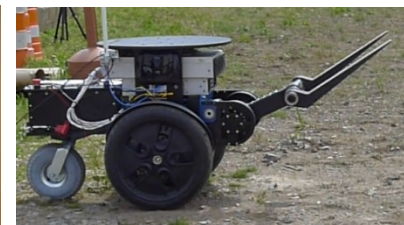# 16-350 Spring'26
Planning Techniques for Robotics

Introduction;
What is Planning for Robotics?

Maxim Likhachev

Robotics Institute

Carnegie Mellon University

About Me

- ## My Research Interests:

  - Planning, Decision-making, Learning

  - Applications: planning for complex robotic systems including aerial and ground robots, manipulation platforms, small teams of heterogeneous robots

- ## More info: *http://www.cs.cmu.edu/~maxim*

- ## Search-based Planning Lab: *http://www.sbpl.net*

About Me

- Also, currently split between CMU and [Waymo](#), where I'm heavily involved in planning for self-driving vehicles

Class Logistics

- Instructor:

  Maxim Likhachev – maxim@cs.cmu.edu

- TA:

  Barath Satheeshkumar - bsathees@andrew.cmu.edu

- Website:

  http://www.cs.cmu.edu/~maxim/classes/robotplanning

- Piazza for Announcements and Questions:

  You should have received an email

Class Logistics

- Books (optional):

  - Planning Algorithms *by Steven M. LaValle*

  - Heuristic Search, Theory and Applications *by Stefan Edelkamp and Stefan Schroedl*

  - Principles of Robot Motion, Theory, Algorithms, and Implementations *by Howie Choset, Kevin M. Lynch, Seth Hutchinson, George A. Kantor, Wolfram Burgard, Lydia E. Kavraki and Sebastian Thrun*

  - Artificial Intelligence: A Modern Approach *by Stuart Russell and Peter Norvig*

Class Prerequisites

- Knowledge of programming (e.g., C, C++)

- Knowledge of data structures

- Some prior exposure to robotics (e.g., Intro to Robotics class) is preferred

Class Objectives

- Understand and learn how to implement most popular planning algorithms in robotics including heuristic search-based planning algorithms, sampling-based planning algorithms, task planning, planning under uncertainty and multi-robot planning

- Learn basic principles behind the design of planning representations

- Understand core theoretical principles that many planning algorithms rely on and learn how to analyze theoretical properties of the algorithms

- Understand the challenges and basic approaches to interleaving planning and execution in robotic systems

- Learn common uses of planning in robotics

Tentative Class Schedule

Date	Day	Topic	HW out	HW due
12-Jan	Mon	Introduction; What is Planning?		
14-Jan	Wed	planning representations: explicit vs. implicit graphs, skeletonization-, grid- and lattice-based graphs		
19-Jan	Mon	NO CLASS		
21-Jan	Wed	planning representations: explicit vs. implicit graphs, skeletonization-, grid- and lattice-based graphs (cont'd)		
26-Jan	Mon	search algorithms: Uninformed A*	HW1	
28-Jan	Wed	search algorithms: A*, Multi-goal A*		
2-Feb	Mon	heuristics, weighted A*, Backward A*		
4-Feb	Wed	interleaving planning and execution: Anytime heuristic search		
9-Feb	Mon	interleaving planing and execution: Freespace assumption, Incremental heuristic search		
11-Feb	Wed	interleaving planning and execution: Limited Horizon search, LRTA*		
16-Feb	Mon	case study: planning for autonomous driving		HW1
18-Feb	Wed	planning representations: PRM for continuous spaces	HW2	
23-Feb	Mon	planning representations/search algorithms: RRT, RRT-Connect, RRT*		
25-Feb	Wed	planning representations/search algorithms: RRT, RRT-Connect, RRT* (cont'd)		
2-Mar	Mon	SPRING BREAK; NO CLASS		
4-Mar	Wed	SPRING BREAK; NO CLASS		
9-Mar	Mon	case study: planning for mobile manipulation and articulated robots		
11-Mar	Wed	search algorithms: Markov Property, dependent vs. independent variables		HW2
16-Mar	Mon	case study: planning for exploration and surveillance tasks		
18-Mar	Wed	final project proposal presentations		
23-Mar	Mon	planning representations: state-space vs. symbolic representation for task planning	HW3	
25-Mar	Wed	search algorithms: symbolic task planning algorithms		
30-Mar	Mon	planning under uncertainty: Minimax formulation		
1-Apr	Wed	planning under uncertainty: Expected Cost Minimization formulation		HW3
6-Apr	Mon	planning under uncertainty: Solving Markov Decision Processes		
8-Apr	Wed	exam		
13-Apr	Mon	multi-robot planning		
15-Apr	Wed	multi-robot planning		
20-Apr	Mon	TBD		
22-Apr	Wed	final project presentations		

Class Structure

- Grading

Three homeworks	33%
Exam	20%
In-class pop quizzes	10%
Final project	32%
Participation	5%

- Exam is tentatively scheduled for April 8 (no final exam)

- Late Policy
  - 3 free late days
  - No late days may be used for the final project!
  - Each additional late day incurs 10% penalty with 50% being the upper limit (grade of 90 becomes 81 for one additional late day)

Three Homeworks + Final Project

- All homeworks are individual (no groups)

- Final project are in groups of 2-3 students

- Homeworks are programming assignments

- Final project is a research-like project. For example:
    - to develop a planner for a robot planning problem of your choice
    - to extend an existing or develop a new planning algorithm
    - to prove novel properties of a planning algorithm

    - Get a feel for doing research: Individual meetings with groups, Two class presentations (initial idea and final)

Three Homeworks + Final Project

• <u>Homework assignments for Masters students will have additional scope</u>

• Undergraduate students will have an option to tackle this additional scope and receive bonus points

What is Planning?

• According to Wikipedia: *"Planning is the process of thinking about an organizing the activities required to achieve a desired goal."*

What is Planning **for Robotics**?

- According to Wikipedia: *"Planning is the process of thinking about an organizing the activities required to achieve a desired goal."*

- *Given*
  - *model (states and actions) of the robot(s) $M^R = <S^R, A^R>$*
  - *a model of the world M^W*
  - *current state of the robot $s^R_{current}$*
  - *current state of the world $s^W_{current}$*
  - *cost function C of robot actions*
  - *desired set of states for robot and world G*

- *Compute a plan π that*
  - *prescribes a set of actions $a_1,...a_K$ in A^R the robot should execute*
  - *reaches one of the desired states in G*
  - *(preferably) minimizes the cumulative cost of executing actions $a_1,...a_K$*

Example

- ***Given***
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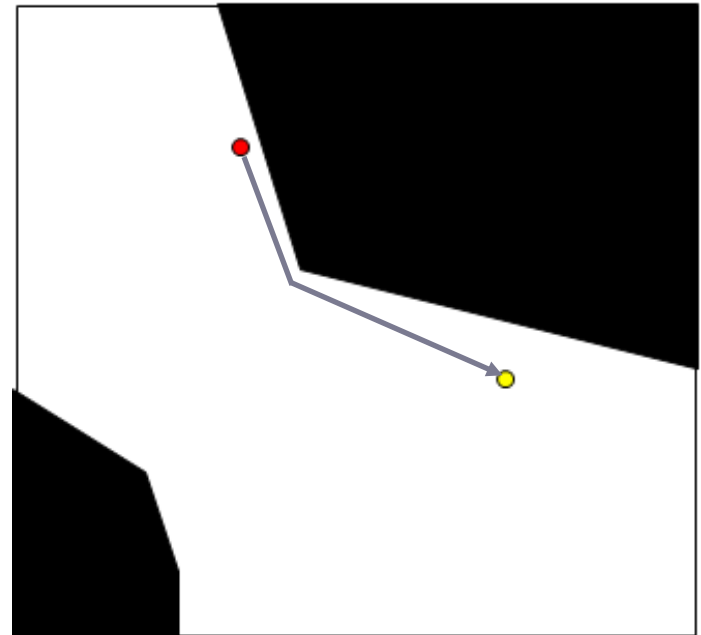Planning for omnidirectional robot:
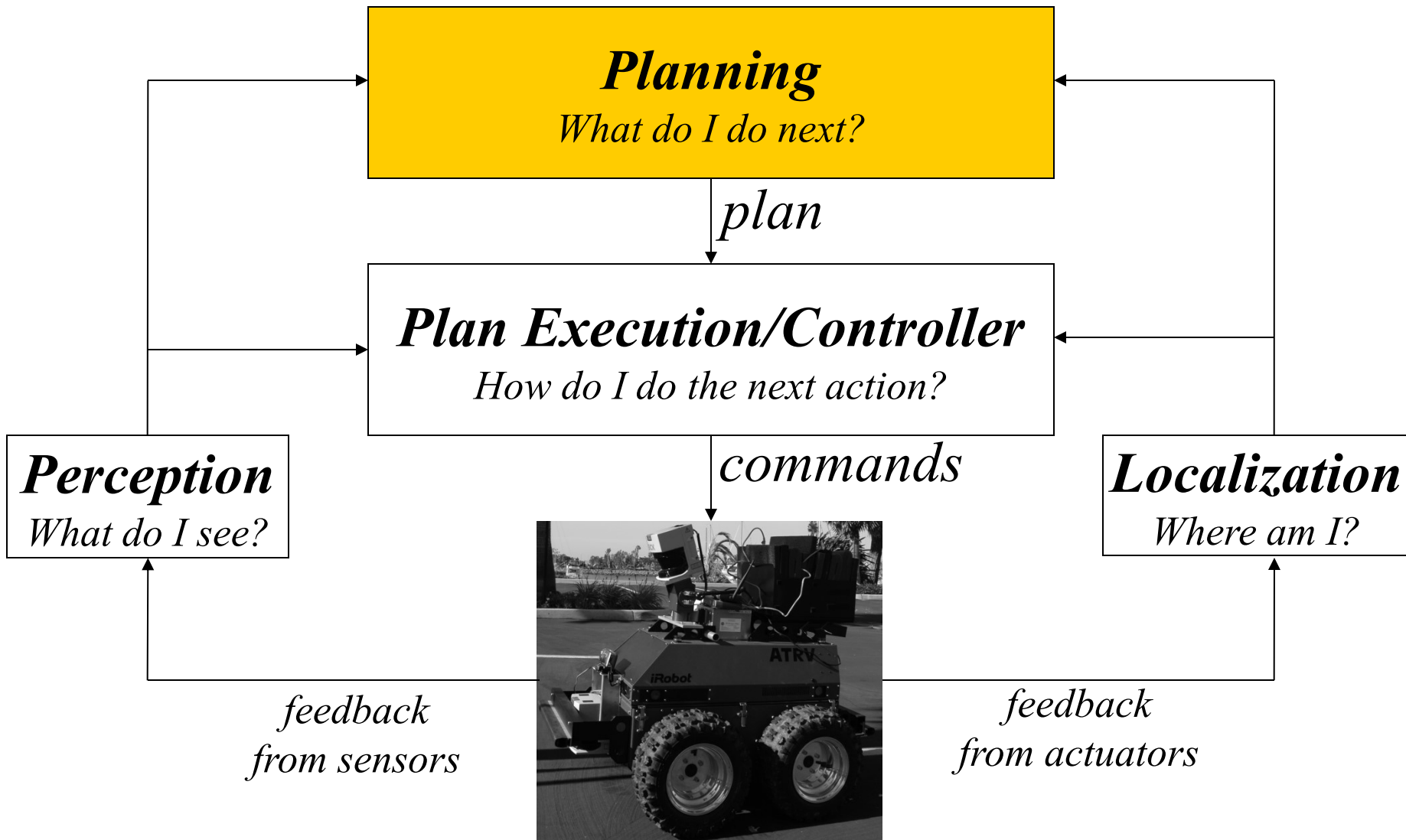
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What is M^W?
What is $s^R_{current}$?
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What is C?
What is G?

Planning within a Typical Autonomy Architecture

Planning
What do I do next?

plan

Plan Execution/Controller
How do I do the next action?

commands

Perception
What do I see?

Localization
Where am I?

*feedback
from sensors*

*feedback
from actuators*

Few More Examples

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Planning for omnidirectional drone:

What is M^R?
What is M^W?
What is $s^R_{current}$?
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MacAllister et al., 2013

Few More Examples

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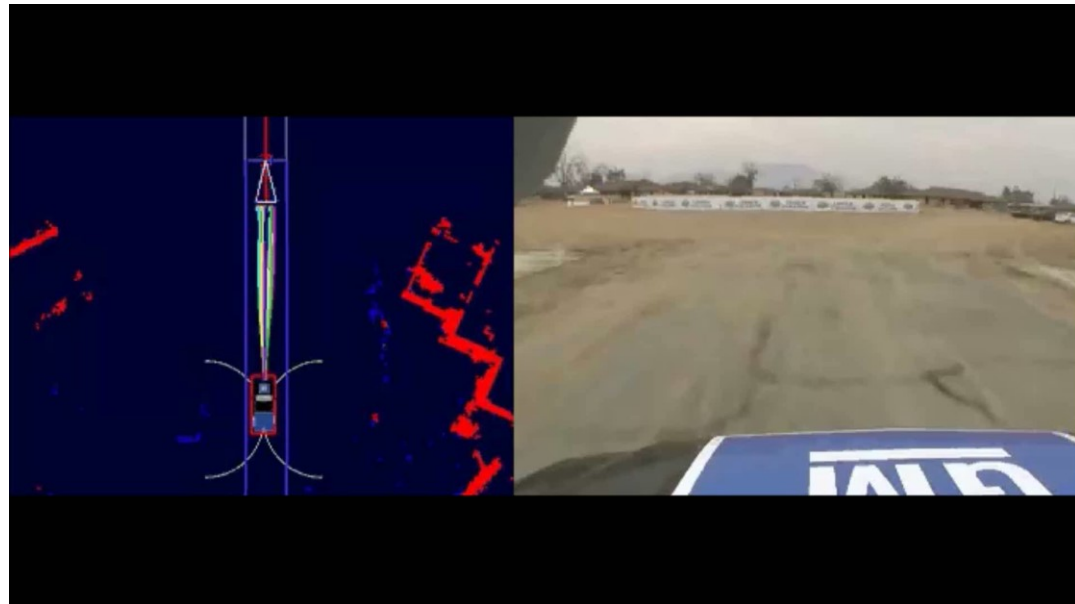
Planning for autonomous navigation:

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Likhachev & Ferguson, '09; part of Tartanracing team from CMU for the Urban Challenge 2007 race

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Planning for autonomous flight among people :

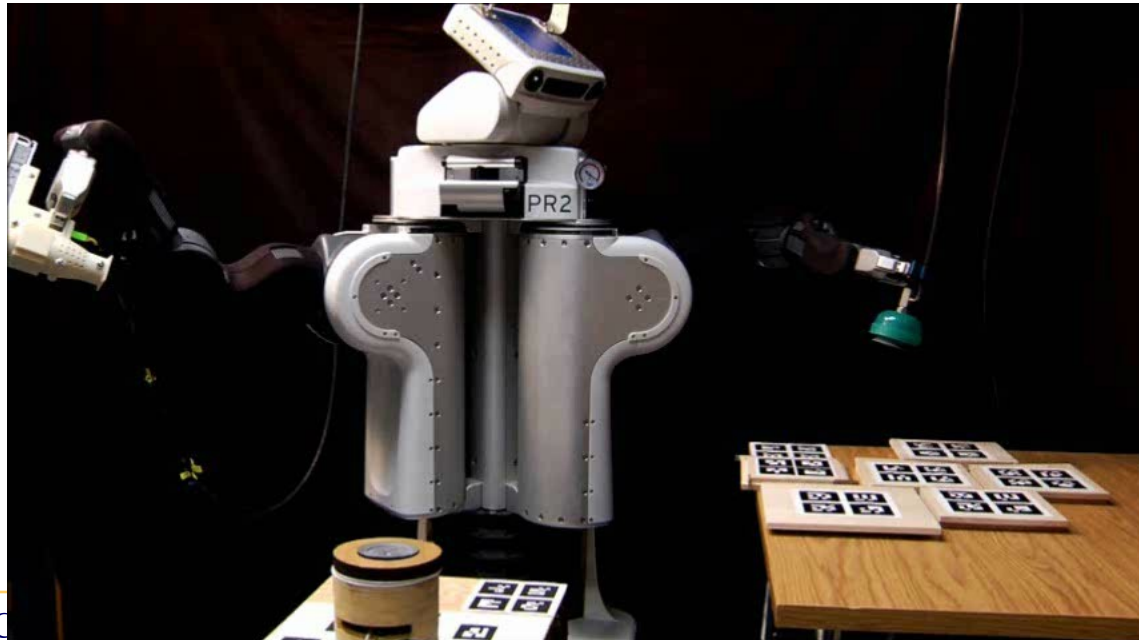*Narayanan et al., 2012*

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Few More Examples

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Planning for a mobile manipulator robot opening a door: *Gray et al., 2013*

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SBPL (Search-based Planning)

1.5x

autonomous opening of a spring-loaded door with full body

Few More Examples

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Planning for a mobile manipulator robot assembling a birdcage: *Cohen et al., 2015*

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Planning for a mobile manipulator unloading a truck:
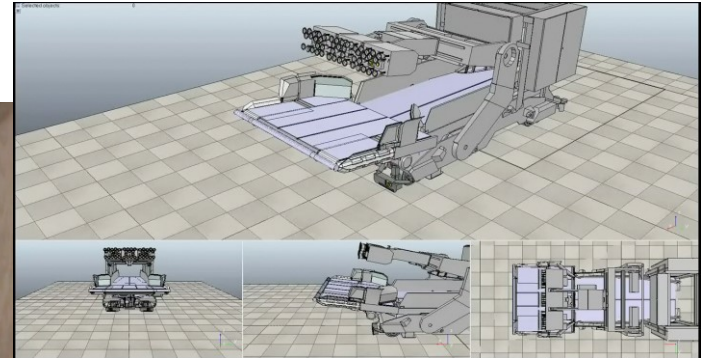
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Assuming Infinite Computational Resources…

Where does Planning break?
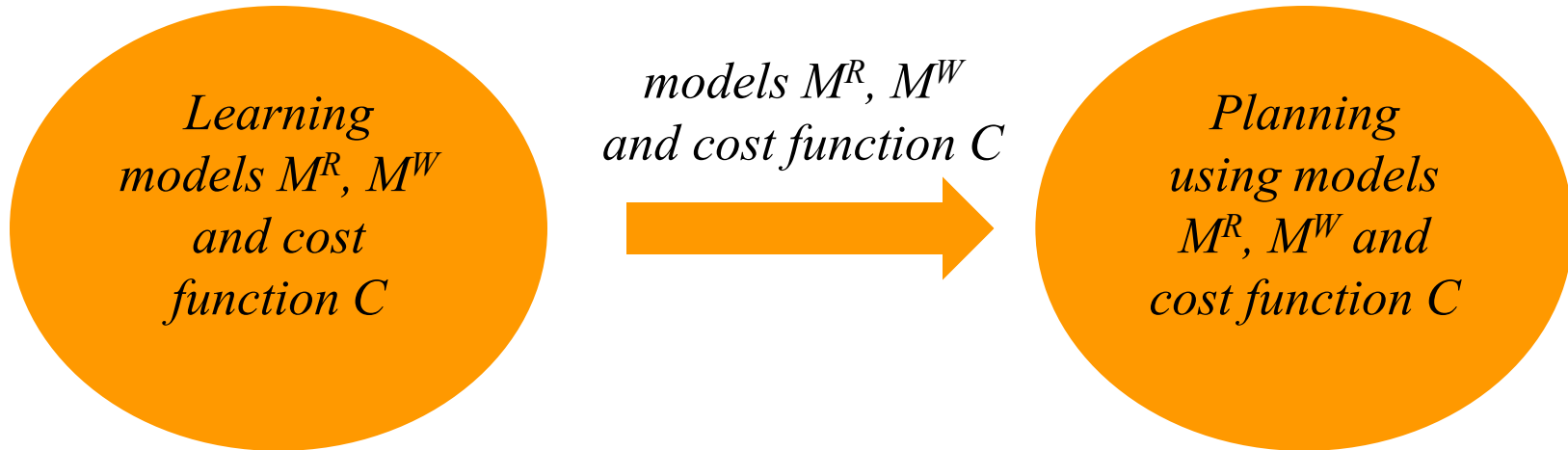
Assuming Infinite Computational Resources…

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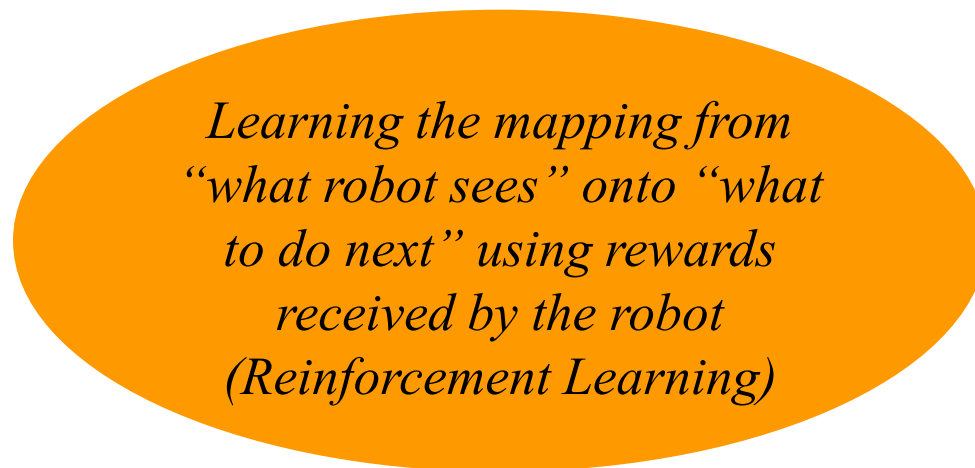*Reliance on the knowledge/accuracy of the model!*

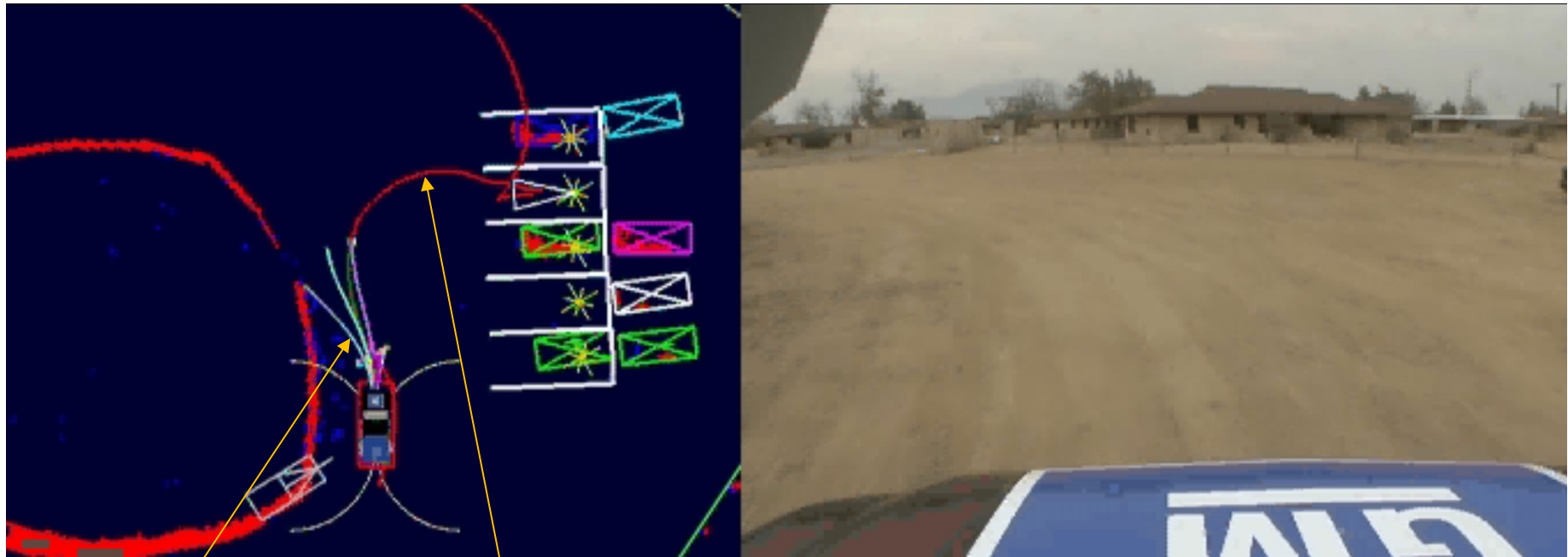*Role of Learning in Planning?*

Planning vs. Learning

Model-based approach

models M^R, M^W and cost function C

Learning models M^R, M^W and cost function C → Planning using models M^R, M^W and cost function C

Model-free approach

Learning the mapping from "what robot sees" onto "what to do next" using rewards received by the robot (Reinforcement Learning)
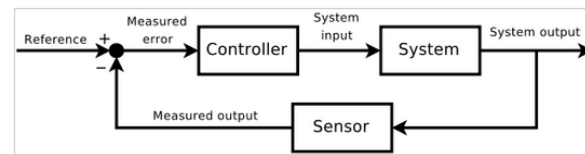
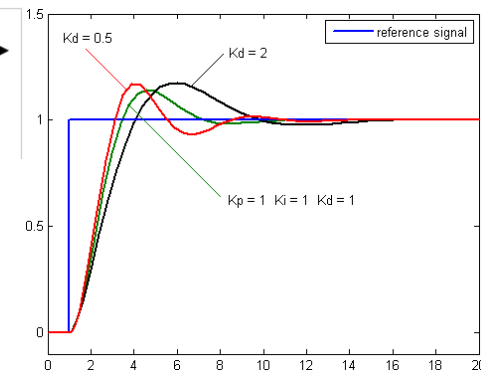# Planning vs. Trajectory Following vs. Control

local planning
(trajectory following)

global planning

controller

Images from wikipedia

Questions about the class?