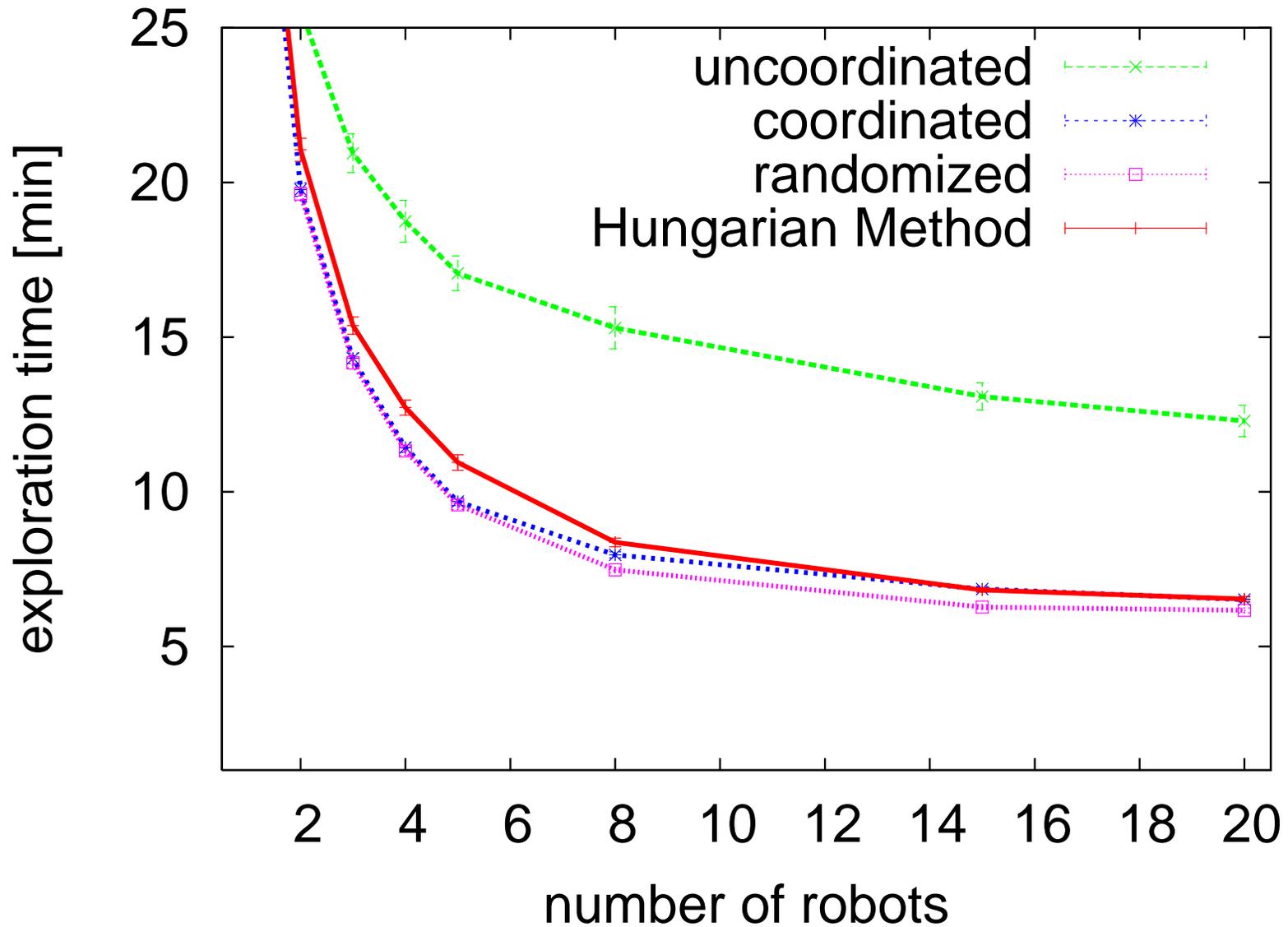
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- 1: Determine the set of frontier cells.
  - 2: Compute for each robot  $i$  the cost  $V_t^i$  for reaching each frontier cell.
  - 3: Determine target locations  $t_1, \dots, t_n$  for the robots  $i = 1, \dots, n$  that maximizes the following evaluation function:  
$$\sum_{i=1}^n U(t_i \mid t_1, \dots, t_{i-1}, t_{i+1}, \dots, t_n) - \beta \cdot (V_{t_i}^i)^2.$$
-

# Other Coordination Techniques

- Hungarian Method:
  - **Optimal assignment** of job to machines given a fixed cost matrix.
  - Similar results that the presented coordination technique.
- Market economy-guided approaches:
  - Robots **trade** with targets.
  - **Computational load is shared** between the robots

# Exploration Time

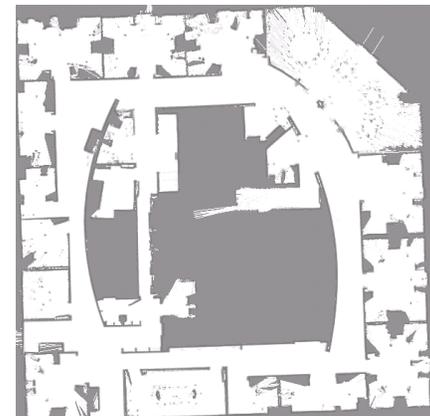
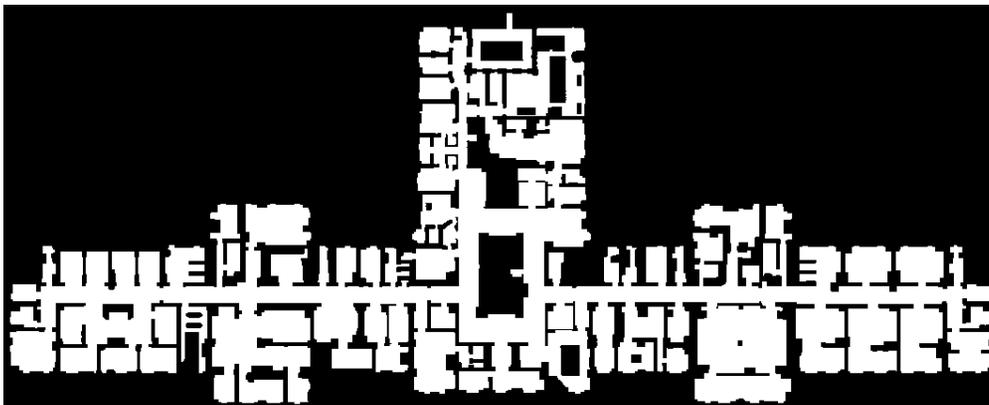


# Summary on Coordination

- Approach to centralized coordination
- Coordination technique that distributes the robots over the environment.
- Considers the cost of an action and the expected utility of reaching the corresponding frontier (target location)
- Significantly reduces the overall exploration time compared to previous approaches.

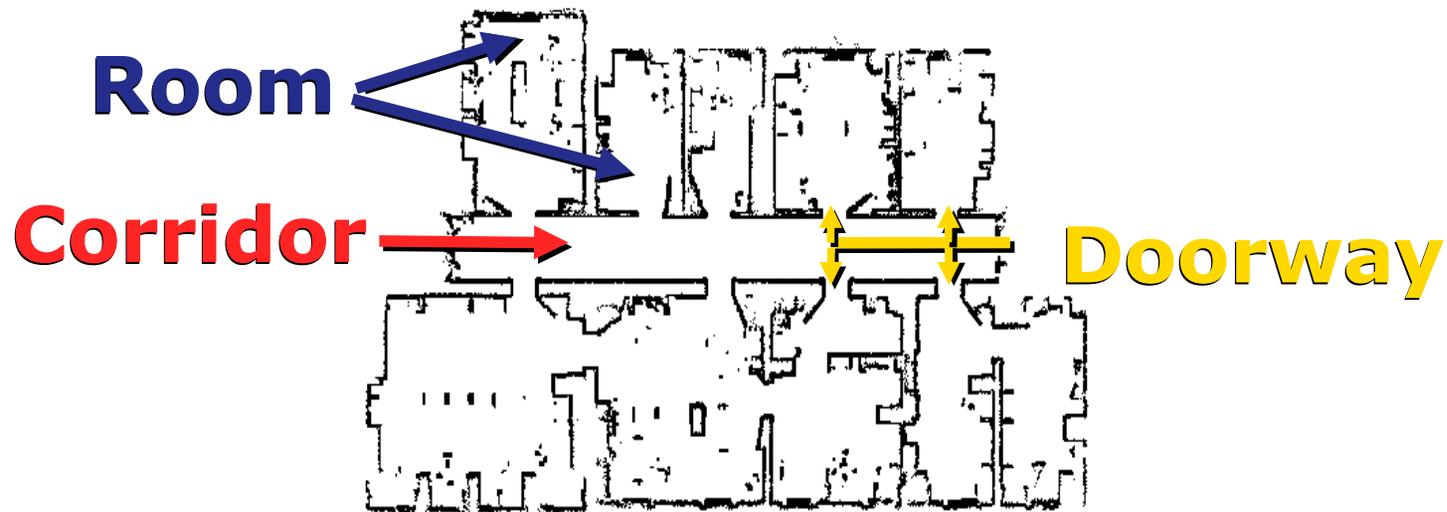
# Using Background Knowledge

- Corridors typically provide multiple transitions to rooms (unobserved places) compared to rooms.
- The more transitions to unknown regions a place has, the better the robots can distribute themselves over the environment.
- Can we extract such information and use it to improve the distribution of the robots?



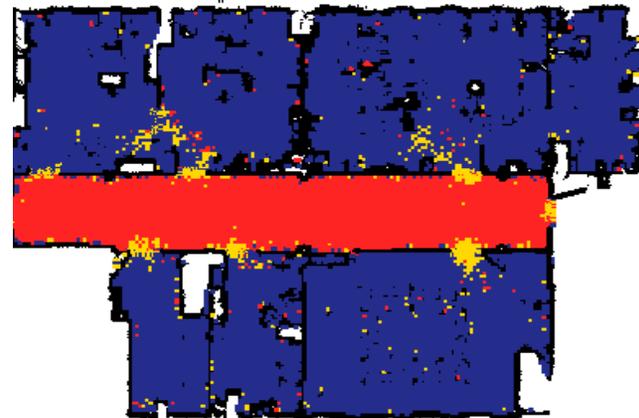
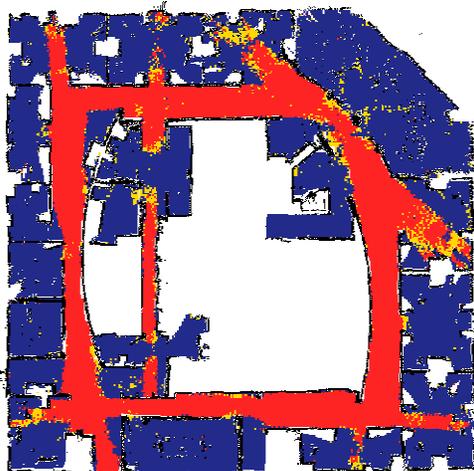
# Using Information about Places

- Given we know in which the type of place the is in, we can do better assignments
- Techniques to classify places exist



# Application to Exploration

- Assign a higher reward to regions that probably provide more frontiers to unknown areas.
- **Advantage:** Nearly no changes to the assignment algorithm are required.



# Improved Coordination for Multi-Robot Exploration

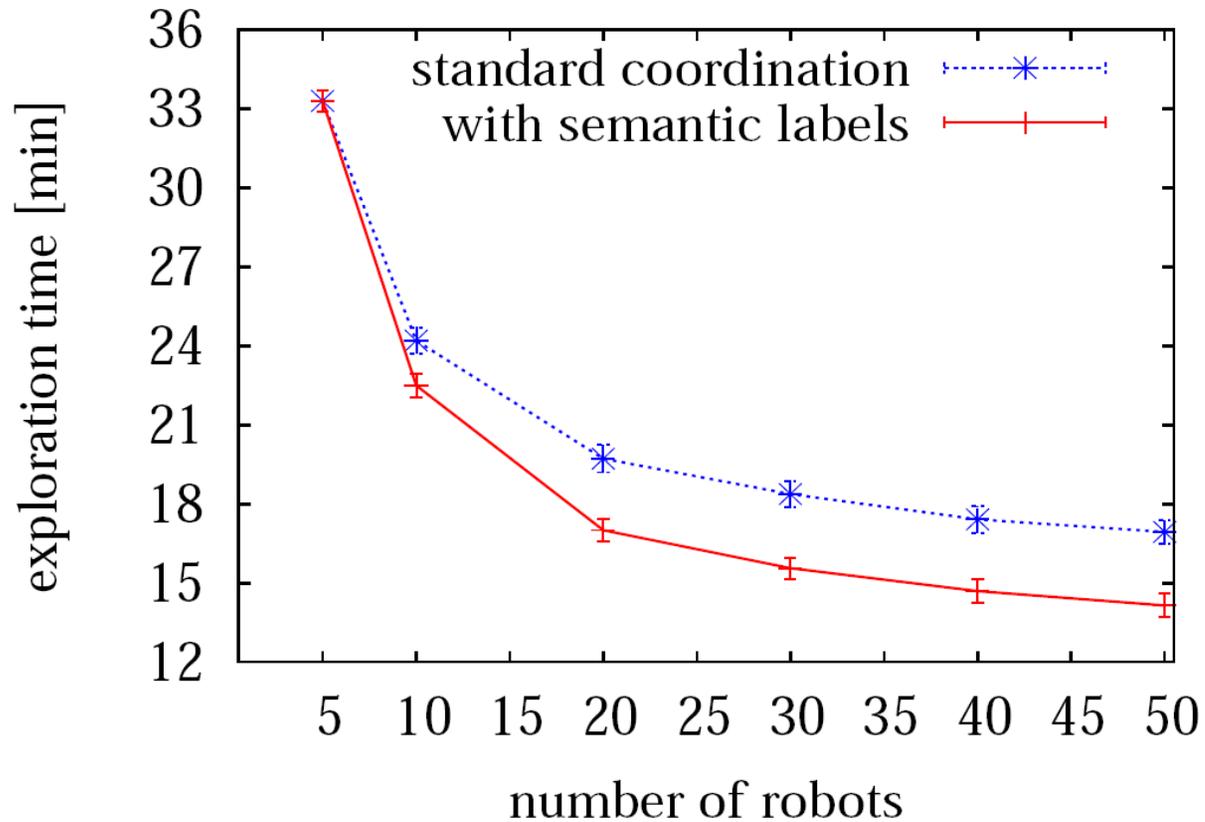
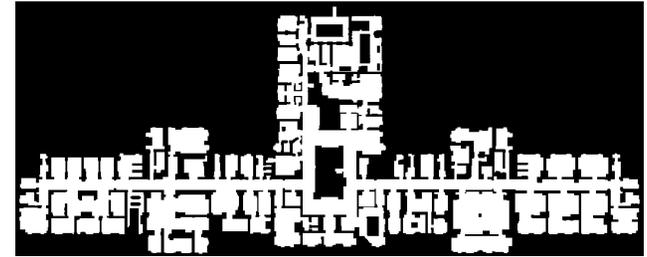
1. Determine the frontiers (targets)
2. Compute the travel cost  $V(i,t)$  of each robot  $i$  to a target  $t$

3. Assign a utility:

$$\begin{aligned} U(t) &= c > 1 && \text{if } t \text{ is a corridor location} \\ U(t) &= 1 && \text{if } t \text{ is not a corridor location} \end{aligned}$$

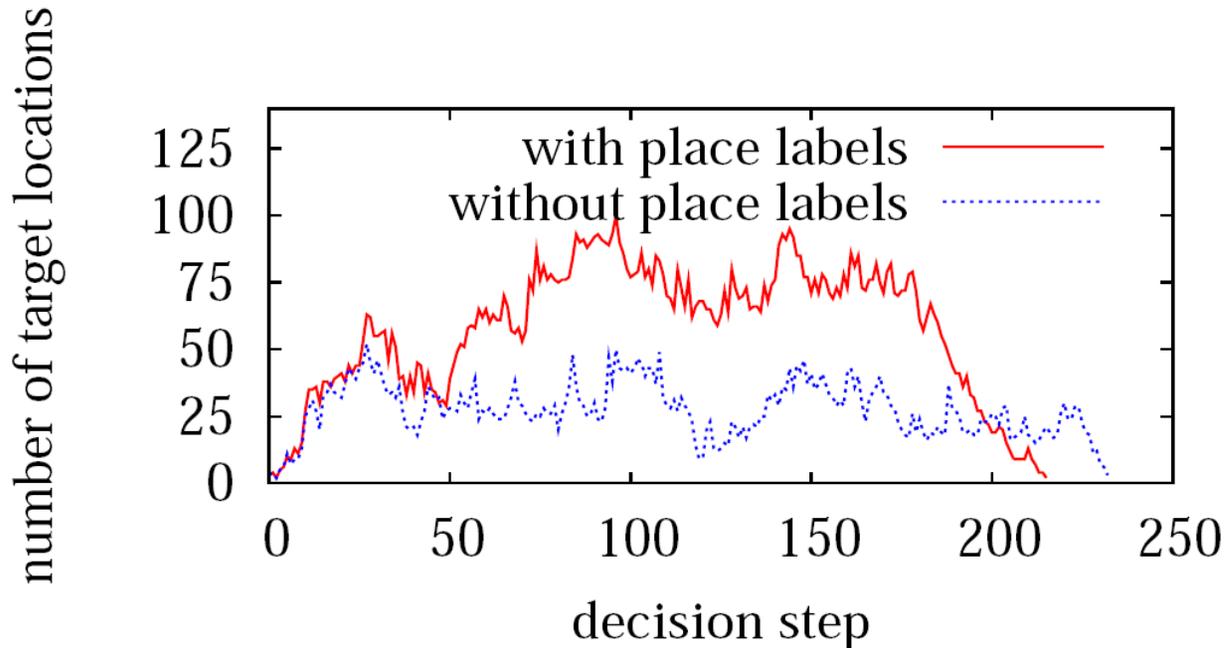
4. While a robot exists that has no target assigned
  - Choose  $(i^*, t^*) = \operatorname{argmax} U(t) - V(i, t)$
  - $U(t') = U(t') - P_{\text{visible}}(t^*, t')$

# Evaluation



- Considering semantic place information leads to a significantly reduced exploration time

# Number of Target Locations



- By focusing the exploration on corridors, more potential target locations are available.
- This often results in a better distribution of robots over the environment.
- Up to  $\sim 20\%$  less interference between robots.

# Conclusions

- **Centralized approach** allows the robots **efficient coordination**.
- By utilizing the information about the type of the place we obtain a significant **speed-up** in **multi-robot exploration**.

# Open Problems

- Unknown starting locations
- Exploration under position uncertainty
- Limited communication abilities
- Efficient exchange of information
- ...