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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Why do we need decentralized planning approaches?

Robust to limits on or loss of communication
Robust to loosing some robots in the team
Computationally more scalable

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Challenges with decentralized planning?

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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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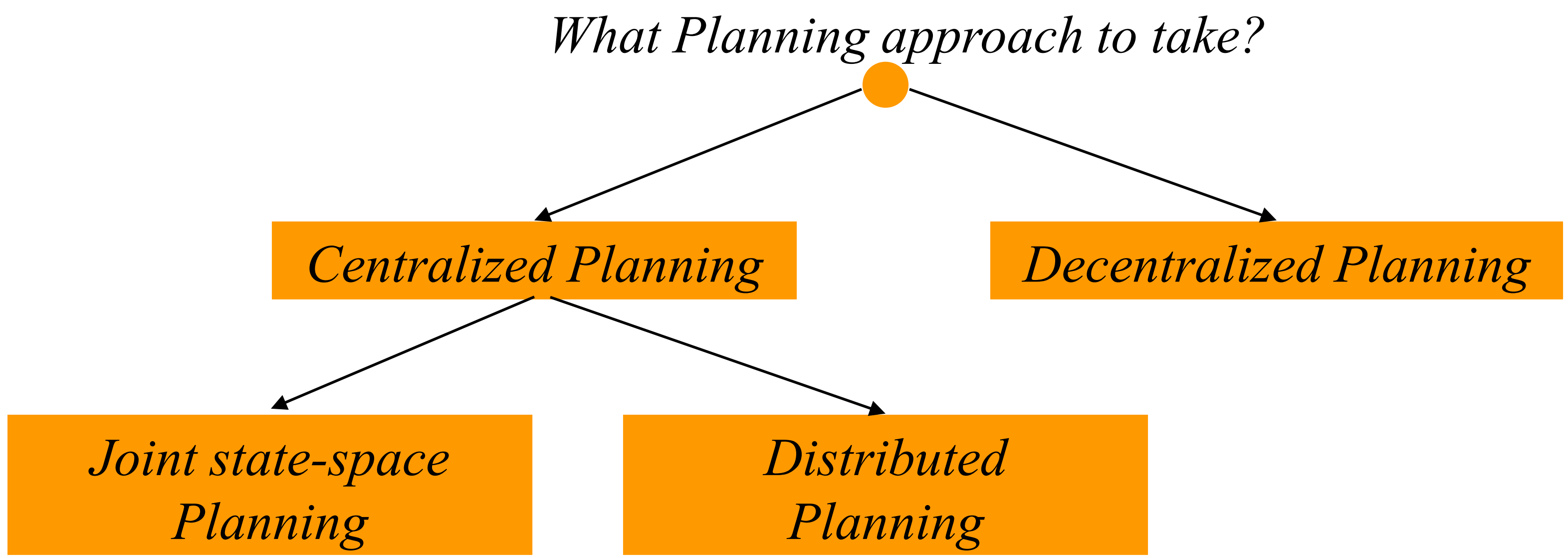
Control of swarms is typically decentralized

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



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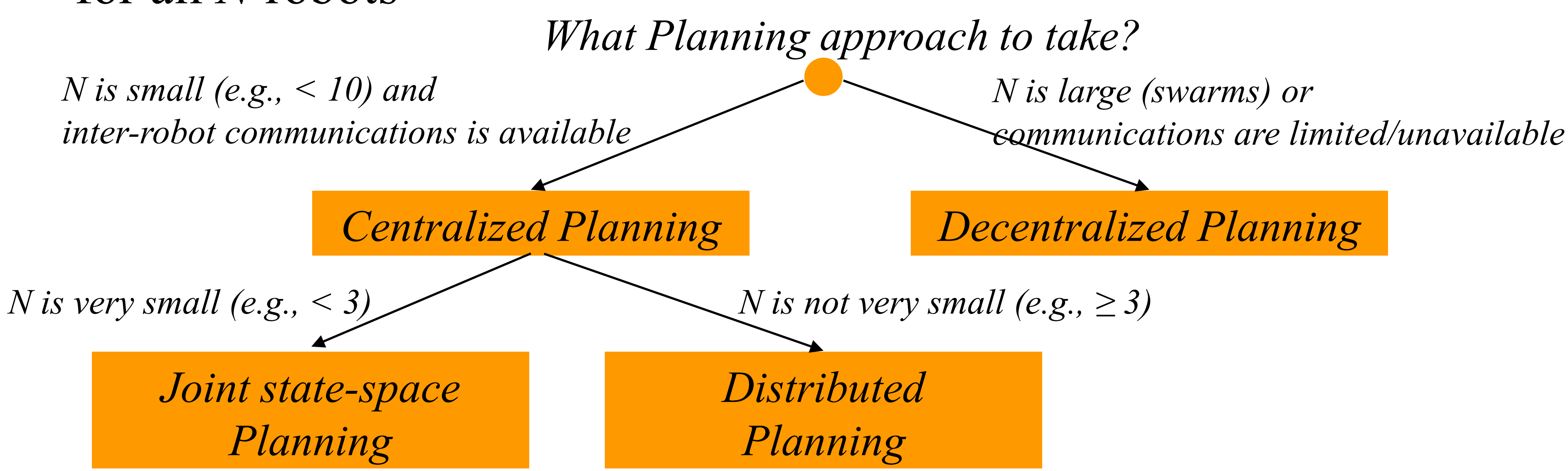
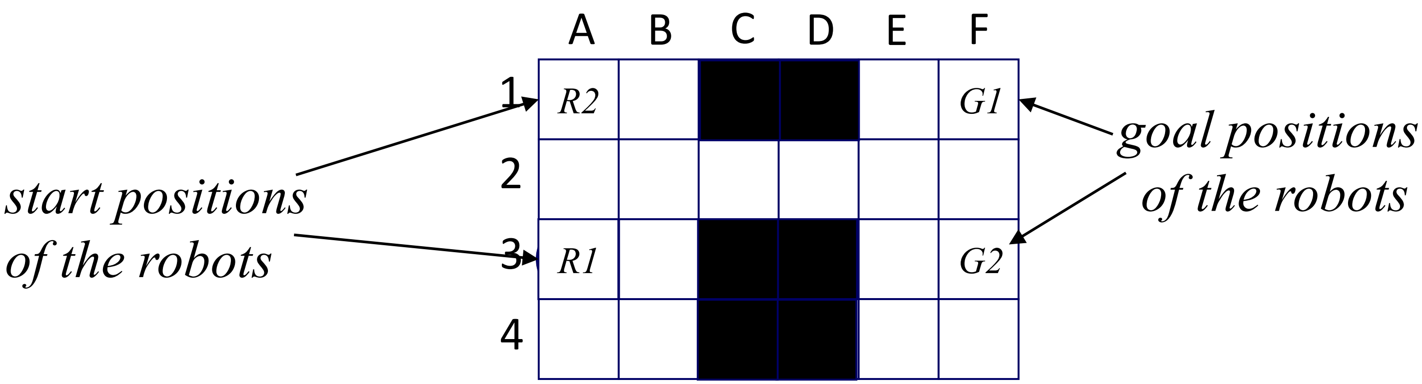


Multi-Robot Path Planning

• 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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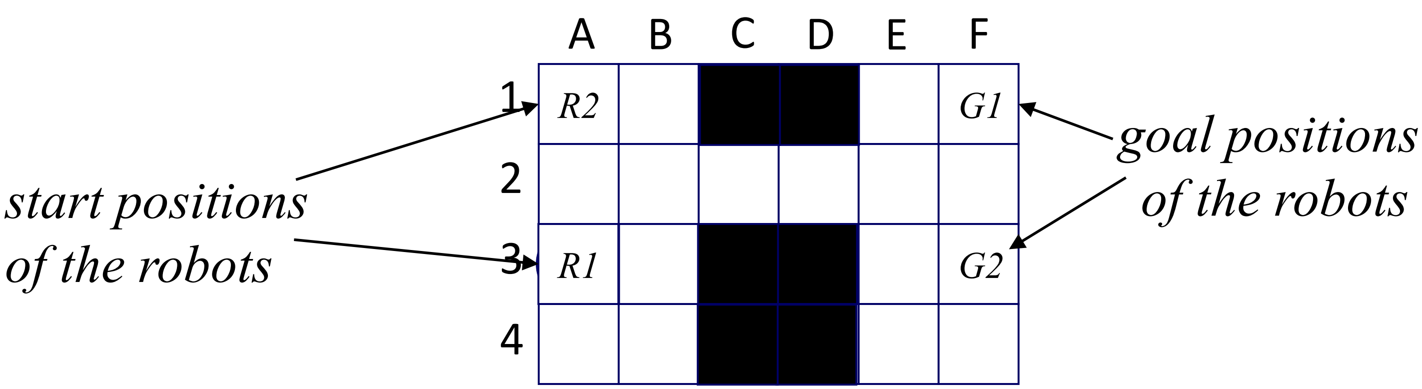
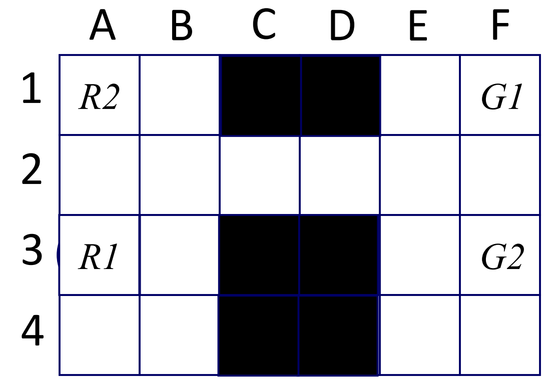


Any examples of this in industry?

Multi-Robot Path Planning

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

Joint state-space planning



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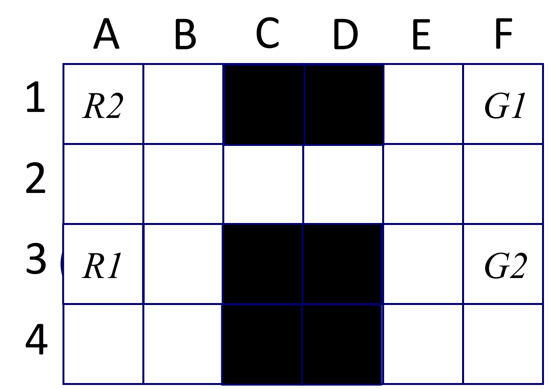
Joint state-space planning



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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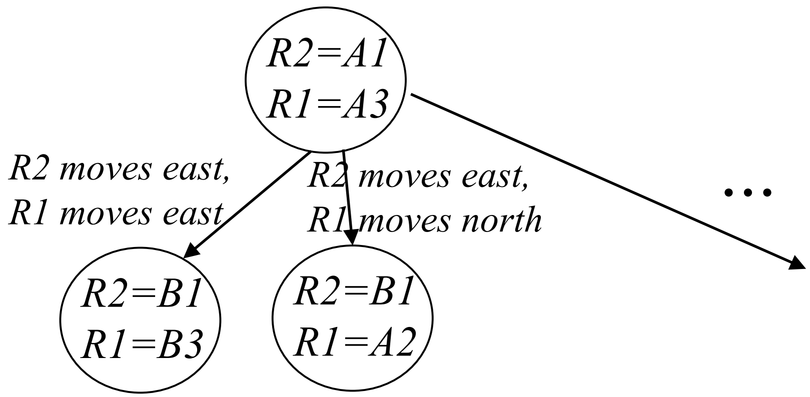

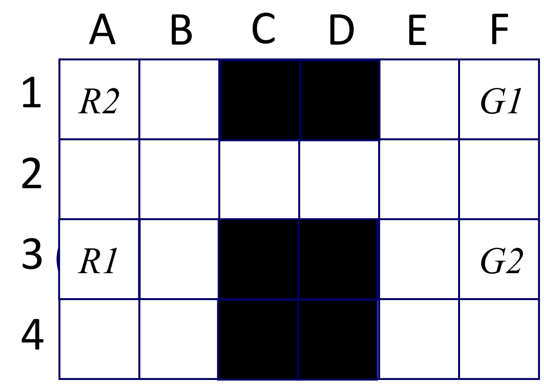

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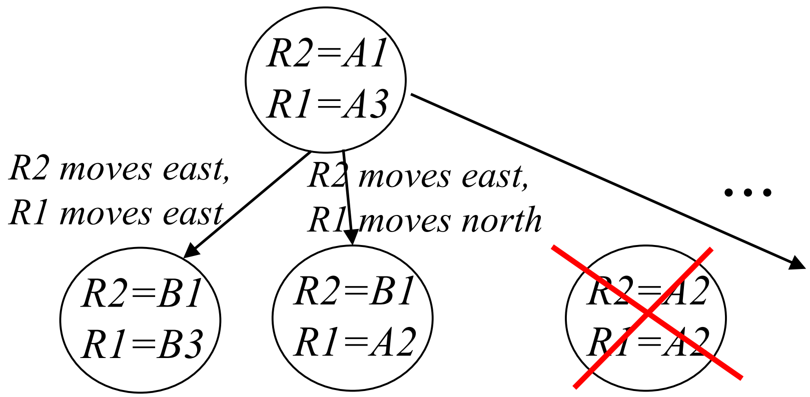
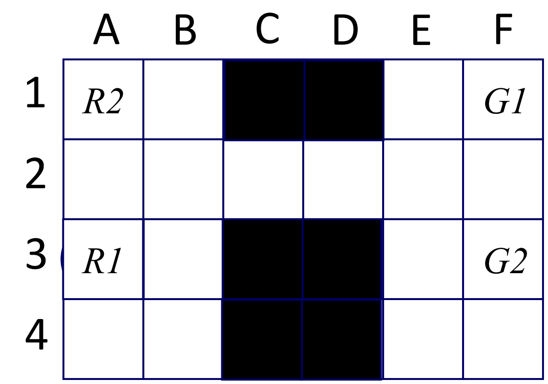
Joint state-space planning





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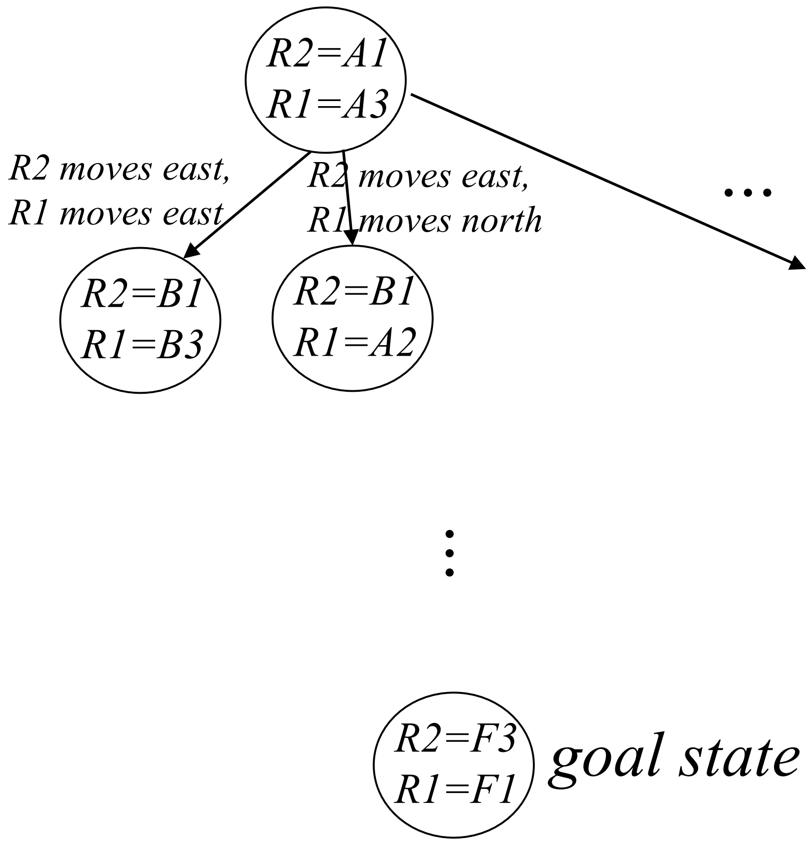
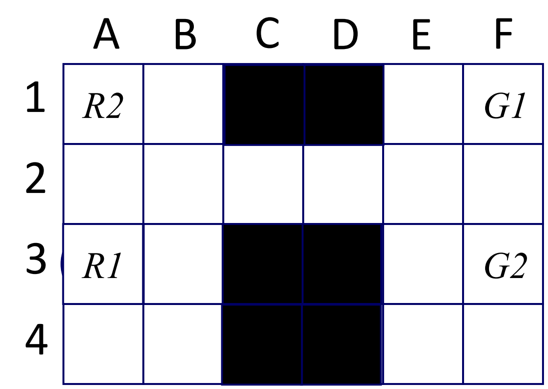


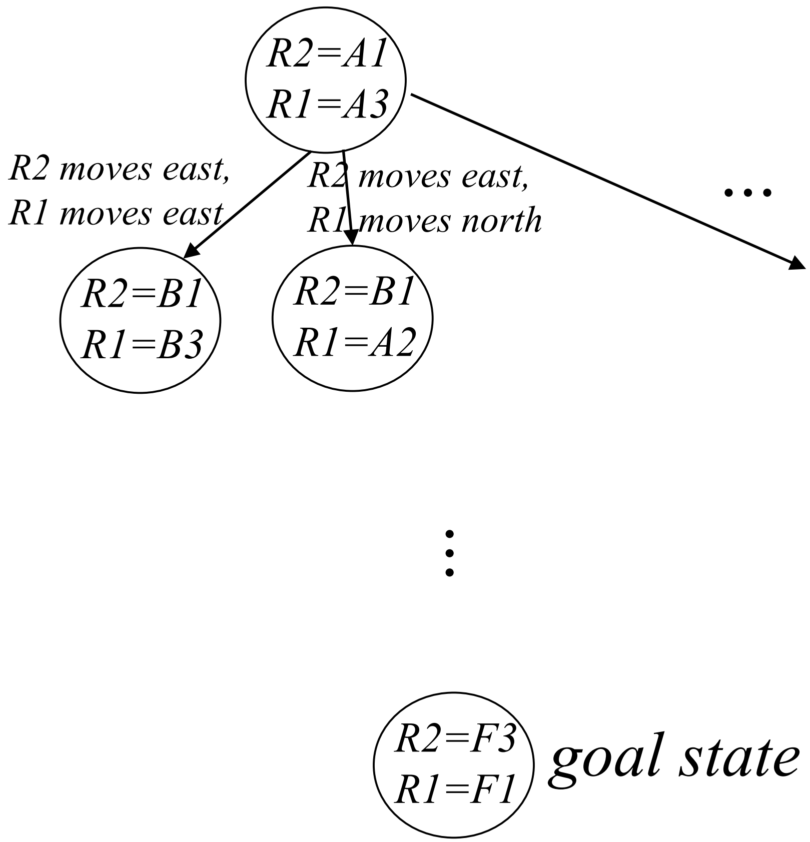


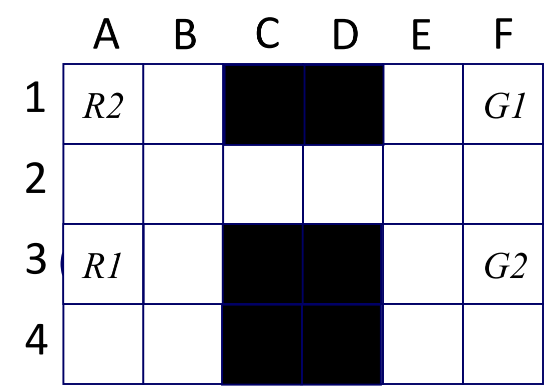
Multi-Robot Path Planning

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

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

Joint state-space planning





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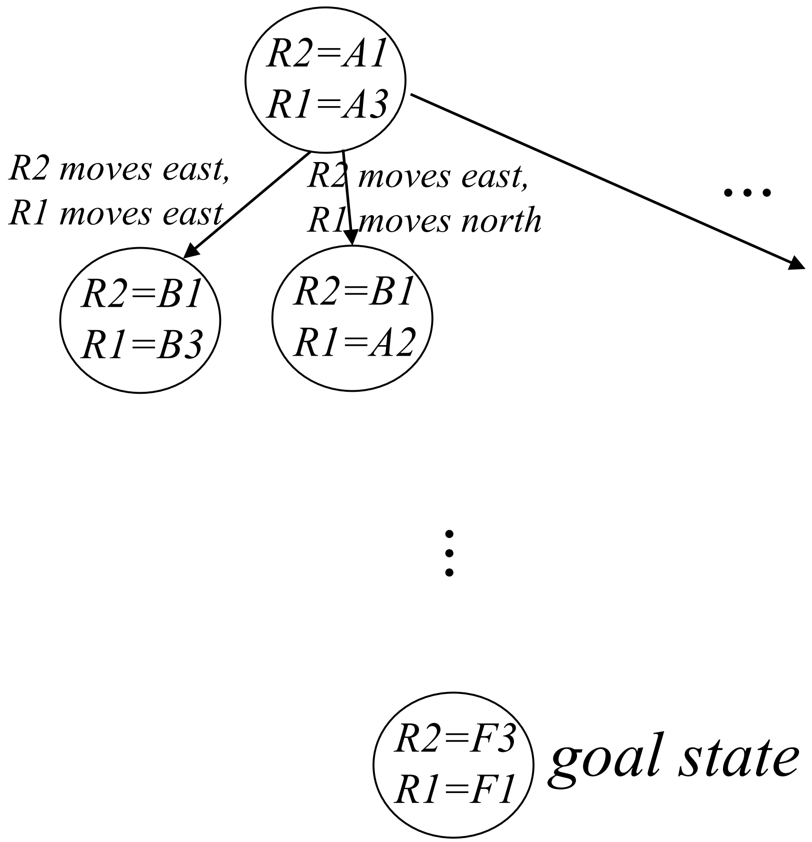
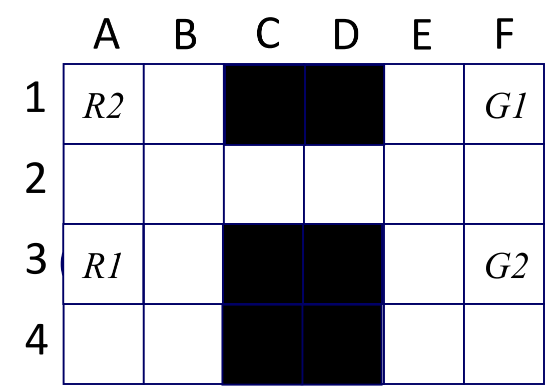
What is the size of the graph?

Joint state-space planning





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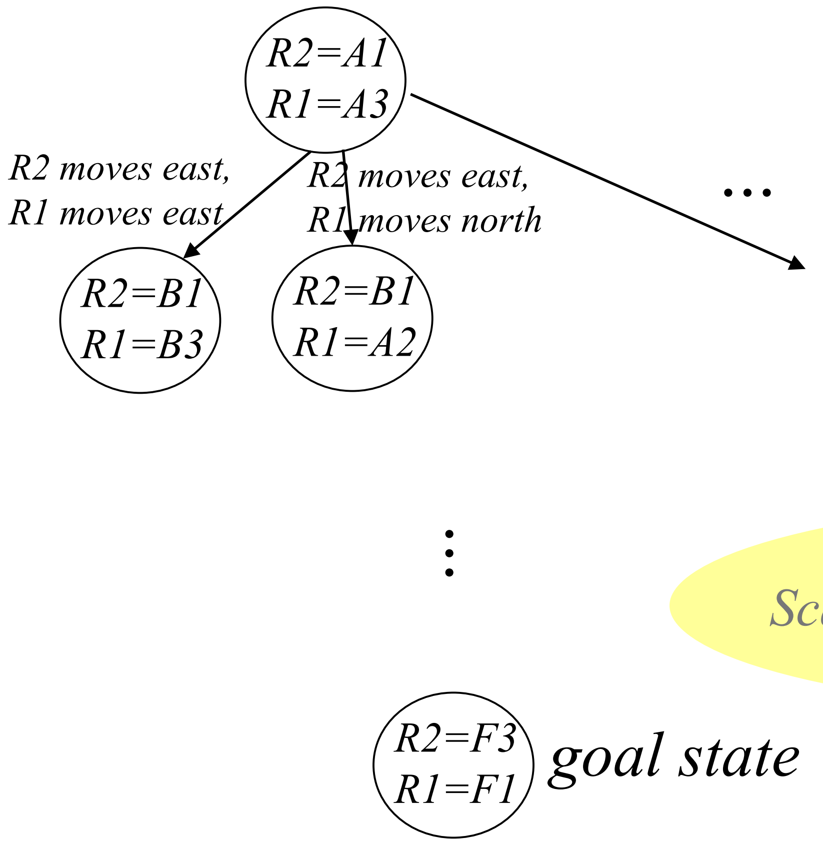
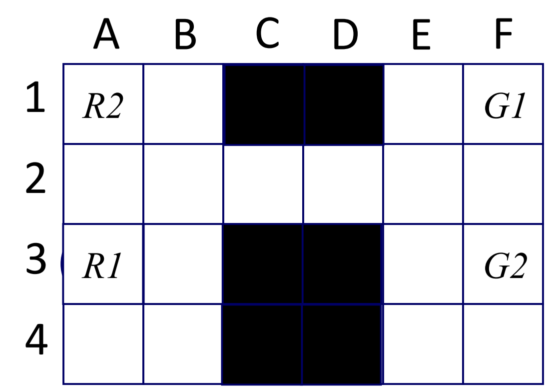


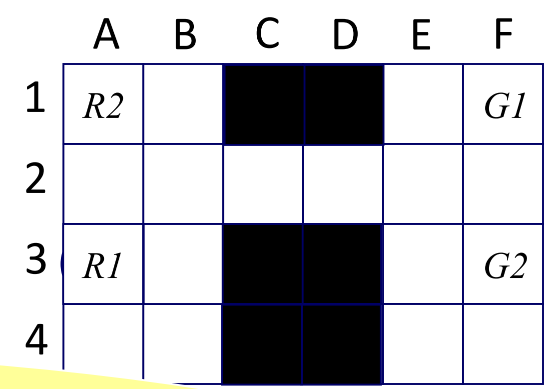


Scalability w.r.t. N is clearly an issue!

Multi-Robot Path Planning

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

Distributed planning



One popular approach: Prioritized Planning

For i = 1:N

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

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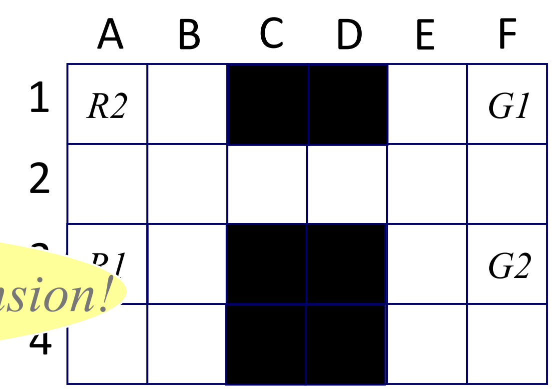
Distributed planning



Each planning needs to include time as a dimension!

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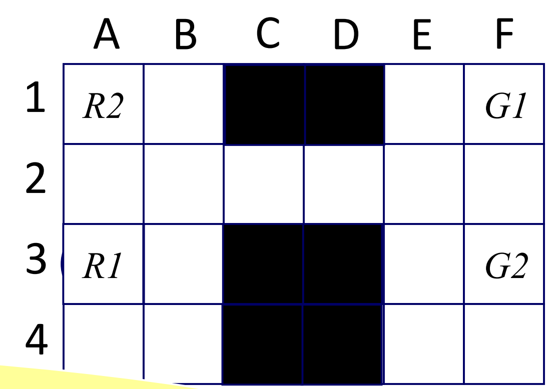

What will be the plan returned by Prioritized Planning?

One popular approach: Prioritized Planning

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Distributed planning

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

Is it complete?

Is it optimal?

What is the complexity of Prioritized Planning?

One popular approach: Prioritized Planning

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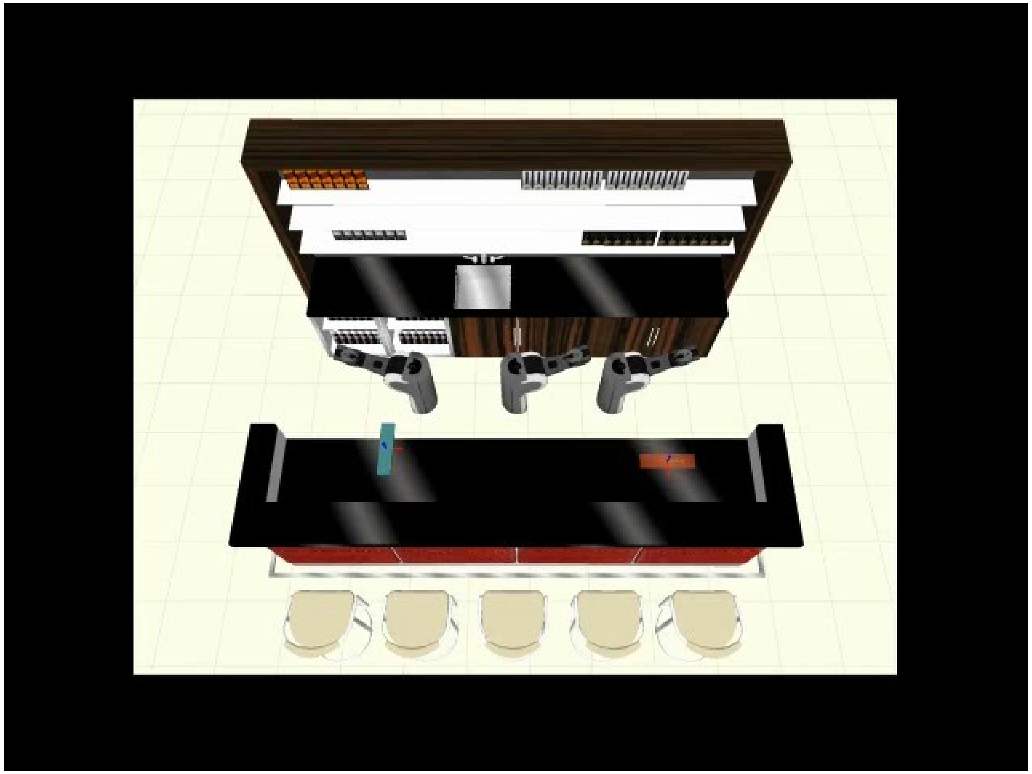
Multi-Robot Cooperative Planning/Task Allocation

- 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

(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

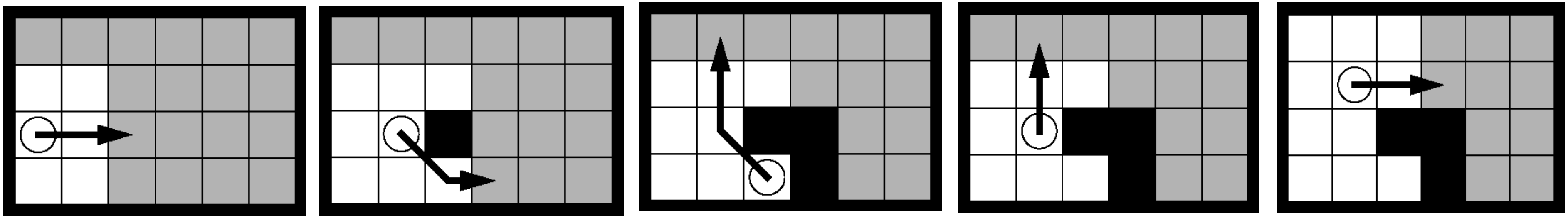
Compute a path using Greedy Mapping approach for robot R_i taking into account what paths were computed for $R_1..R_{i-1}$ (and what cells they would see)

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

[Butzke et al., '11]

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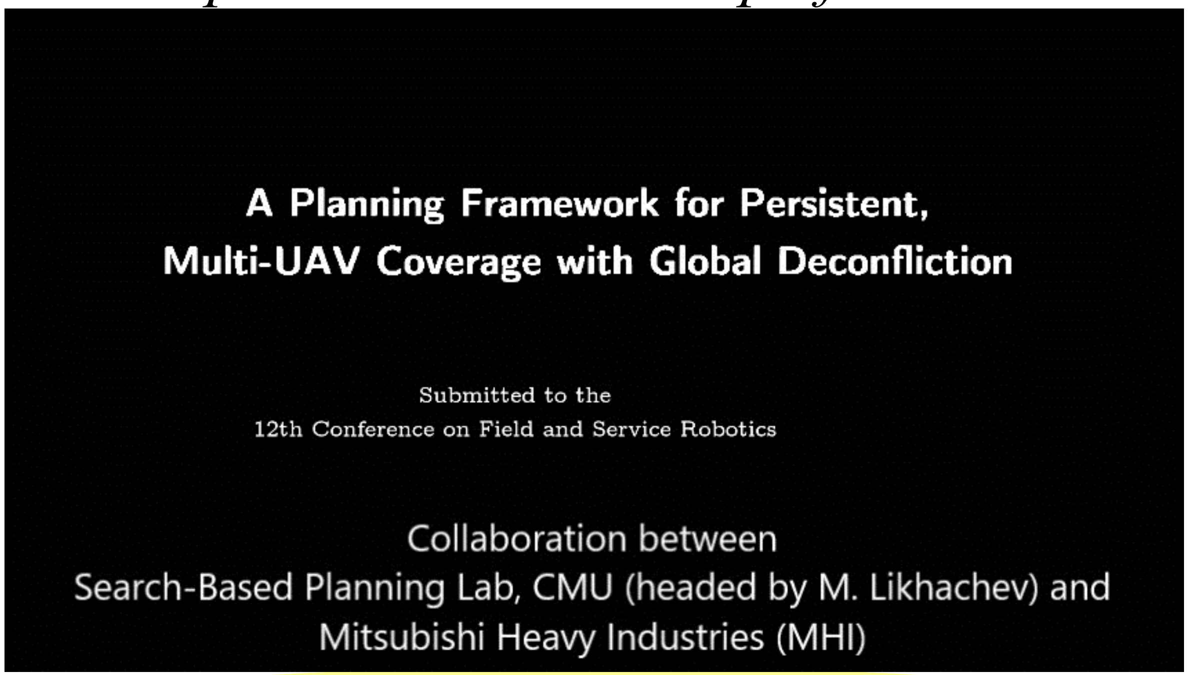

[Kusner et al., ’19]

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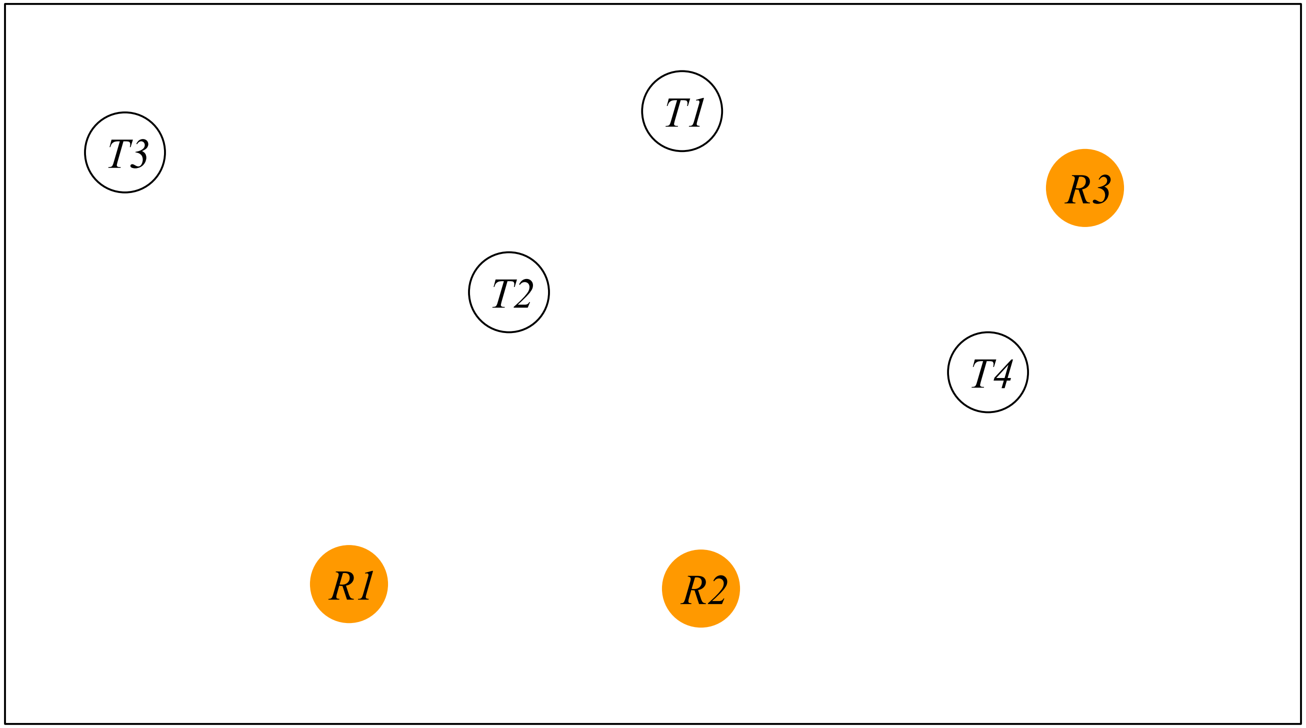
Multi-Robot Cooperative Planning/Task Allocation

- 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*

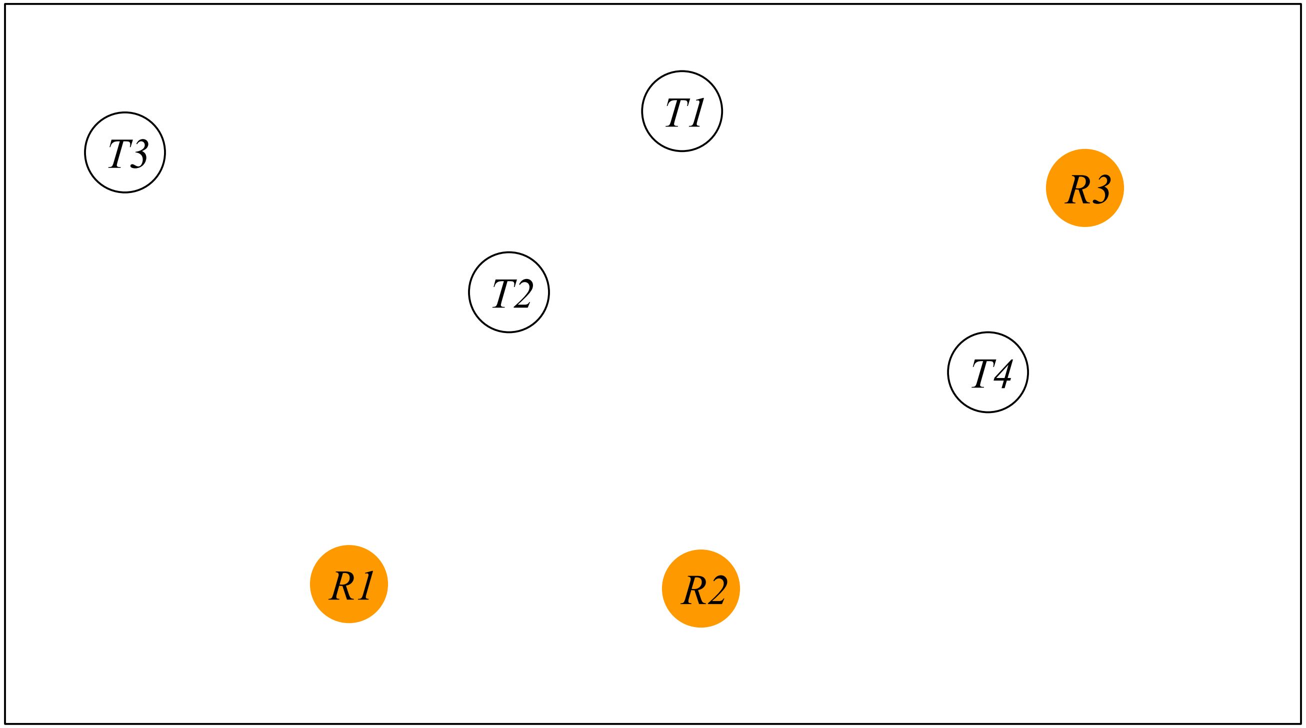


Market-based Approach

Given N robots $R_1 \ldots R_N$, M tasks $T_1 \ldots T_M$, and C_i^{Rj} – 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) $\pi^*: T_i \rightarrow R_j$ *such that* $\pi^* = \text{argmin} \sum C_i^{\pi(Ti)}$



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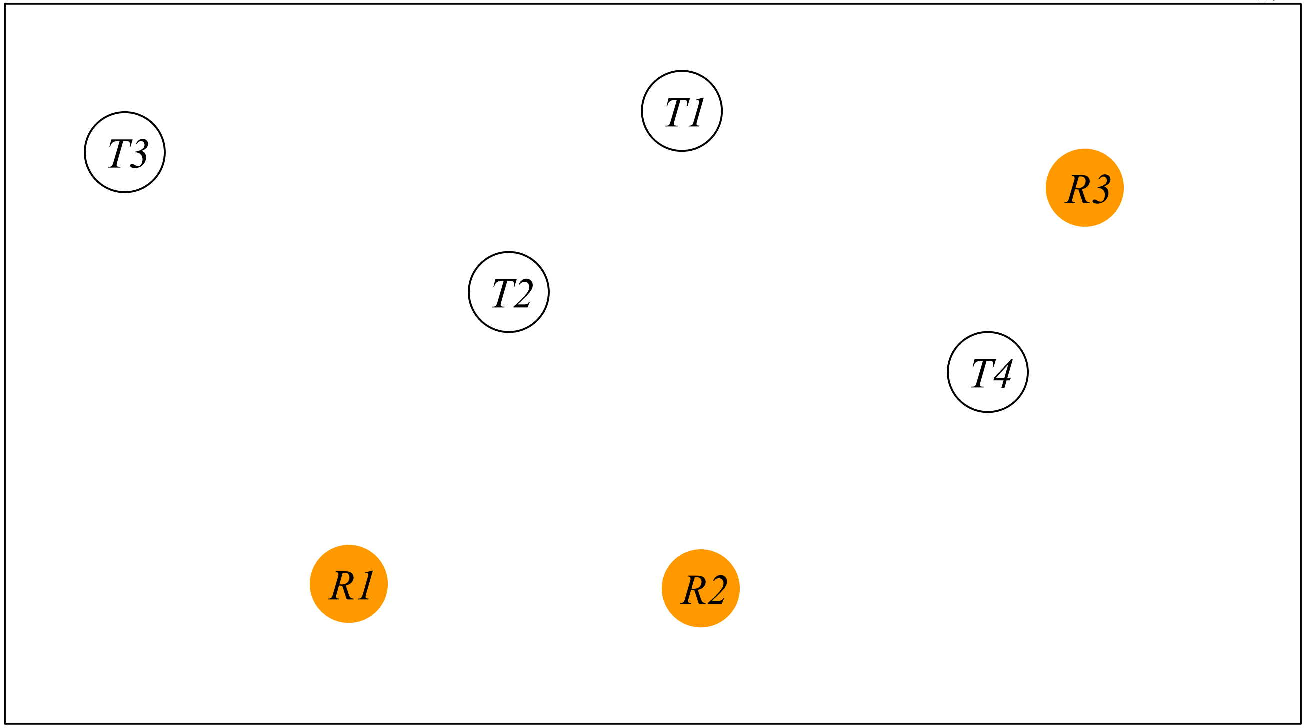
Iterate over steps 1-4 until convergence or planning time expires

Step 1: start with an arbitrary plan π

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

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

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



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Given N robots $R_1 \ldots R_N$, M tasks $T_1 \ldots T_M$, and C_i^{Rj} – 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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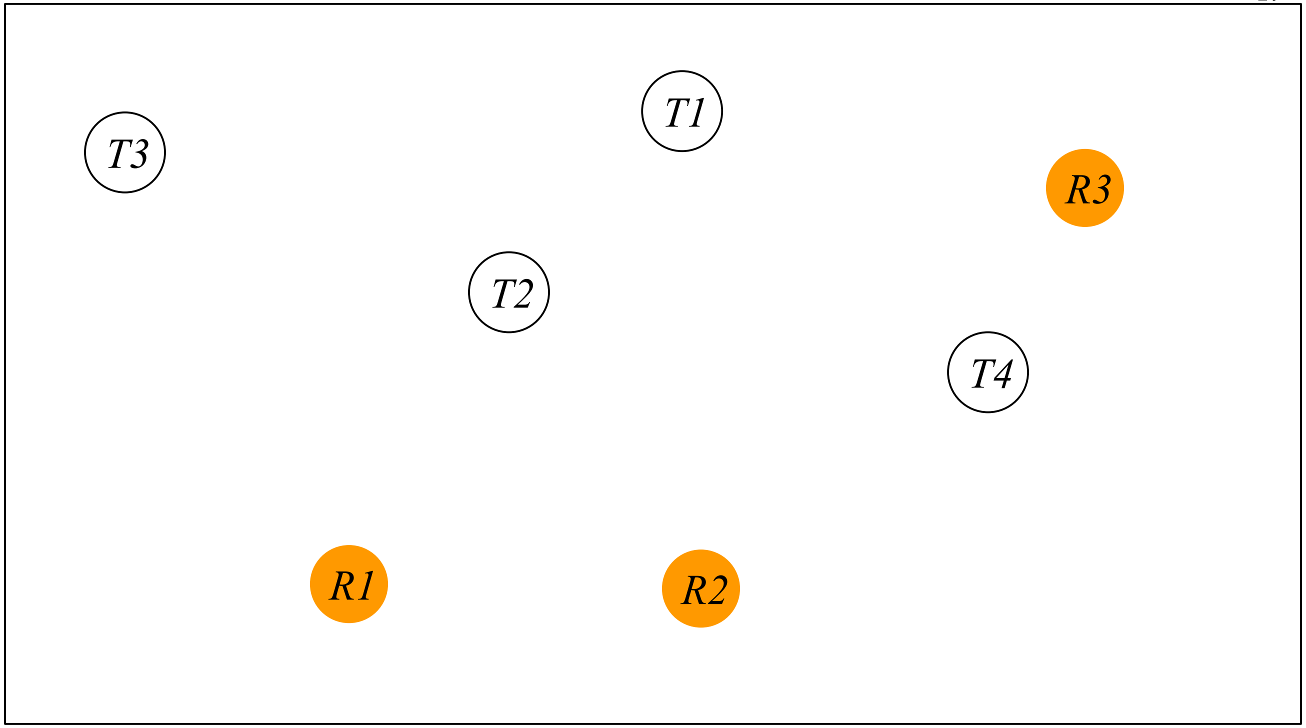
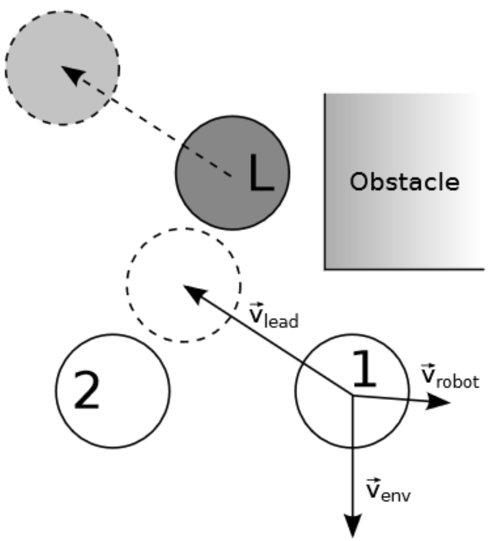


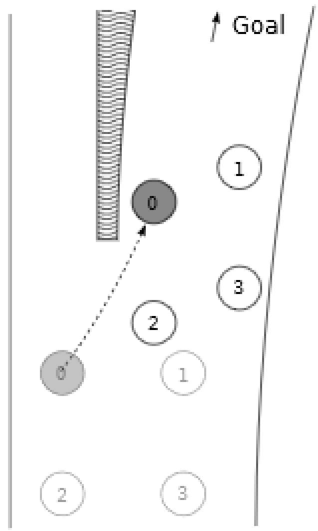
Planning for Leader-based Coordination

• **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