

16-782

Planning & Decision-making in Robotics

Multi-Robot Planning

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Different Categorizations of Multi-Robot Planning

- Centralized vs. Decentralized
 - **Centralized:** one central control of (planning for) all the robots
 - **Decentralized:** each robot decides/plans what to do on its own

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Robust to limits on or loss of communication

Robust to losing some robots in the team

Computationally more scalable

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Challenges with decentralized planning?

How to guarantee that the overall team accomplishes its goal?

Different Categorizations of Multi-Robot Planning

- Multi-robot Path Planning vs. Multi-robot Cooperative Task Planning
 - **Multi-robot Path Planning:** how to plan paths for N robots so that they don't collide with each other during execution
 - **Multi-robot Cooperative Task Planning:** how to compute plans for N robots so that they achieve the overall goal that may require cooperation

Different Categorizations of Multi-Robot Planning

- Small teams vs. large teams (swarms) of robots
 - **Planning for small teams:** Compute plans for N (potentially heterogeneous) robots, where N is typically 2-10
 - **Planning for (control of) swarms of robots:** how to control a swarm of N (usually homogeneous) robots, where N is typically 10-1000

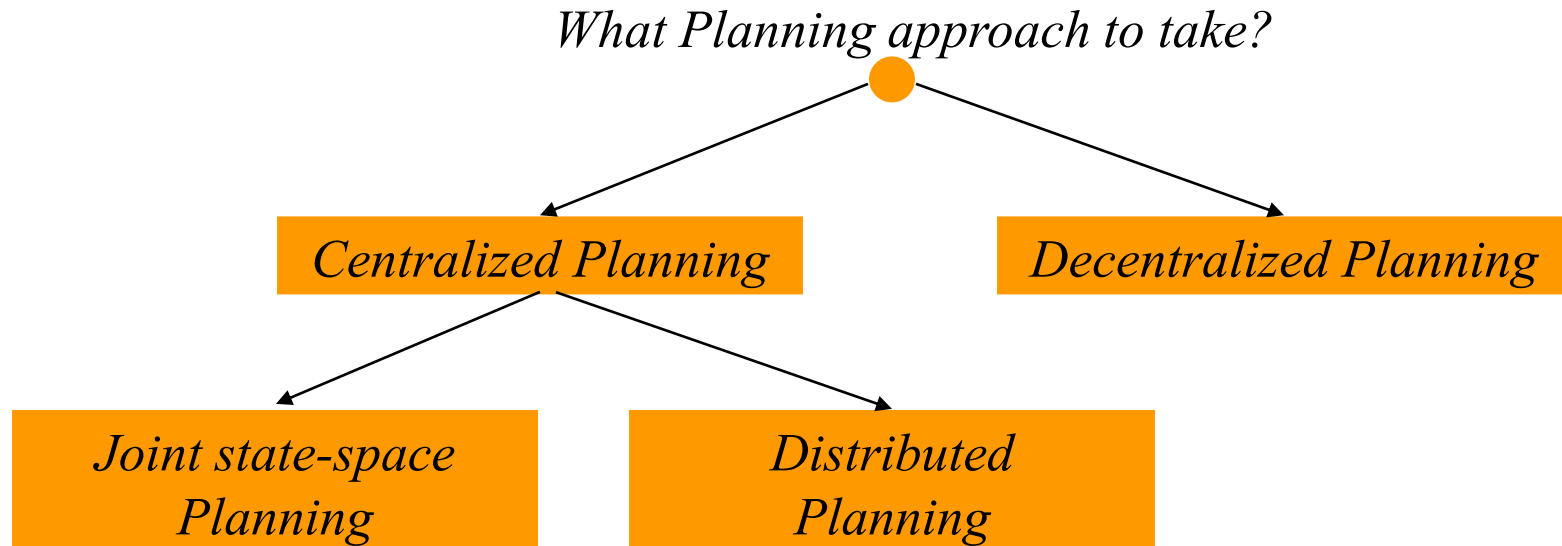
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Control of swarms is typically decentralized

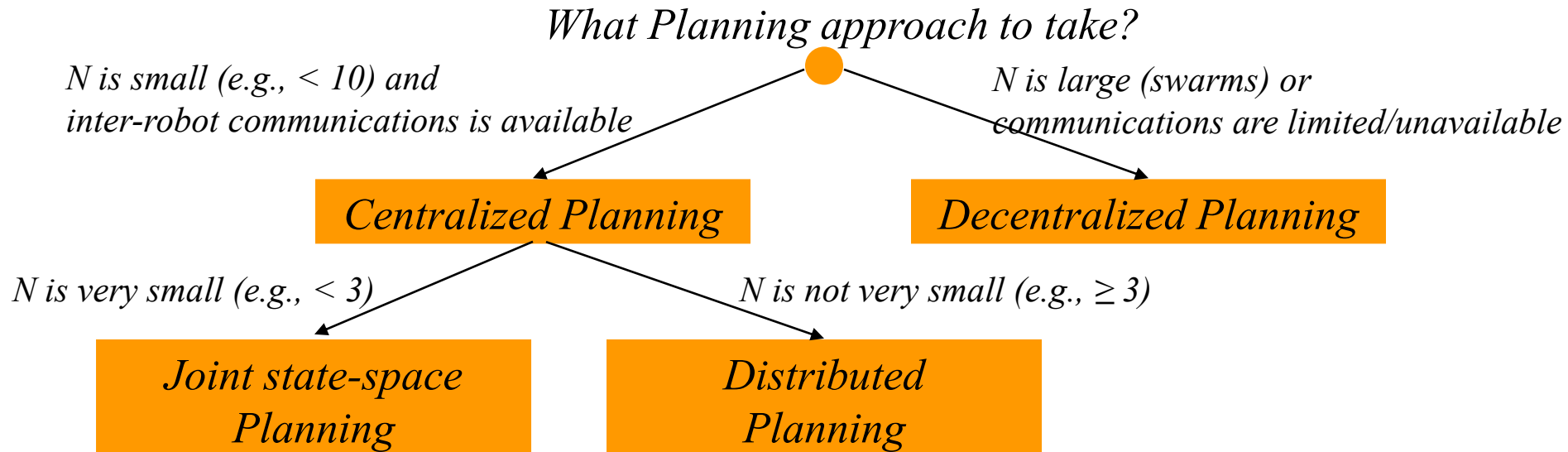
Different Categorizations of Multi-Robot Planning

- Joint state-space vs. distributed planning (within centralized)
 - **Joint state-space planning:** Planning for N robots in a state-space that represents joint configurations of robots
 - **Distributed planning:** Planning is split into N individual planners that share their results (and potentially re-plan) to obtain a final plan for all N robots



Different Categorizations of Multi-Robot Planning

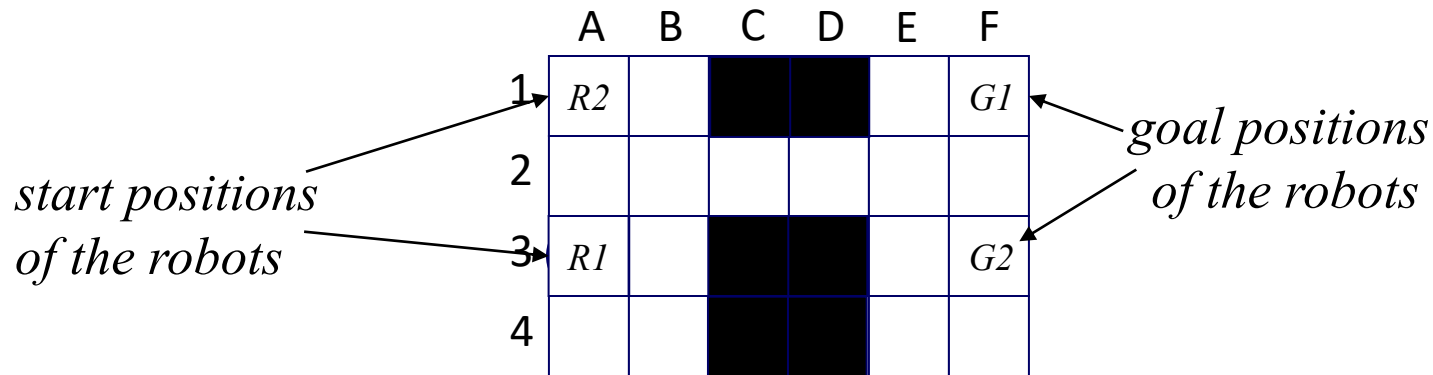
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Multi-Robot Path Planning

- Path planning for N robots to get to their goals w/o collisions

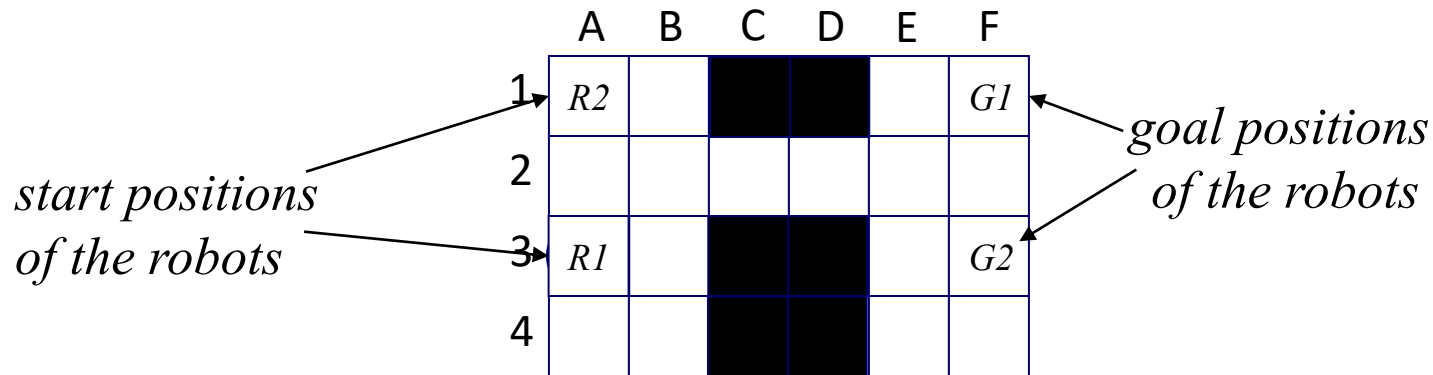
simple example for two omnidirectional point-size robots



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simple example for two omnidirectional point-size robots



Any examples of this in industry?

Multi-Robot Path Planning

- Path planning for N robots to get to their goals w/o collisions

Joint state-space planning

	A	B	C	D	E	F
1	$R2$					$G1$
2						
3	$R1$					$G2$
4						

Multi-Robot Path Planning

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Joint state-space planning

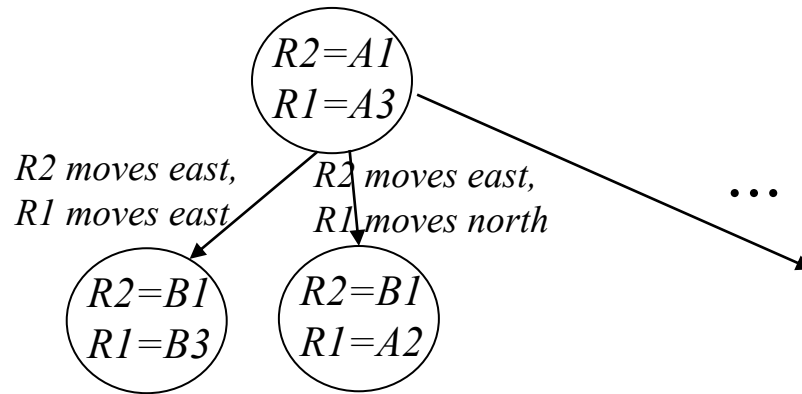
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The simplest approach: construct and search a graph, where each state encodes positions of all the robots and each action encodes all possible movements

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Joint state-space planning



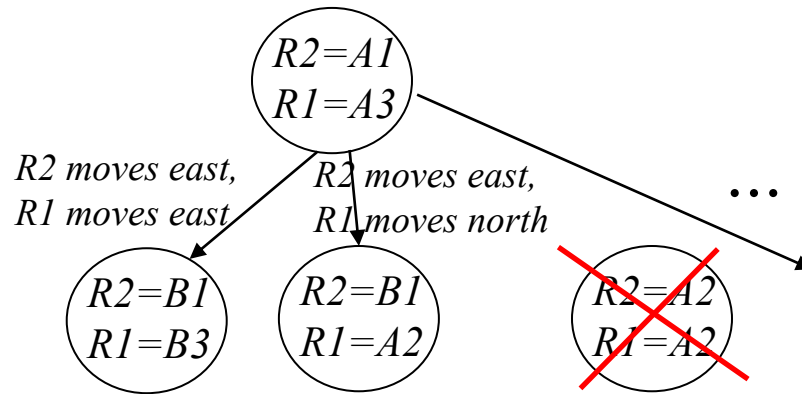
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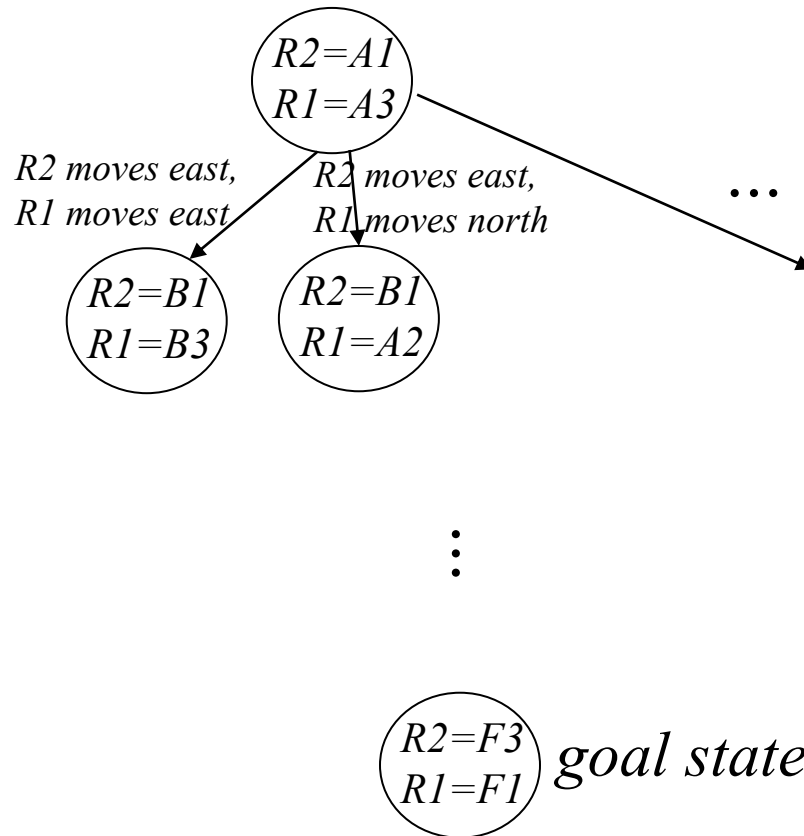
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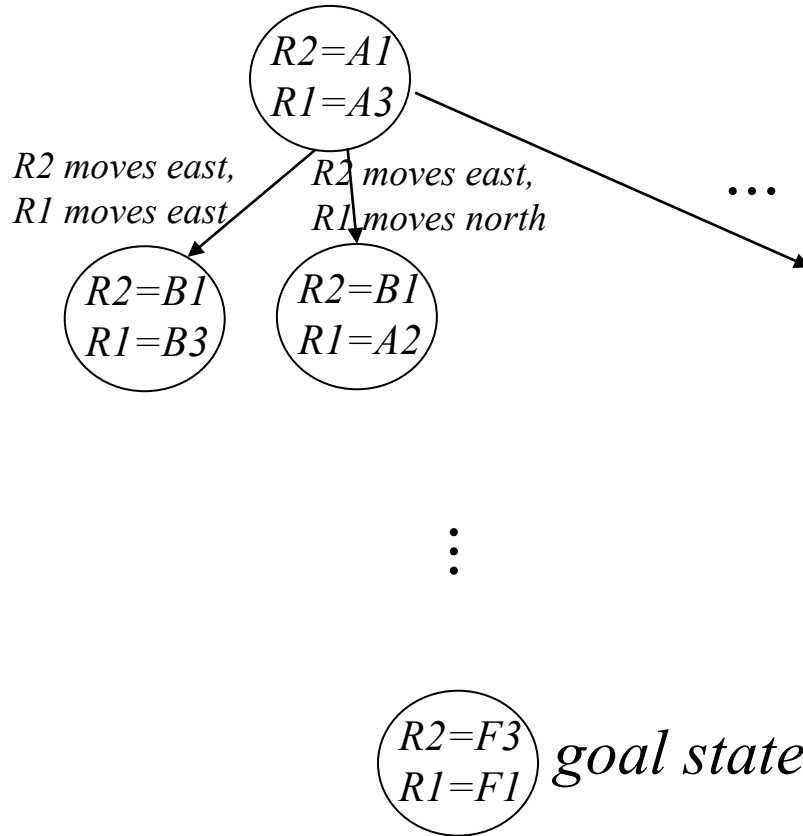
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Multi-Robot Path Planning

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Assuming 4-connected grid,
 what is the maximum branching factor
 (how many actions/successors)?

Joint state-space planning

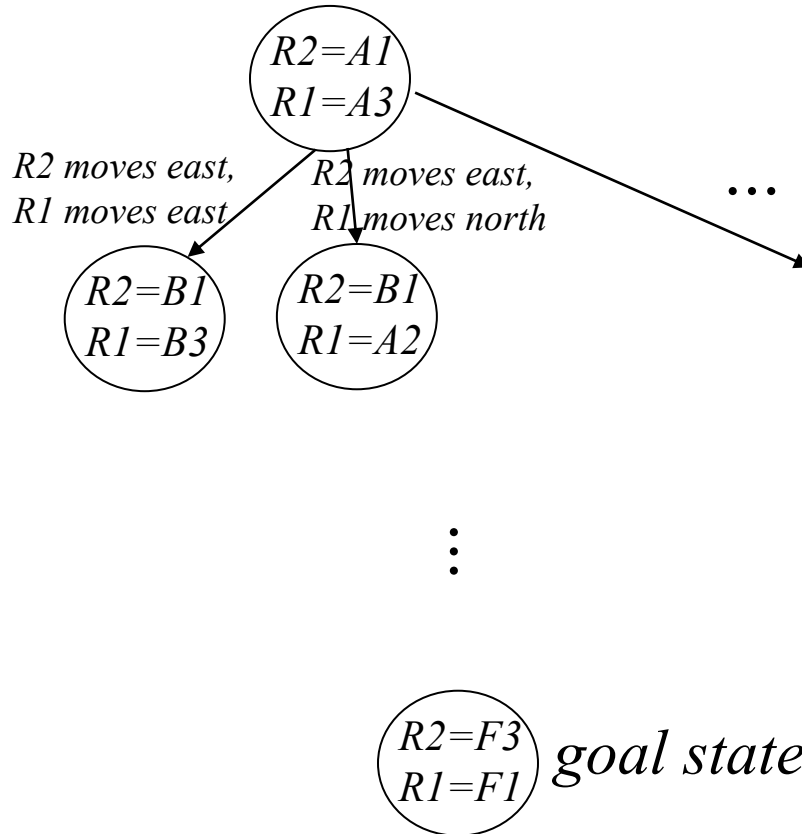


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Multi-Robot Path Planning

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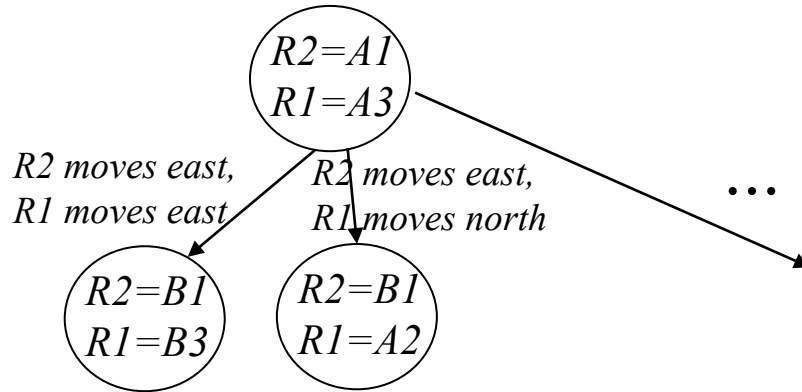
What is the size of the graph?

	A	B	C	D	E	F
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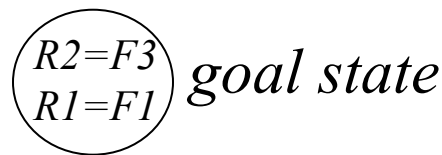
Multi-Robot Path Planning

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⋮



What is the size of the graph?

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Scalability w.r.t. N is clearly an issue!

Multi-Robot Path Planning

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Distributed planning

	A	B	C	D	E	F
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One popular approach: Prioritized Planning

For $i = 1:N$

Compute path for robot R_i that avoids collisions with paths for robots $R_1..R_{i-1}$

Multi-Robot Path Planning

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Each planning needs to include time as a dimension!

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What will be the plan returned by Prioritized Planning?

One popular approach: Prioritized Planning

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Distributed planning

Is it complete?

Is it optimal?

What is the complexity of Prioritized Planning?

One popular approach: Prioritized Planning

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Distributed planning

complete & optimal approach

Conflict-based Search (CBS)

$C(S_{start}) = \{\}$; //no constraints on paths at the start state

$OPEN = \{S_{start}\}$; $g(S_{start}) = 0$;

while ($OPEN \neq \emptyset$)

 remove S with the smallest g -value from $OPEN$

 if no collisions between paths associated with S , then return them as the overall plan
 for each (or at least one) collision of robots R_i and R_j at vertex v at time t

$C1 = C(S) \cup \{R_i(t) \neq v\}$ // R_i can't be at vertex v at time t

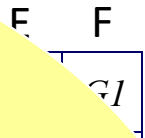
 compute N paths that satisfy $C1$ constraints (w/o collision-checking
 between paths) and the overall cost $PLANCOST1$

$C2 = C(S) \cup \{R_j(t) \neq v\}$ // R_j can't be at vertex v at time t

 compute N paths that satisfy $C2$ constraints (w/o collision-checking
 between paths) and the overall cost $PLANCOST2$

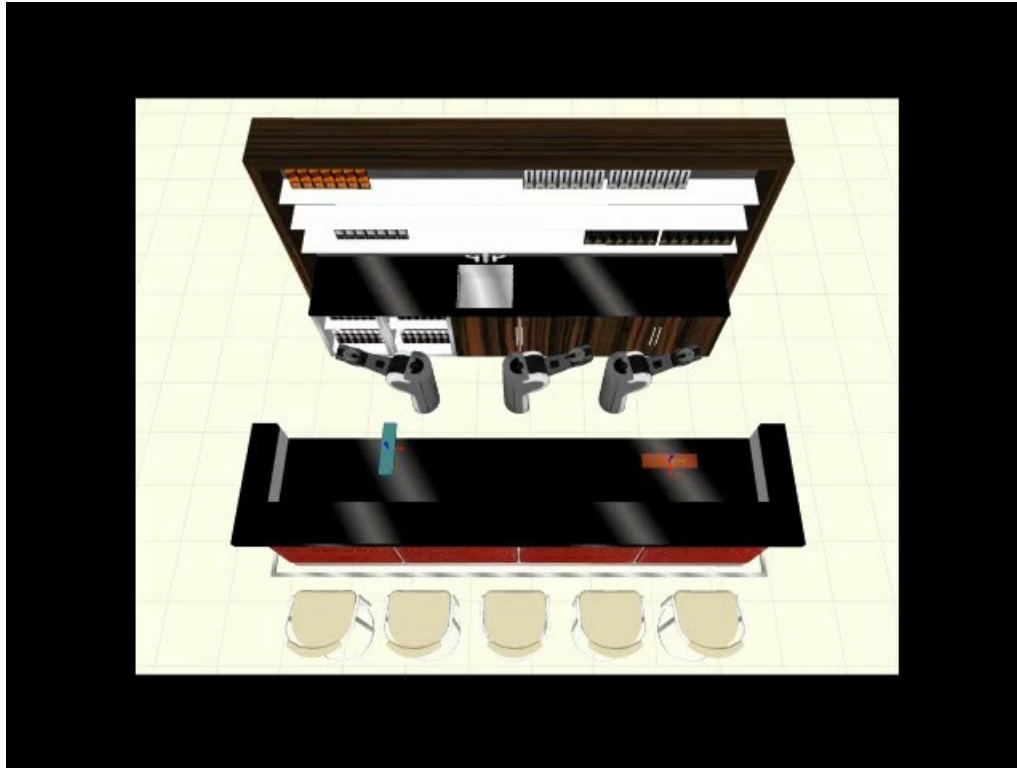
 insert state $S1$ with $C(S1) = C1$ and $g(S1) = PLANCOST1$

 insert state $S2$ with $C(S2) = C2$ and $g(S2) = PLANCOST2$



Multi-Robot Cooperative Planning/Task Allocation

- Example: planning for N robotic arms to move an object



*[Cohen et al., '14]
(performs joint state-space planning)*

Multi-Robot Cooperative Planning/Task Allocation

- Example: planning for N robotic arms to move an object



Search-Based Planning Lab

Master of Science
Robotic Systems Development | Carnegie Mellon University
The Robotics Institute

Collaborative Manipulation

Dr. Maxim Likhachev

Ishani Chatterjee	Clare Cui
Andrew Dornbush	Brad Factor
Sung Kyun Kim	Maitreya Naik
Tae-Hyung Kim	Angad Sidhu
Venkatraman Narayanan	Logan Wan

(planning is distributed: plan on Roman platform first, then on PR2)

Multi-Robot Cooperative Planning/Task Allocation

- Example: planning for multi-robot exploration/mapping

N robots need to explore and build a map of unknown environment

One approach: Distributed Greedy Mapping

For $i = 1:N$

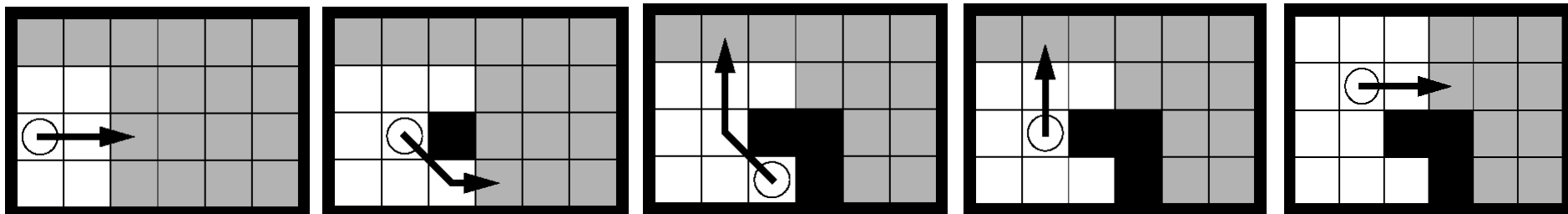
Compute a path using Greedy Mapping approach for robot R_i taking into account what paths were computed for $R_1..R_{i-1}$ (and what cells they would see)

Multi-Robot Cooperative Planning/Task Allocation

- Example: planning for multi-robot exploration/mapping

N robots need to explore and build a map of unknown environment

- Greedy Mapping for a single robot:
 - always move the robot on a shortest path to the closest unobserved (or unvisited) cell
 - it always achieves a gain in information.
 - thus, it is guaranteed to map the environment that is reachable (assuming all moves are reversible)



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[Butzke et al., '11]

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A Planning Framework for Persistent, Multi-UAV Coverage with Global Deconfliction

Submitted to the
12th Conference on Field and Service Robotics

Collaboration between
Search-Based Planning Lab, CMU (headed by M. Likhachev) and
Mitsubishi Heavy Industries (MHI)

[Kusner et al., '19]

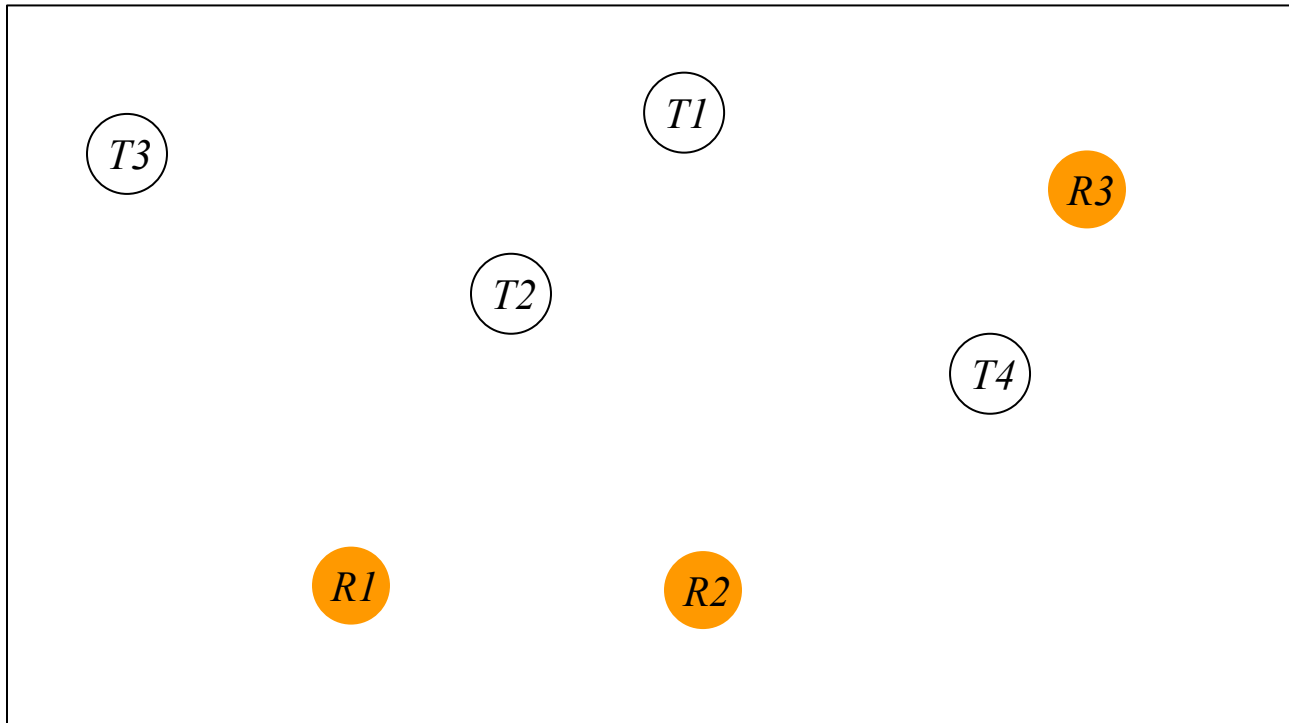
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Multi-Robot Cooperative Planning/Task Allocation

- Market-based approach (very popular distributed approach)
 - Consider planning the allocation of tasks to N robots
 - General scheme: *robots auction out their tasks to their teammates with the goal of increasing their own revenue*

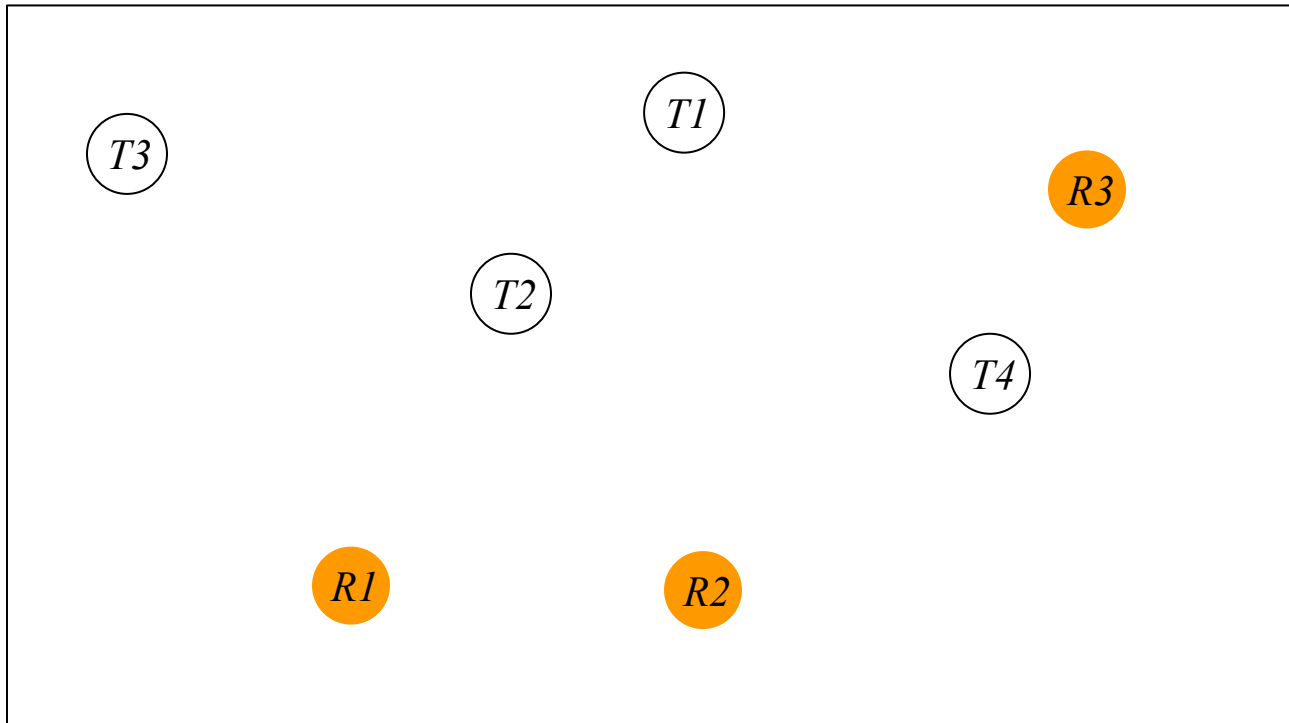


Market-based Approach

Given N robots $R_1 \dots R_N$, M tasks $T_1 \dots T_M$, and $C_i^{R_j}$ – cost of executing task i by robot R_j (cost may depend on other tasks executed by this robot)

Planner needs to decide: Which task gets executed by which robot?

Find a plan(mapping) π^ : $T_i \rightarrow R_j$ such that $\pi^* = \operatorname{argmin} \Sigma C_i^{\pi(T_i)}$*



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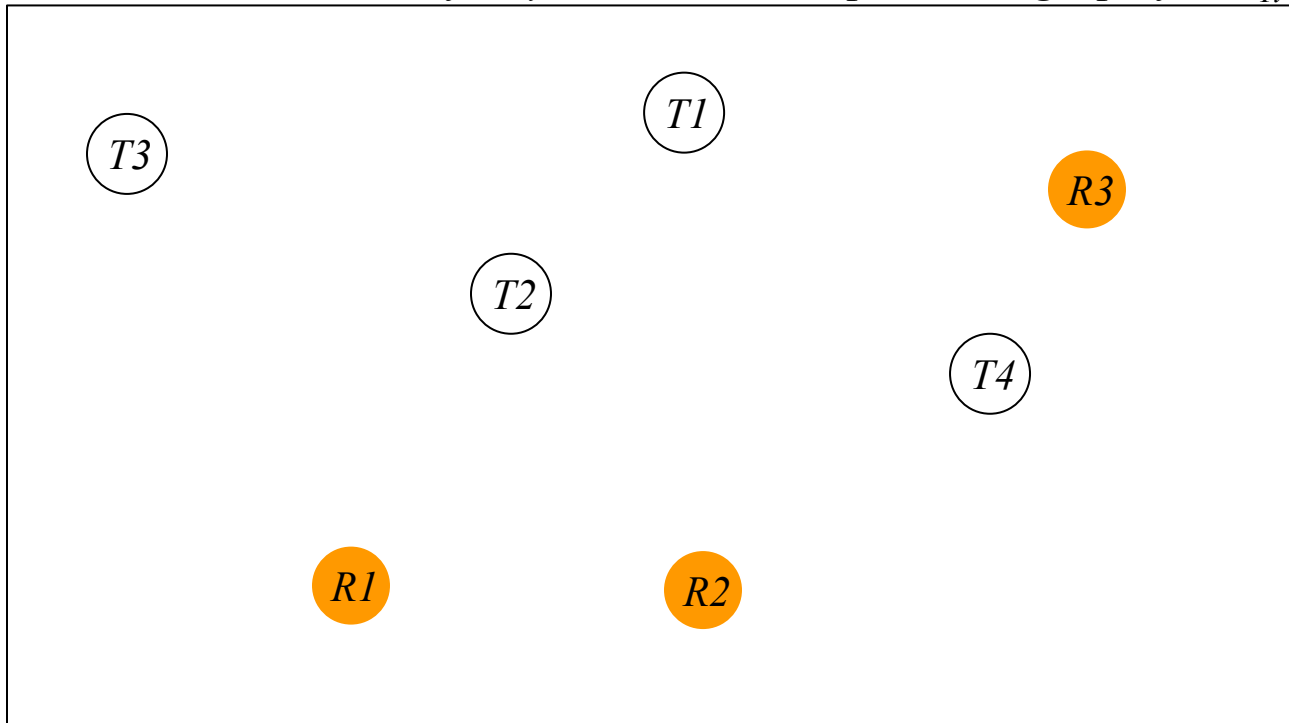
Iterate over steps 1-4 until convergence or planning time expires

Step 1: start with an arbitrary plan π

Step 2: all robots offer their tasks T_i at auction at the max. price of $C_{T_i}^{\pi(T_i)} - \epsilon$

Step 3: all robots R_j bid on the offered tasks T_i with the bid = $C_i^{R_j} + \epsilon$

Step 4: robots sell to the lowest bidders if they are below max. price and get profit: $C_{T_i}^{\pi(T_i)} - C_i^{R_j} - \epsilon$



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Given N robots $R_1 \dots R_N$, M tasks $T_1 \dots T_M$, and $C_i^{R_j}$ – cost of executing task i by robot R_j (cost may depend on other tasks executed by this robot)

When does it converge in one iteration?

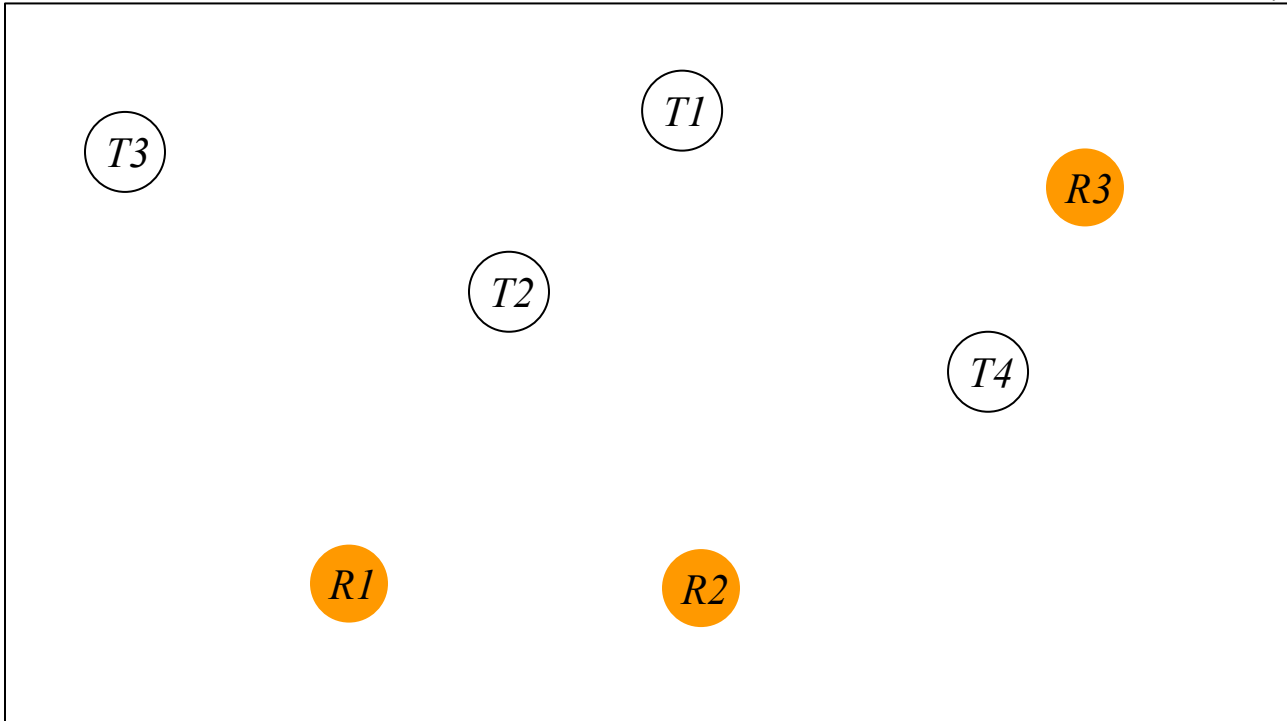
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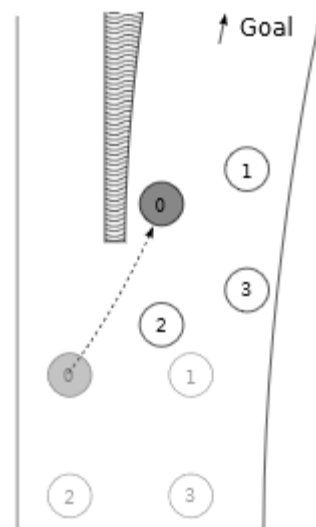
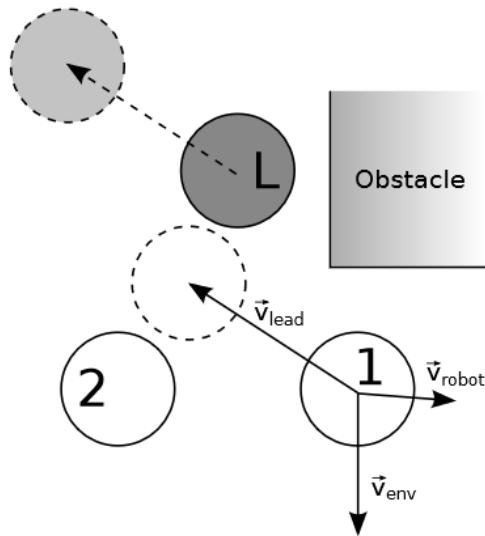
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Planning for Leader-based Coordination

- **Fully decentralized approach** (doesn't rely on the presence of communication between robots)
- Plan for the “leader” robot (sometimes leader can be just a centroid of the team or some other reference point)
- All other robots execute either “follow the leader” or “follow neighbors within field-of-view” behaviors while avoiding collisions



What You Should Know...

- Different styles of multi-robot planning
 - Centralized vs. decentralized
 - Joint state-space planning vs. distributed planning
 - Multi-robot path planning vs. cooperative task planning
- Prioritized Multi-robot Path Planning
- Market-based Approach to multi-robot planning