ECE-GY 9243 / ME-GY 7973

Optimal and Learning Control for Robotics

Ludovic Righetti

Lecture 1
(Introduction)

Organization

Goals of the class how to get a robot to move "optimally"

1 Algorithms to compute complex robot movements
Emphasis on optimal control and reinforcement learning

2 Practical application examples of the algorithms in real world applications

Organization

(incomplete) List of topics

- Bellman Optimality Principle / Dynamic Programming
- LQ problems (LQR)
- Model predictive control
- Differential Dynamic Programming (DDP)
- Trajectory optimization
- Fundamentals of reinforcement learning, Q-learning
- Policy Improvement
- Deep reinforcement learning

Organization

Course website

All necessary material will be posted on NYUClasses

Schedule

Lectures	Tuesday 3:20pm to 5:50pm - 2MTC 9.009
Office Hours	Friday 10am to 12pm - RH517I
	(any other time by appointment only)

Contact

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Organization

Course Project
Goal: implement in simulation algorithms seen in class

Homework
To be handed in every few weeks
(theory + programming exercises in Python)

Exams (tentative)
Midterm March 26th
Final replaced by a paper report

Grading
25% mid-term + 25% paper report + 25% homework + 25% project

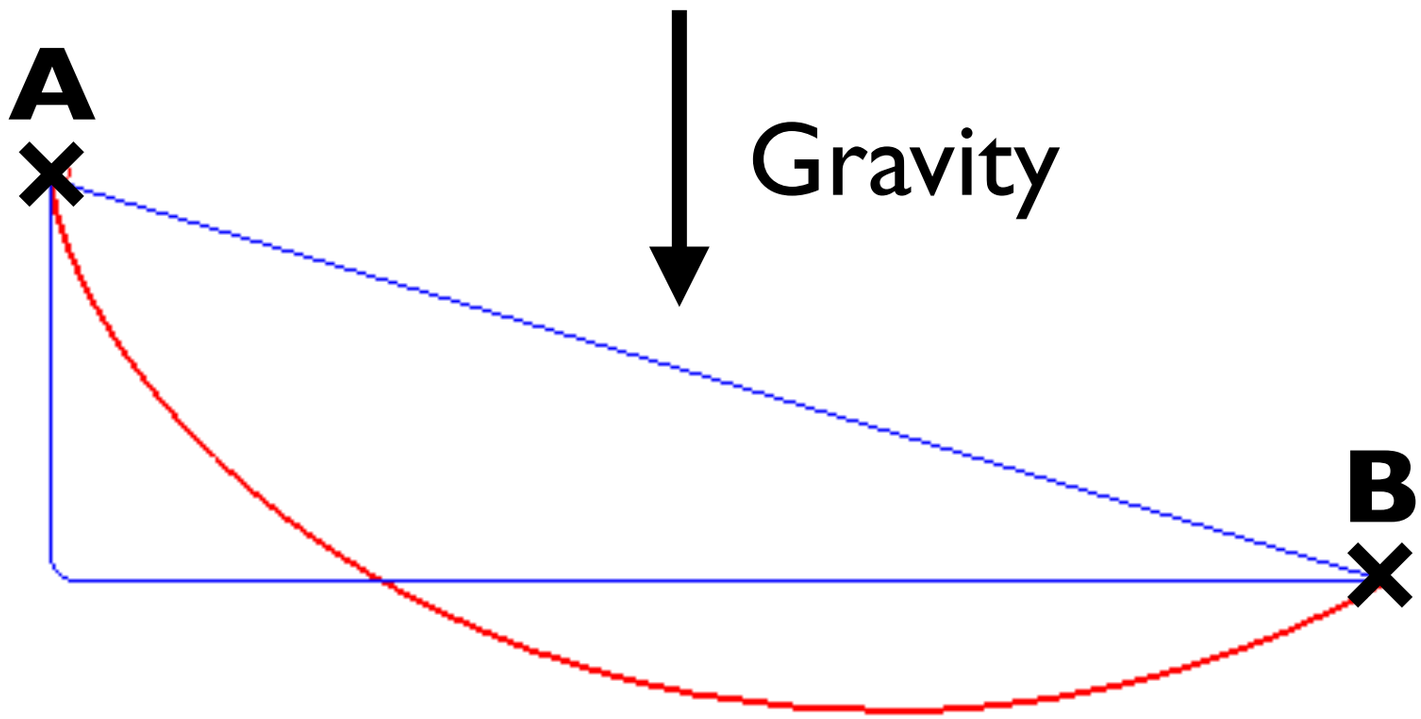
Questions?

What is optimal control?

What is reinforcement learning?

Optimal Control Problems date back to XVIIth century

Johann Bernoulli posed the question in 1696
what is the shape of the ground that allows a ball
to reach B from A in the fastest time?

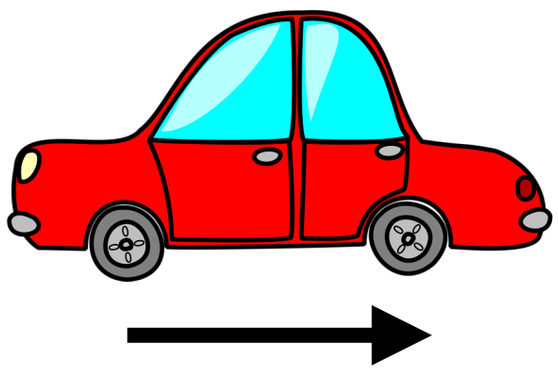


The optimal curve is called the Brachistochrone curve

What is optimal control?

Optimal control allows to answer questions such as:

- How to accelerate a car to reach a goal in minimum time?
- How to accelerate a car to reach a goal with minimum energy?
- How to accelerate a car to reach a goal with maximum speed?

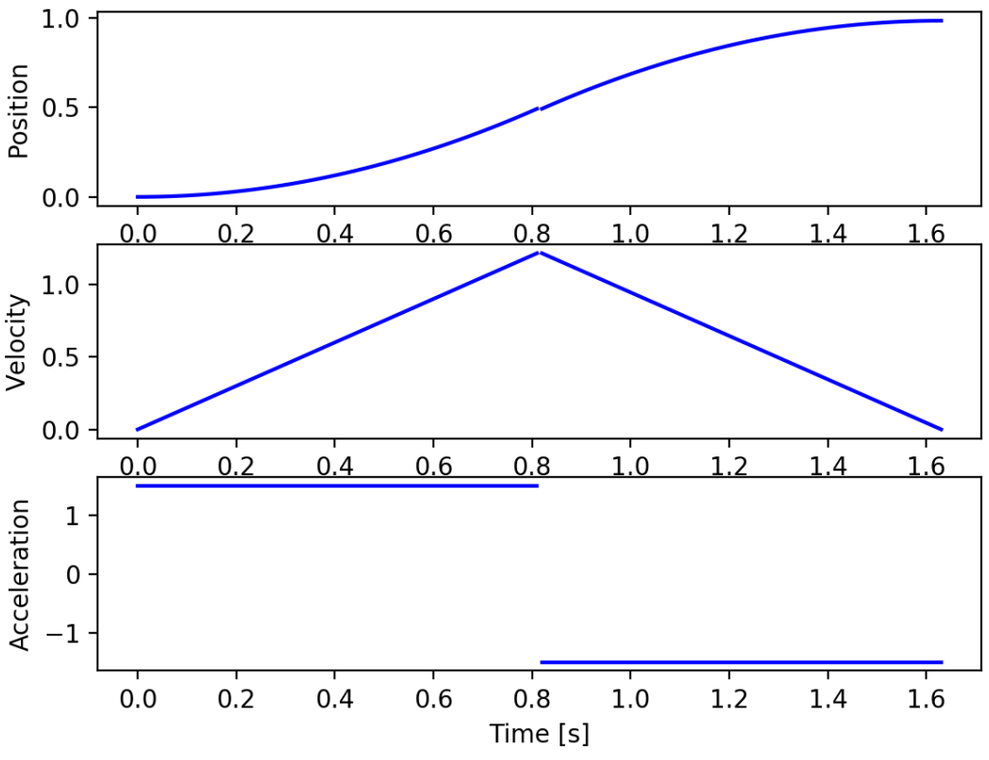


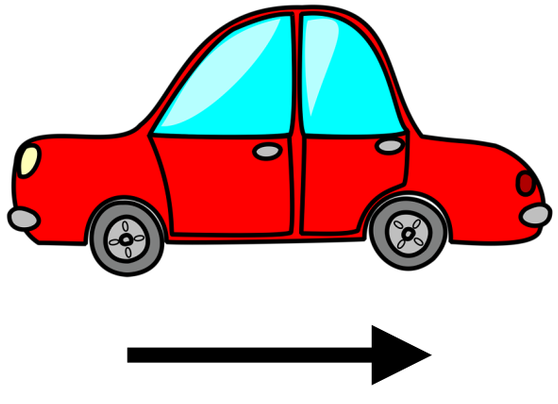
Goal

What is optimal control?

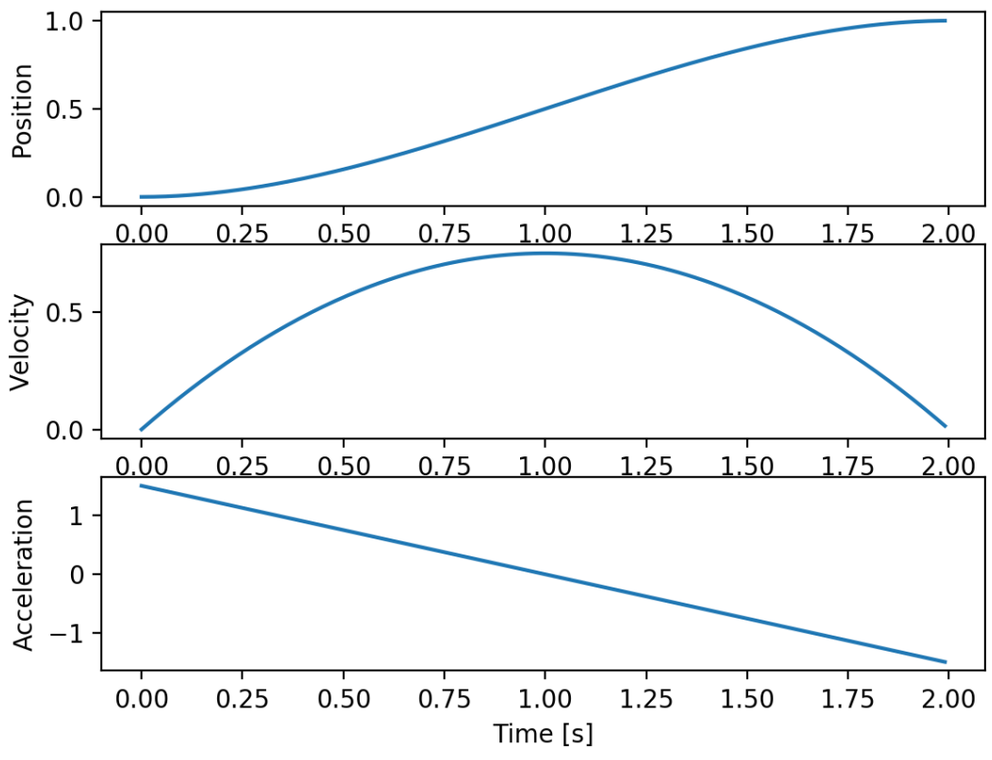
Each question leads to very different answers

minimum time?





minimum acceleration?



Goal

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Structure of an optimal control problem

Cost to minimize

Subject to:

Model of the system (differential equation)

Constraints

What is optimal control?

Traditionally this problem, in continuous time, is studied using the calculus of variations or solving Hamilton Jacobi Bellman equations

- We need to minimize a function u(t) => very difficult!
- Analytic solutions cannot be found for complex, high dimensional problems (i.e. all robotics problems)

In discrete time we can use Bellman Principle of Optimality (i.e. Dynamic Programming)

- Scales exponentially with the number of dimensions (curse of dimensionality)!

In robotics

- We often discretize and approximate the problem
- We resort to optimization algorithms to find a solution

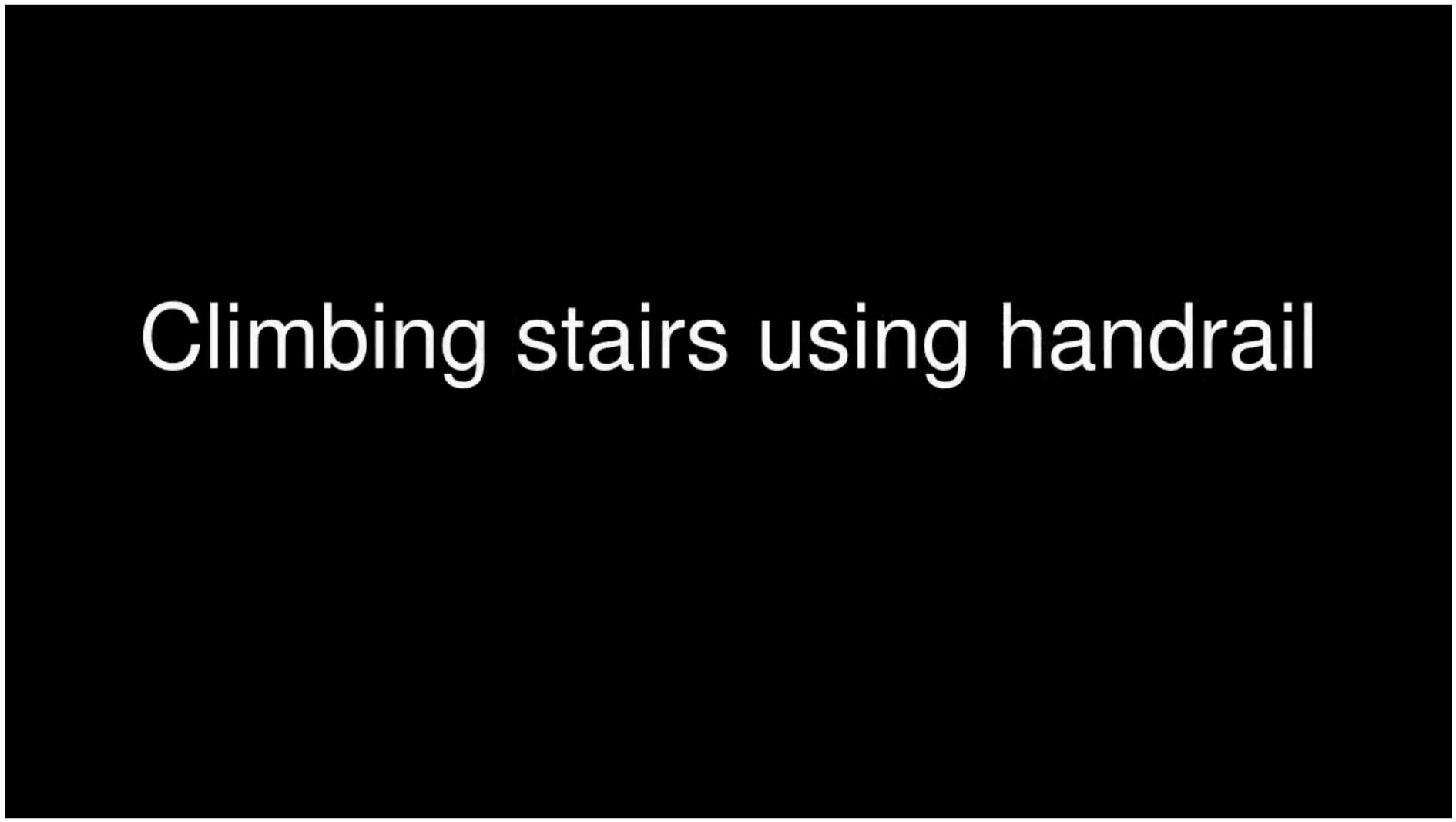
Optimal control in robotics

How to walk at a certain speed while guaranteeing balance?

[Herdt et al. 2010]
"Walking without thinking about it"

Optimal control in robotics

What is the best way to climb the stairs?



[Carpentier et al. 2017]
"A versatile and efficient pattern generator for generalized legged locomotion"

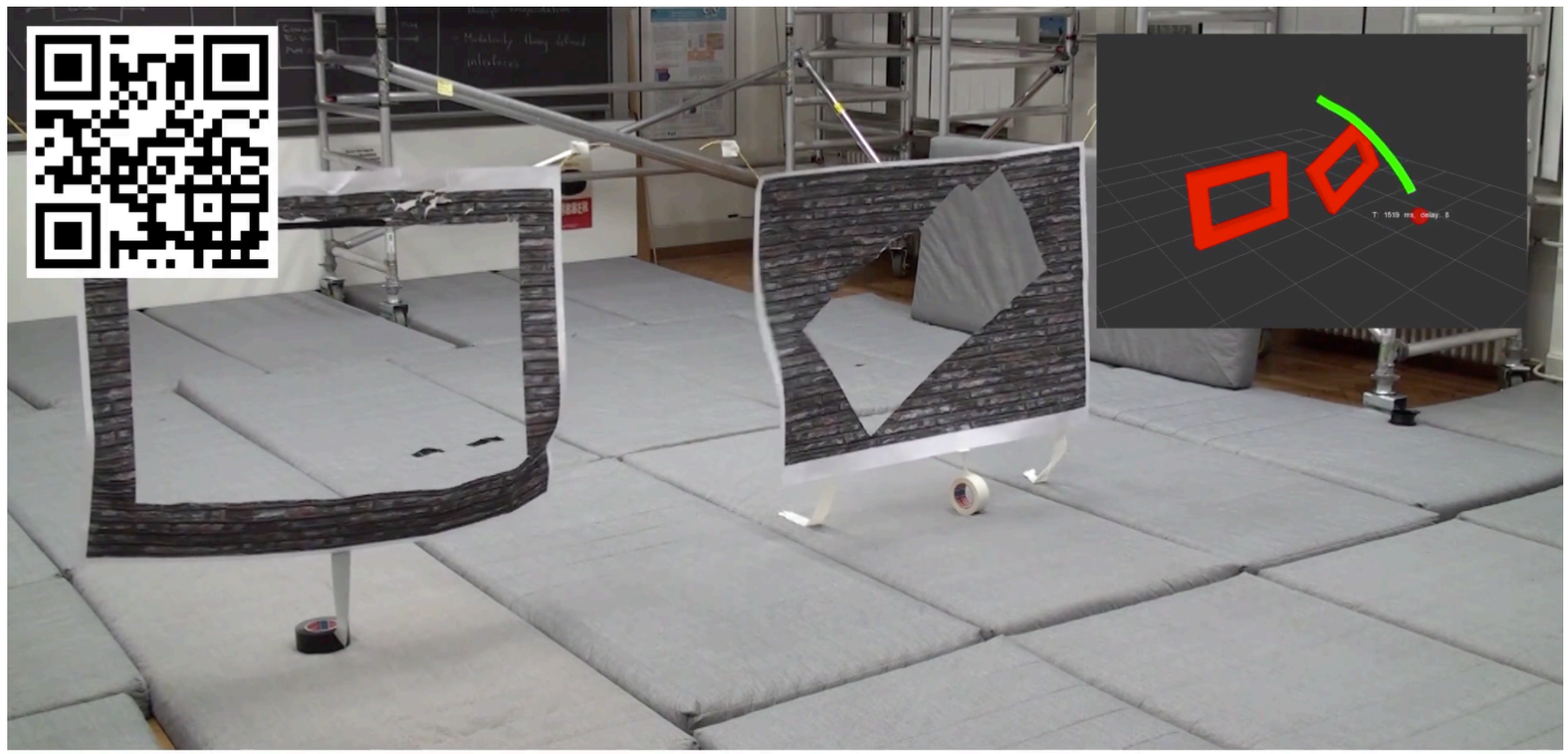
Optimal control in robotics

Optimal time-parametrization for dynamic tasks

[Pham et al. 2015]

Optimal control in robotics

How can the drone cross the



ADRL

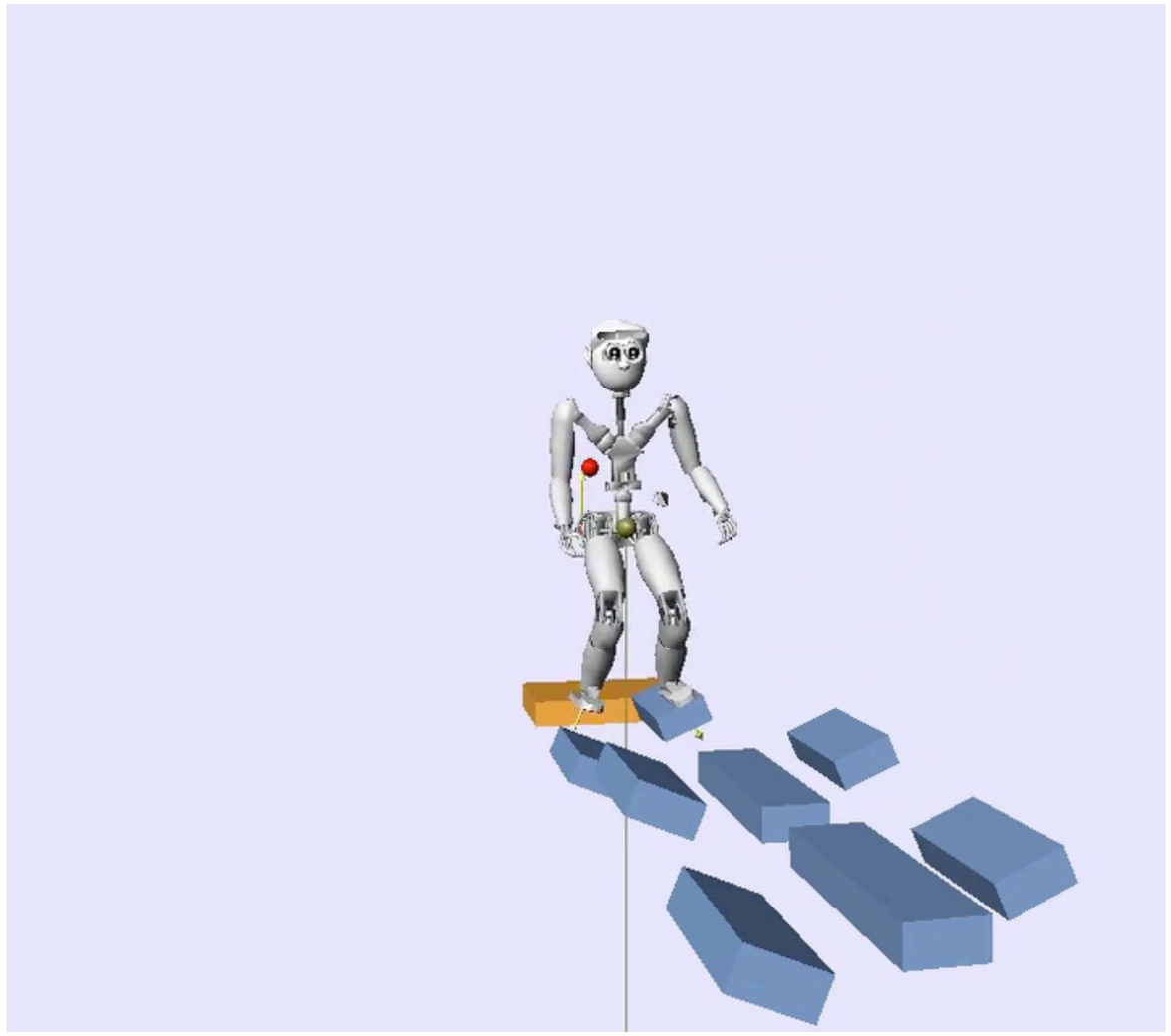
ETH zürich

Autonomous Systems Lab

[Neunert et al. 2016]
"Fast Nonlinear Model Predictive Control for Unified Trajectory Optimization and Tracking"

Optimal control in robotics

Find the best way to cross complex terrains



[Ponton et al. 2016]
"A Convex Model of Humanoid Momentum Dynamics for Multi-Contact Motion Generation"

Optimal control in compute graphics

Find the best way to cross complex terrains

[Mordatch et al. 2012]

What is reinforcement learning?

Cost to minimize

Subject to:

Mod t ystem (differe quation)

ns s

Only information comes from real experiments on robots

Learning to play GO

[Google Deepmind]

What is reinforcement learning?

In discrete time we will also use Bellman Principle of Optimality (with a twist to deal with unknown dynamics)

- Scales exponentially with the number of dimensions (curse of dimensionality)!
- Does not generalize well to continuous-state / continuous-action spaces (we need approximations!)

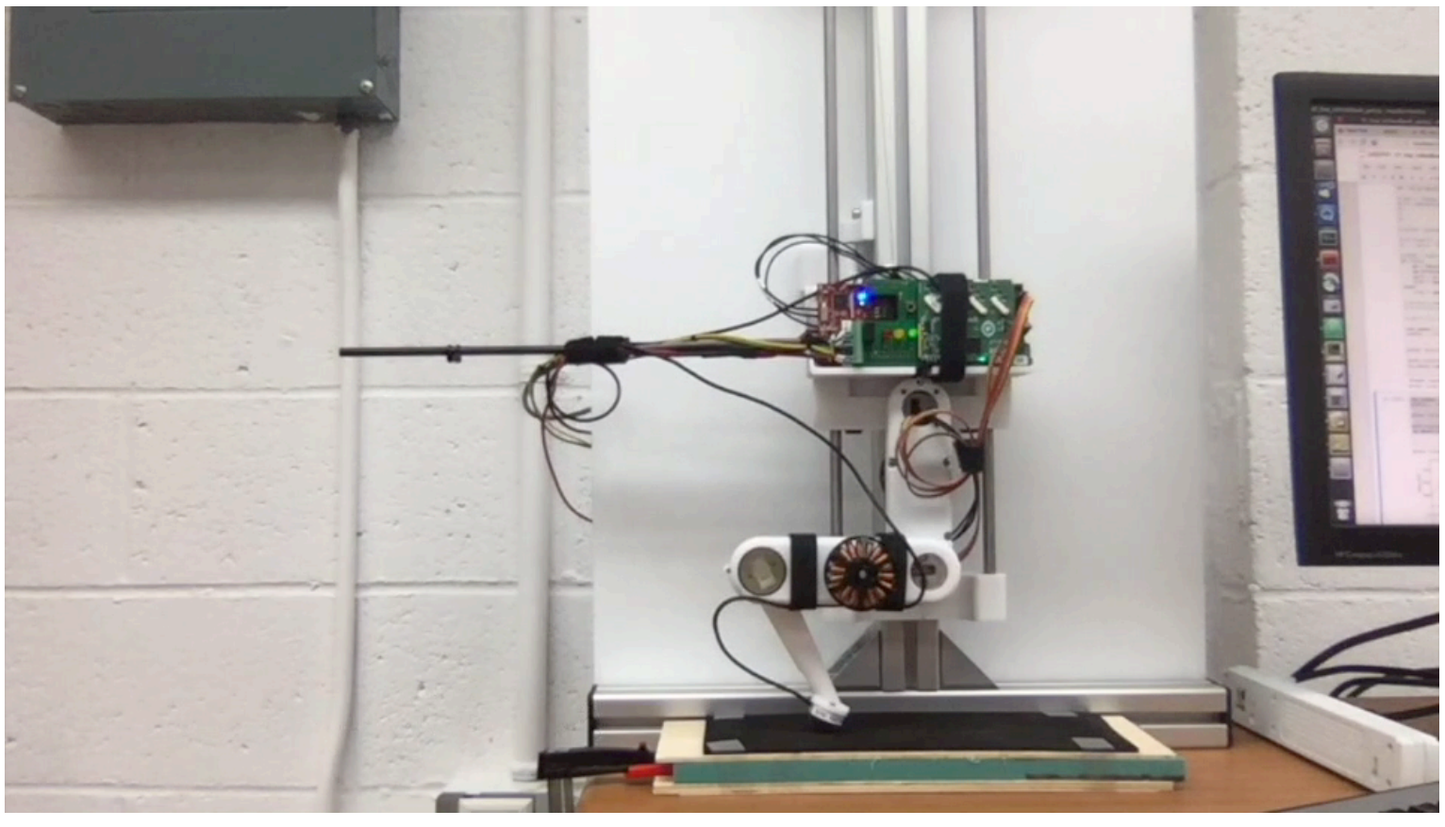
Reinforcement learning in robotics

Policy improvement

[Kalakrishan et al. 2011]

Reinforcement learning in robotics

Model-based reinforcement learning



[Viereck et al. 2018]

Reinforcement learning in robotics

Model-free reinforcement learning

[Levine et al. 2016]

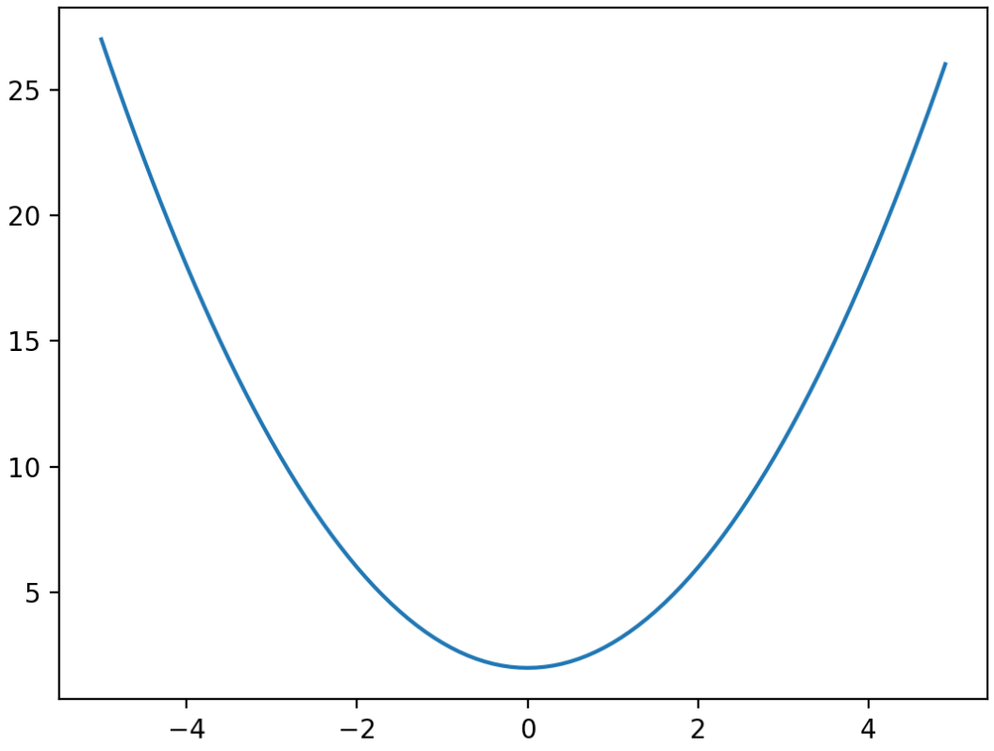
Reinforcement learning in robotics

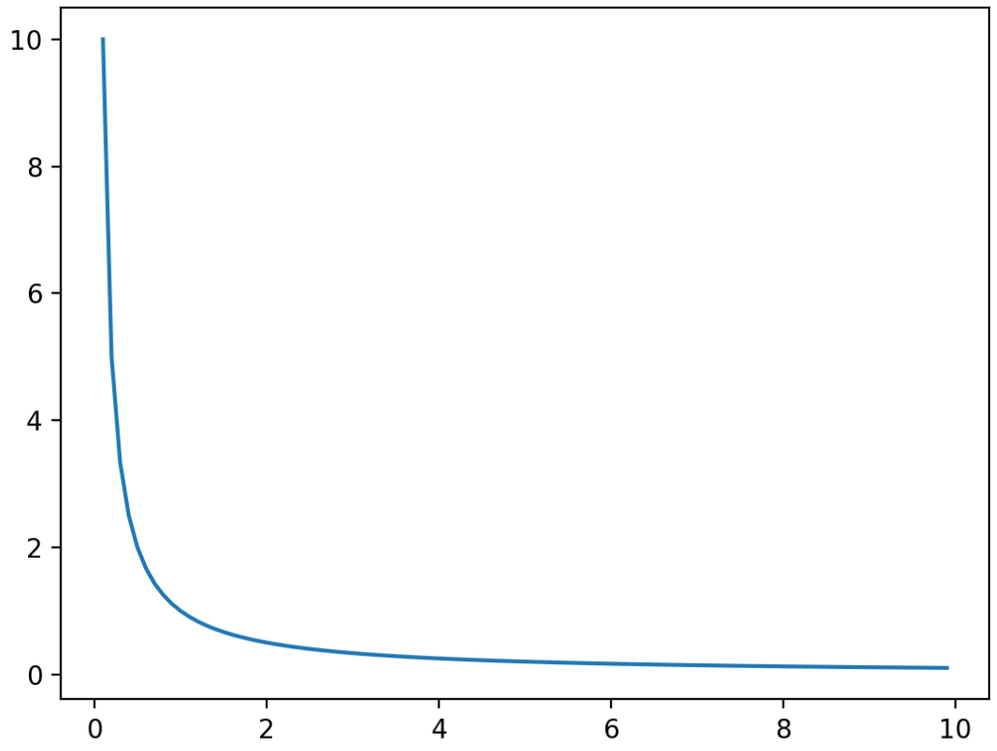
Actor-critic algorithms and deep neural networks

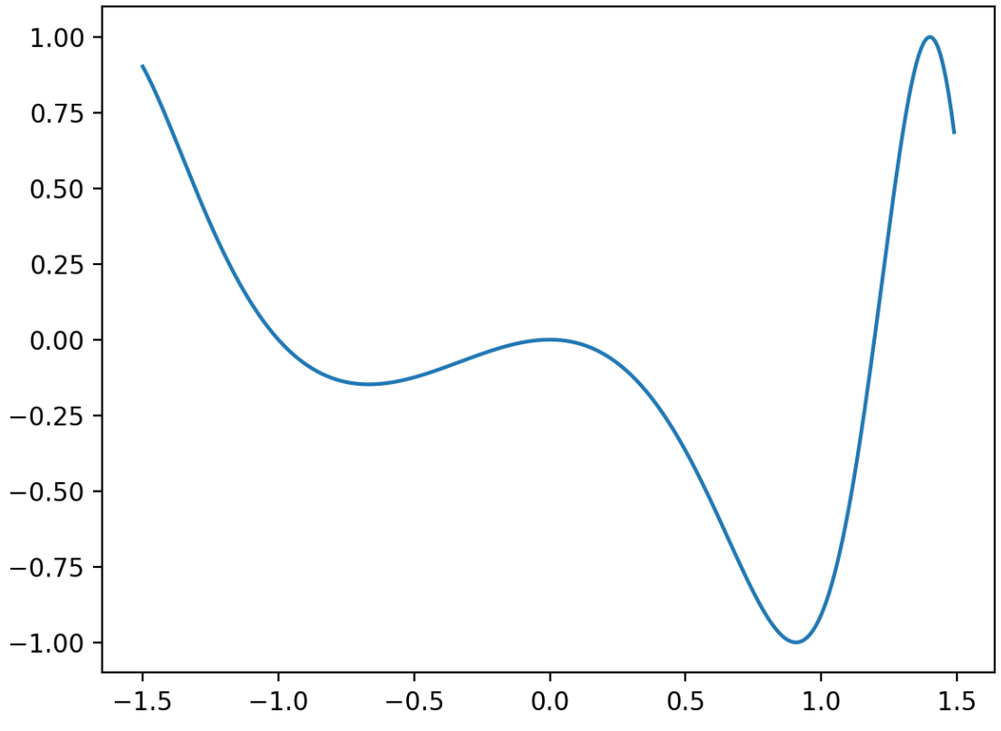
[Deepmind 2017]

Minimizing a function

Minimizing a function







Minimizing a function

Convex functions

Non convex functions

Constrained minimization

Questions?