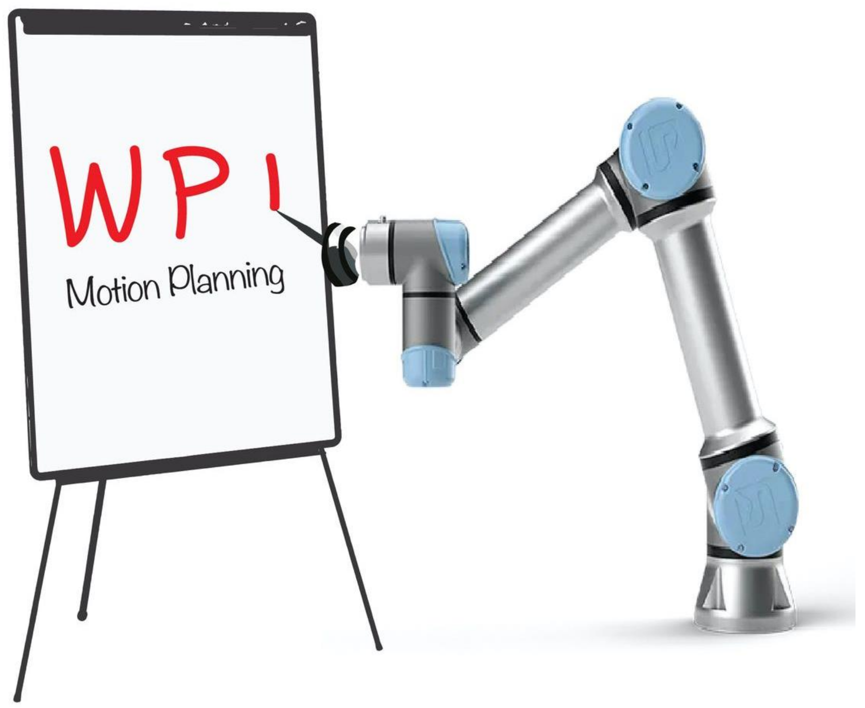
RBE550
Motion Planning
Introduction



Constantinos Chamzas
www.cchamzas.com
www.elpislab.org

Today's Overview

- Instructor/Lab Introduction
- Introduction to Motion Planning
- Examples of Motion Planning in Real Robots
- Course Logistics

Prof. Constantinos Chamzas

- **Assistant Professor, WPI**
  - Joined WPI Fall2023!
  - RBE Faculty, CS&EE background
  - Ph.D. in CS at Rice University
  - Teaching RBE550 Motion Planning
  - Teaching RBE577 ML for Robotics

Constantinos Chamzas
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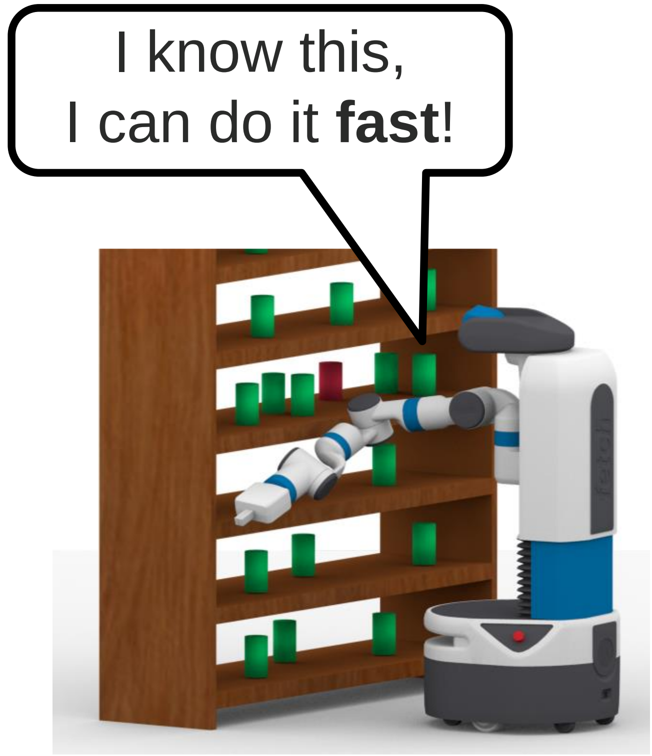
Office Hours: Mondays 4:00-5:00 p.m.
Email : cchamzas@wpi.edu
Website: cchamzas.com
Lab Website: elpsilab.org

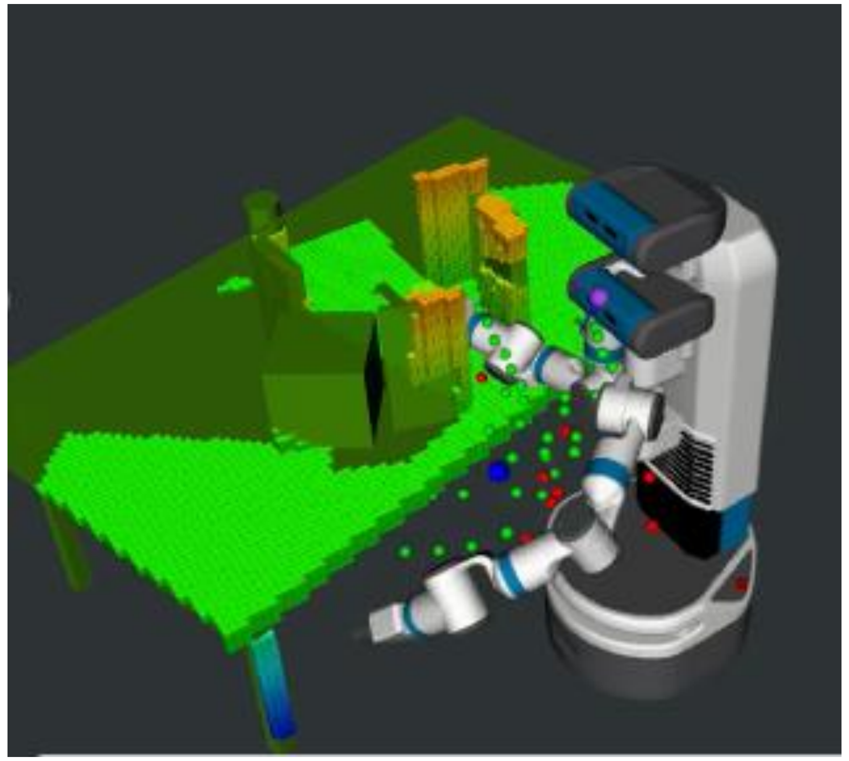
ELPIS Lab

Efficient Learning and Planning for Intelligent Systems

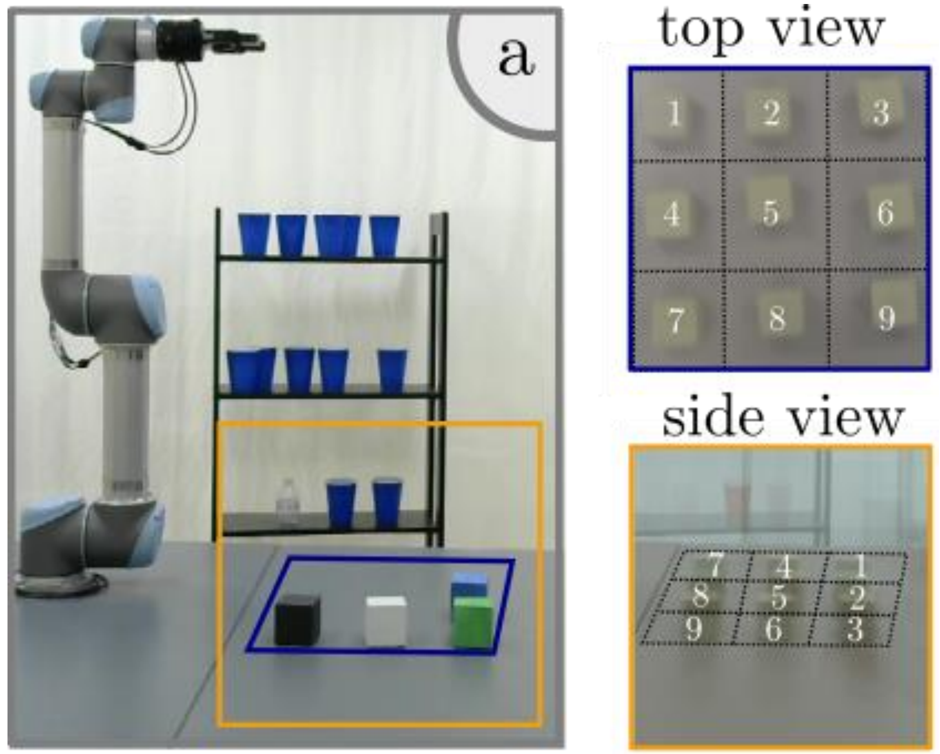
Research Directions/Projects



Leaning For Planning Efficiency



Planning Robustly with uncertainty

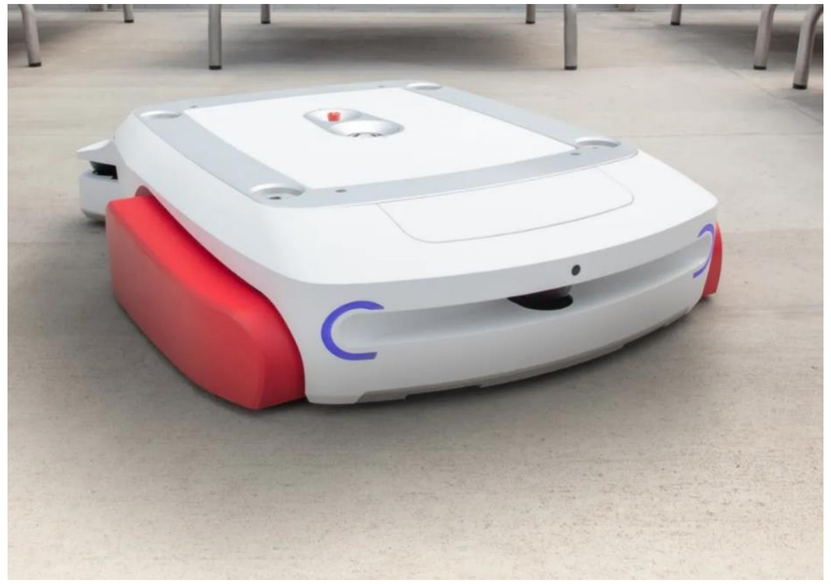


Vision-Based Planning

Available Hardware

Universal Robotics UR-10
6-Dof Industrial Manipulator

Deep Learning Workstation:
4xA6000 Nvidia GPU,
28-core Intel Xeon



Iron Ox Grover
Wheeled robot with
1000-pound lift

How you can join

- Take RBE550 (Motion Planning) and perform well
- We are looking for:
  - Proficiently in algorithms and coding (Python/C++) is desirable
  - At least 2 semester commitment
- Ways to learn more and get involved:
  - Submit your application at elpislab.org/join
  - Drop by my office UH271

What operating system are you using

Linux

Windows

MacOs

What operating system are you using

Linux

0%

Windows

0%

MacOs

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What operating system are you using

Linux 0%

Windows 0%

MacOs 0%

Motion Planning Introduction

Disclaimer and Acknowledgments

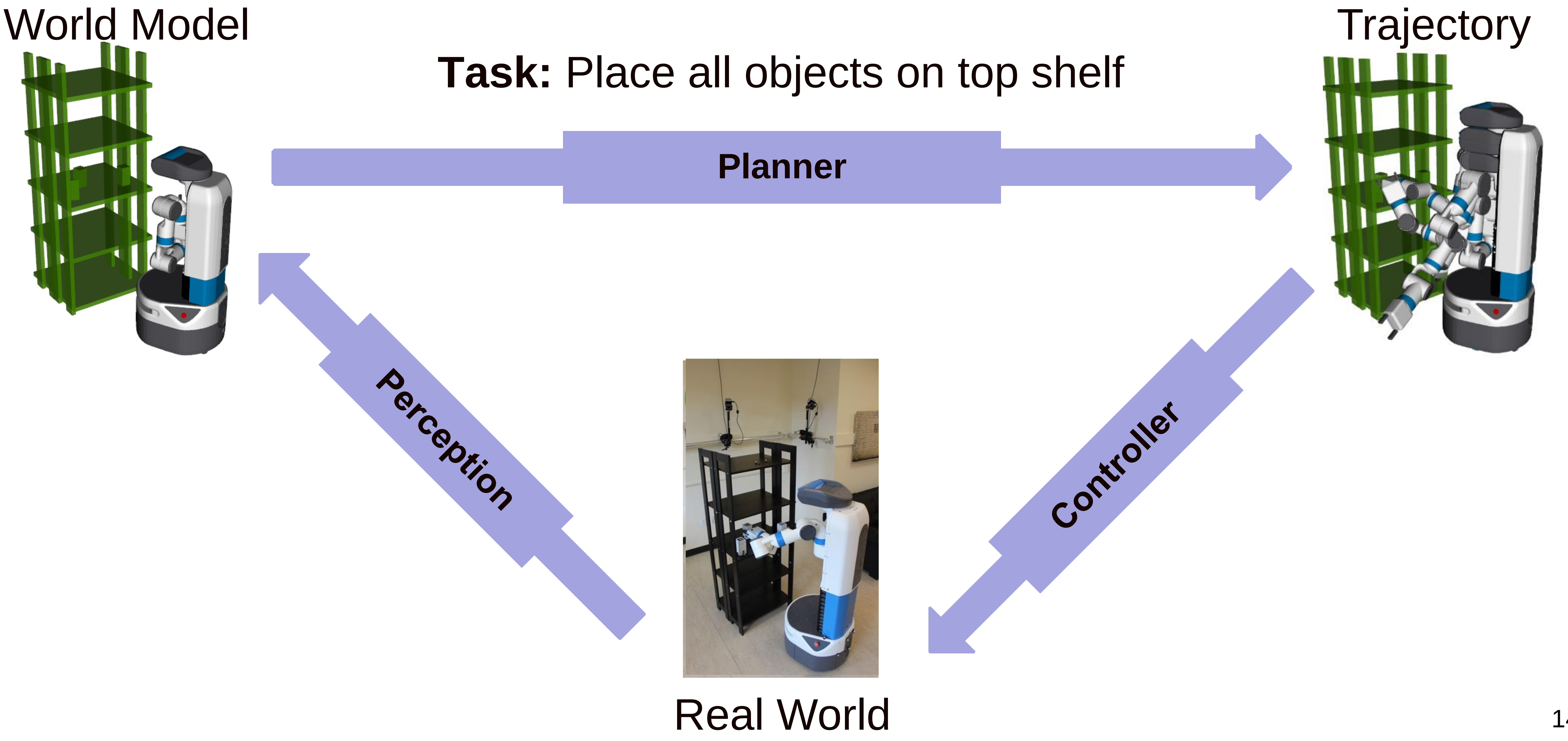
The slides are a compilation of work based on notes and slides from Constantinos Chamzas, Lydia Kavraki, Jane Li, Zak Kingston, Howie Choset, David Hsu, Greg Hager, Mark Moll, G. Ayorkor Mills-Tetty, Hyungpil Moon, Zack Dodds, Nancy Amato, Steven Lavalle, Seth Hutchinson, George Kantor, Dieter Fox, Vincent Lee-Shue Jr., Prasad Narendra Atkar, Kevin Tantiseviand, Bernice Ma, David Conner, Morteza Lahijanian, Erion Plaku, students taking comp450/comp550 at Rice University, and students Taking RB550 at Worcester Polytechnic Institute.

A Simple Robotic Task

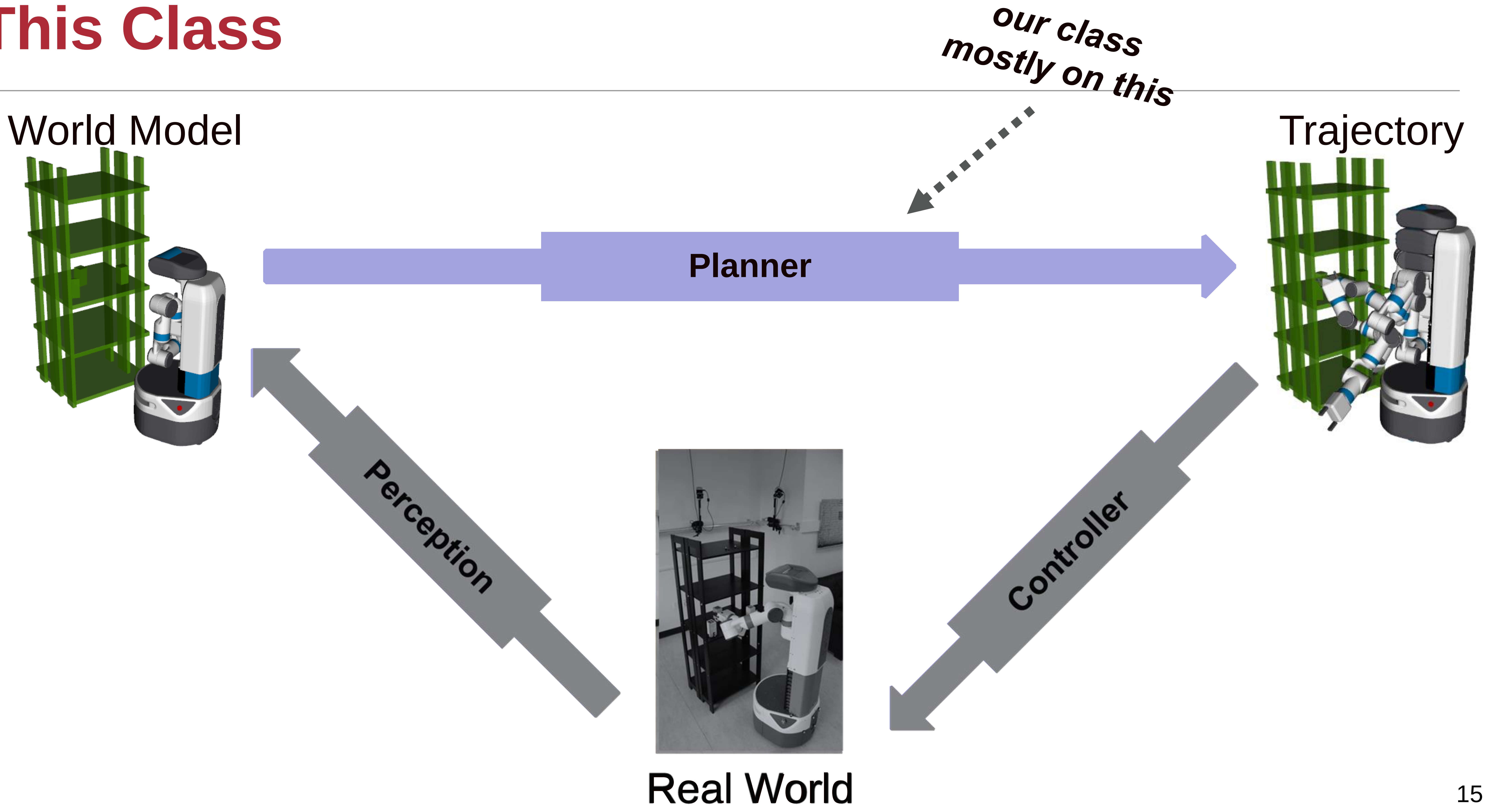
Task: Place all objects on top shelf

Fetch Robot

A Simple Robotic Task

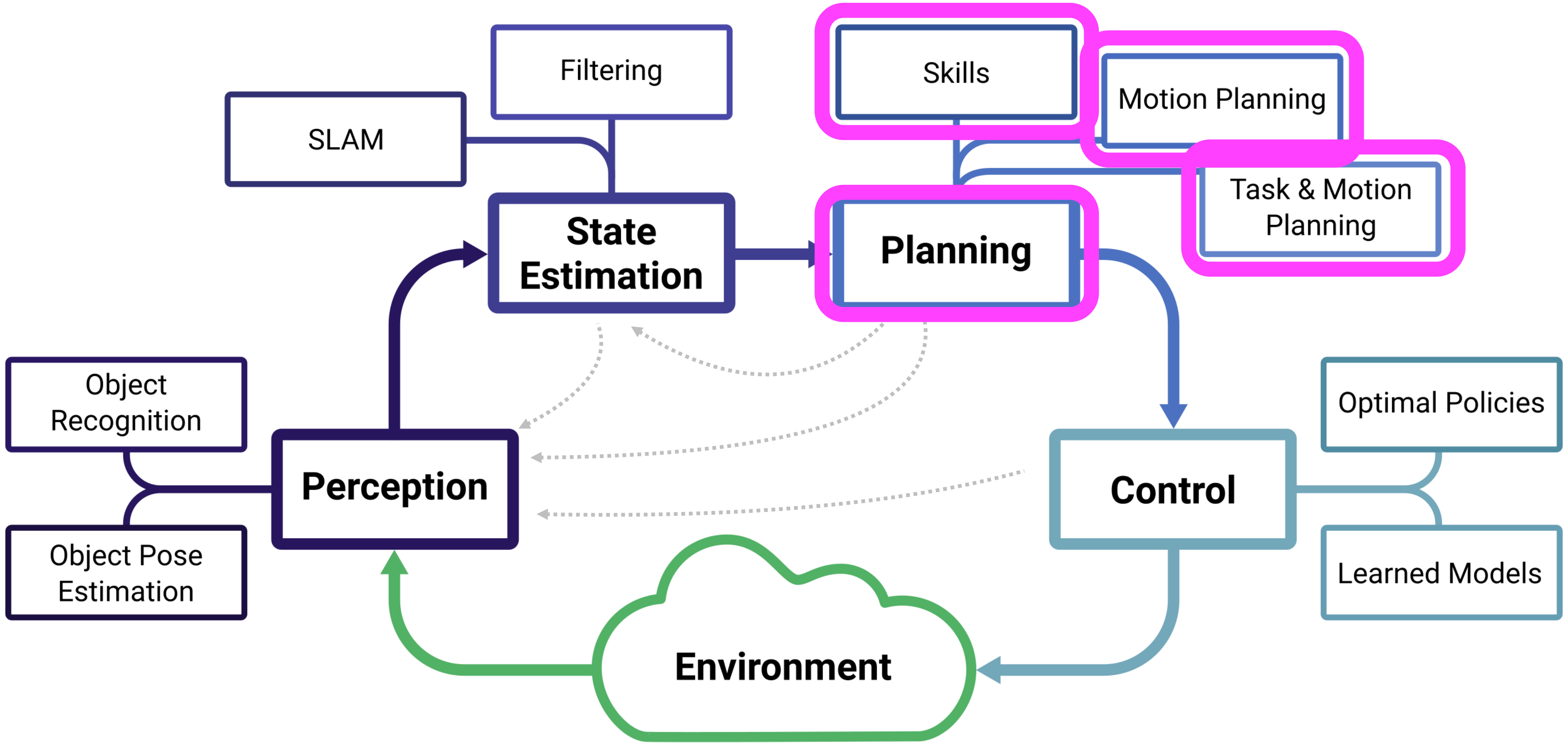


This Class



our class
mostly on this
World Model
Trajectory
Planner
Perception
Controller
Real World

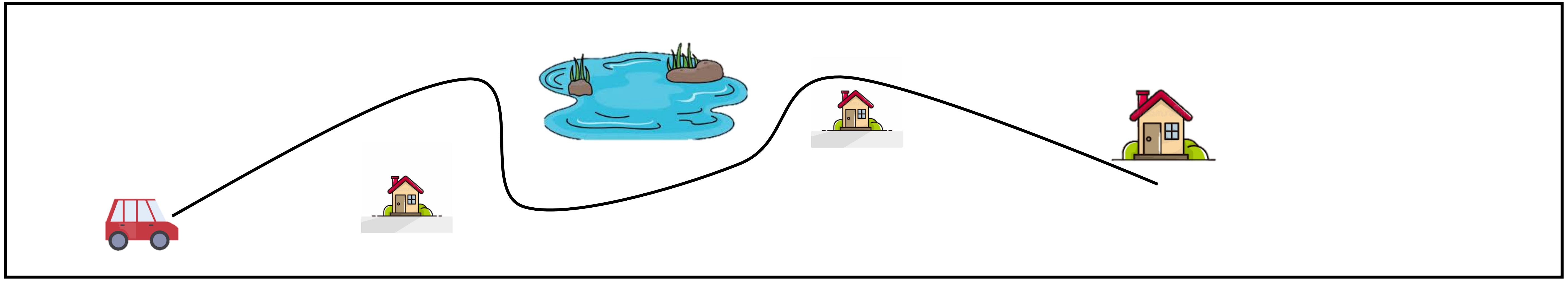
This Class



Filtering
SLAM
Skills
Motion Planning
Task & Motion Planning
State Estimation
Planning
Object Recognition
Perception
Optimal Policies
Control
Object Pose Estimation
Learned Models
Environment

What is the difference between Planning and Control

- In a nutshell: The planner designs the path and the controller follows it
  - Planner finds reference motion (plan) from current robot pose to goal pose – *path finding, trajectory optimization, or trivial interpolation/PD*
  - Controller reactively (policy) sends motor commands to follow the reference motion – *inverse dynamics, PD control, Riccati (RBE 502)*



* Planning is not strictly required e.g., (OSC, Model-Free DRL), e.g., control directly to the goal

**For some methods/applications the boundary between planning and control is blurry e.g., MPC

What is Motion Planning?

- Research field that <u>computes</u> the <u>trajectories</u> for a robot to follow

Start

Path

Goal

What is Motion Planning?

- Research field that <u>computes</u> the <u>trajectories</u> for a robot to follow

Start

Goal

Formally: The General Motion Planning

- Let $x \in \mathcal{X}$ denote the state and state-space
- Let $u \in \mathcal{U}$ denote the control and control-space of a robot
- Let f denote the forward dynamics of the robot such that:

$$x(\mathcal{T}) = x(0) + \int_0^{\mathcal{T}} f(x(t), u(t))dt \qquad (1)$$

- Let $\mathcal{X}_{\text{obs}} \subset \mathcal{X}$ denote the invalid state space, e.g., validating kinematic constraints, collisions, etc.
- Then the valid state space is denoted as $\mathcal{X}_{\text{free}} = \mathcal{X} \setminus \mathcal{X}_{\text{obs}}$
- The start state as $x_{\text{start}} \in \mathcal{X}_{\text{free}}$
- The goal region as: $X_{\text{goal}} \subseteq \mathcal{X}_{\text{free}}$

The Motion planning problem:

Find a time $\mathcal{T}$ and a set of controls $u : [0, \mathcal{T}] \to \mathcal{U}$ such that the motion described by (1) satisfies

$$x(0) = x_{\text{start}}$$

$$x(\mathcal{T}) \in \mathcal{X}_G$$

$$x(t) \in \mathcal{X}_{\text{free}}.$$

Geometric Motion Planning or Path Planning

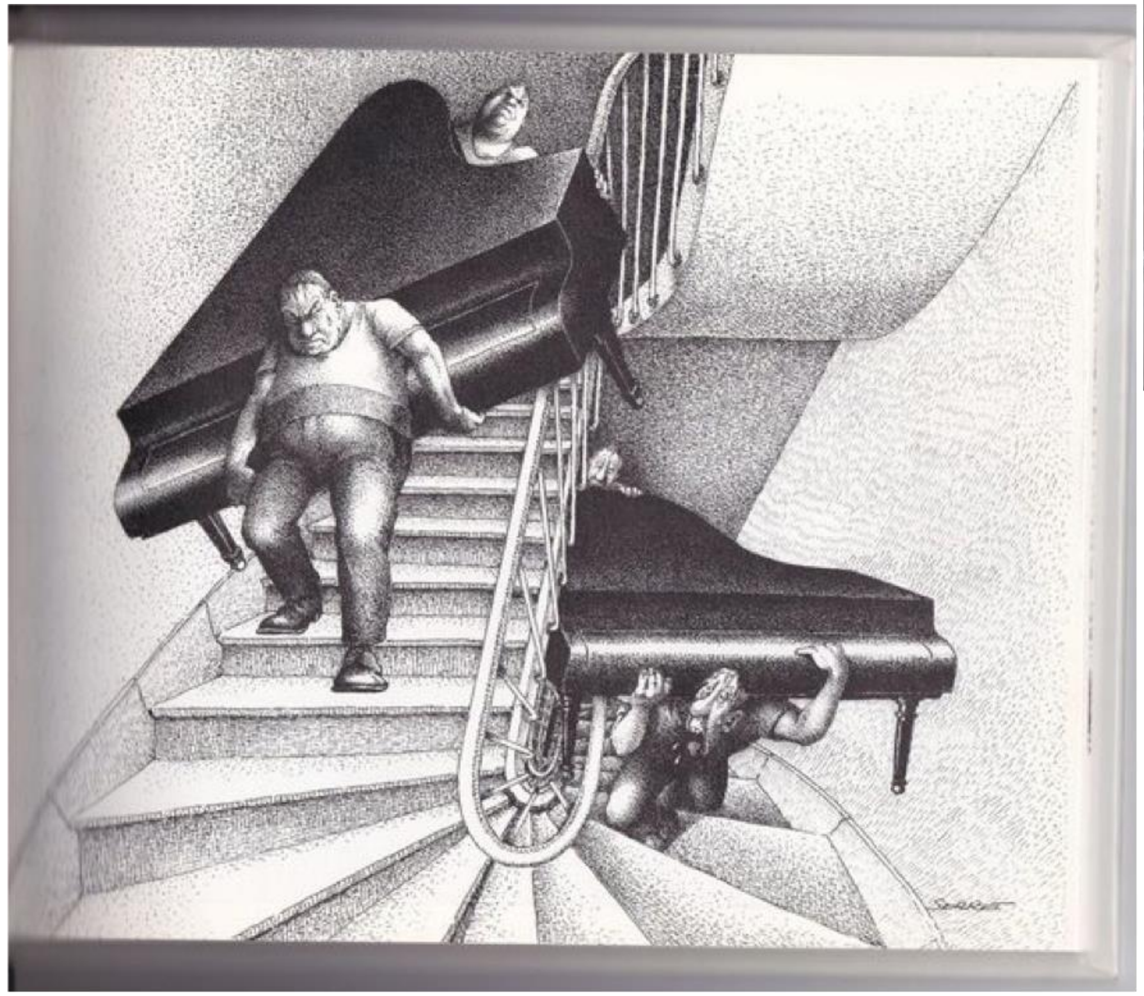
- If the quasi-static assumption holds (geometric position of the robot fully specifies its state) then the motion planning problem simplifies to:

  - Let $x \in \mathcal{X}$ denote the configuration and C-space of the robot
  - Let $\mathcal{X}_{\text{obs}} \subset \mathcal{X}$ denote the obstacle c-space (collisions, and violated joint limits)
  - Then the free C-space is denoted as $\mathcal{X}_{\text{free}} = \mathcal{X} \setminus \mathcal{X}_{\text{obs}}$
  - The start state as $x_{\text{start}} \in \mathcal{X}_{\text{free}}$
  - The goal state as: $\mathbf{x}_{\text{goal}} \subseteq \mathcal{X}_{\text{free}}$

The geometric motion planning problem is defined as, finding a path **σ** such that:

$$\sigma(0) = \mathbf{x}_{\text{start}}, \; \sigma(1) \in \mathbf{x}_{\text{goal}}, \quad \sigma(t) \in X_{\text{free}} \quad \forall t \in [0, 1]$$

Motion Planning Historically- The Piano's Movers Problem

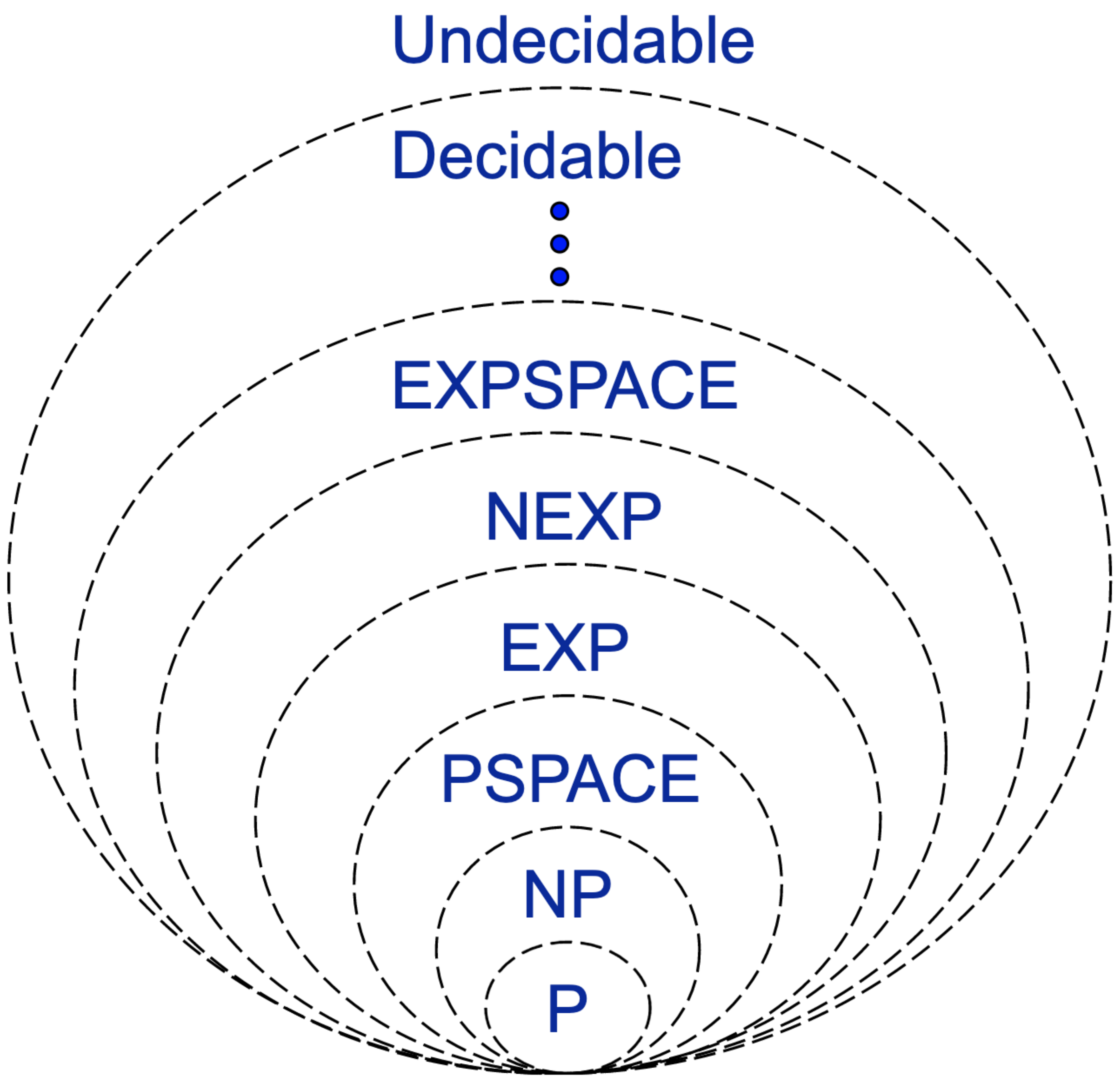


Picture credit: https://www.pinterest.com/pin/178736678931496070/

Motion Planning is Hard

Problem	Complexity
Sofa Mover (3 DOF)	$O(n^{2+\varepsilon})$ not implemented
Piano Mover (6 DOF)	Polynomial – no practical algorithm known
n Disks in the Plane	NP-hard
n Link Planar Chain	PSPACE-Complete
Generalized Mover	PSPACE-Complete
Shortest Path for a Point in 3D	NP-hard
Curvature Constrained Point in 2D	NP-hard
Simplified Coulomb Friction	Undecidable

Computational Complexity



$\text{PSPACE} \subset \text{EXPSPACE}$

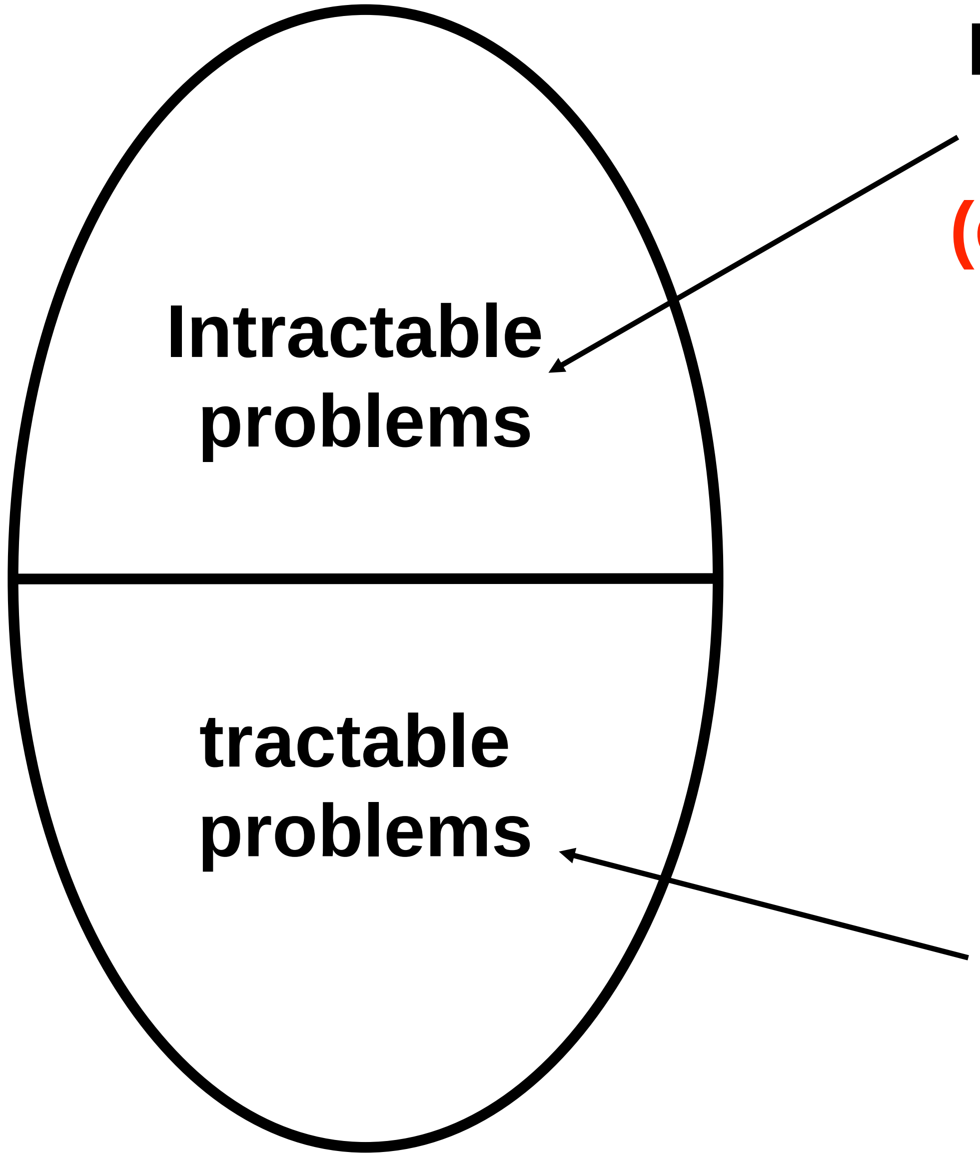
$\text{P} \subset \text{EXP}$

$\text{PSPACE} = \text{NPSPACE}$

$\text{P} \subseteq \text{NP} \subseteq \text{PSPACE}$

$\text{P} =? \text{NP}$

Computational Tractability



Problems not admitting reasonable algorithms (exponential algorithms)

Problems admitting reasonable (polynomial-time) algorithms

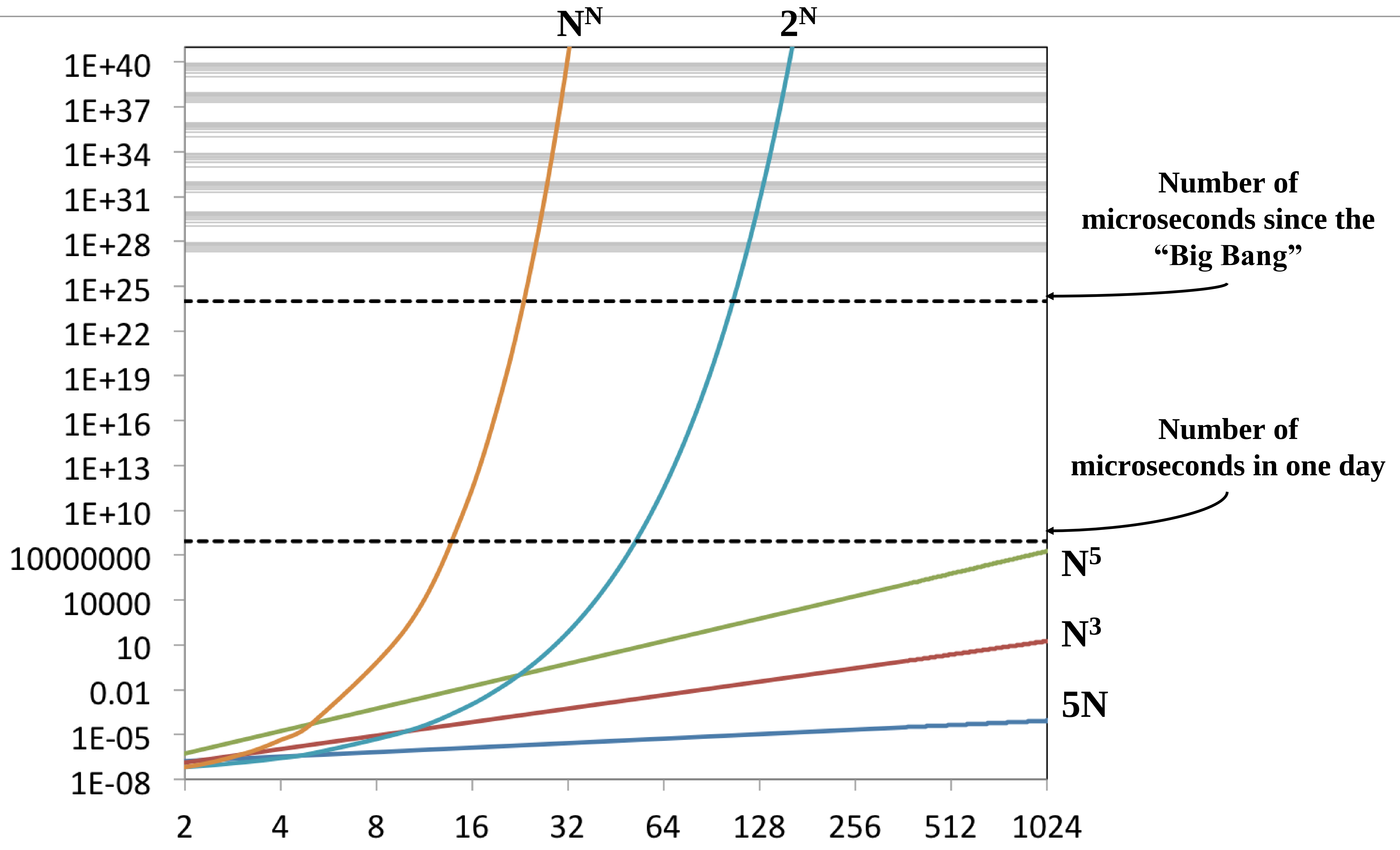
Polynomial in terms of N (size of the input)

Functions

Function \ N	10	50	100	300	1000
$5N$	50	250	500	1500	5000
N^2	100	2500	10000	90000	1 million (7 digits)
N^3	1000	125000	1 million (7 digits)	27 million (8 digits)	1 billion (10 digits)
2^N	1024	a 16-digit number	a 31-digit number	a 91-digit number	a 302-digit number
N^N	10 billion (11 digits)	an 85-digit number	a 201-digit number	a 744-digit number	unimaginably large

[The number of microseconds since the 'Big Bang' has 24 digits]

Growth Rates



Some extensions/variations of the basic problem

- Optimal Planning
- Non-Holonomic Constraints
- Anytime Planning
- Multiple robots
- Movable objects
- Kinodynamic constraints
- Stability constraints
- Constrained-Based Motion Planning
- Dynamical unknown environments
- Integration of planning and control
- Integration with higher-level planning
- Planning under Uncertainty

Examples of Motion Planning in Real Robots

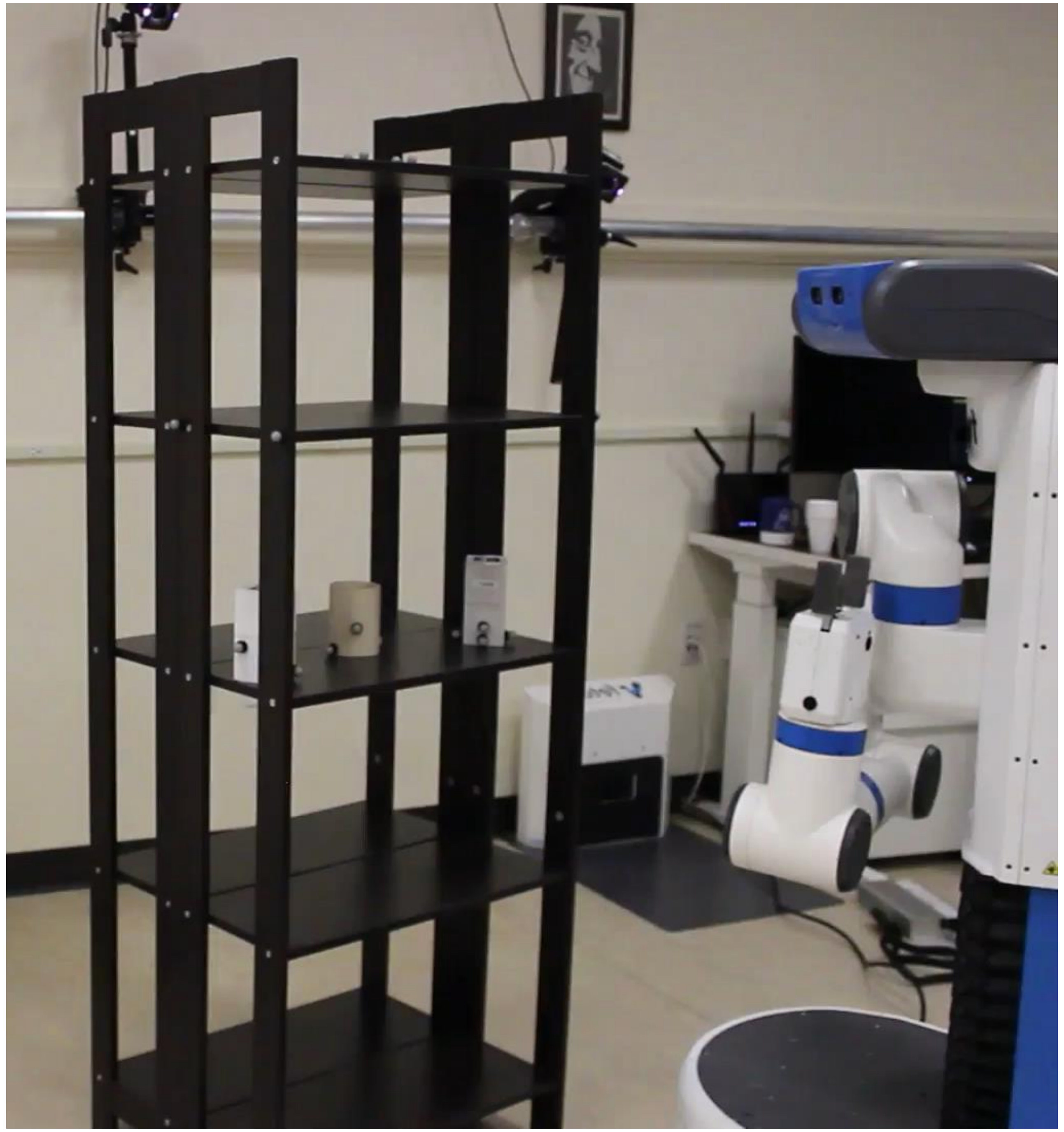
Roomba: vacuum cleaning robot

Amazon warehouse robots

Industrial Automation

Waymo Autonomous Car

Planning to Pick up an Object is still Hard!



Such problems can take up to 15 seconds to compute

Failures are common in robotics (even in 2024)

- Check these spectacular videos: https://www.youtube.com/user/bostondynamics

- Check these spectacular failures: https://www.cnn.com/videos/business/2021/08/19/boston-dynamics-robots-falling-down-orig.cnn-business/video/playlists/business-news/

Have you seen a robot helping with household chores?

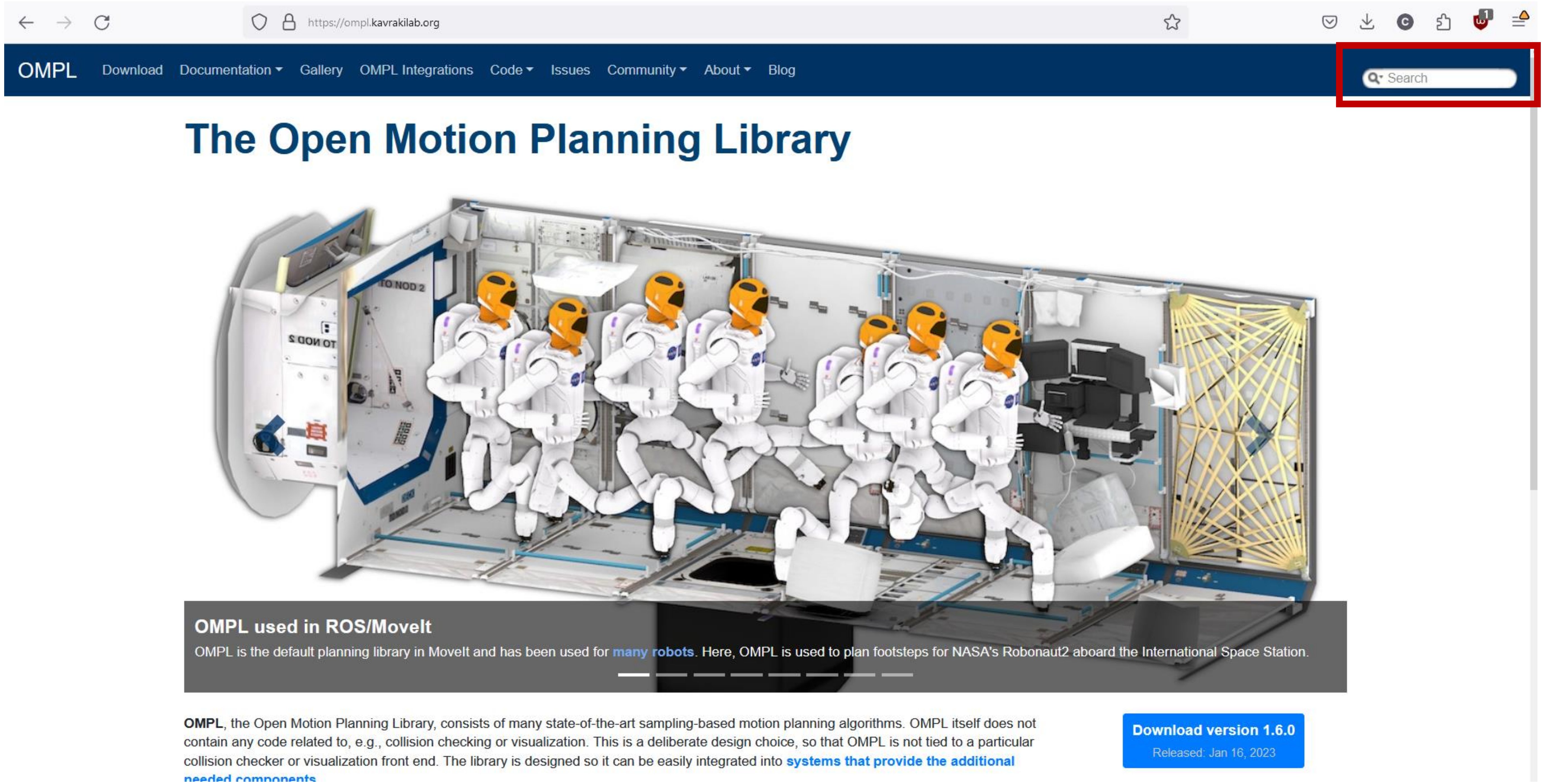
Motion Planning is still a very active research area!

Course Logistics

Teaching Assistant

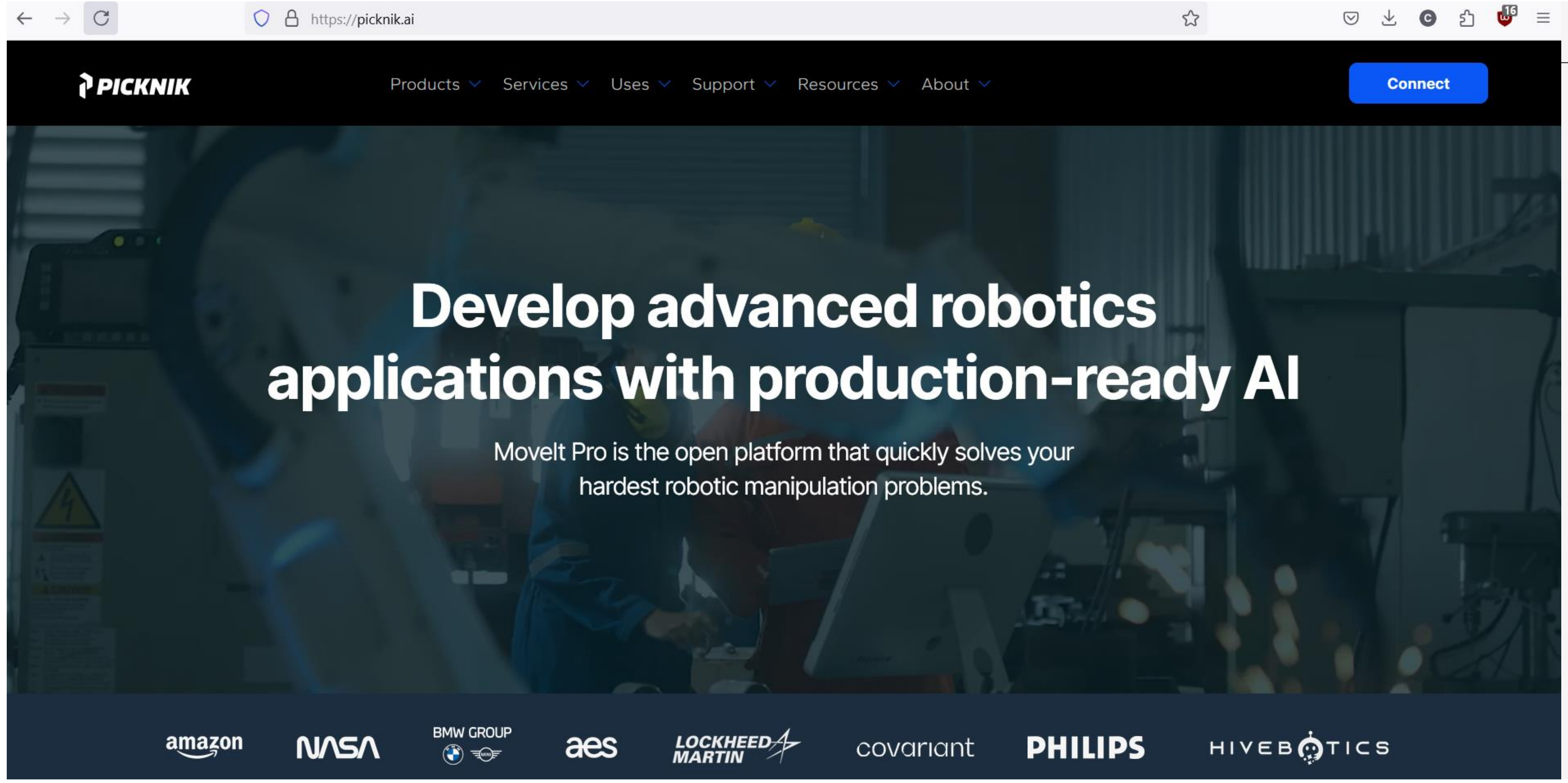
- Name: Mr. Zhuoyun Zhong
- Email: zzhong3@wpi.edu,
- Office Hours: 11am-12pm Fridays
- Zoom link: https://wpi.zoom.us/my/zhuoyunzhong
- Office Location: 200A Unity Hall

The Open Motion Planning Library

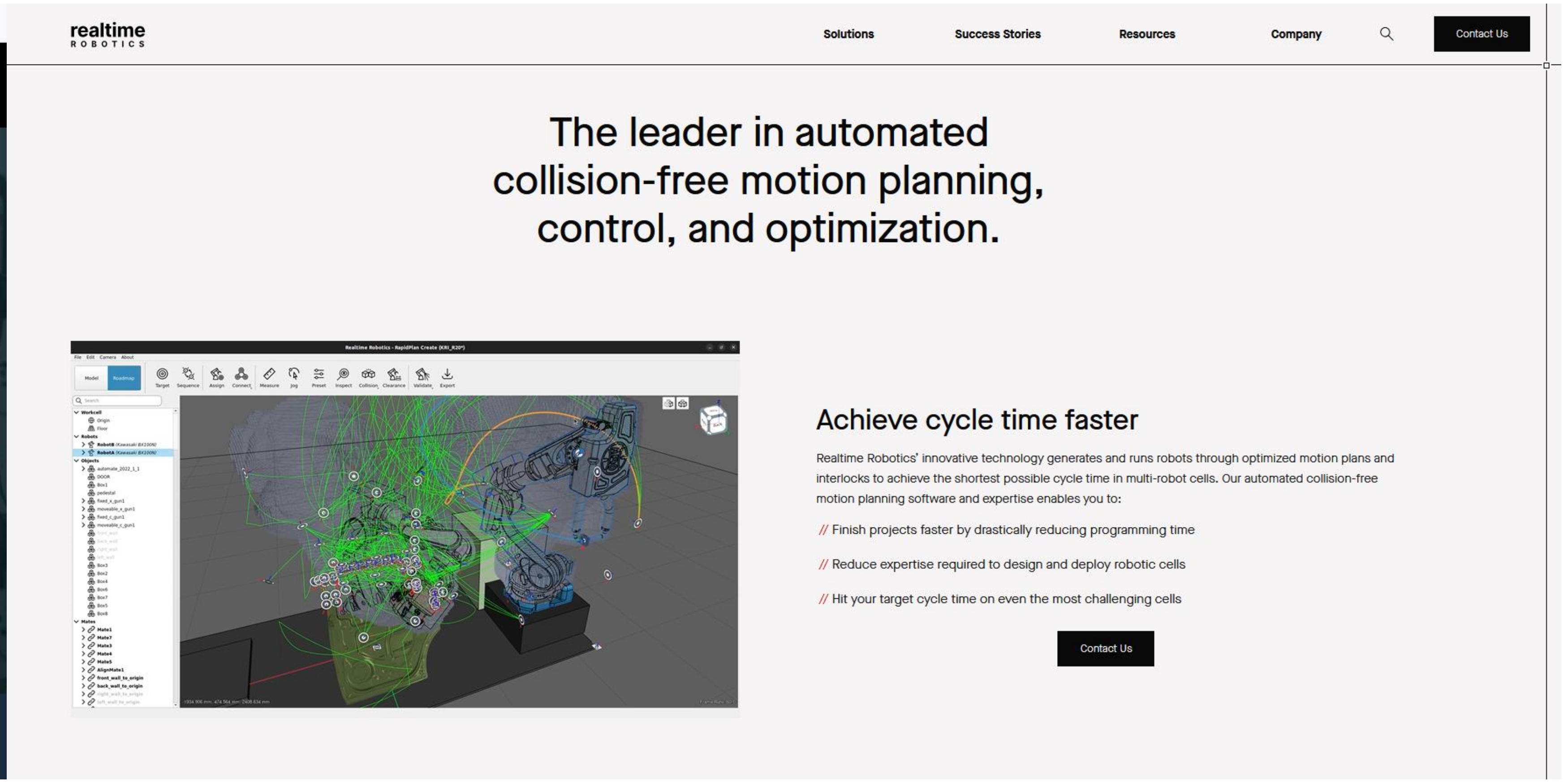


https://ompl.kavrakilab.org/

OMPL In Industry



PickNik (Moveit Maintainers)



Realtime Robotics

Prerequisites

- Be familiar with the following:
  - Undergraduate Linear Algebra
  - Kinematics in Robotics
  - Basic Algorithms
  - Proficiency in C++ and Python, or have the ability to pick up quickly!
- Project 0/1 aims to test your preparedness for this class, by covering these topics

Logistics of the Class

- CANVAS - we will make heavy use of this tool

- Piazza – use Piazza if you want your questions answered promptly.
  Signup Link: https://piazza.com/wpi/fall2024/rbe550

- **Read "Course Information" in Canvas:** It contains details for the grading, the policy for late assignments or projects, the cut-off date for all work to be graded in this class, and what you are expected and not expected to do. Also, a lot of information about the class in general.

Projects and grading (RBE550)

Grade Policies

Category	Percentage of Final Grade
Project0	4%
Project1	6%
Project2	10%
Project3	10%
Project4	10%
Midterm Exam	20%
Final Exam	20%
Final Project	20%

Table 2: Grade Policies

Category	Final Grade
A	$\geq 90\%$
B	$\geq 80\%$
C	$\geq 70\%$
D	$\geq 50\%$
F	$< 50\%$

Table 3: Letter Grade Percentages

Projects (40%)

- Constituted of two parts:
  - Theoretical Questions that aim to test different concepts taught in class
  - Programming Component in C++/Python3 that will usually include implementations of planning algorithms, or critical components of planners
- All projects(except Project0) can be completed in pairs of two or individually
- All the written components must be in LaTeX, handwritten or Word documents will **not** be accepted and will be graded with zero (An Overleaf template Is provided in “Course Information” document in Canvas)

Midterm (20%)- Final (20%)

- Midterm scheduled for March 7 and will be in-class
- Finals scheduled for April 22 and will also be in-class

Final Project (20%)

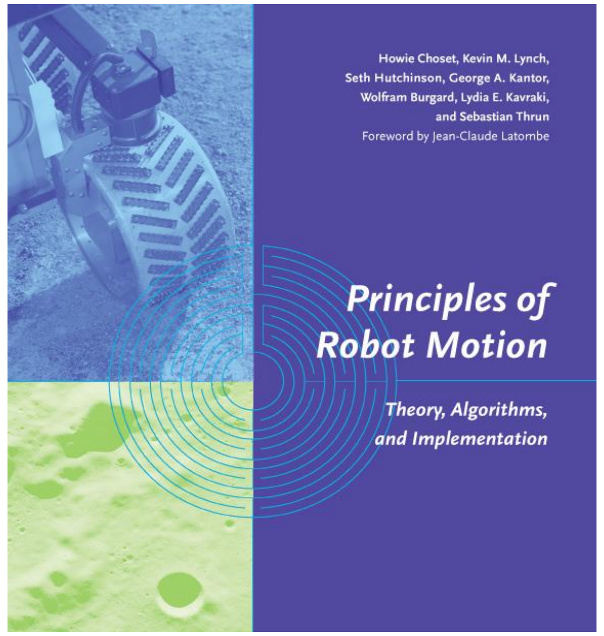
- Will be released in the second half of the semester
- It will be a big project than can be:
  - One of the instructors’ proposed projects
  - A research paper reproduction
  - Part of your research

Tentative Schedule

This schedule is subject to change but we will try to keep as close as possible to the schedule below.

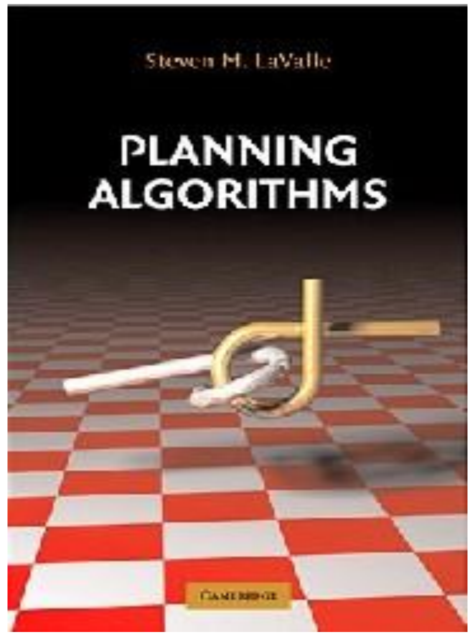
Date	Topic	Instructor	Projects
1/17	Introduction	C.Chamzas	Project0 & Project1 out
1/21	Bug Algorithms, Potential Fields	C.Chamzas	
1/24	Roadmaps and Discrete Search	C.Chamzas	Project0 due
1/28	Configuration Space	C. Chamzas	
1/31	Tree-Based Planners and OMPL	C. Chamzas	Project1 due, Project2 out
2/4	Configuration Space Obstacles	C. Chamzas	
2/7	Probabilistic Roadmap Planners	C. Chamzas	
2/11	Theoretical Issues	C. Chamzas	
2/14	Welness Day **(No Class)**		
2/18	Asymptotically Optimal Planning	C. Chamzas	Project2 due, Project3 out
2/21	Collision Checking	C. Chamzas	
2/25	SPARS/Dynamic Roadmaps	C. Chamzas	
2/28	Kinodynamic Planning I	C. Chamzas	
3/4	Kinodynamic Planning II	C. Chamzas	Project3 due, Project4 out
3/7	Midterm (In Class)	C. Chamzas	
3/11	Spring Break **(No Class)**		
3/14	Spring Break **(No Class)**		
3/18	Learning and Planning I	C. Chamzas	
3/21	Learning and Planning II	C. Chamzas	Final-Project out
3/25	Midterm & Final Projects Discussion	C. Chamzas	Project 4 due
3/28	Task and Motion Planning	C. Chamzas	Declare Final-Project
4/1	Monday Schedule **(No Class)**	C. Chamzas	
4/4	Task and Motion Planning II	C. Chamzas	
4/8	Planning under Uncertainty	C. Chamzas	
4/11	Class Overview	C. Chamzas	
4/15	Mid-Report Presentation	Students	Mid Report due
4/18	TBD	TBD	
4/22	Final Exams (In Class)	C. Chamzas	
4/25	UG Research Show Day **(No Class)**		
4/29	Guest Lecture	TBD	
5/2	Guest Lecture	TBD	
5/6	Final-Project Pres.		
5/7	Final-Project Pres. (**Friday Schedule**)	Students	Final Report due

Relevant books



Principles of Robot Motion: Theory, Algorithms, and Implementations

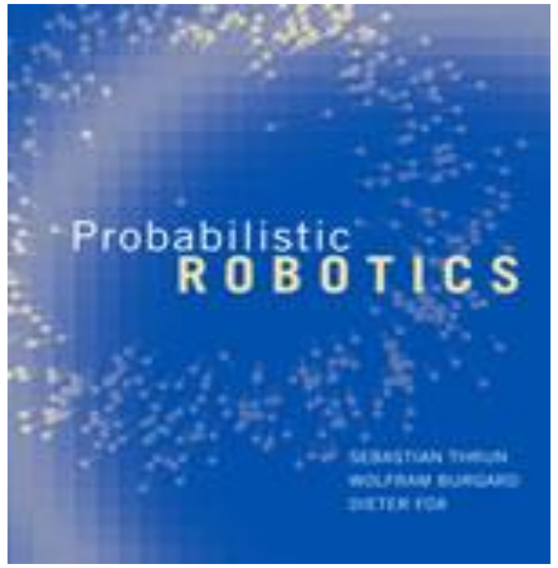
H. Choset, K.M. Lynch, S. Hutchinson, G. Kantor, W. Burgard, L.E. Kavraki and S. Thrun, MIT Press



Planning Algorithms, Steven Lavalle, Cambridge University Press, 2006

Free download: http://planning.cs.uiuc.edu/

Robot Motion Planning, Jean-Claude Latombe, Kluwer, 1991.



Probabilistic Robotics
S. Thrun, W. Burgard, D. Fox
MIT Press, 2006

Handbook of Robotics
B. Siciliano et al
MIT Press, 2018

Project 0 is already posted in Canvas

- Due at **11:59 PM** on **Jan24**
- This project should be done **individually** not in pairs
- It will test your preparedness for the class

Project 1 released today

- Due at **11:59 PM** on **Jan 31st**
- This project **can** be done in pairs
- It will also test your preparedness for the class

Welcome to RBE550!