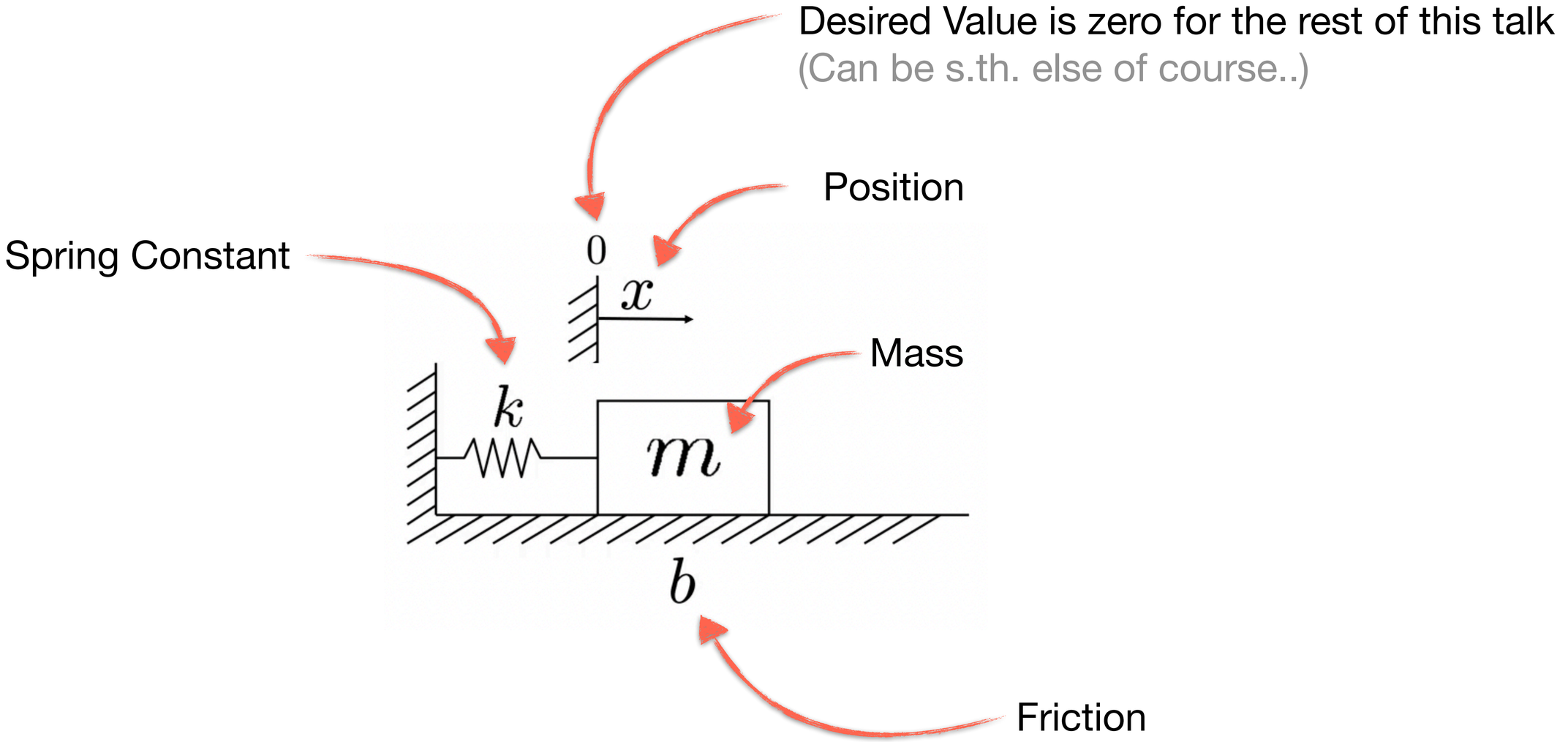
Human-Robot Interaction

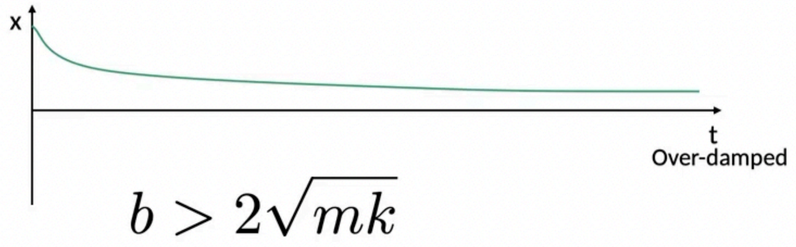
Impedance Control

Spring-Mass-Damper System

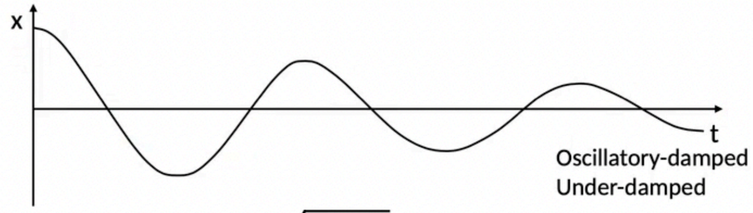
Spring-Mass-Damper System



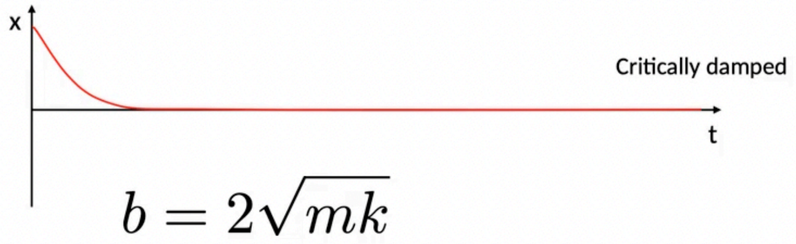
Spring-Mass-Damper System



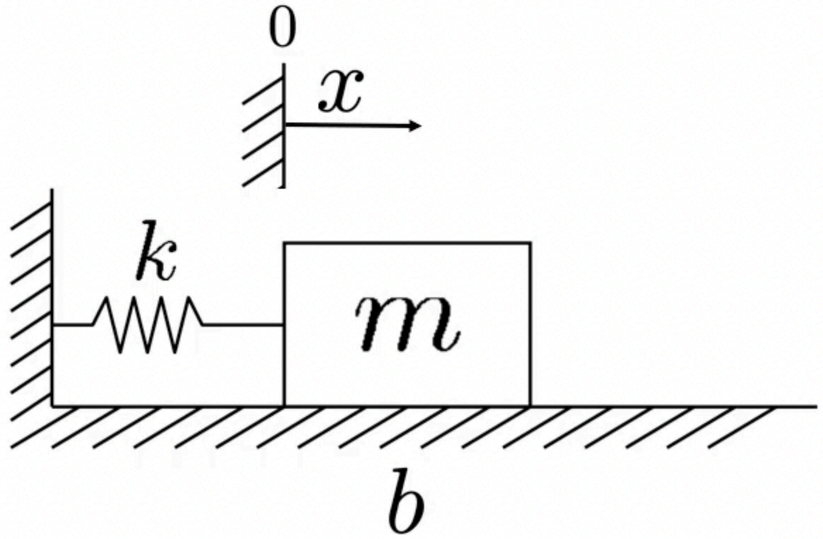
$$b > 2\sqrt{mk}$$



$$b < 2\sqrt{mk}$$

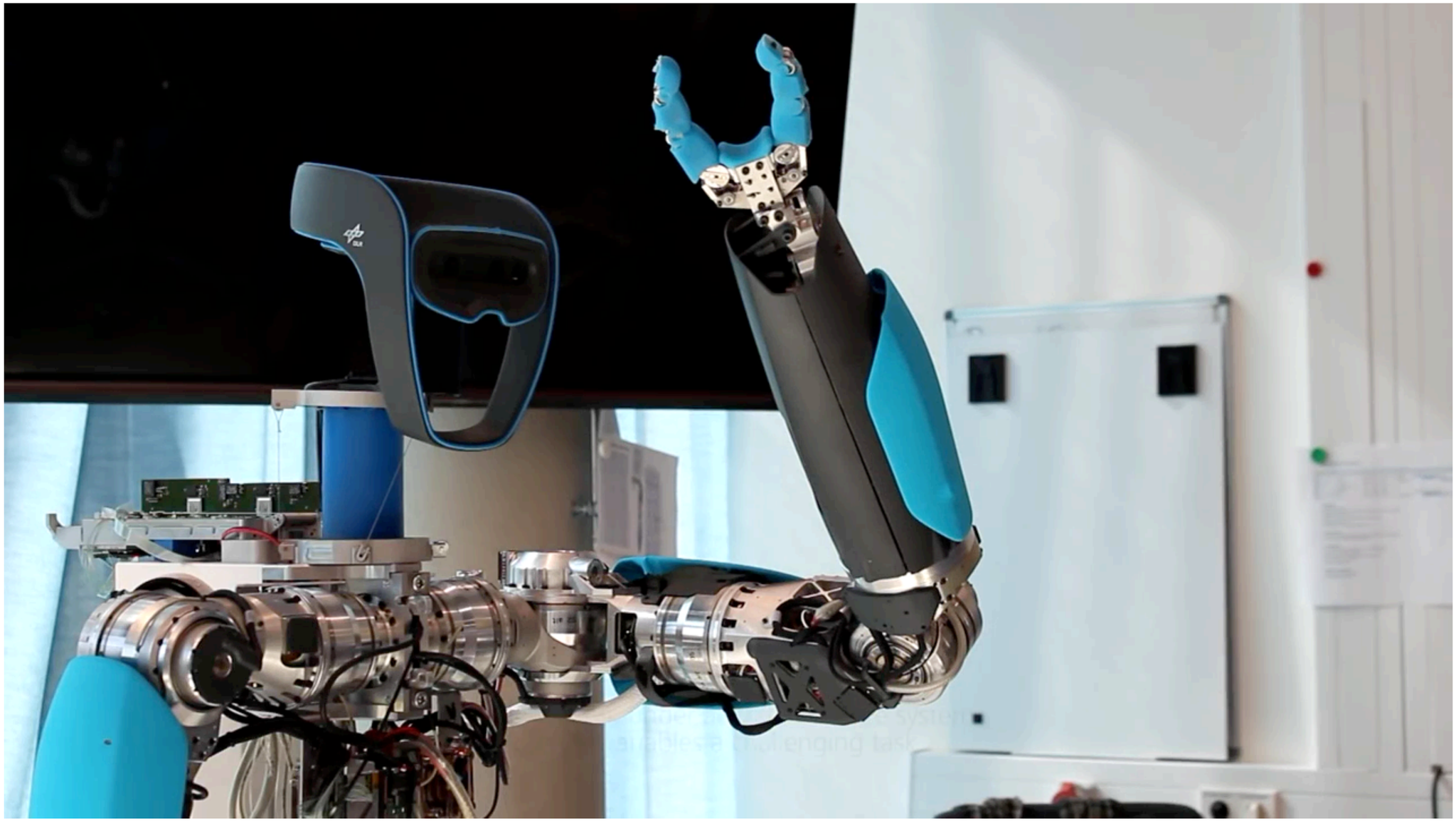


$$b = 2\sqrt{mk}$$

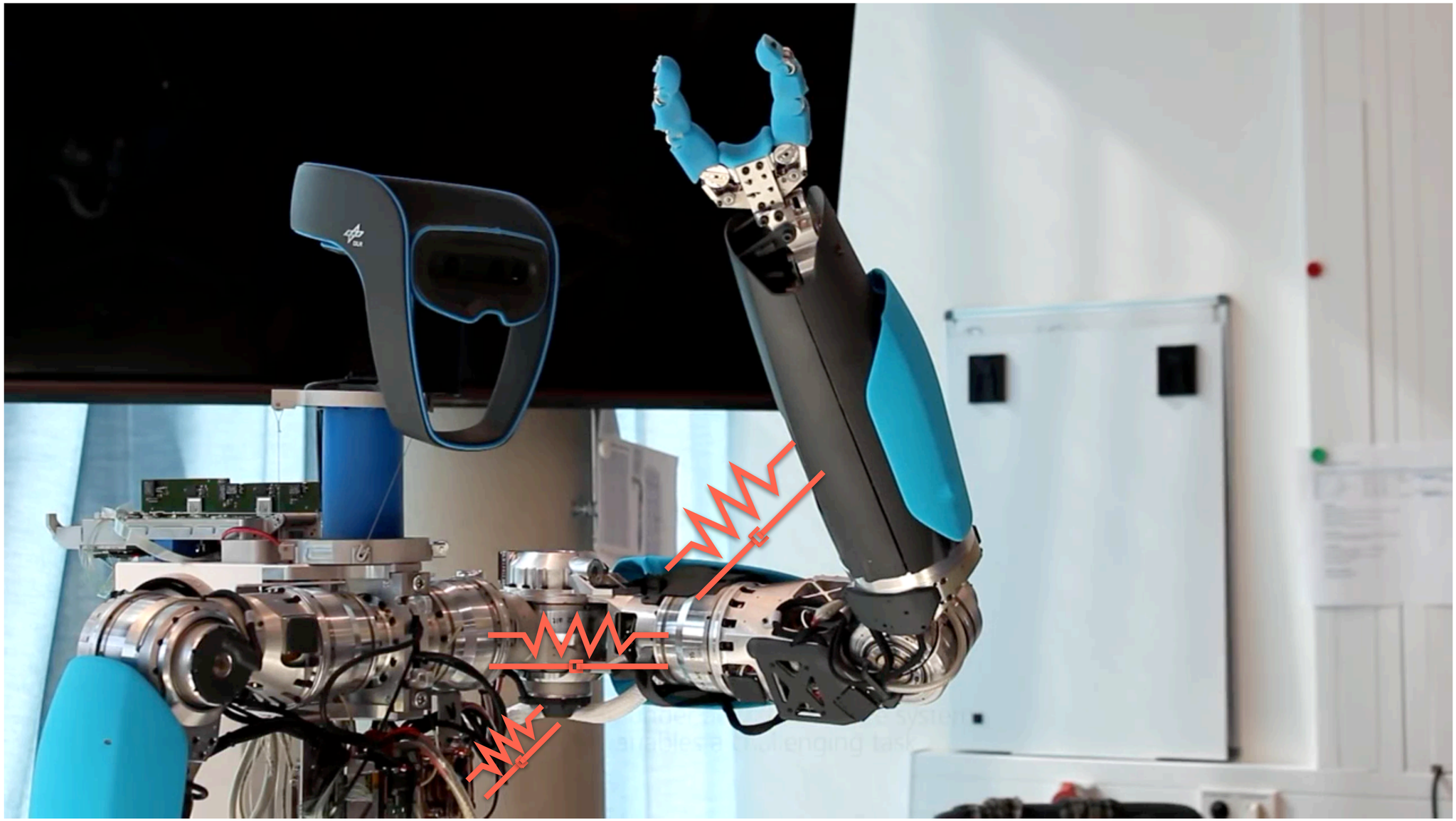


$$m\ddot{x} + b\dot{x} + kx = 0$$

Critical Damping thanks to Spring-Mass-Damper System

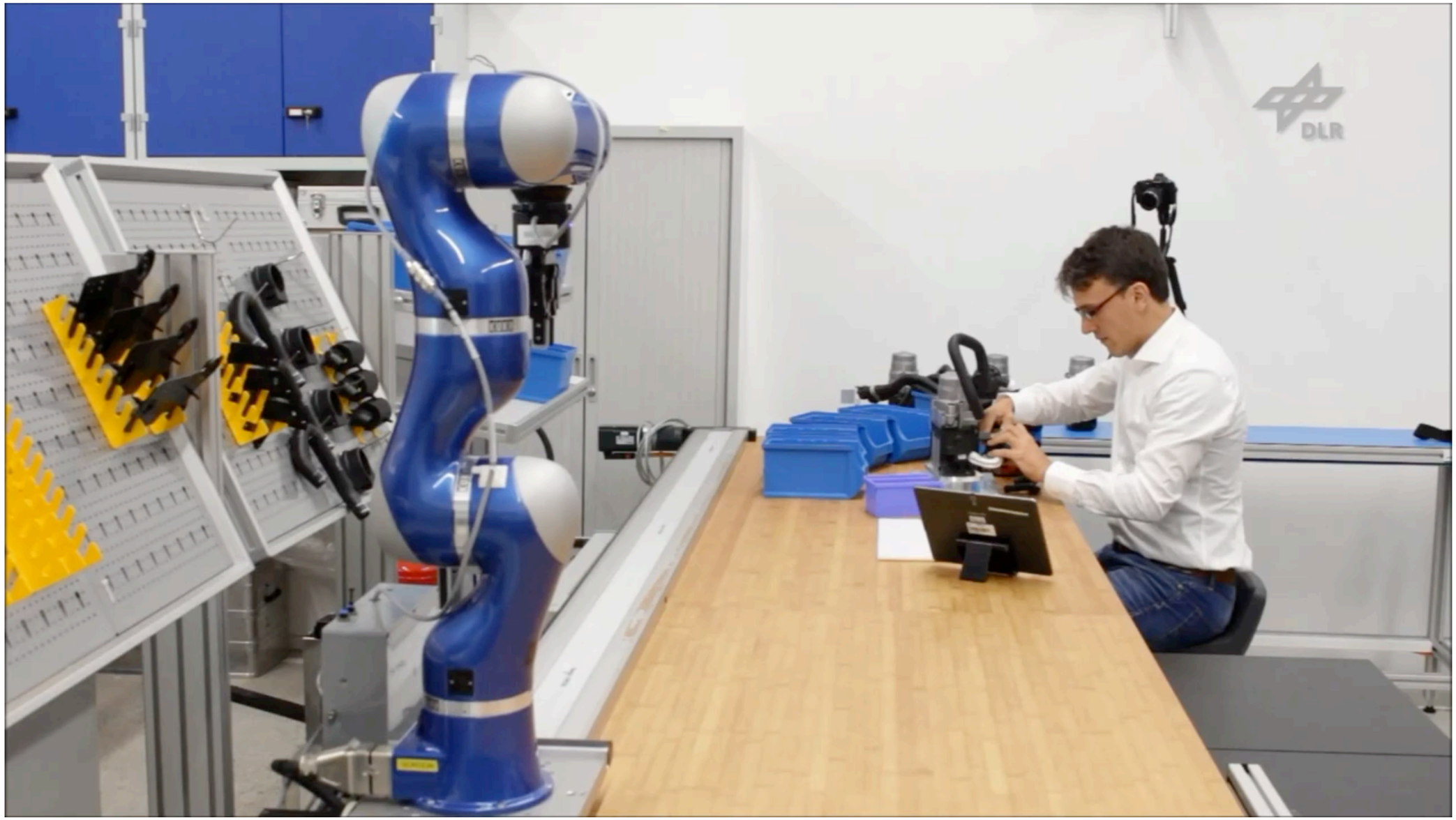


Critical Damping thanks to Spring-Mass-Damper System

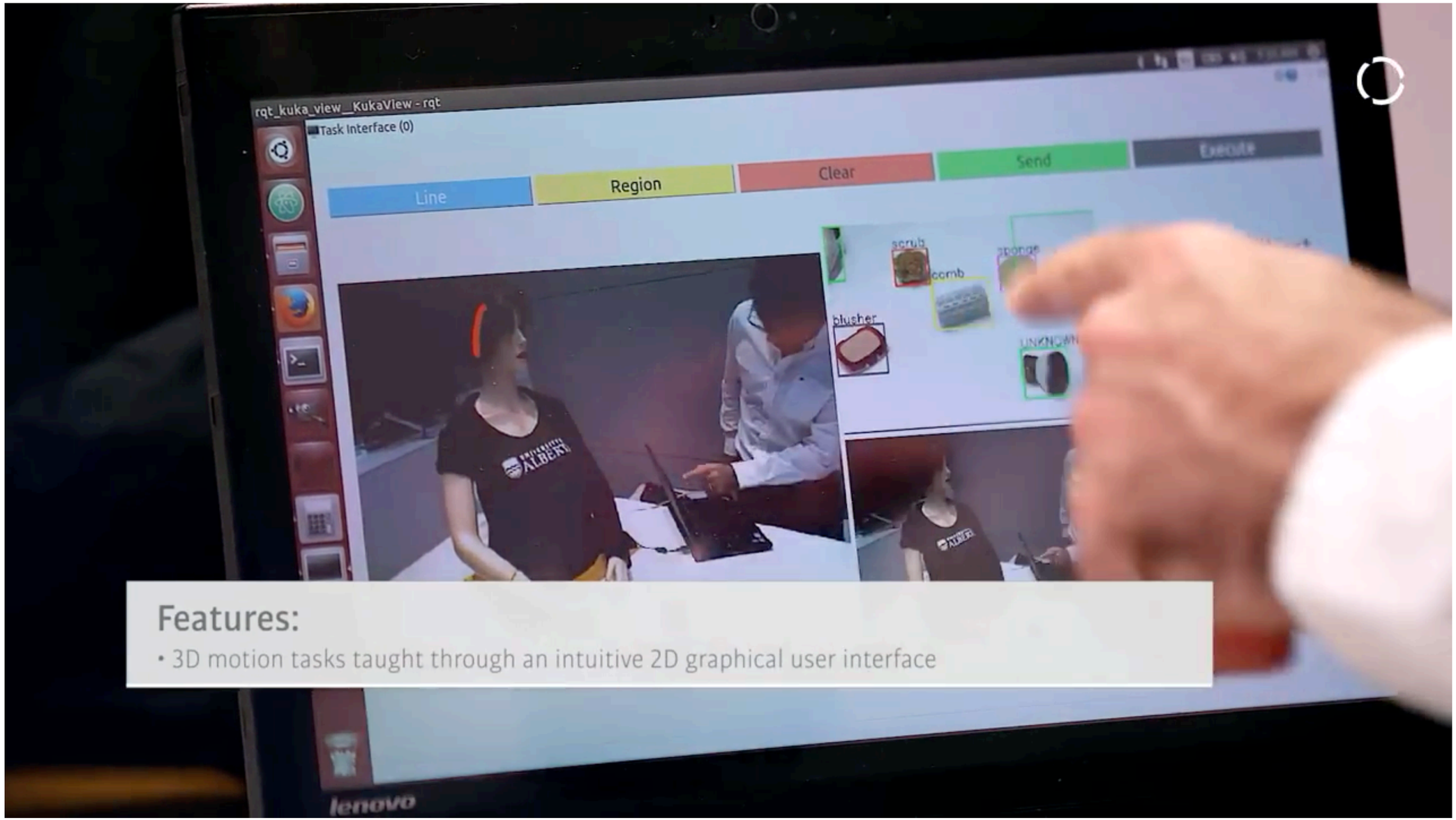


So far, everything happened in **free space**
without physical interaction between
the robot and the environment.

Interactive Robotics

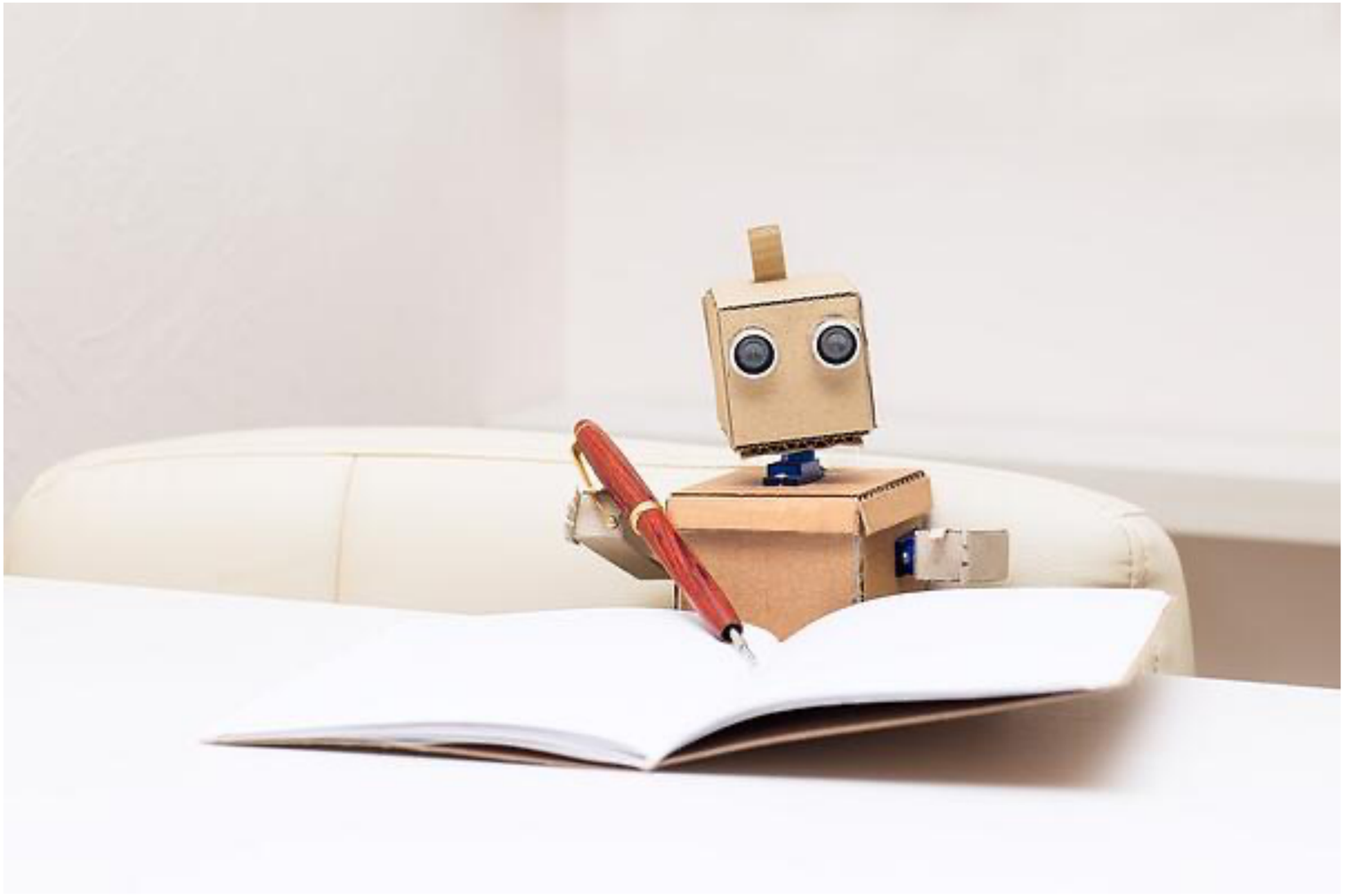


Interactive Robotics

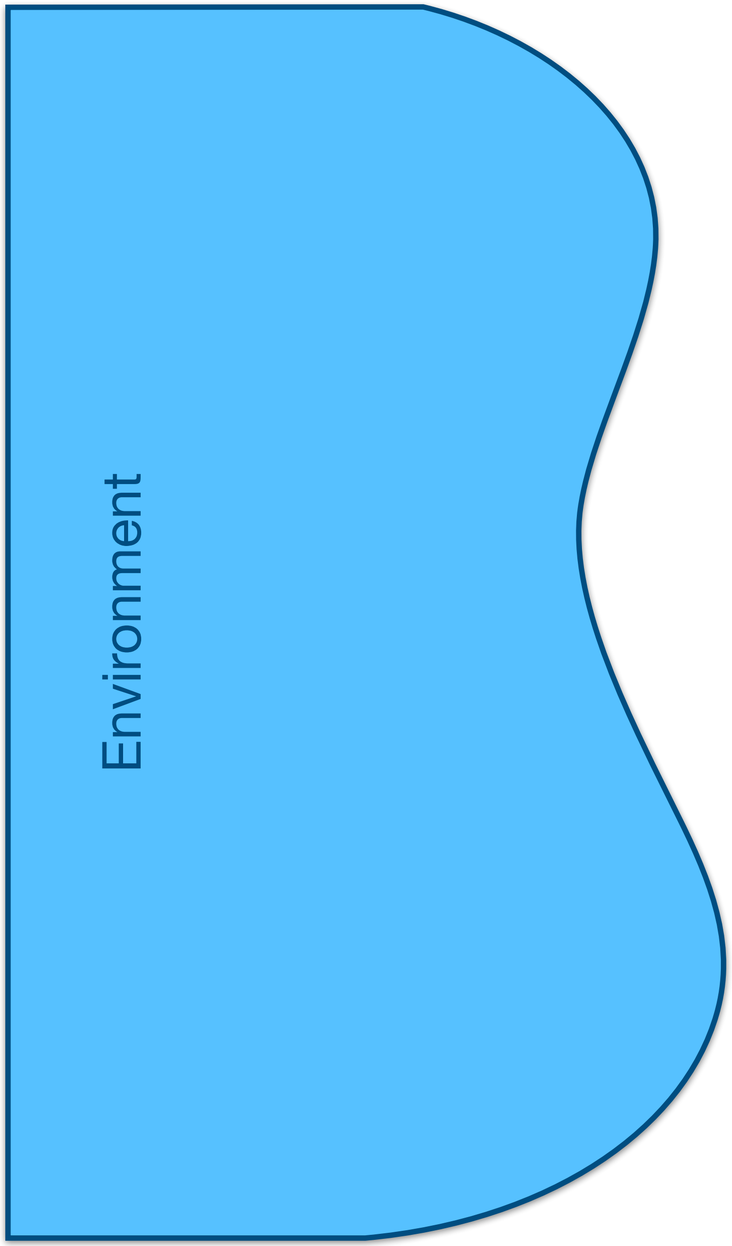


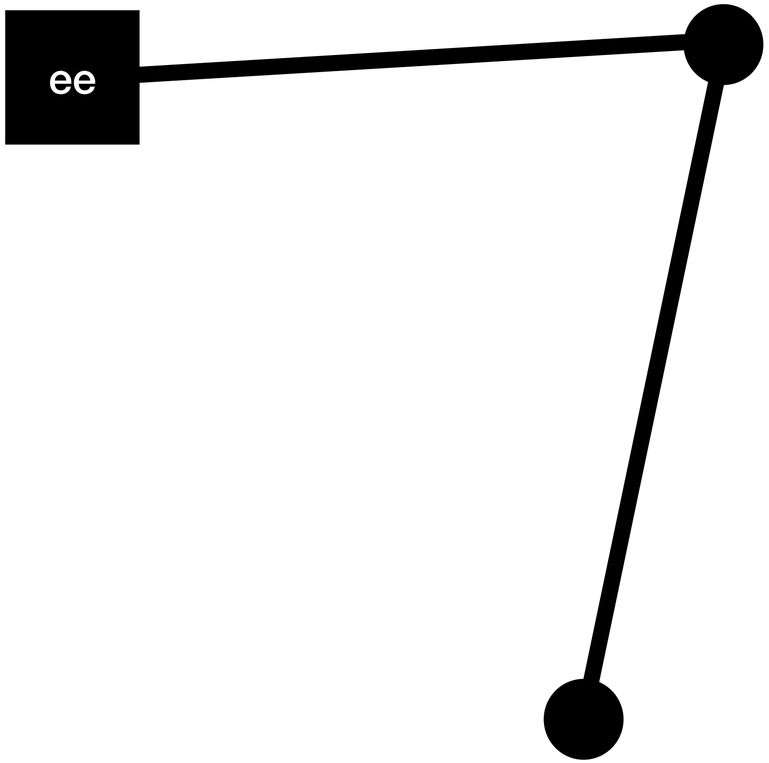
We want the robot to physically interact
with its environment!

Example of Physical Interaction between Robot and Environment

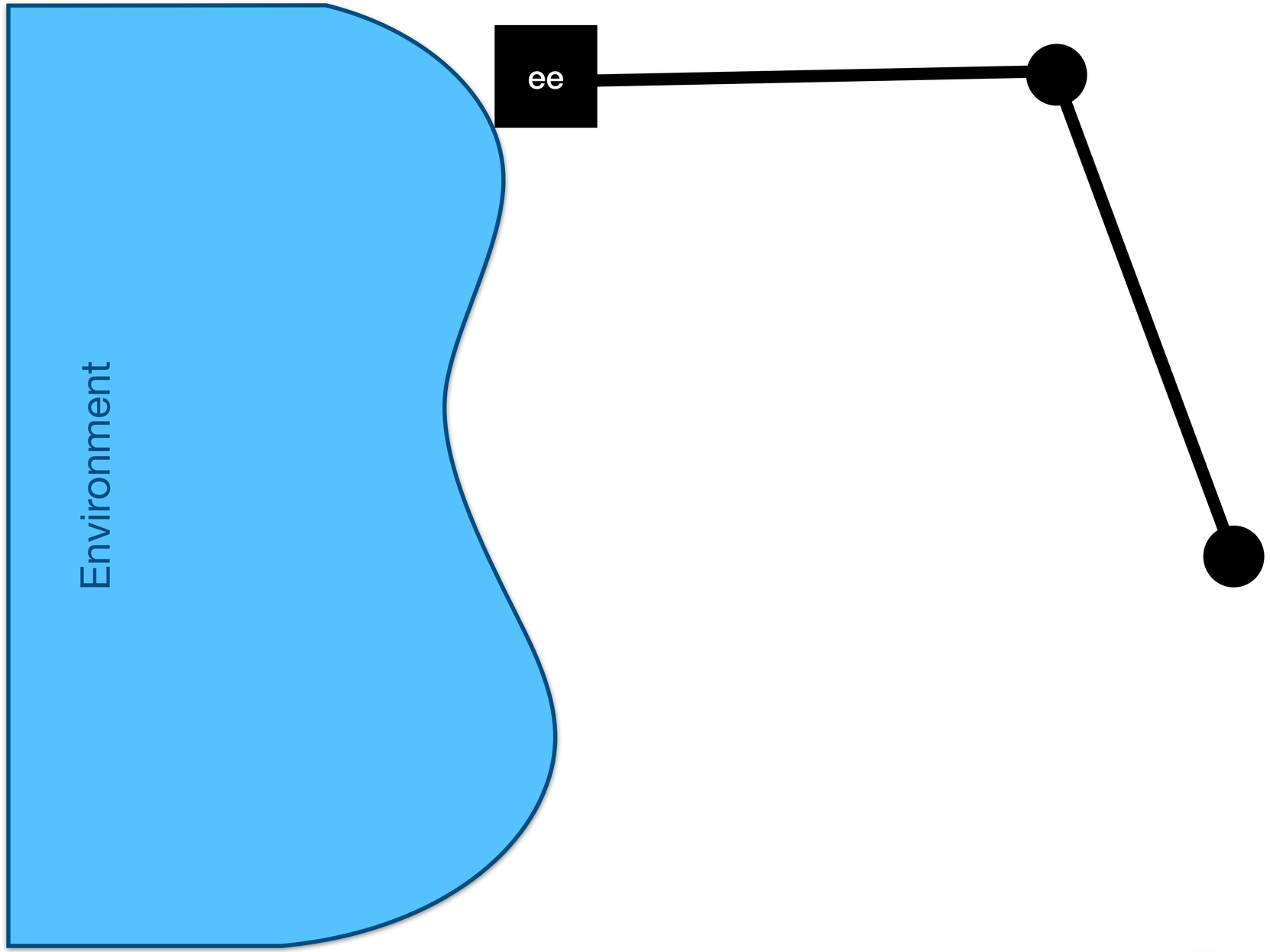


Task: Writing on a curved, compliant surface.

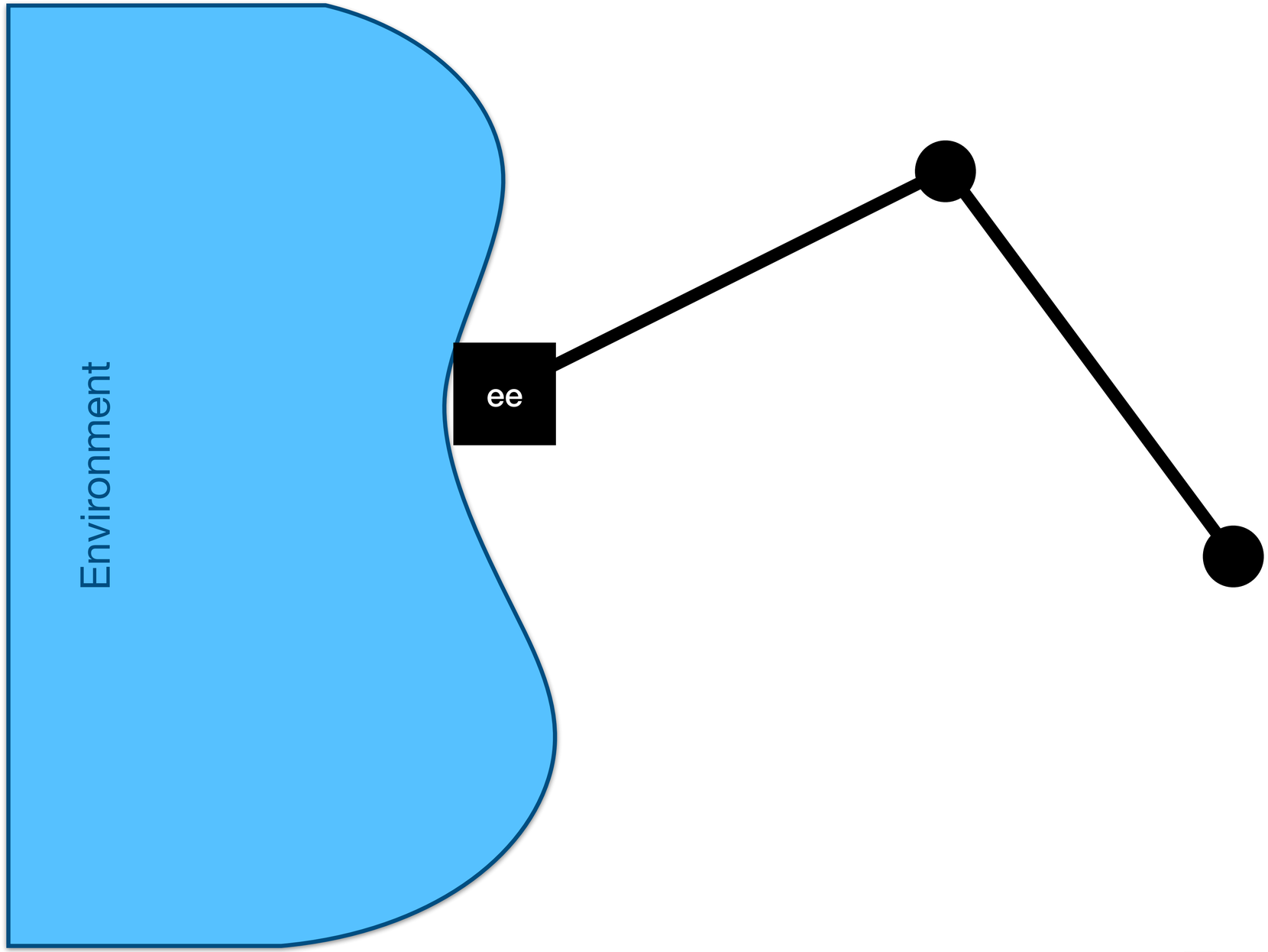




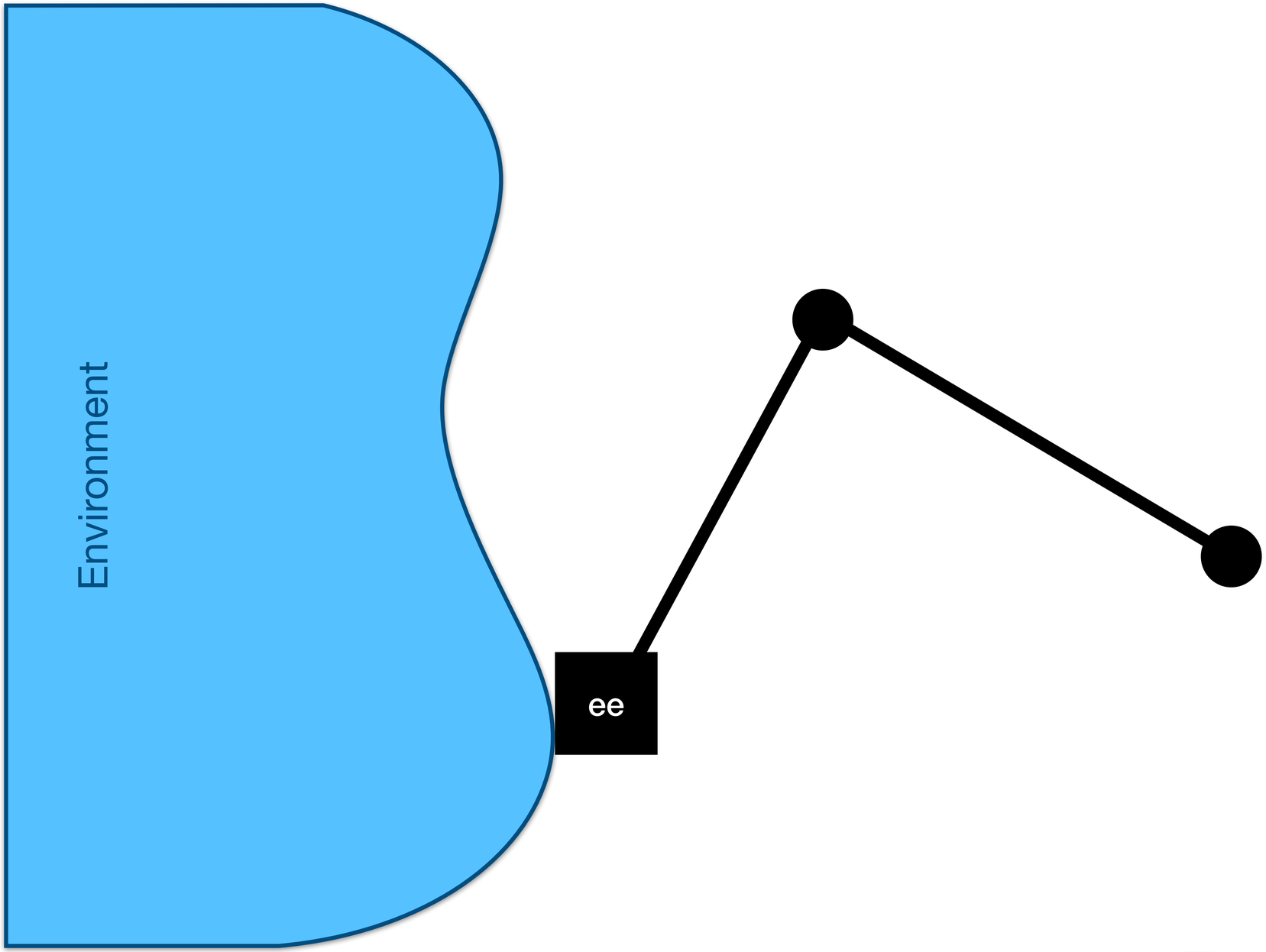
Task: Slide over surface



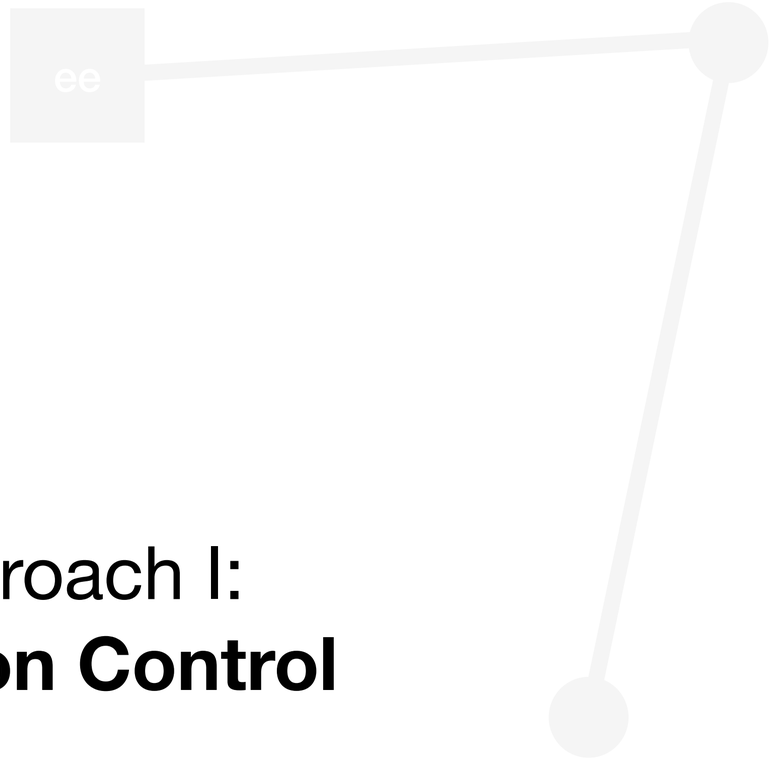
Task: Slide over surface



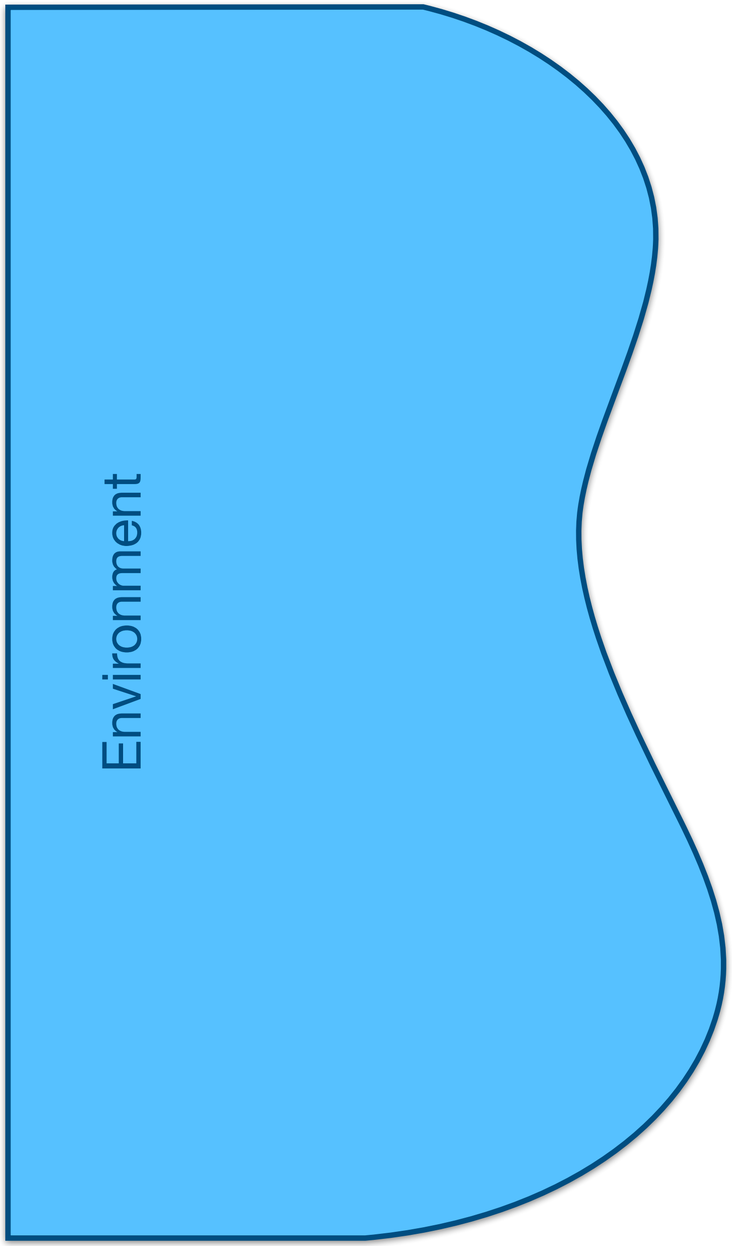
Task: Slide over surface

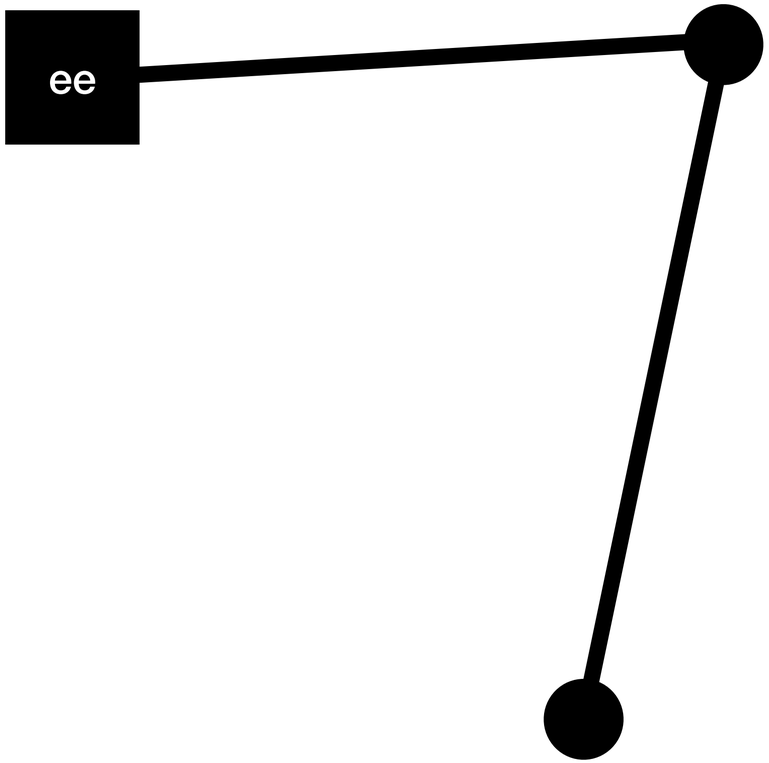


Task: Slide over surface

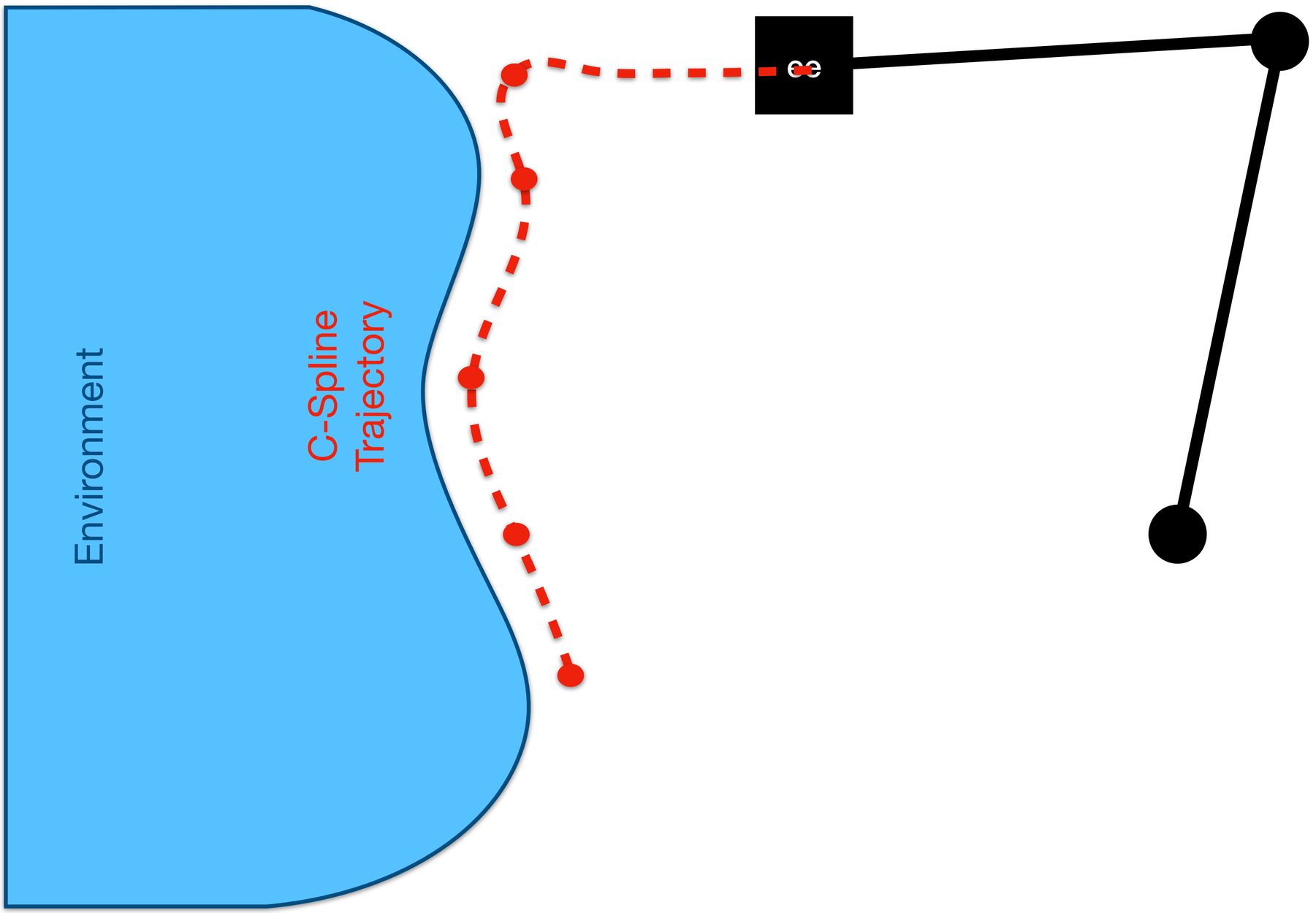


Approach I:
Position Control



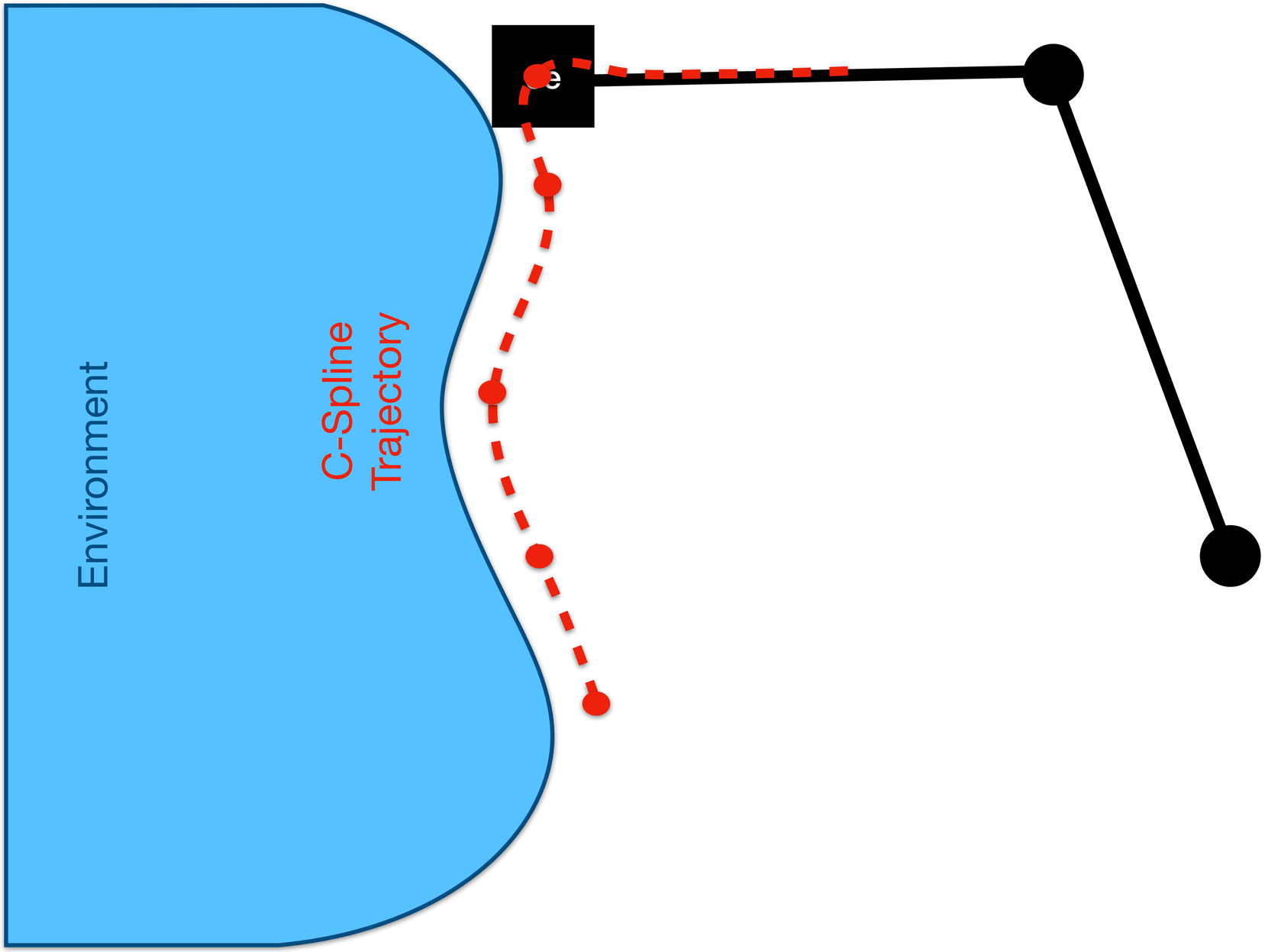


Robot tries to move along a desired trajectory with high precision



Robot tries to move along a desired trajectory with high precision

High precision requires high gains!



Robot tries to move along a desired trajectory with high precision

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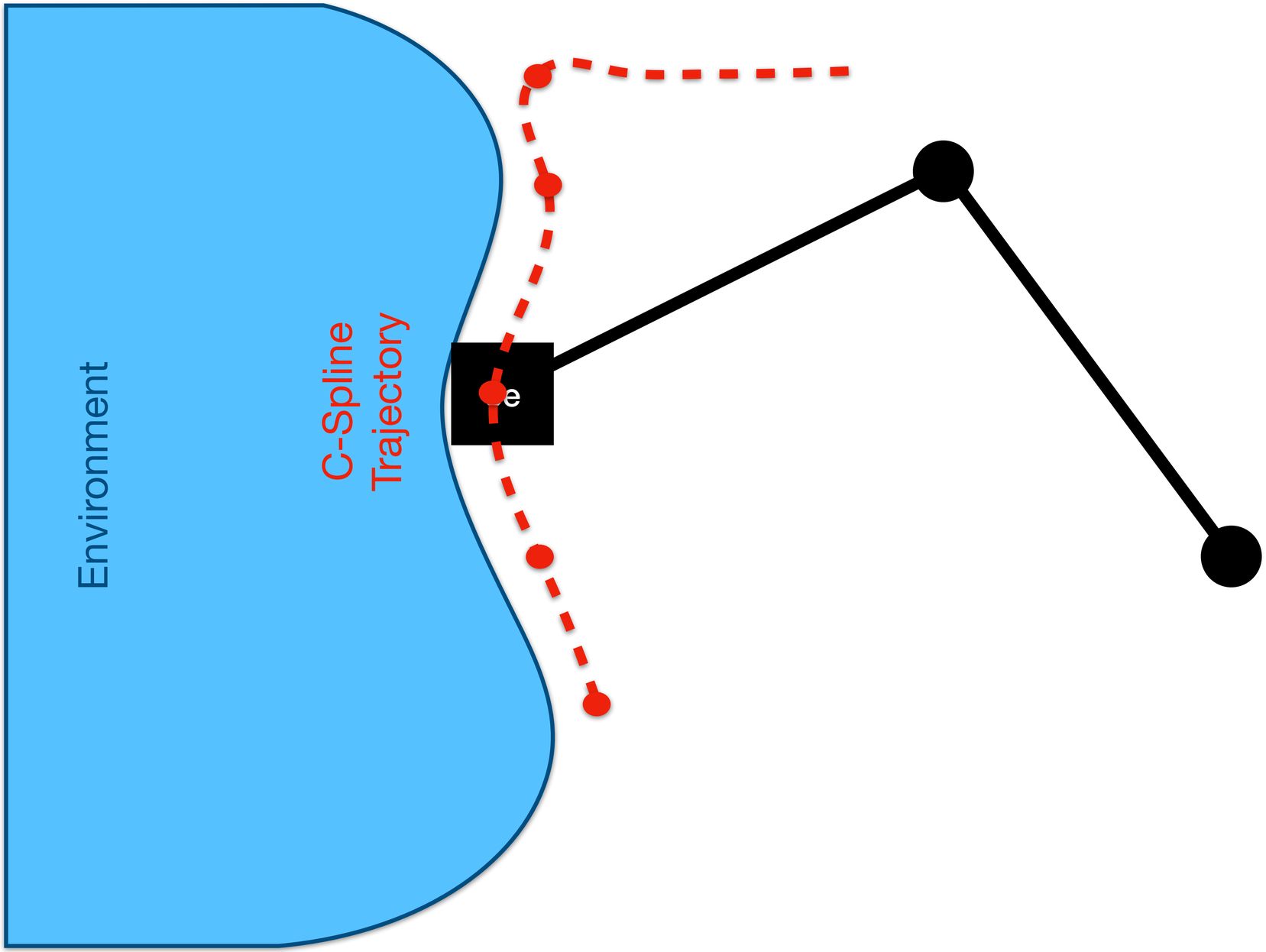
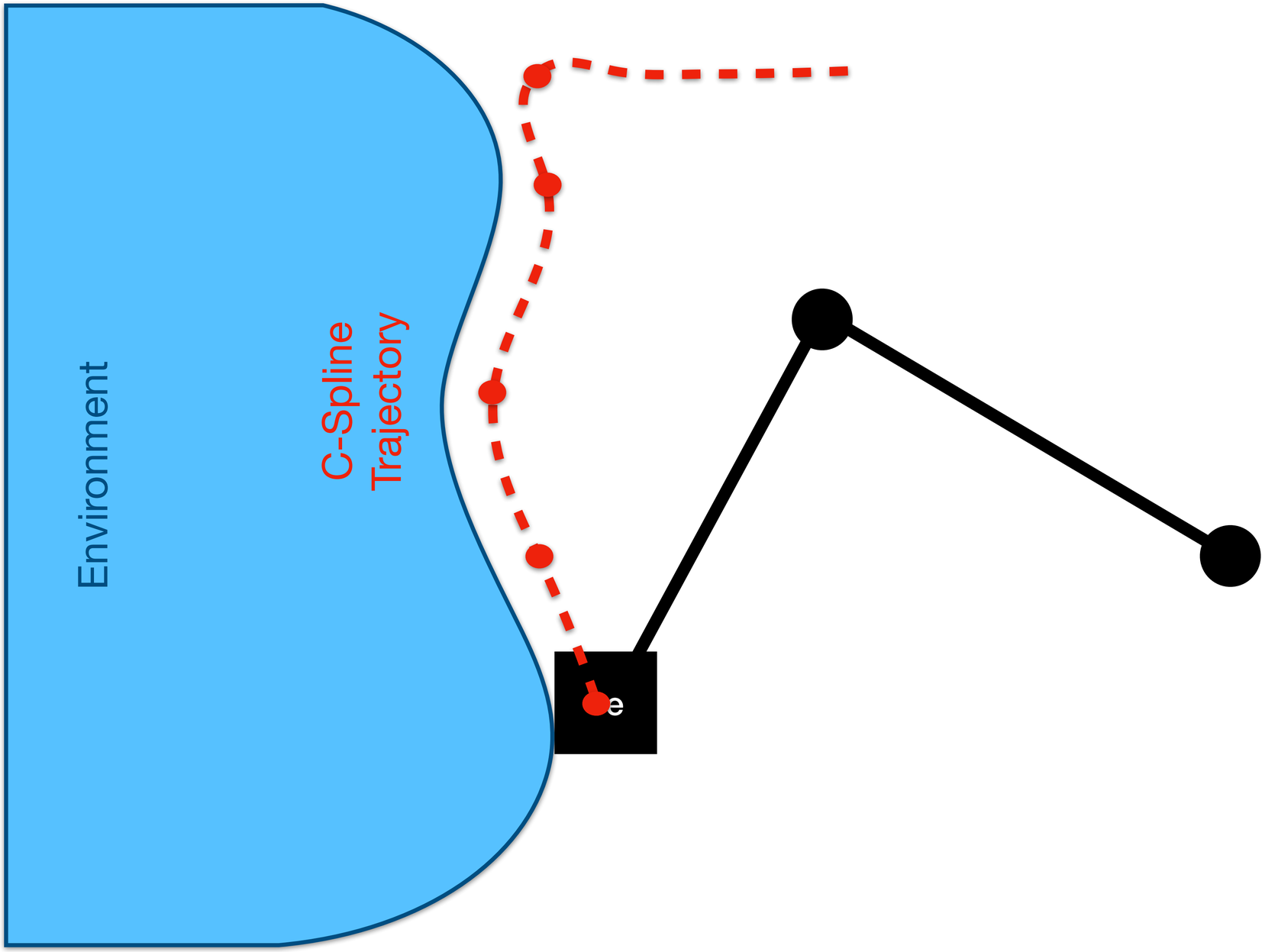


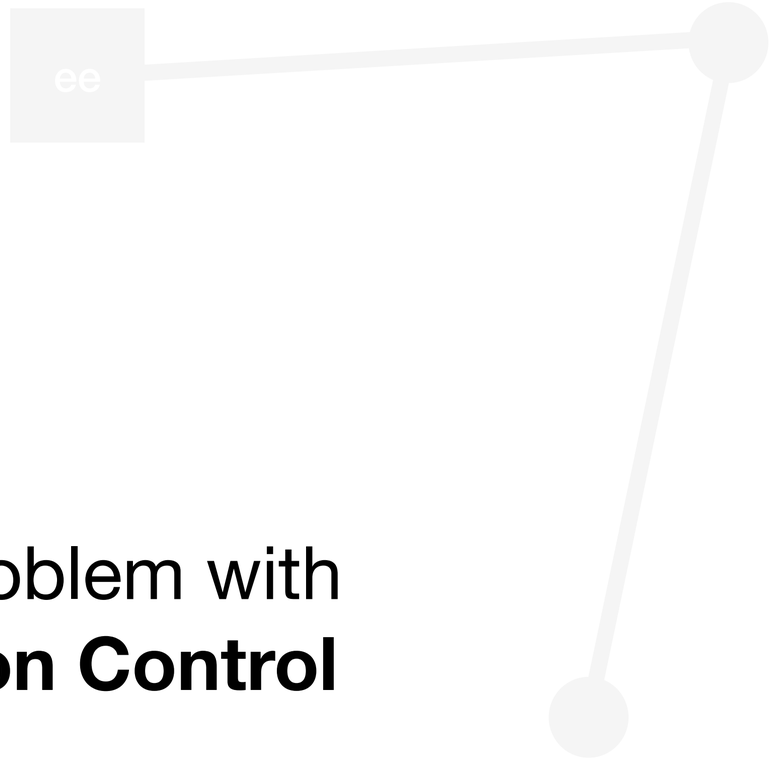
Robot tries to move along a desired trajectory with high precision

High precision requires high gains!

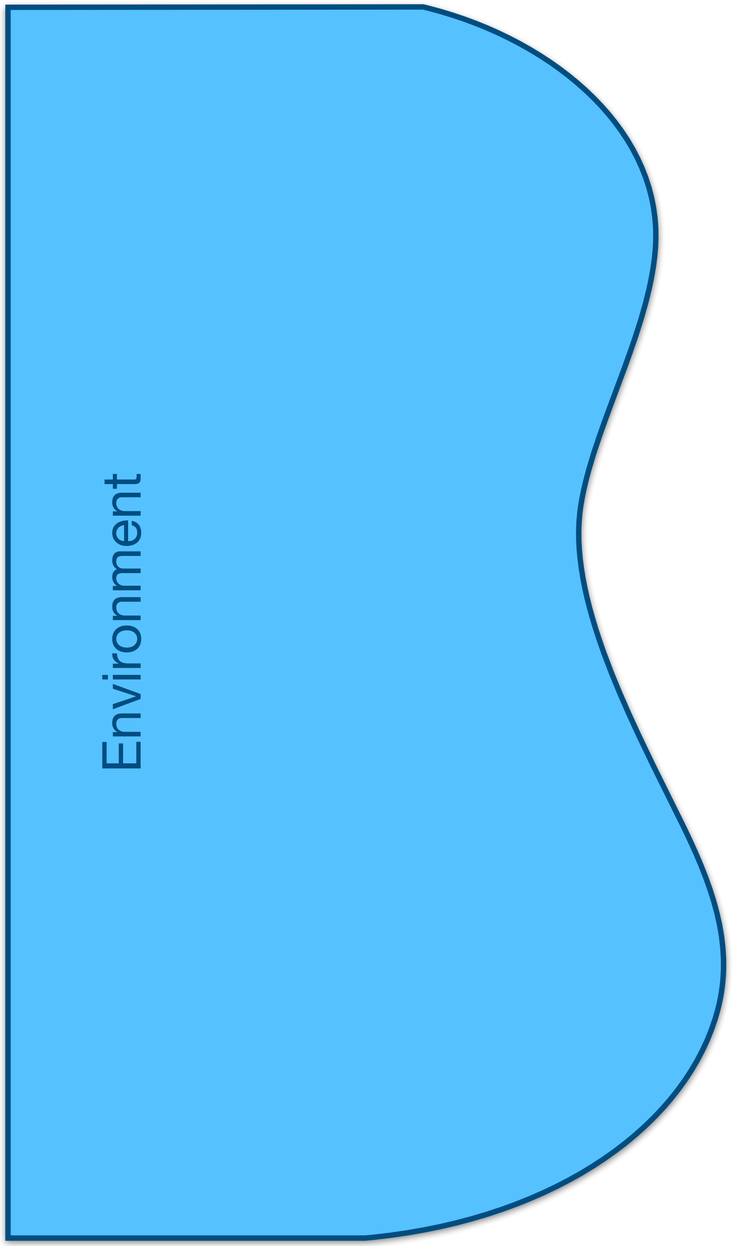
Robot tries to move along a desired trajectory with high precision

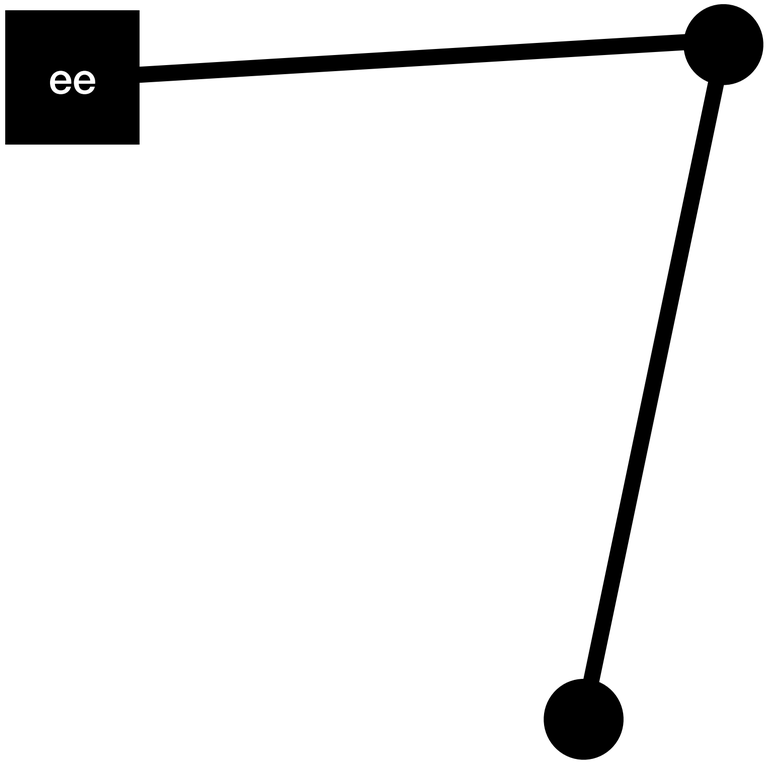


High precision requires high gains!



The Problem with **Position Control**





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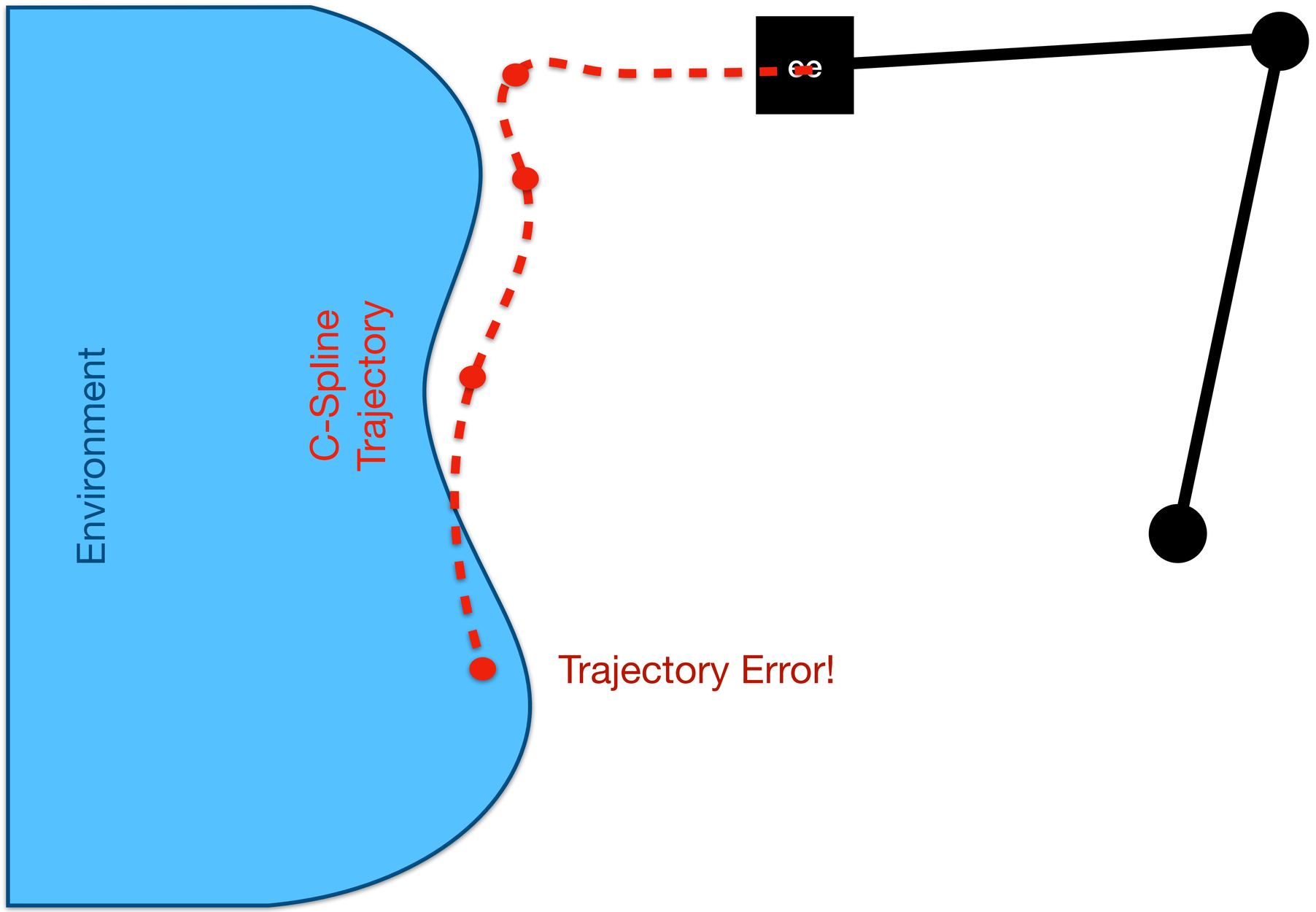

Robot tries to move along a desired trajectory with high precision

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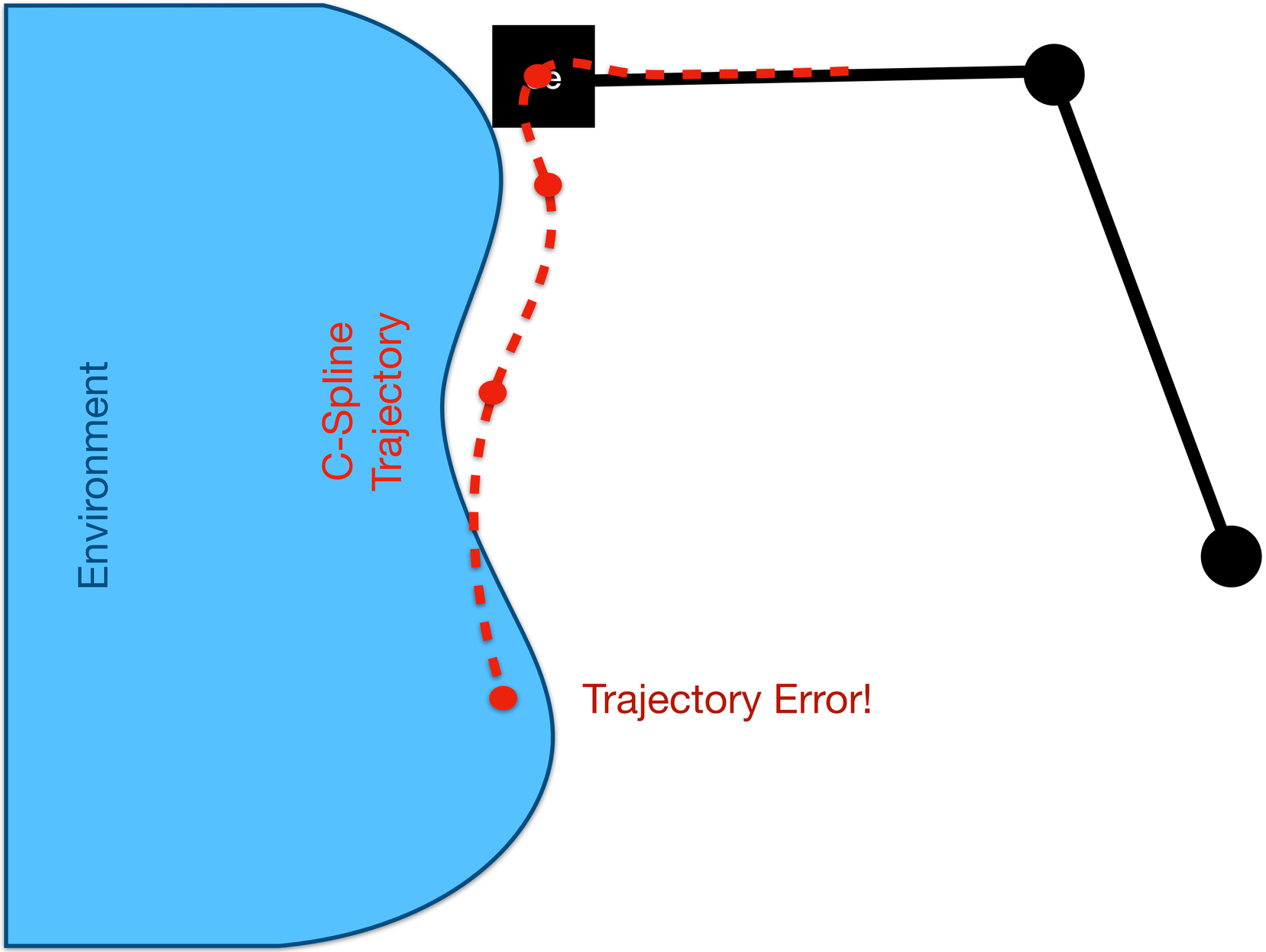

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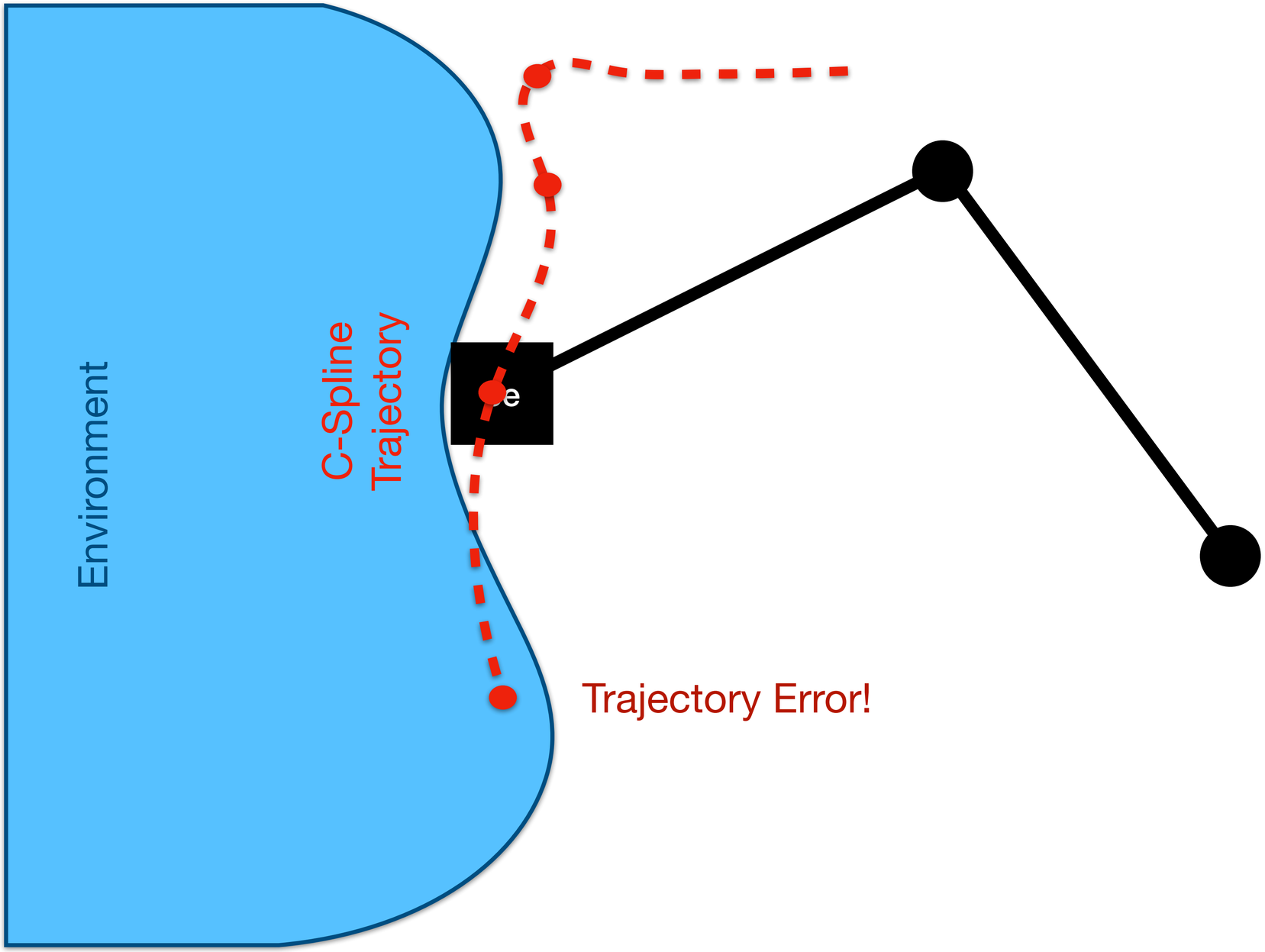

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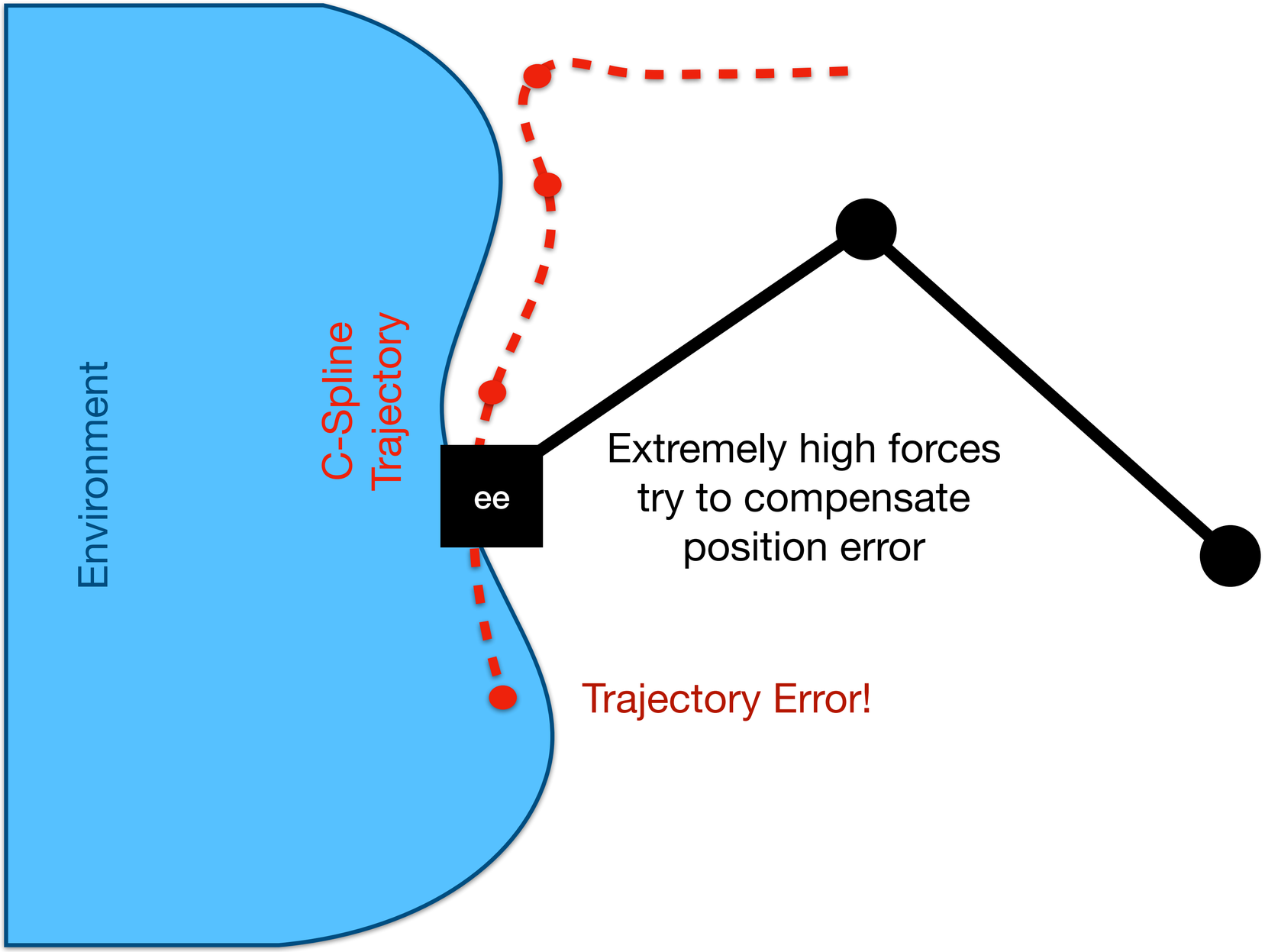
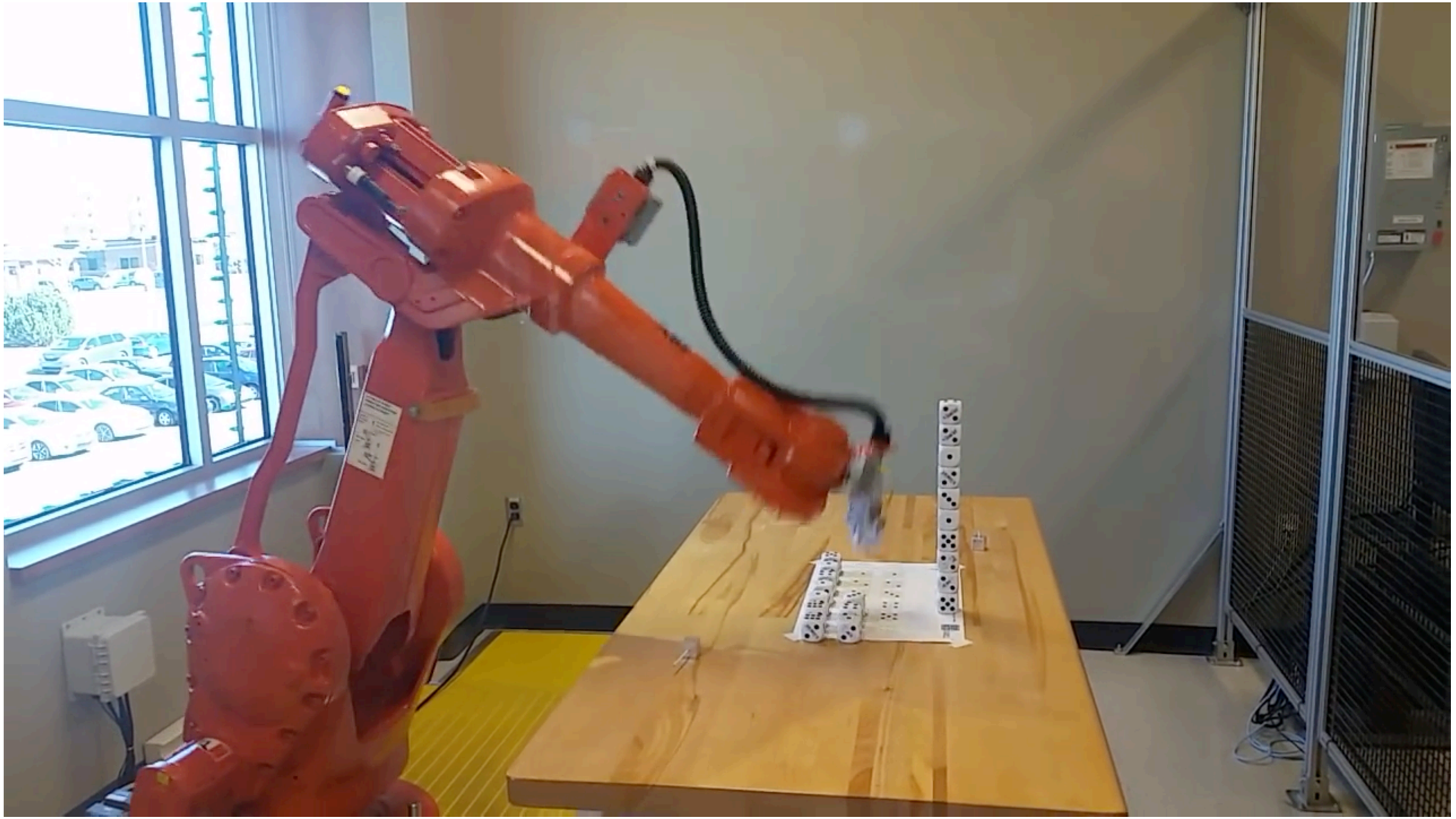
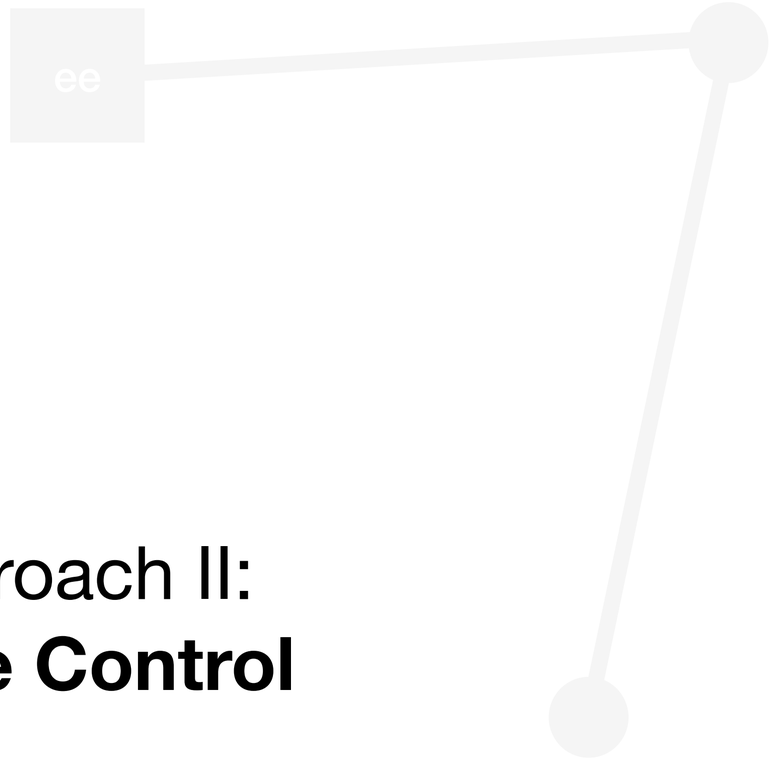


High precision requires high gains!

The Problem with Position Control

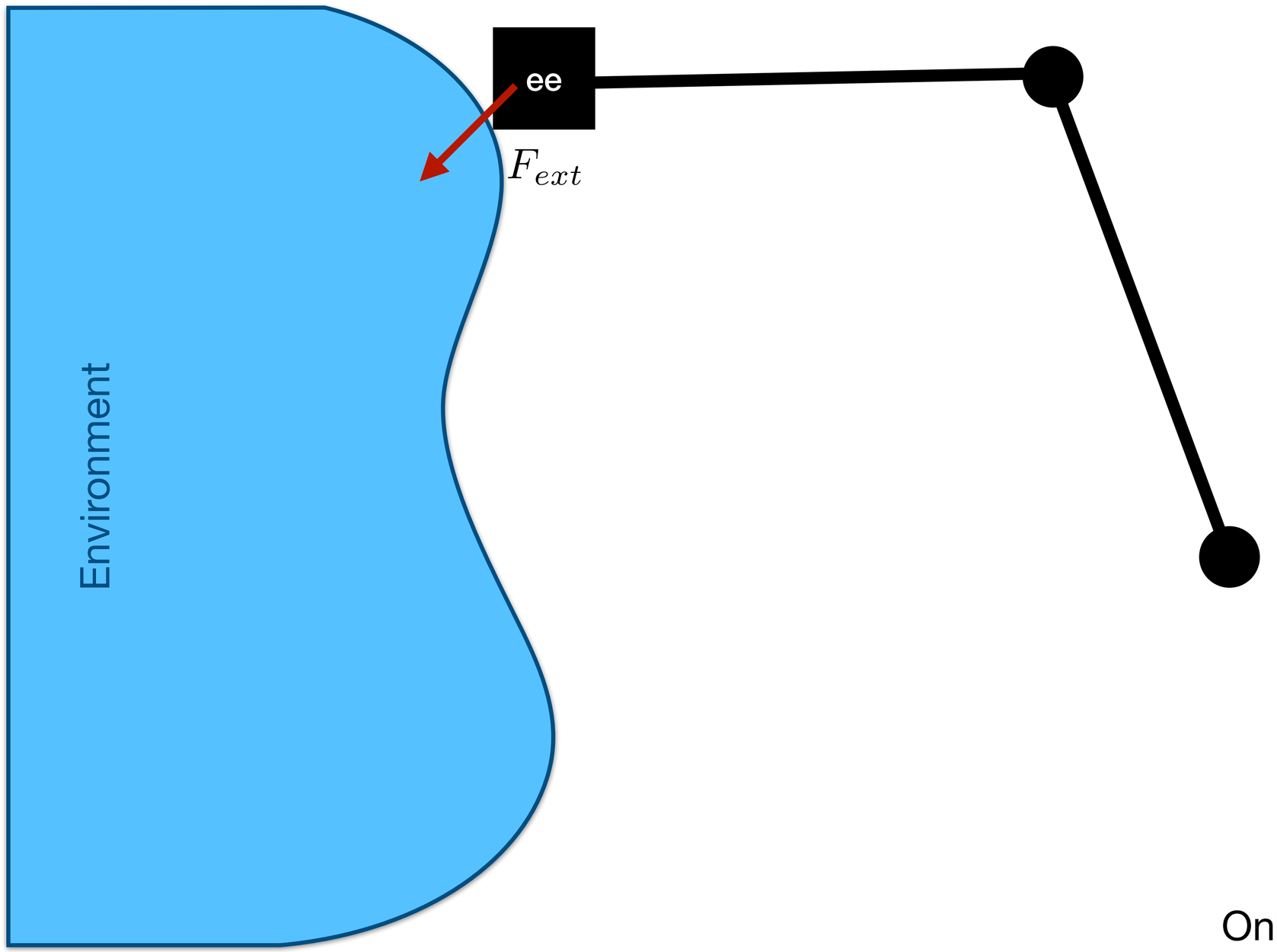


The Problem with Position Control



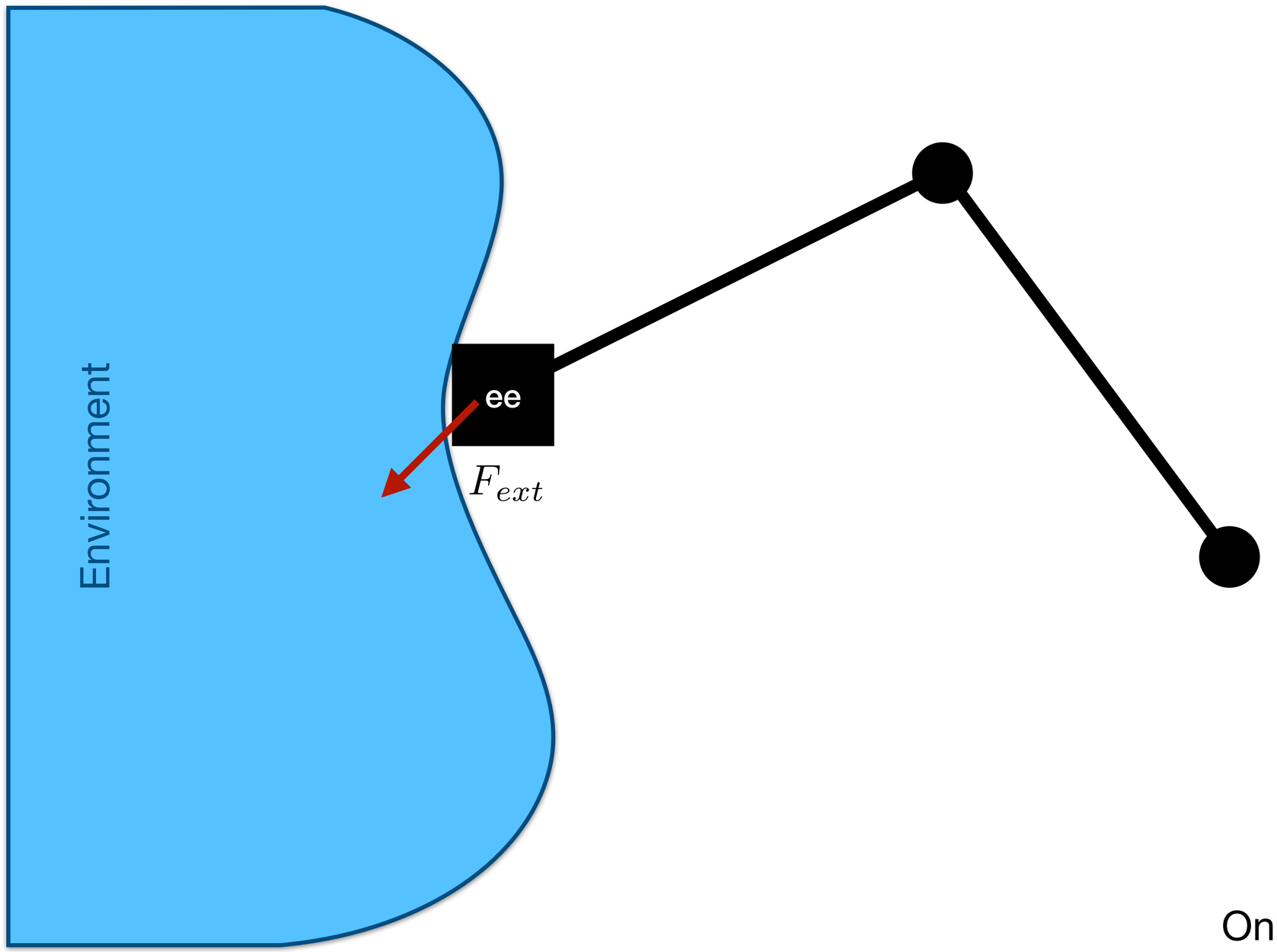
Approach II:
Force Control

Task: Slide over surface



Robot tries to establish and maintain a desired contact force between EE and env.

Only works when contact has already been established!



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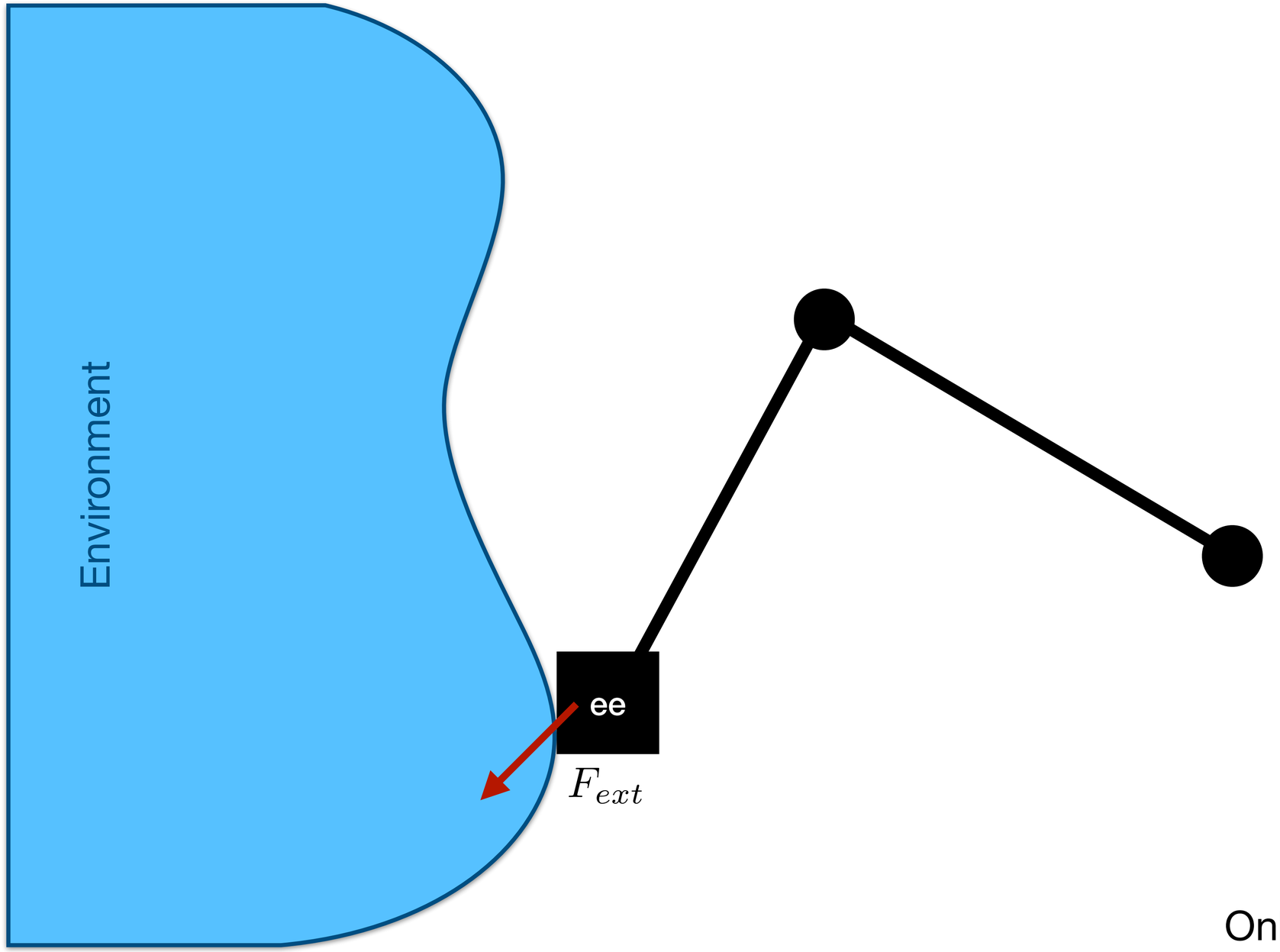

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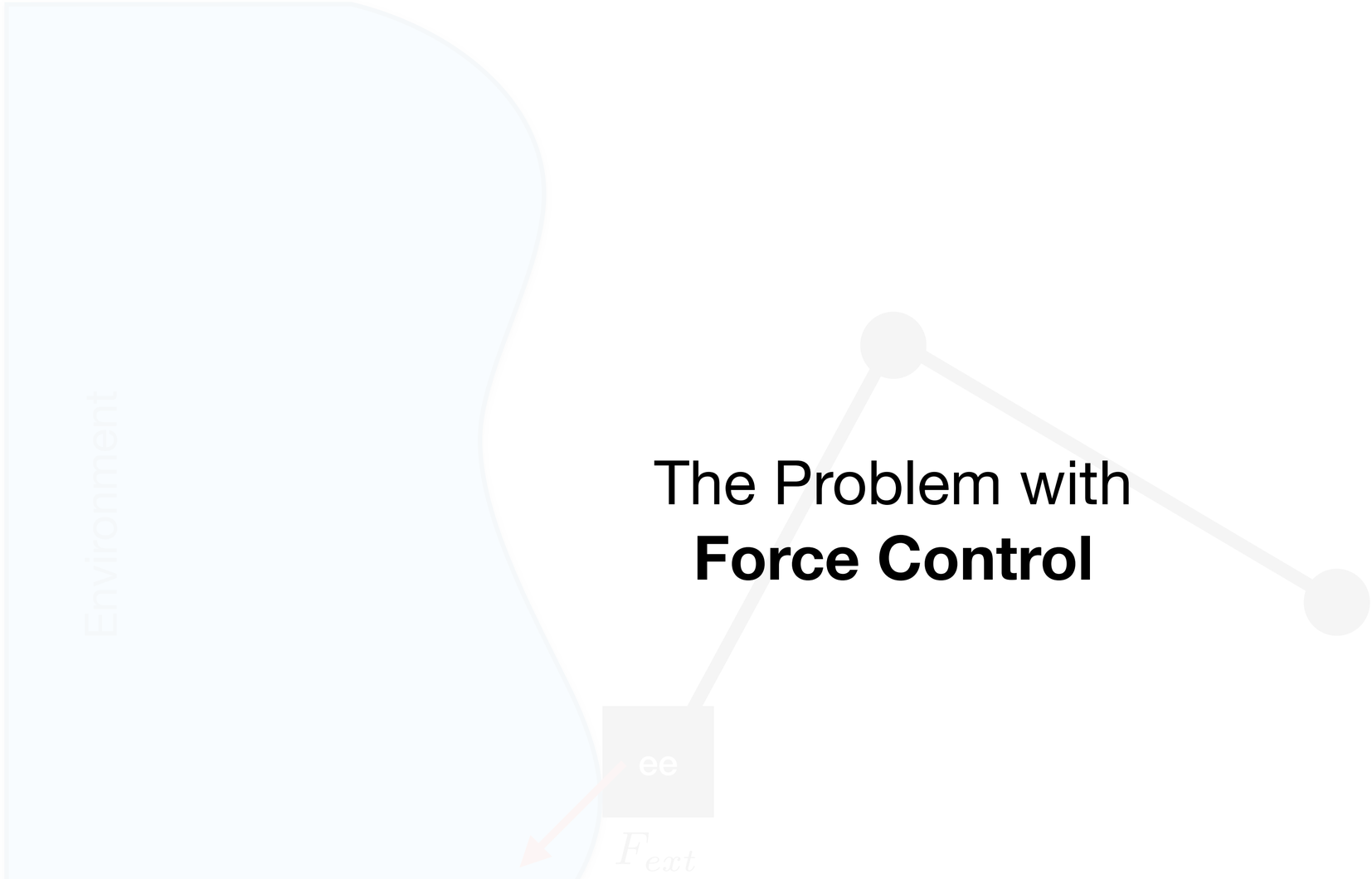
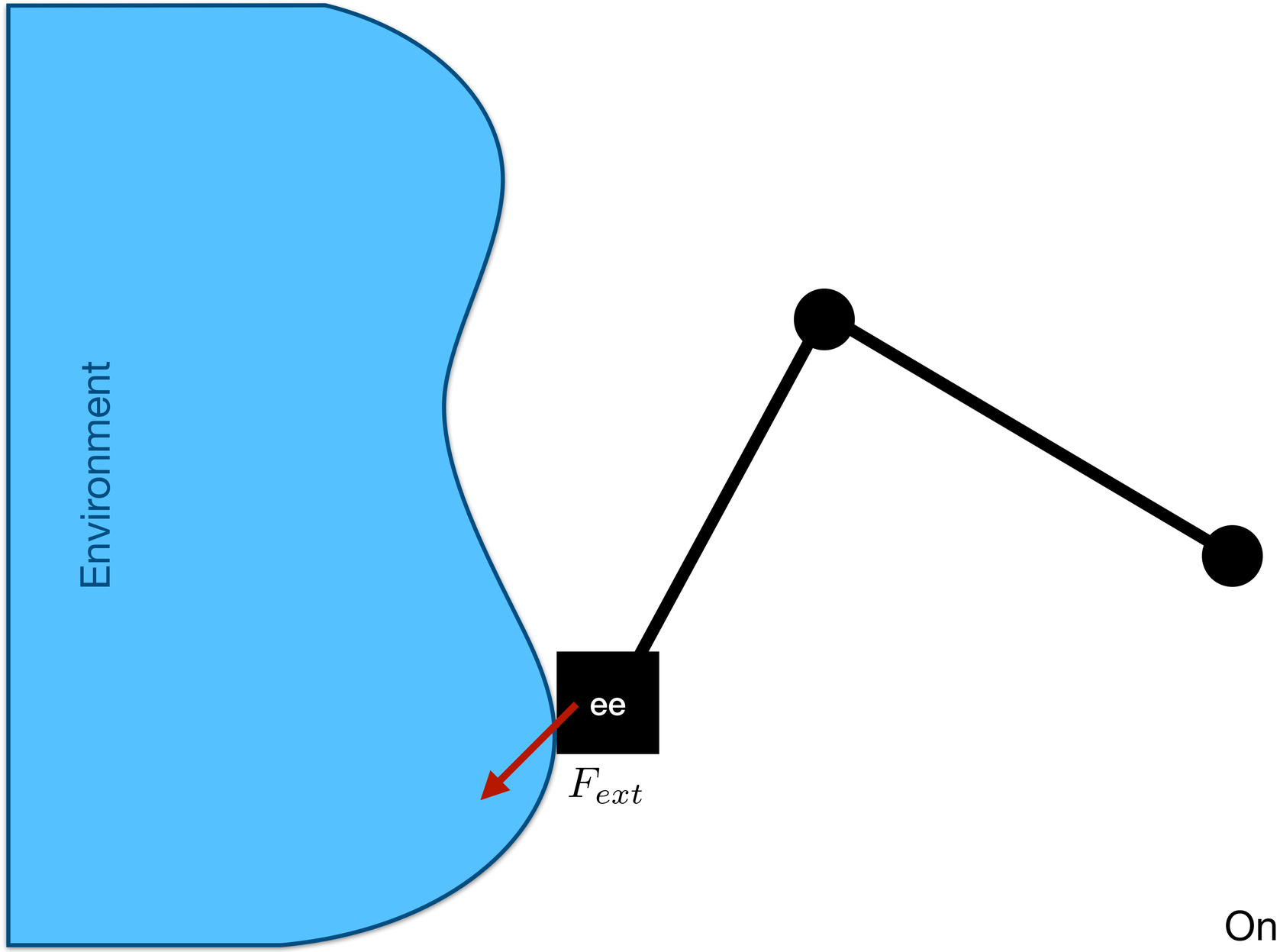


The Problem with **Force Control**

Only works when contact has already been established!

Task: Slide over surface
Approach: Force Control

Robot tries to establish and maintain a desired contact force between EE and env.



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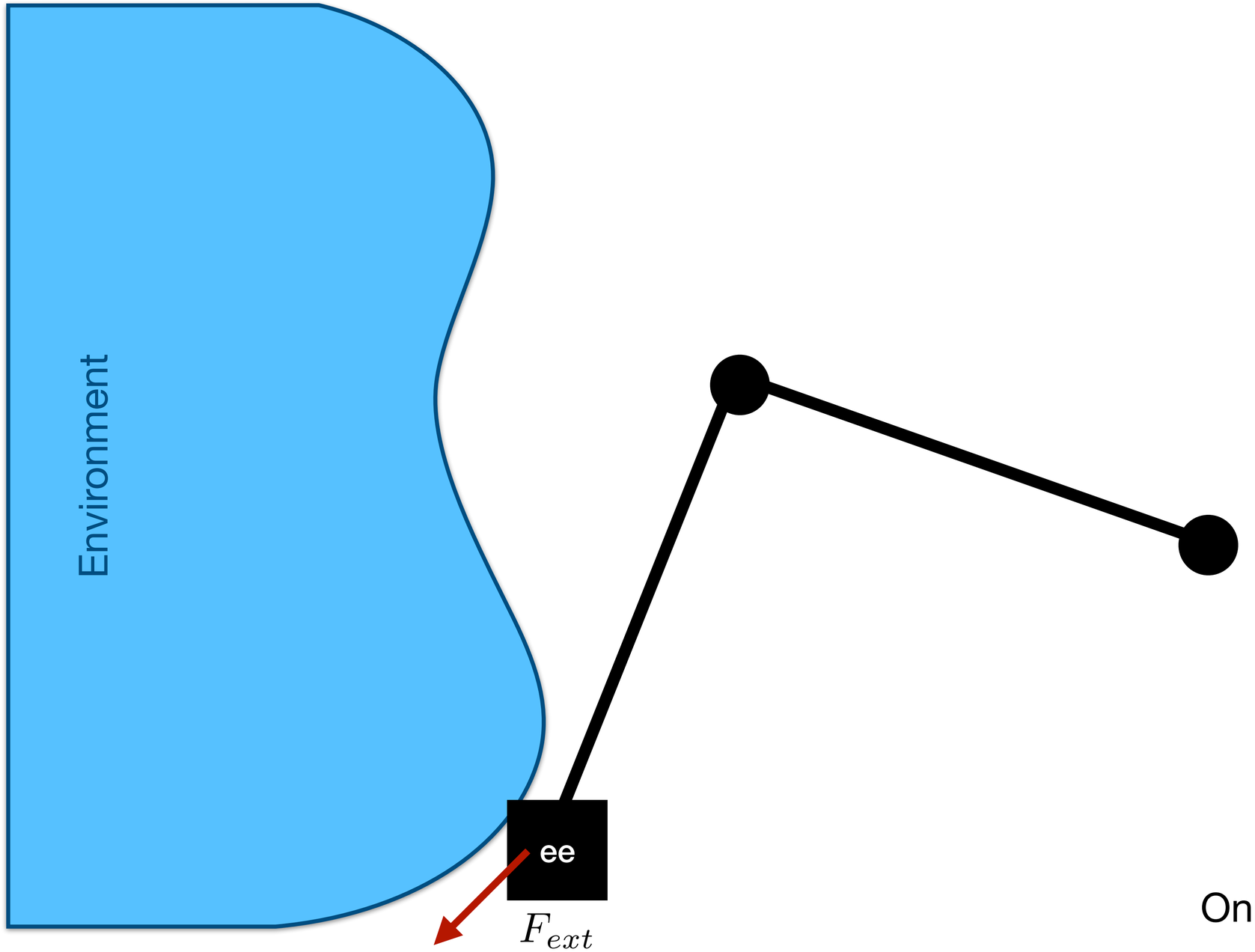

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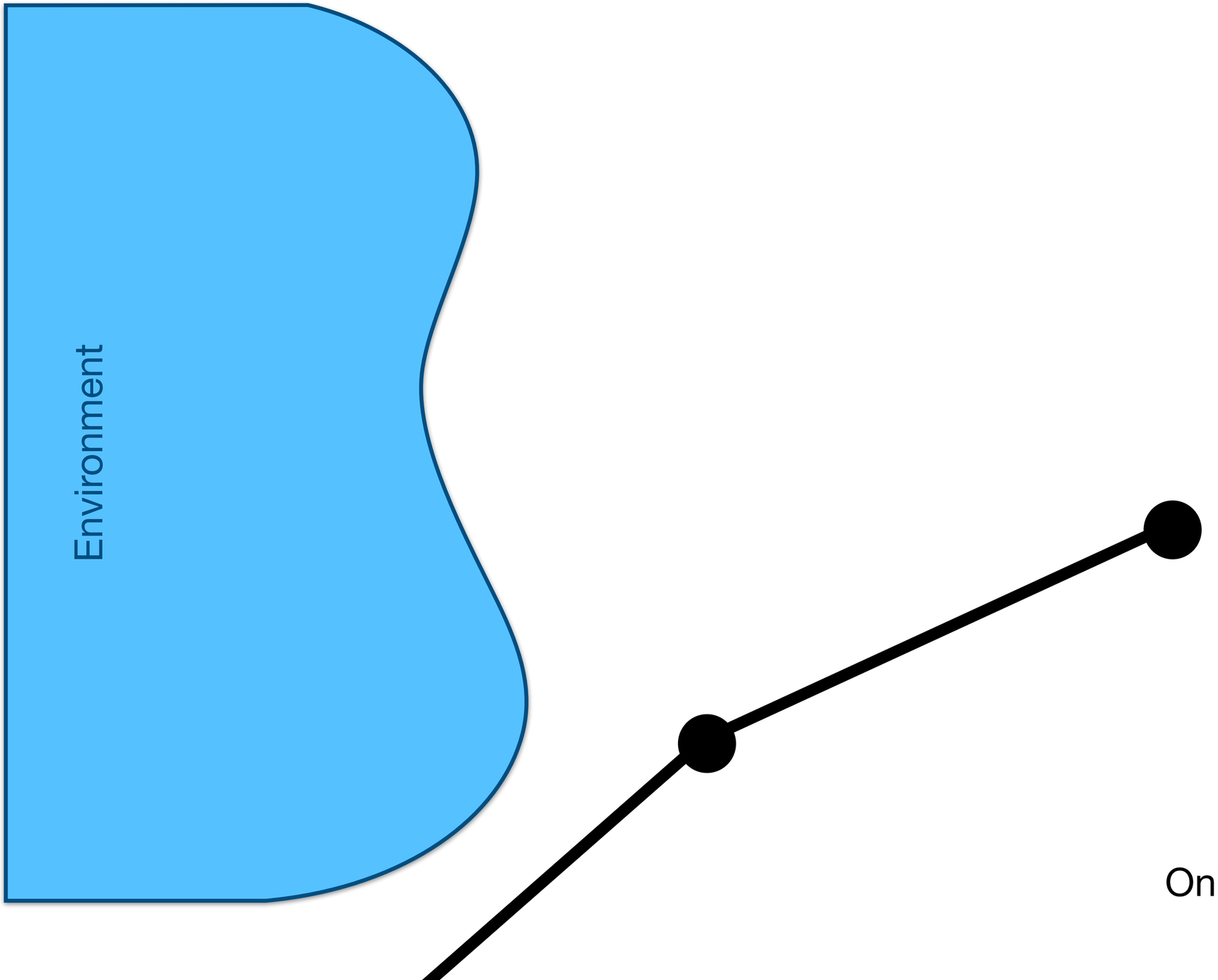

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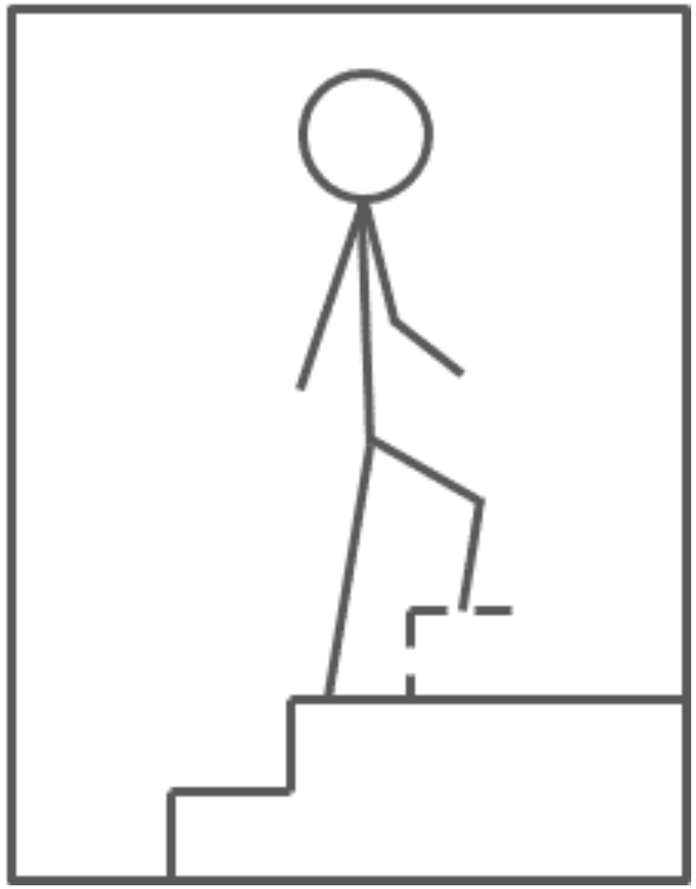

Bad Idea:
Climbing Stairs with Force Control

Approach III:

Hybrid Position/Force Control

Workspace is divided into two subspaces:

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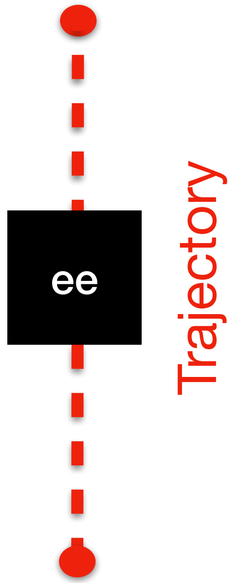
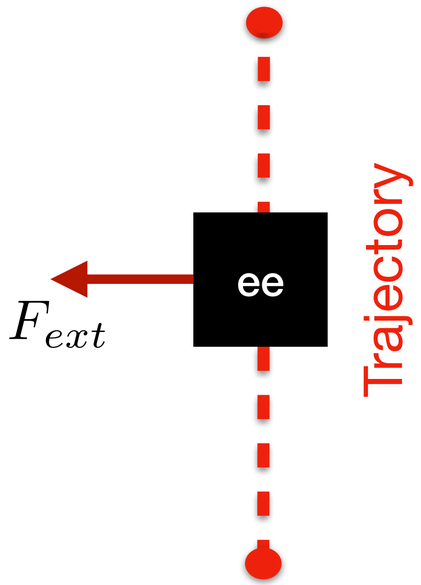
* Subspace for Position Control



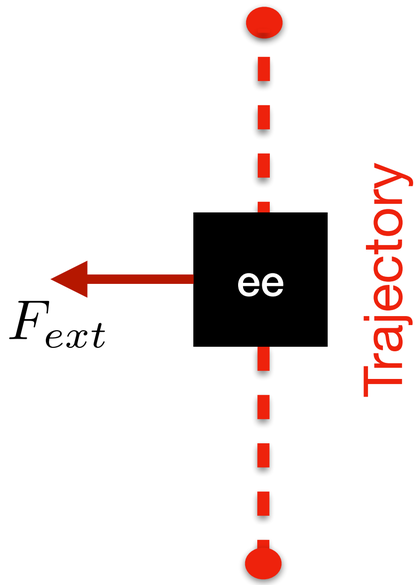
Workspace is divided into two subspaces:

* Subspace for Position Control
* Subspace for Force Control



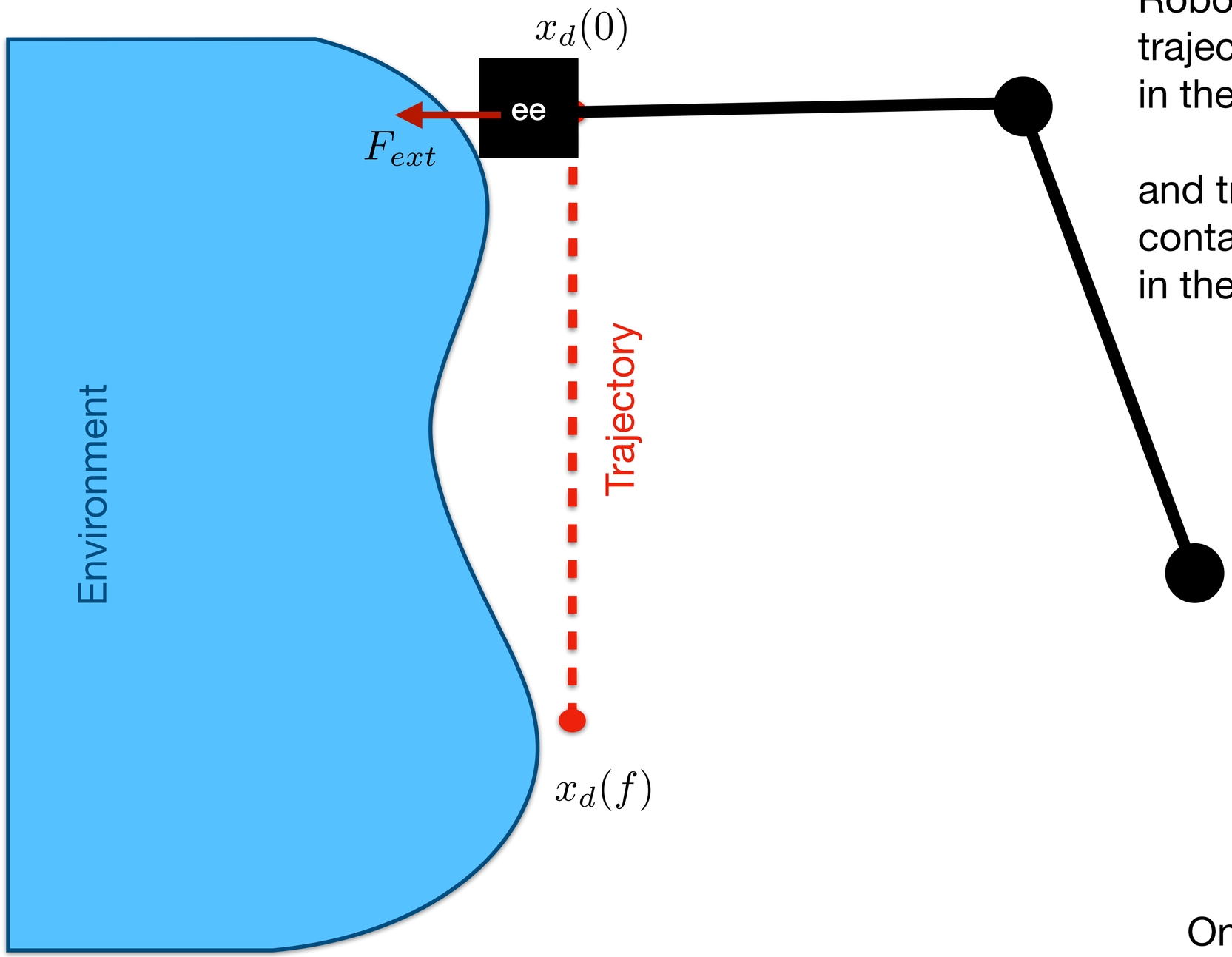
Workspace is divided into two subspaces:

* Subspace for Position Control
* Subspace for Force Control



Robot moves along desired trajectory with high precision in the one subspace

and tries to maintain desired contact force between EE and env in the other subspace.



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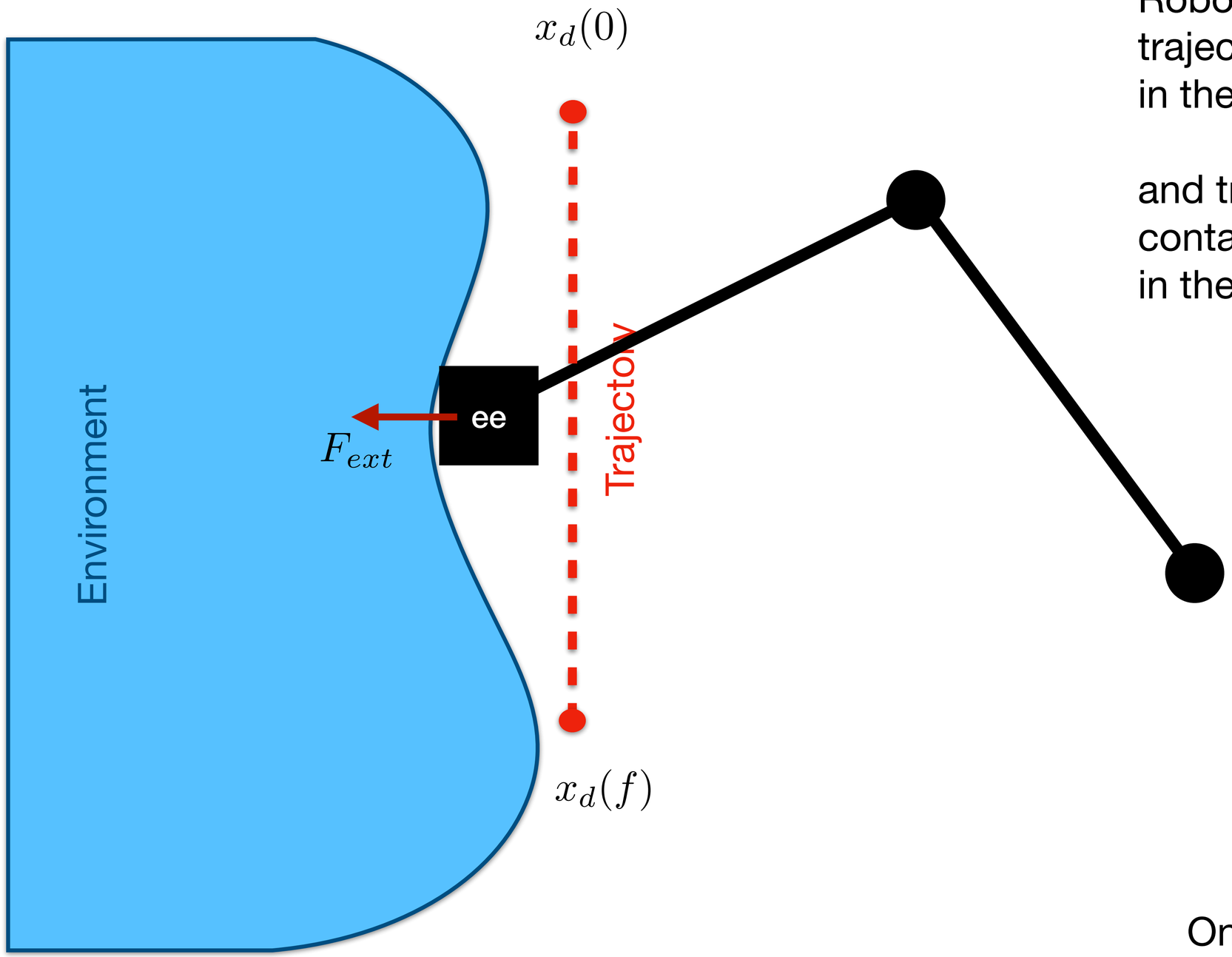

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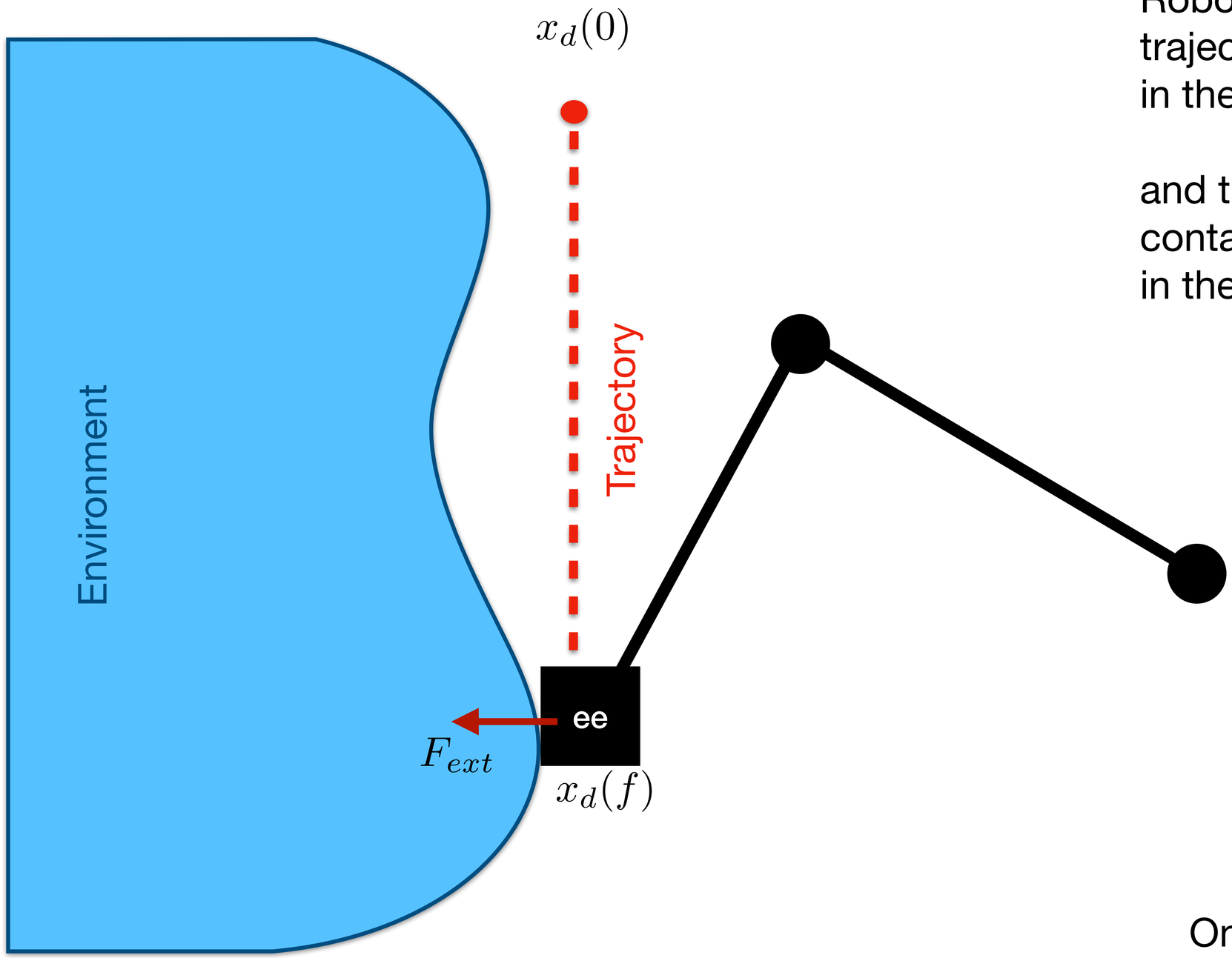

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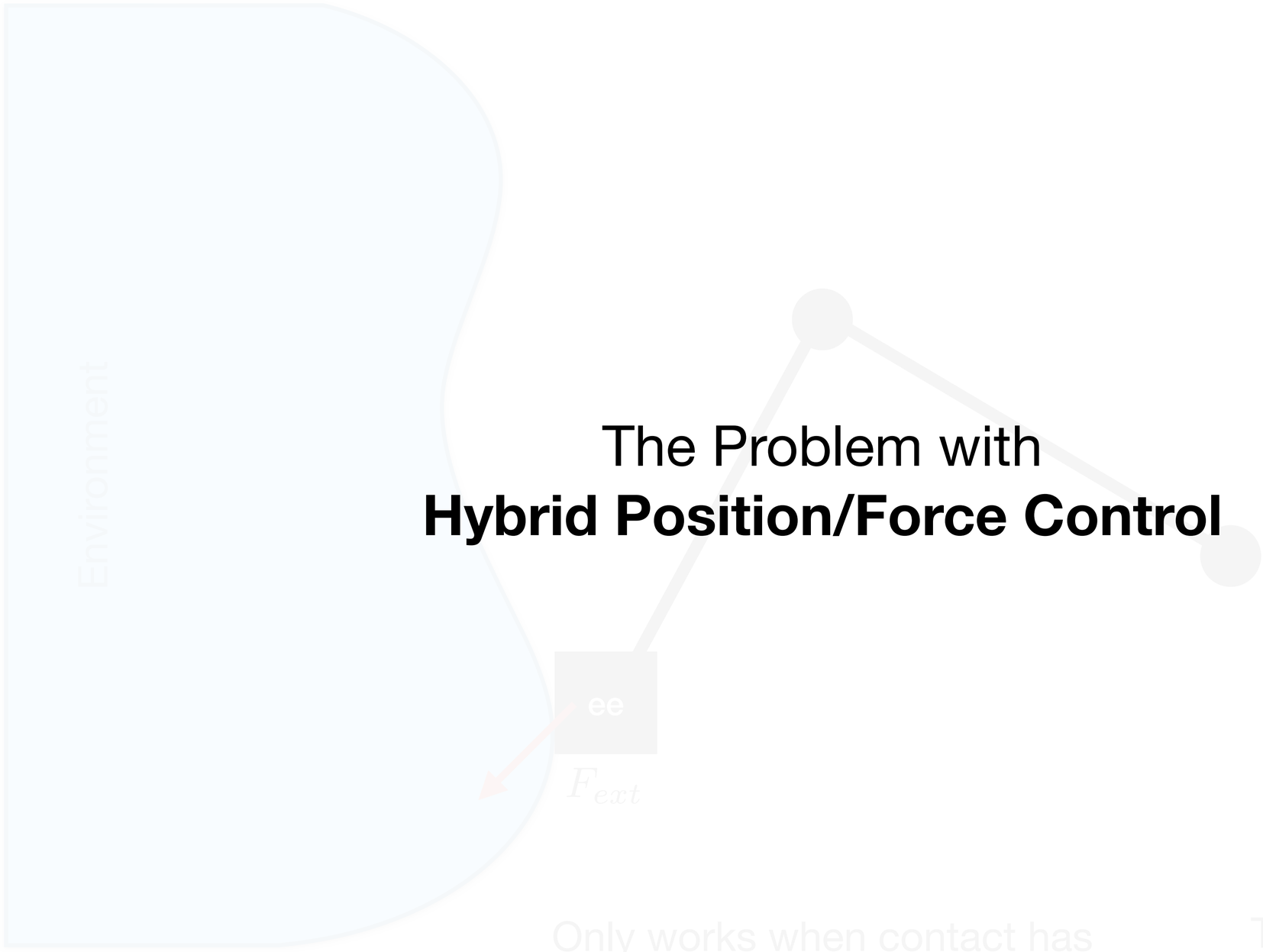
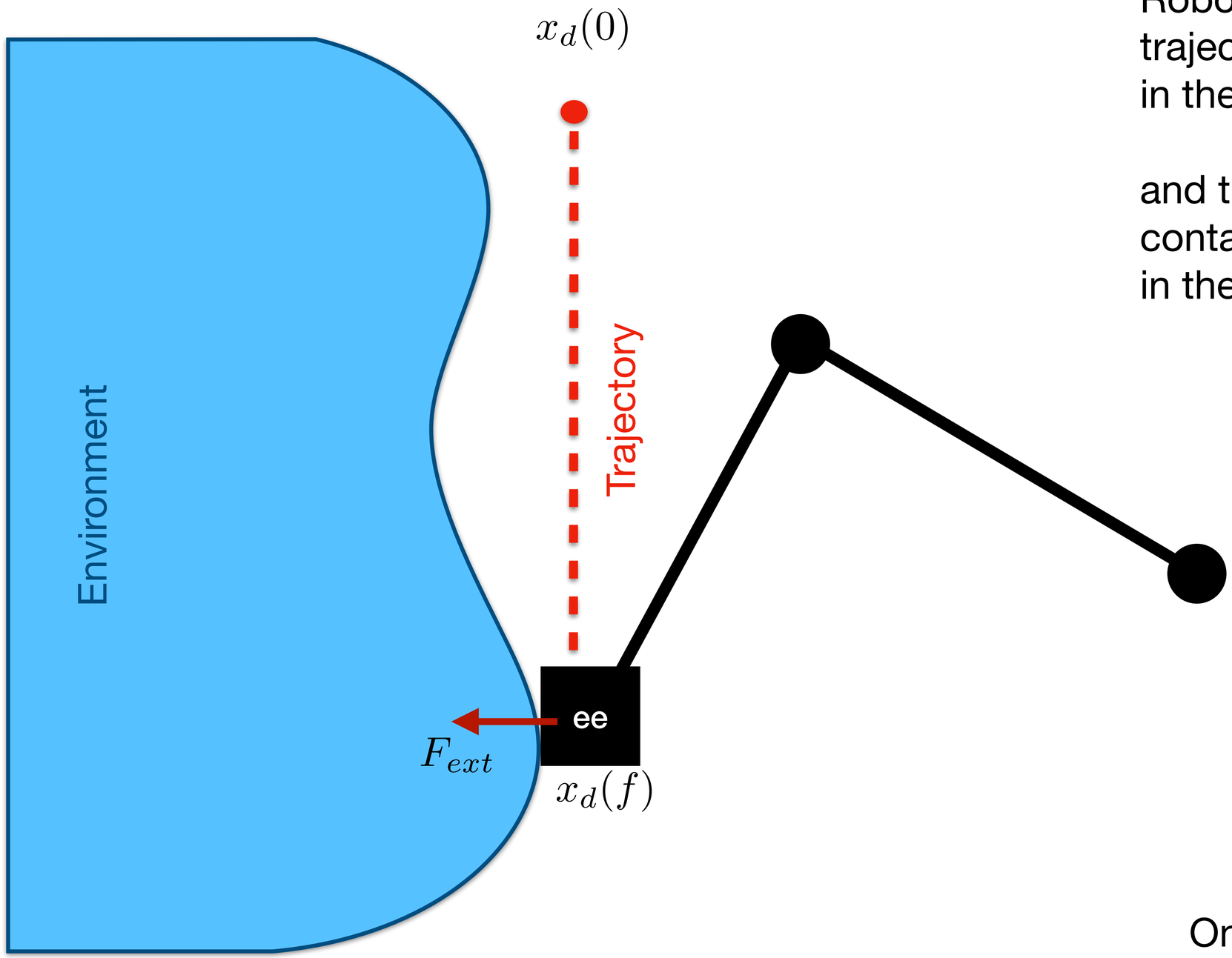


The Problem with **Hybrid Position/Force Control**

Only works when contact has already been established!

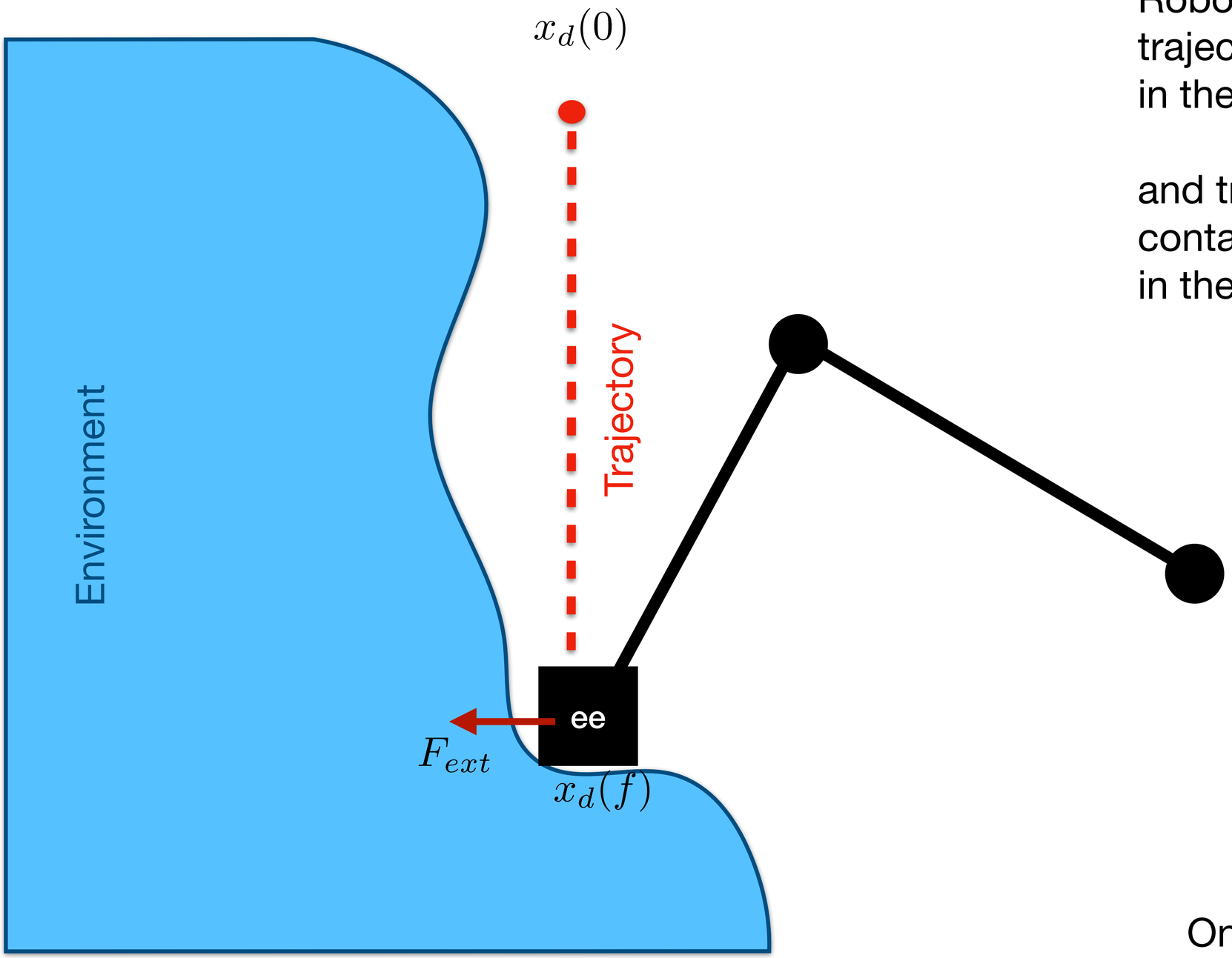
Task: Slide over surface
Approach: Force Control



Robot moves along desired trajectory with high precision in the one subspace

and tries to maintain desired contact force between EE and env in the other subspace.

Only works when contact has already been established!



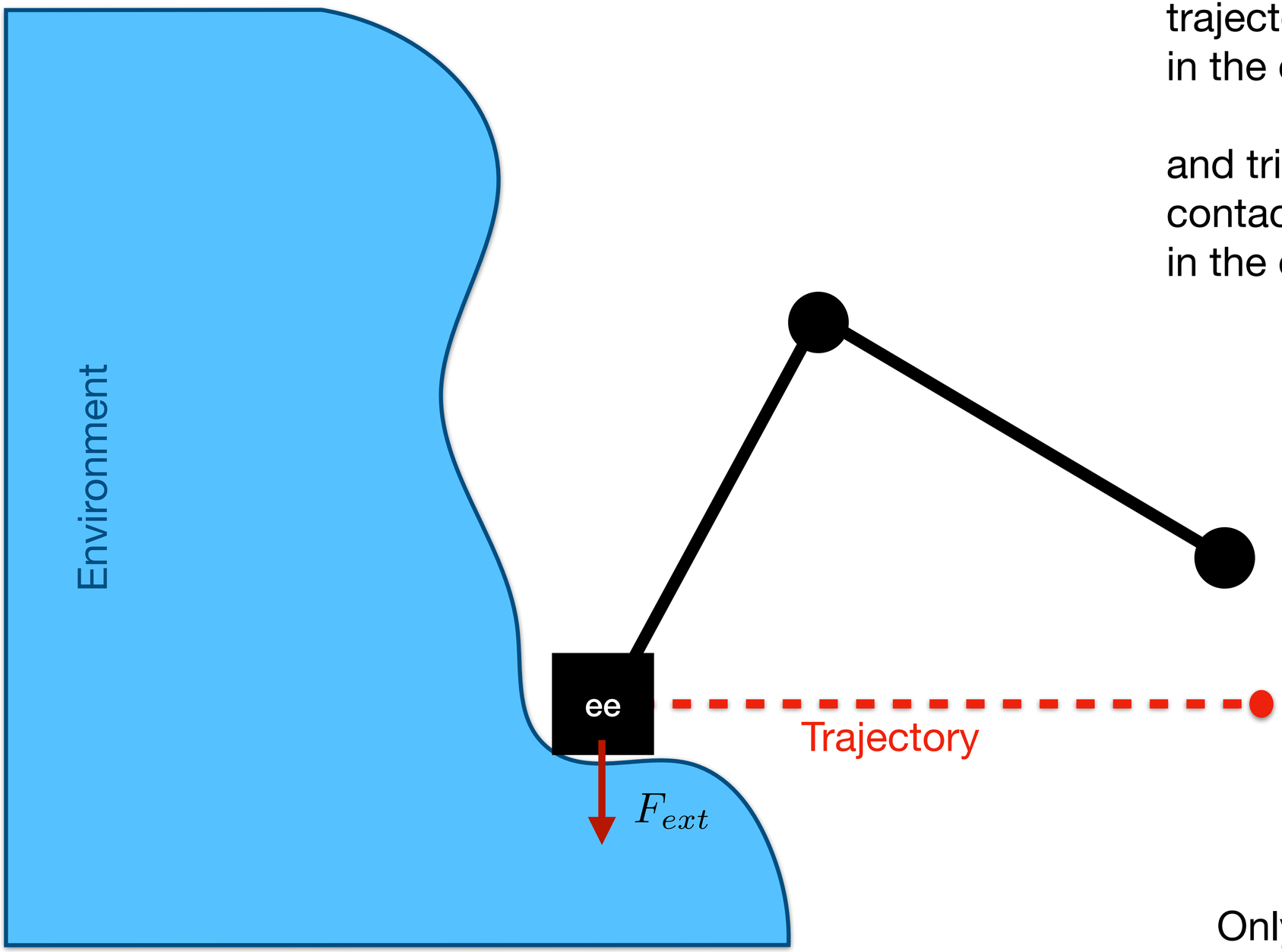
Robot moves along desired trajectory with high precision in the one subspace

and tries to maintain desired contact force between EE and env in the other subspace.

Only works when contact has already been established!

Robot moves along desired trajectory with high precision in the one subspace

and tries to maintain desired contact force between EE and env in the other subspace.



Only works when contact has already been established!

Approach IV:

Impedance Control

Impedance Control

Impedance Control

(Impedance: Measure of how much a structure resists motion)

Impedance Control

(Impedance: Measure of how much a structure resists motion)

$$Z = \frac{F}{\Delta X}$$

Impedance Control

(Impedance: Measure of how much a structure resists motion)

Impedance

$$Z = \frac{F}{\Delta X}$$

Impedance Control

(Impedance: Measure of how much a structure resists motion)

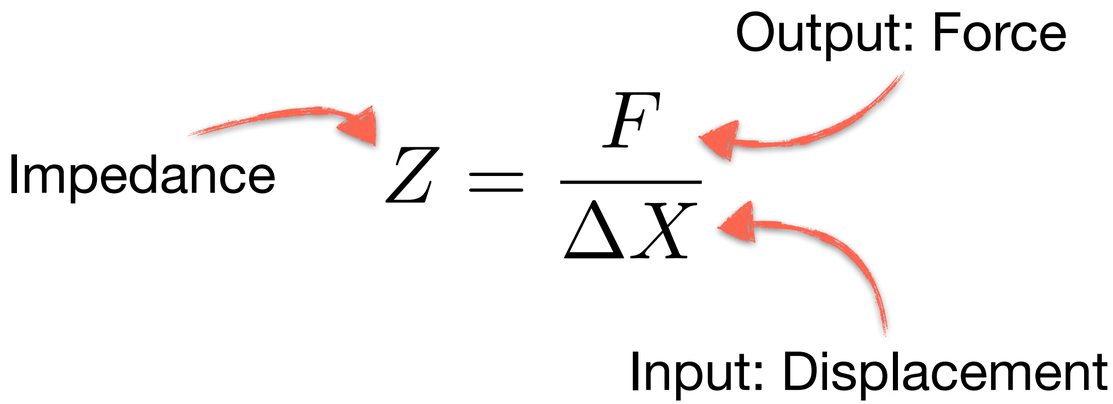
Impedance

$$Z = \frac{F}{\Delta X}$$

Input: Displacement

Impedance Control

(Impedance: Measure of how much a structure resists motion)



Impedance Control

(Impedance: Measure of how much a structure resists motion)

Output: Force

Impedance $Z = \frac{F}{\Delta X}$

Input: Displacement

$$Z^{-1} = \frac{\Delta X}{F}$$

Impedance Control

(Impedance: Measure of how much a structure resists motion)

Output: Force

Impedance $Z = \frac{F}{\Delta X}$

Input: Displacement

Admittance $Z^{-1} = \frac{\Delta X}{F}$

Impedance Control

(Impedance: Measure of how much a structure resists motion)

Impedance

$$Z = \frac{F}{\Delta X}$$

Output: Force

Input: Displacement

Admittance

$$Z^{-1} = \frac{\Delta X}{F}$$

Output: Displacement

Impedance Control

(Impedance: Measure of how much a structure resists motion)

Impedance

$$Z = \frac{F}{\Delta X}$$

Output: Force

Input: Displacement

Admittance

$$Z^{-1} = \frac{\Delta X}{F}$$

Output: Displacement

Input: Force

Impedance Control

(Impedance: Measure of how much a structure resists motion)

Impedance

$$Z = \frac{F}{\Delta X}$$

Output: Force

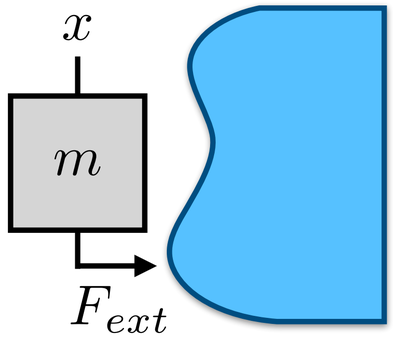
Input: Displacement

Admittance

$$Z^{-1} = \frac{\Delta X}{F}$$

Output: Displacement

Input: Force



Impedance Control

(Impedance: Measure of how much a structure resists motion)

Impedance

$$Z = \frac{F}{\Delta X}$$

Output: Force

Input: Displacement

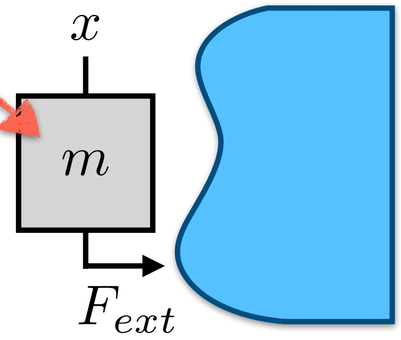
Admittance

$$Z^{-1} = \frac{\Delta X}{F}$$

Output: Displacement

Input: Force

Impedance



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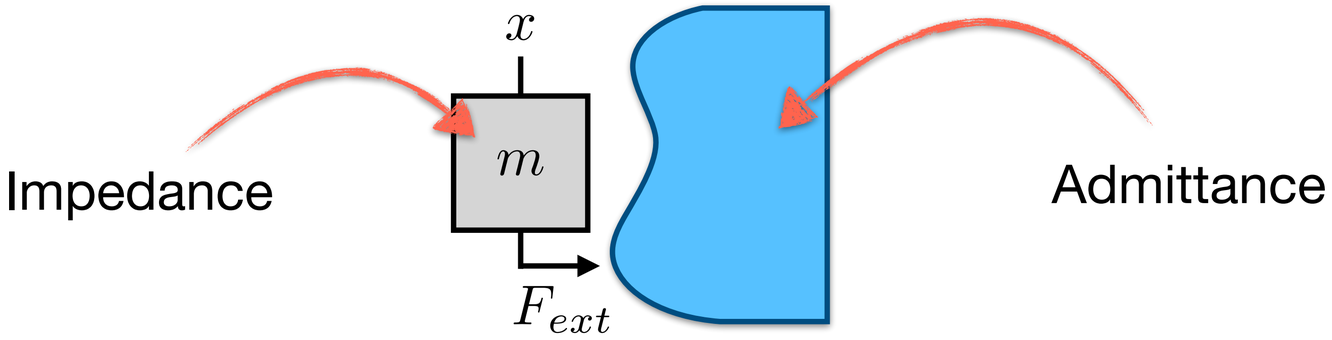

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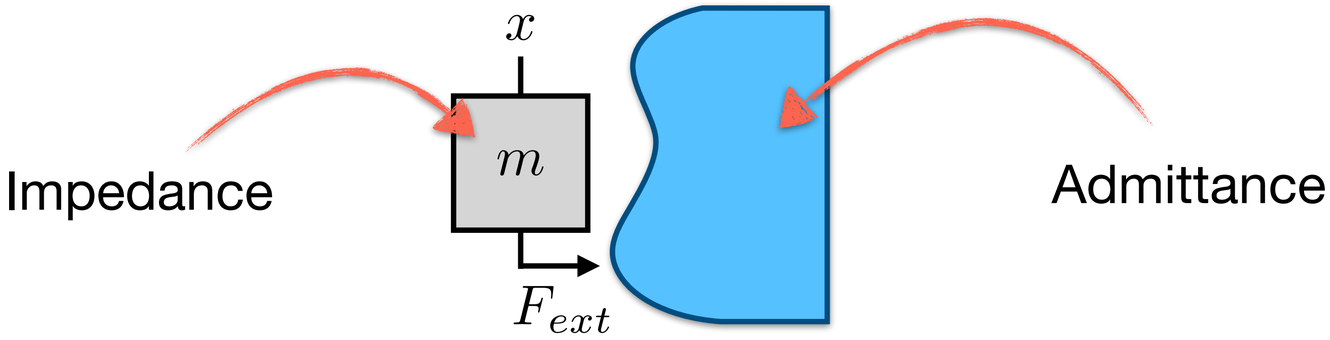

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Admittance

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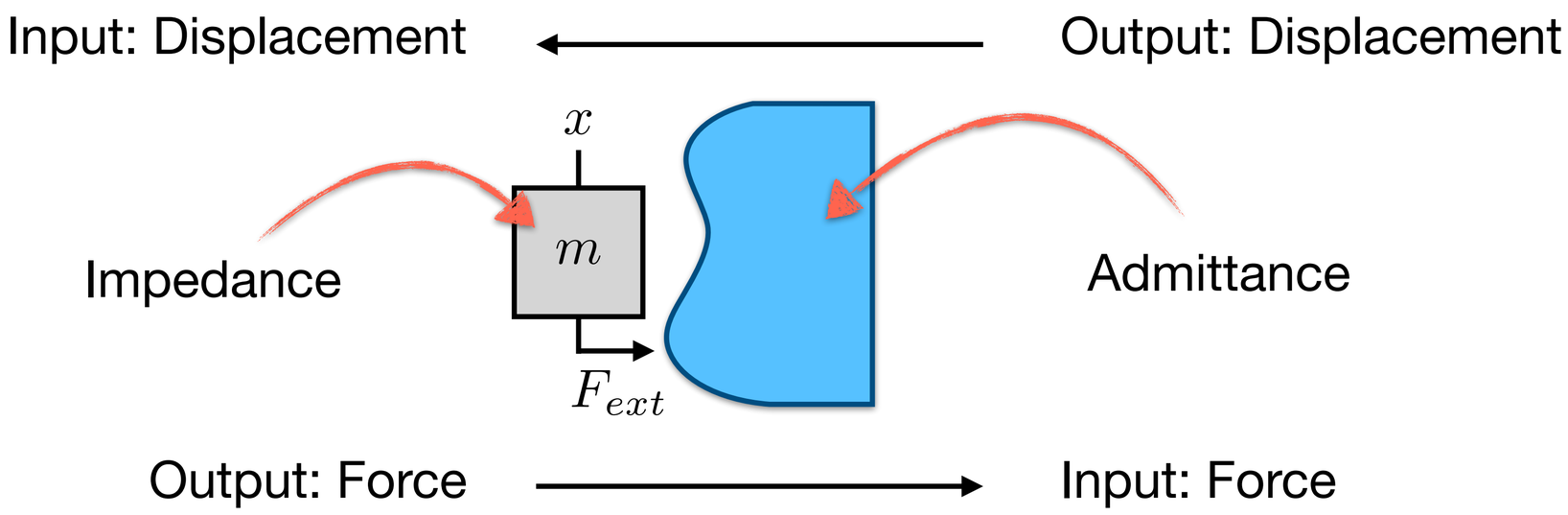

How to model impedance?

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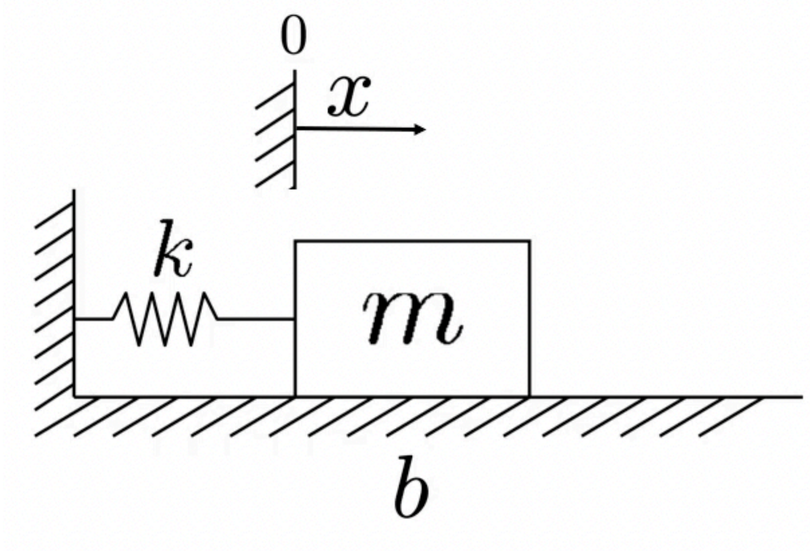

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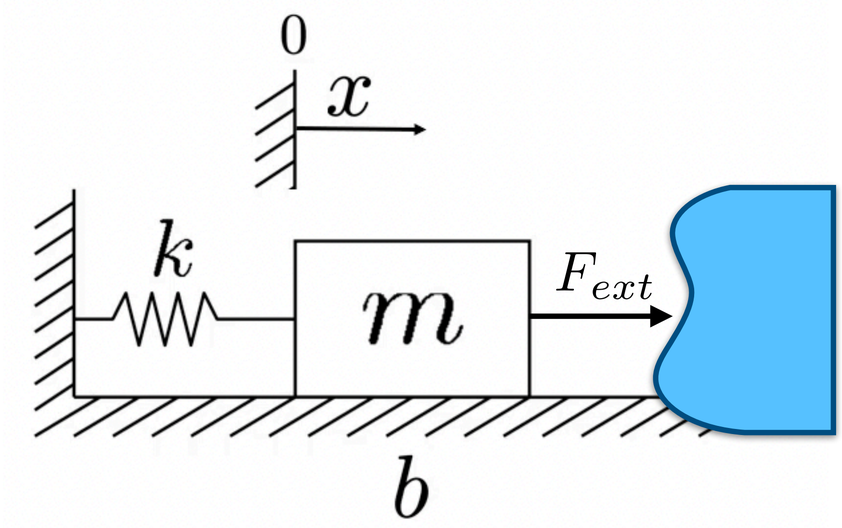
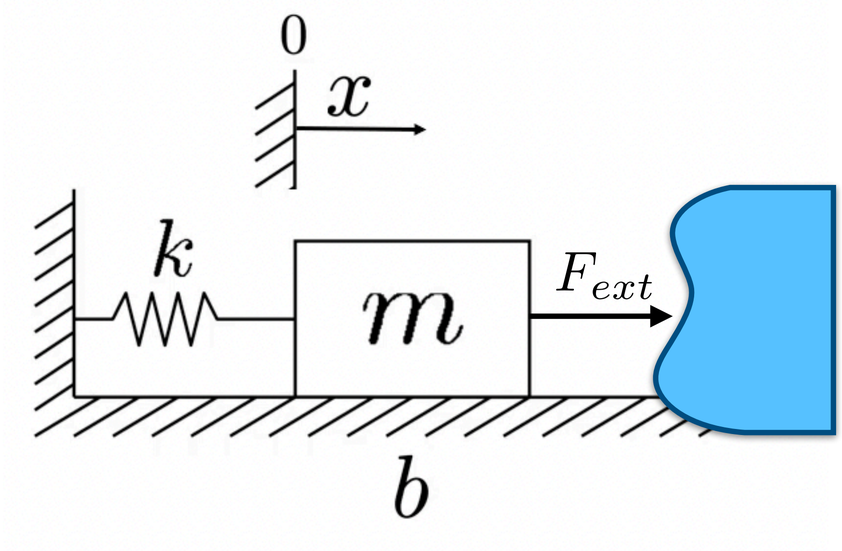


How to model impedance?

$$f_{ext} = m\ddot{x} + b\dot{x} + kx$$

$$Z = \frac{F}{\Delta X}$$



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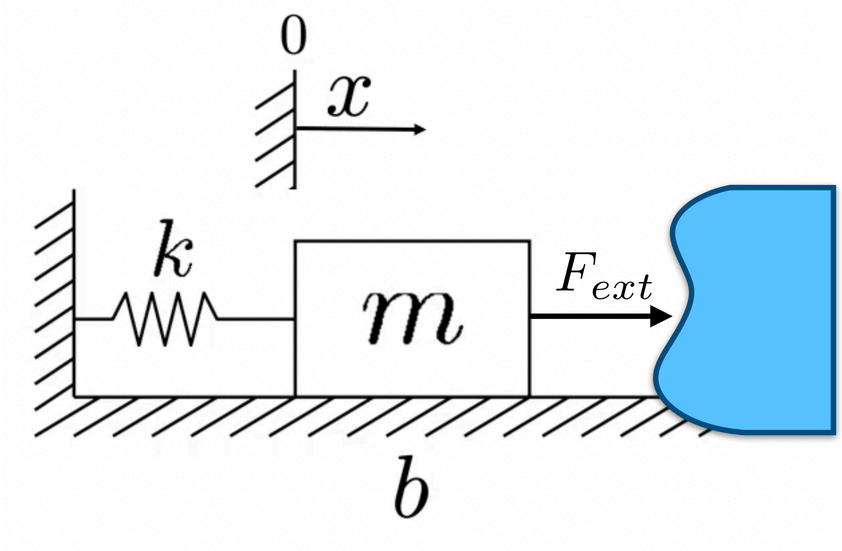

$$m\ddot{x} = -kx - b\dot{x} + f_{ext}$$

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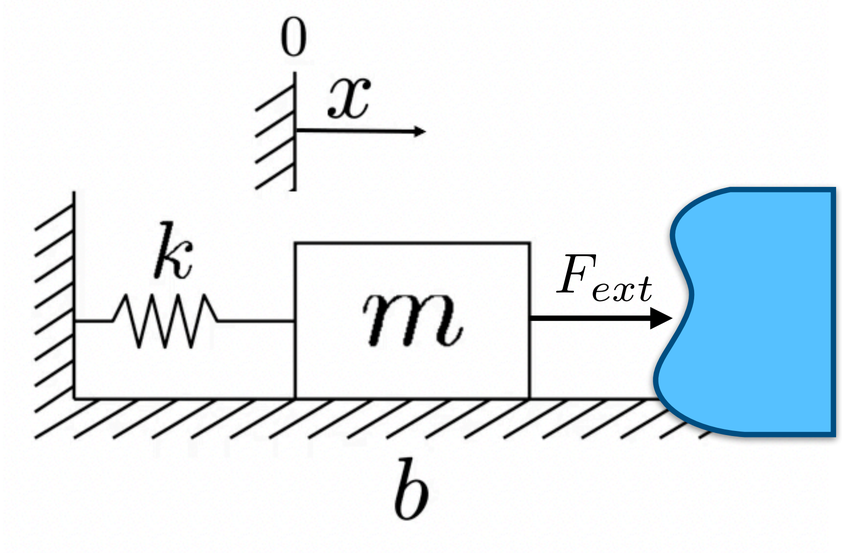

$$m\ddot{x} = -kx - b\dot{x} + f_{ext}$$

$$m(\ddot{x} - \ddot{x}_d) = -k(x - x_d) - b(\dot{x} - \dot{x}_d) + f_{ext}$$

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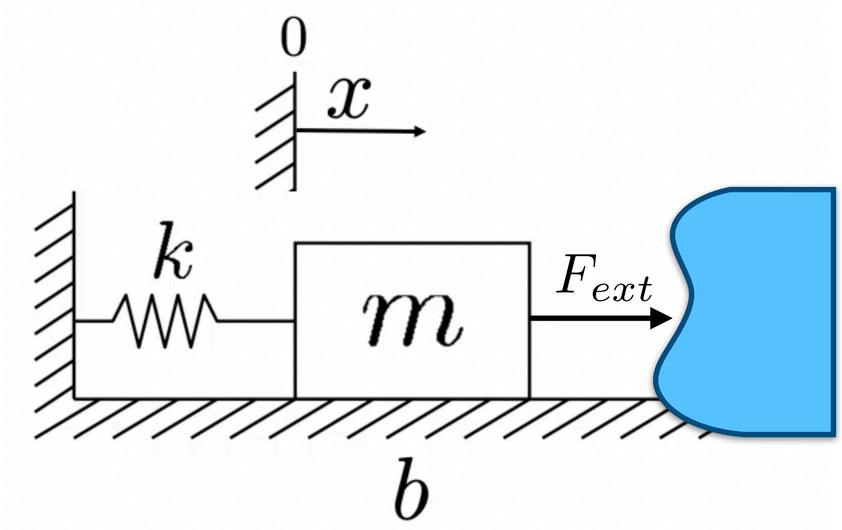

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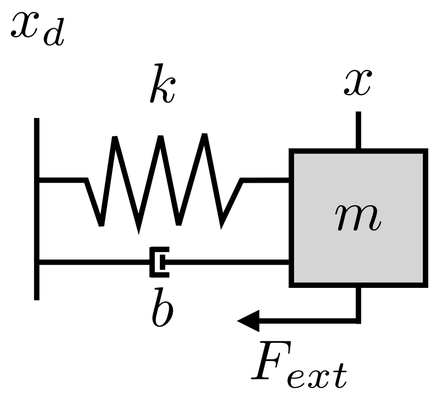
$$m(\ddot{x} - \ddot{x}_d) + b(\dot{x} - \dot{x}_d) + k(x - x_d) = +f_{ext}$$

Spring-Mass-Damper System revisited



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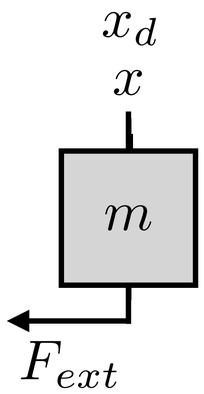
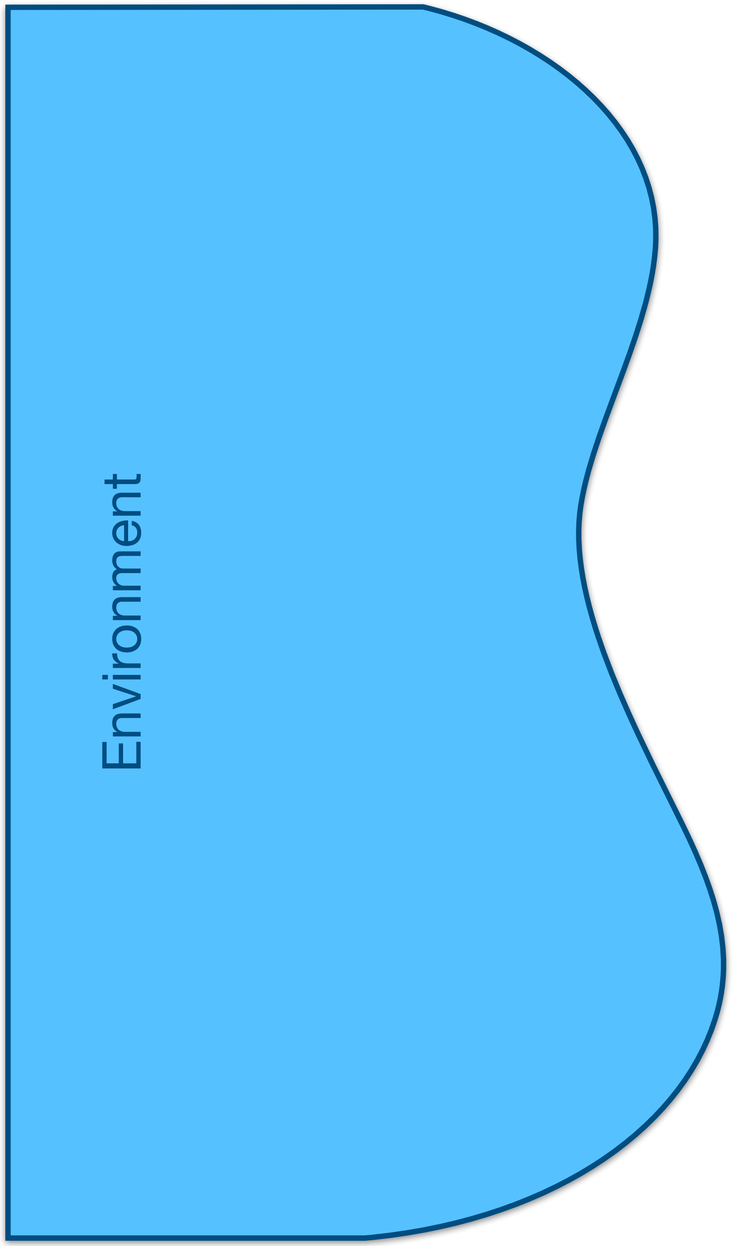
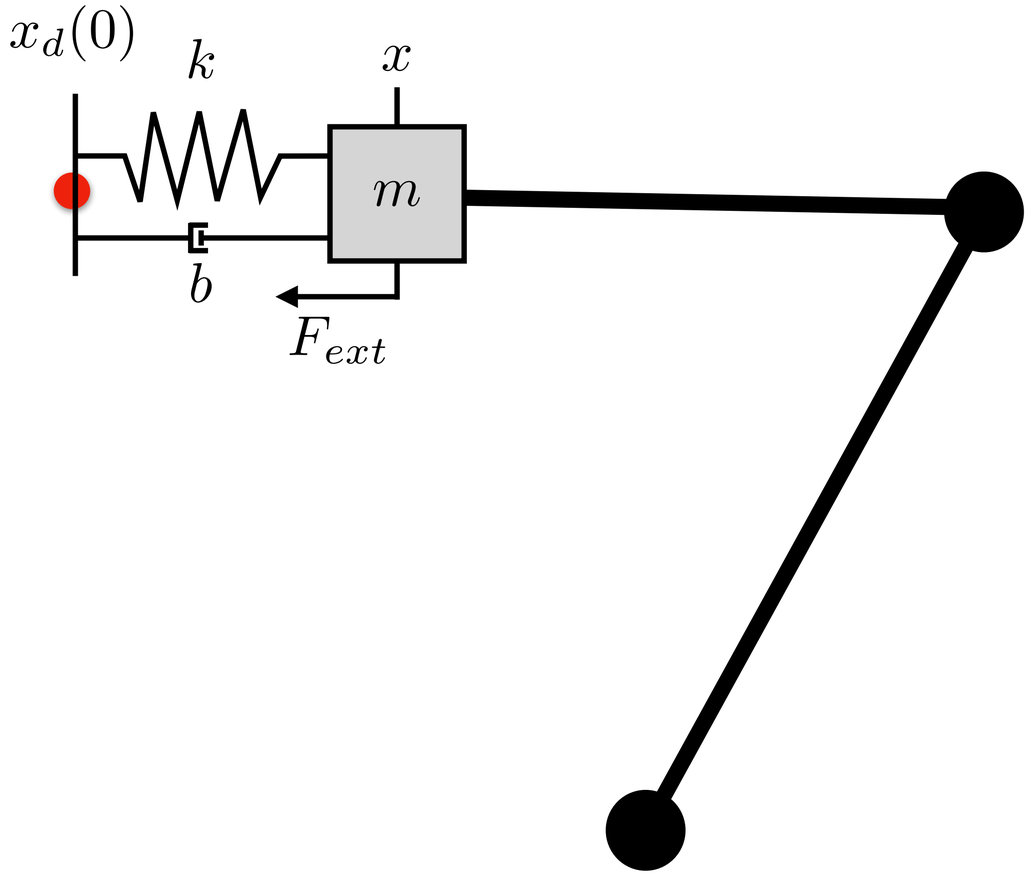
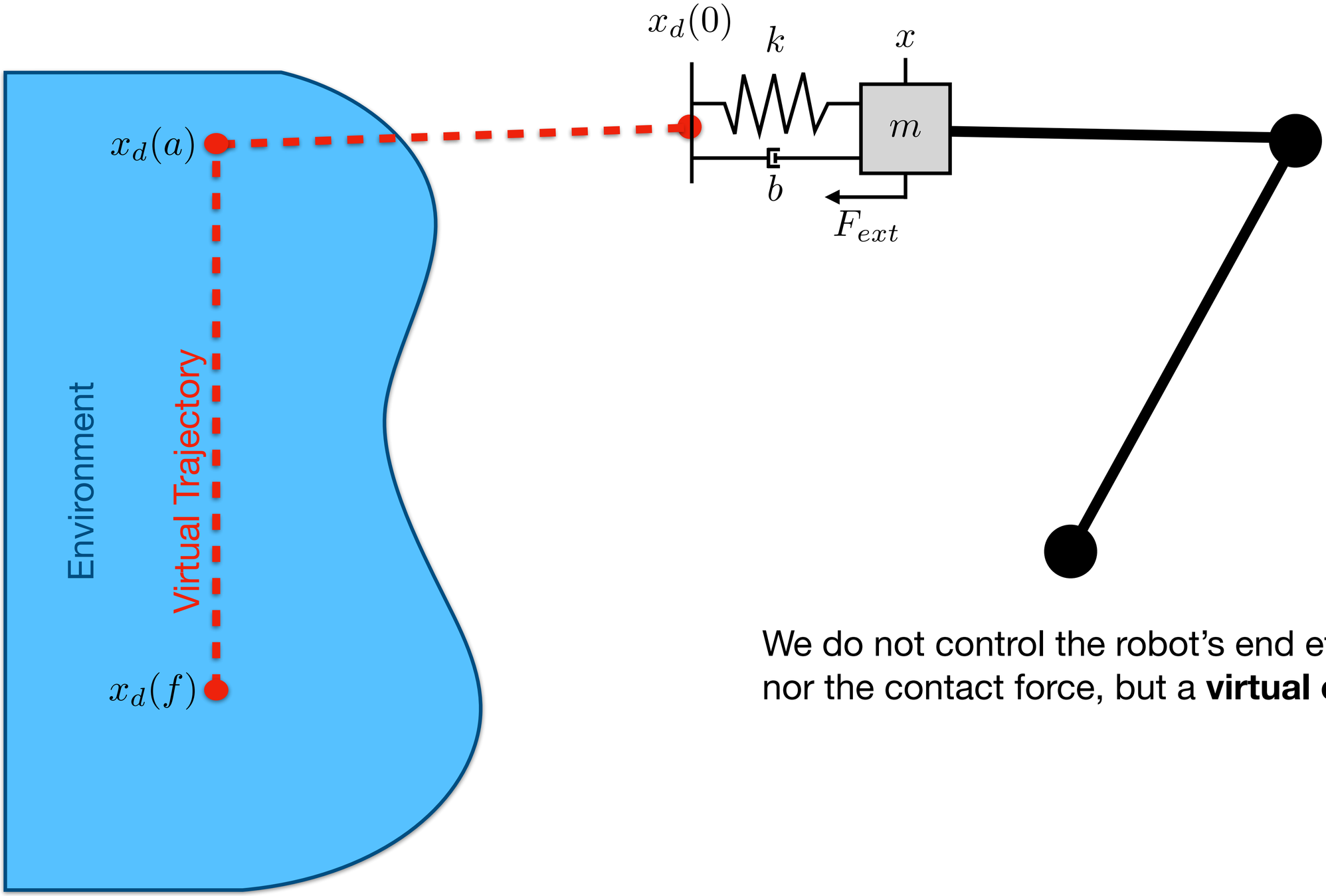


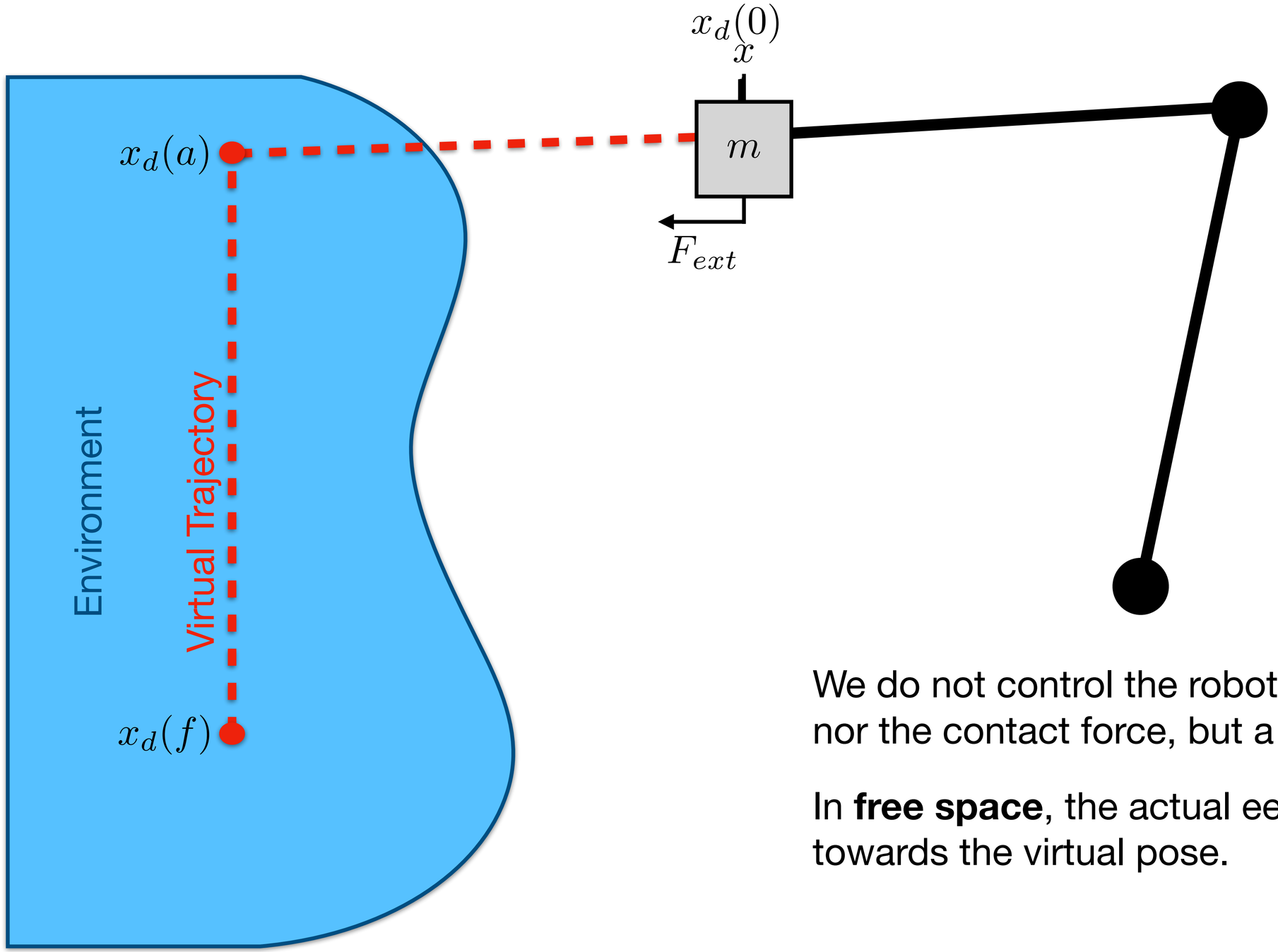
In free space (without contact), the end effector
reaches the desired position and no forces are exerted


Environment


$x_d(0)$
k
x
m
b
F_{ext}



We do not control the robot's end effector pose, nor the contact force, but a **virtual ee pose**.



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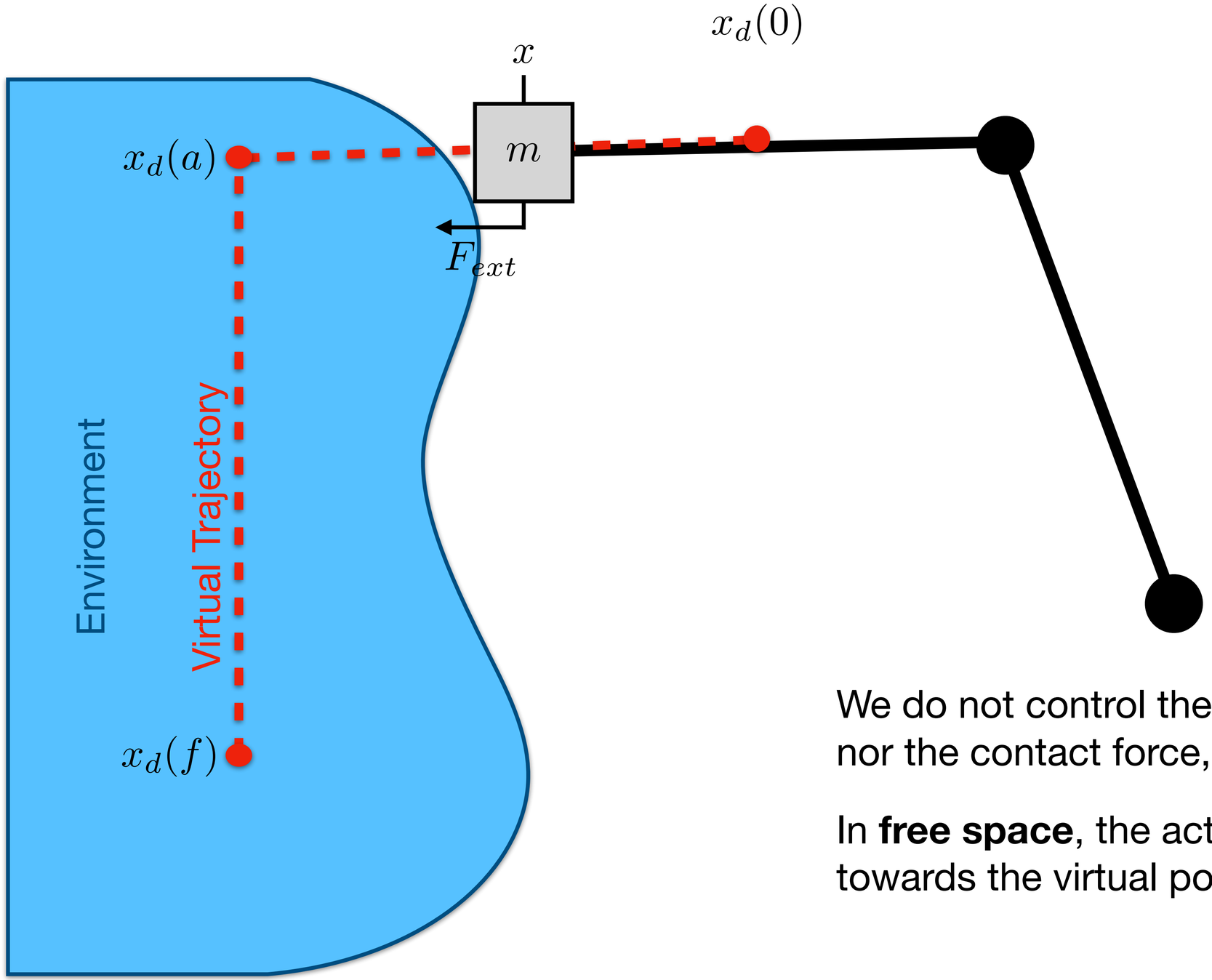

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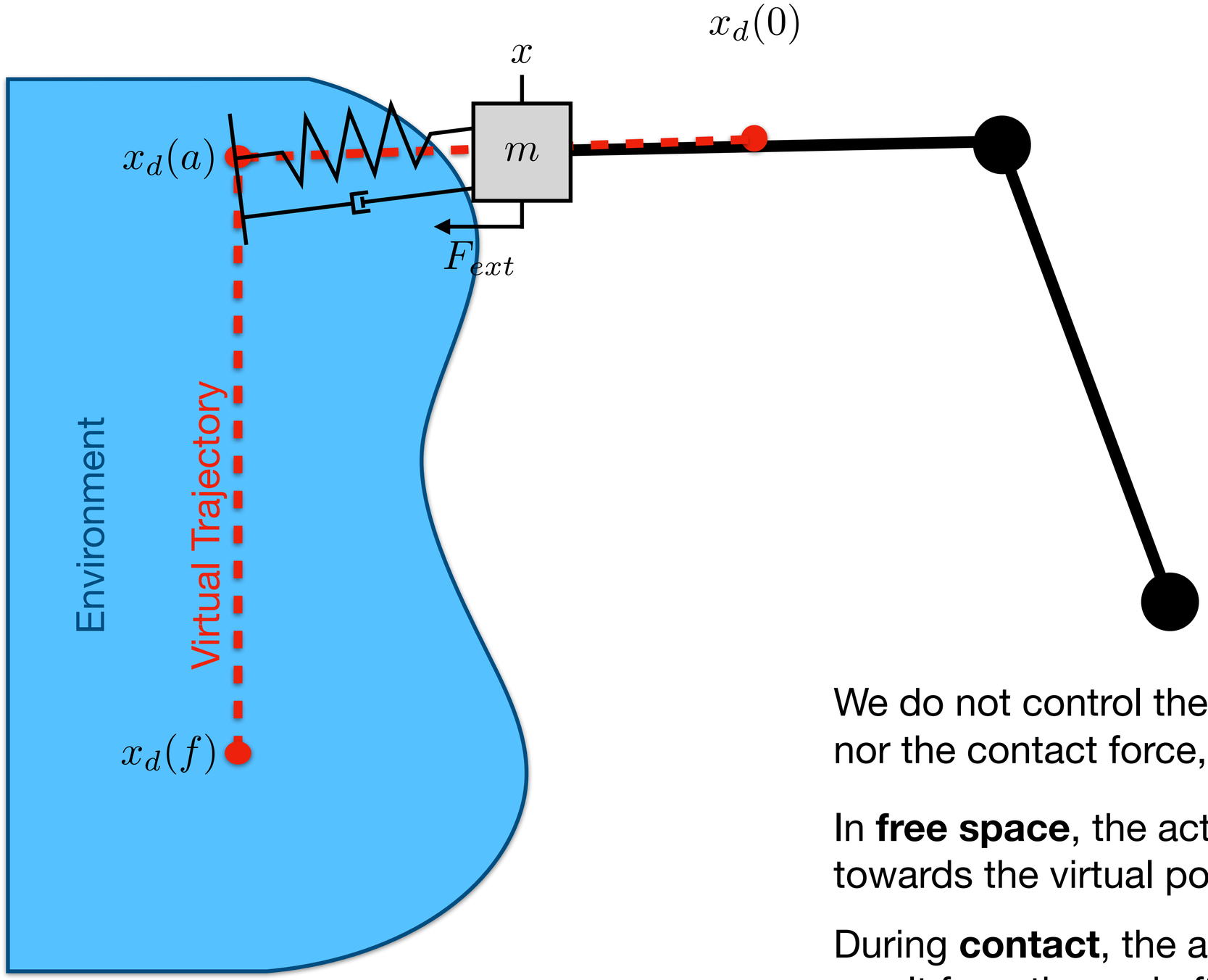

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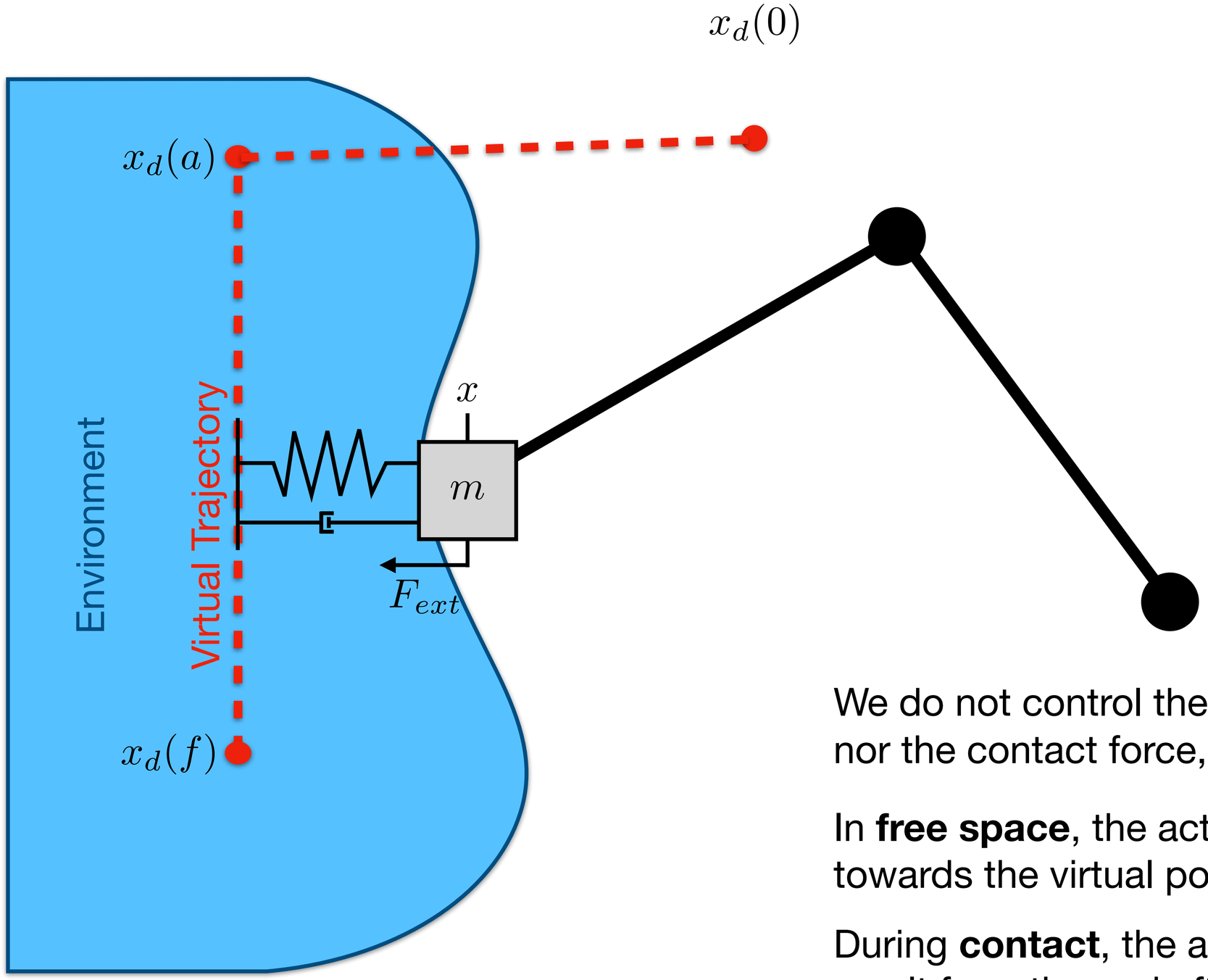
During **contact**, the actual ee pose and forces result from the end effector's impedance (SMD)



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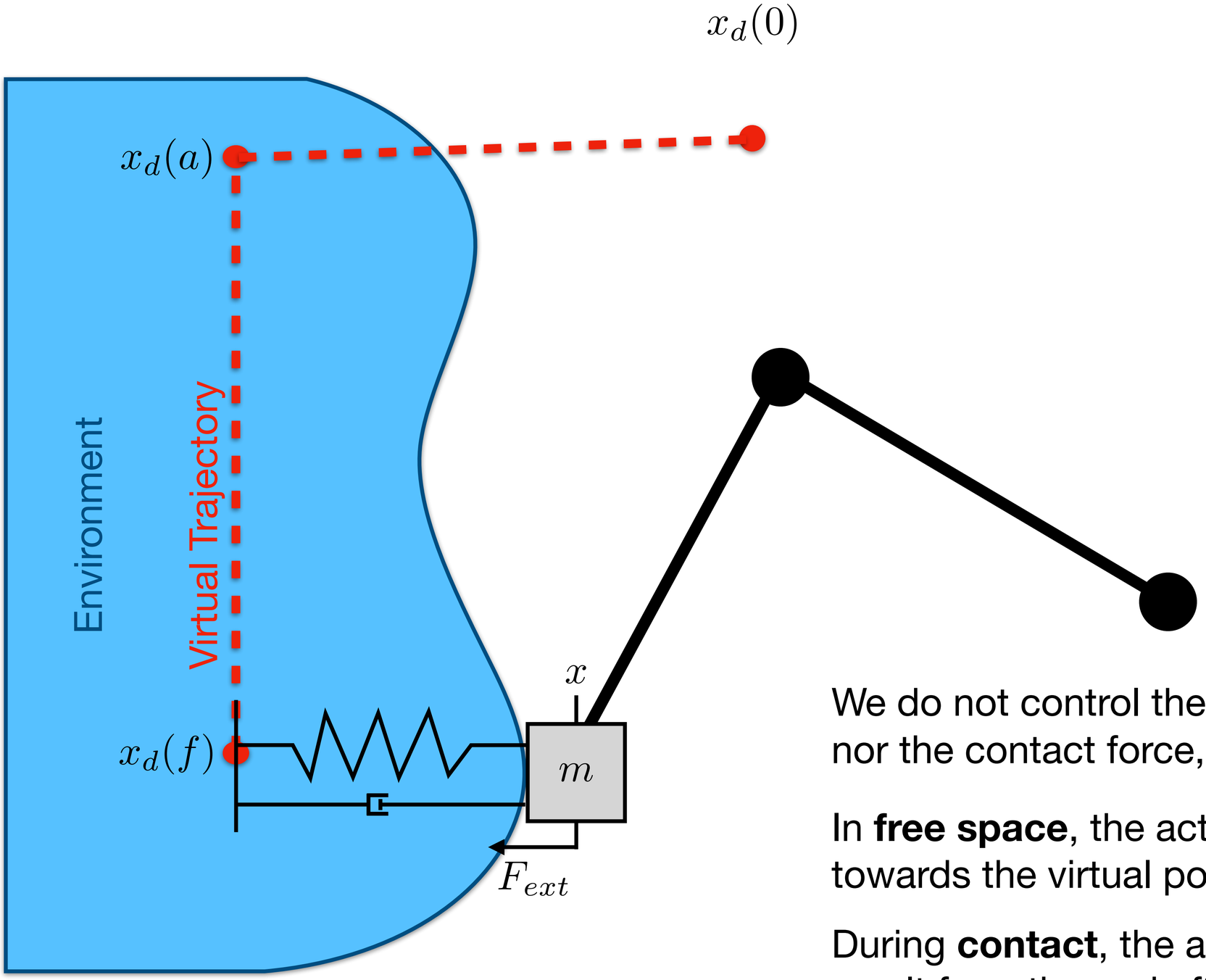

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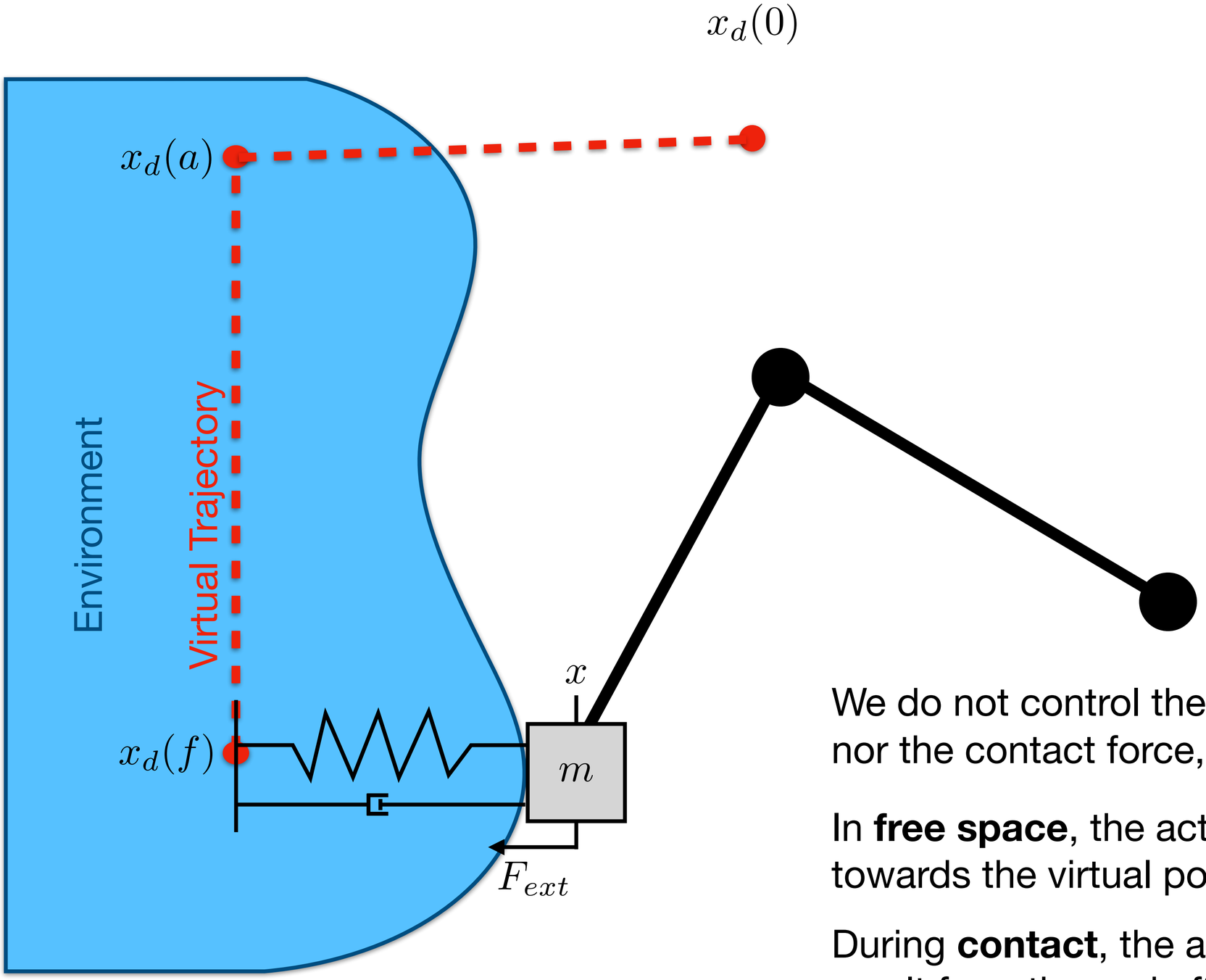

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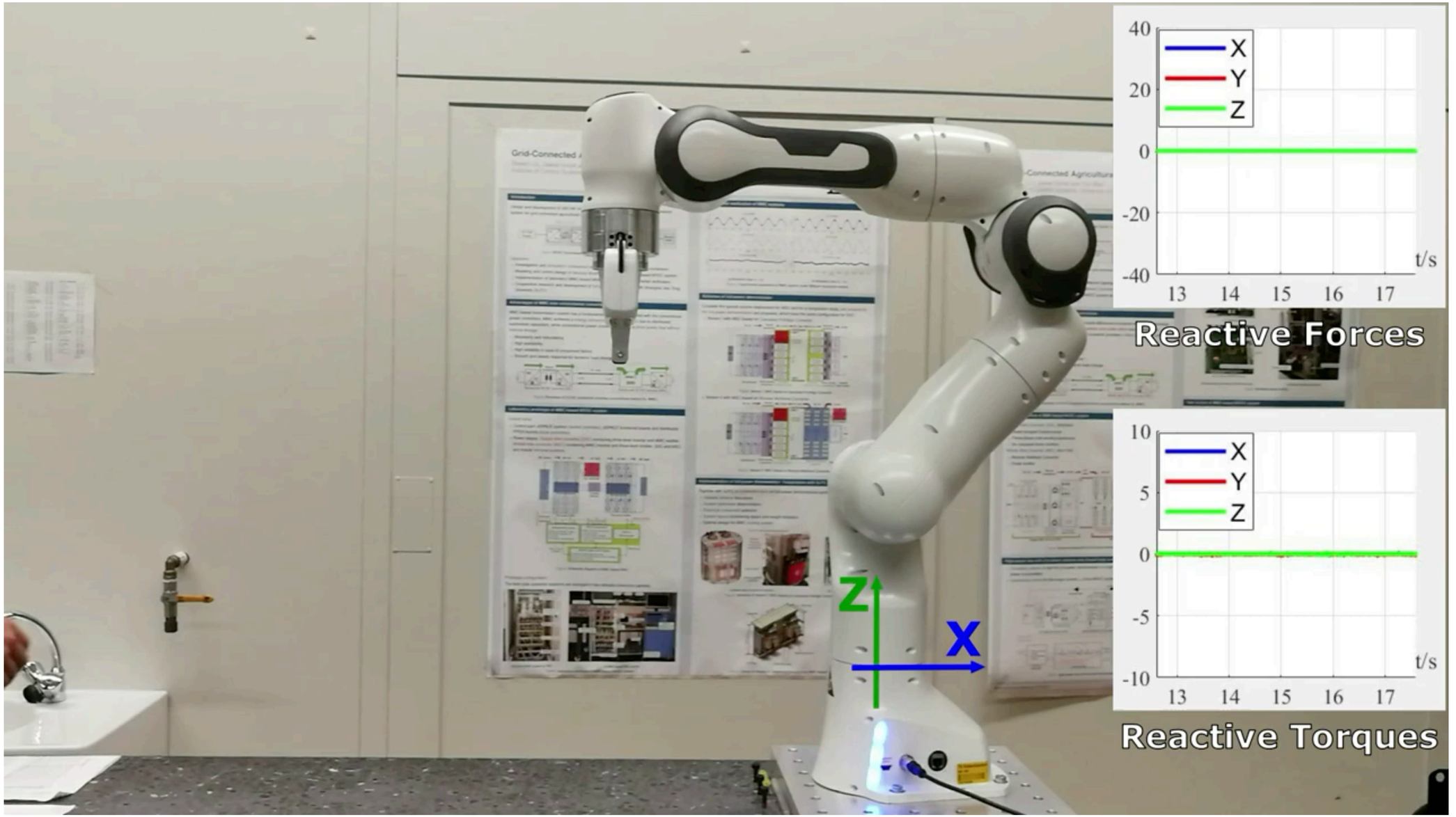
Impedance Control



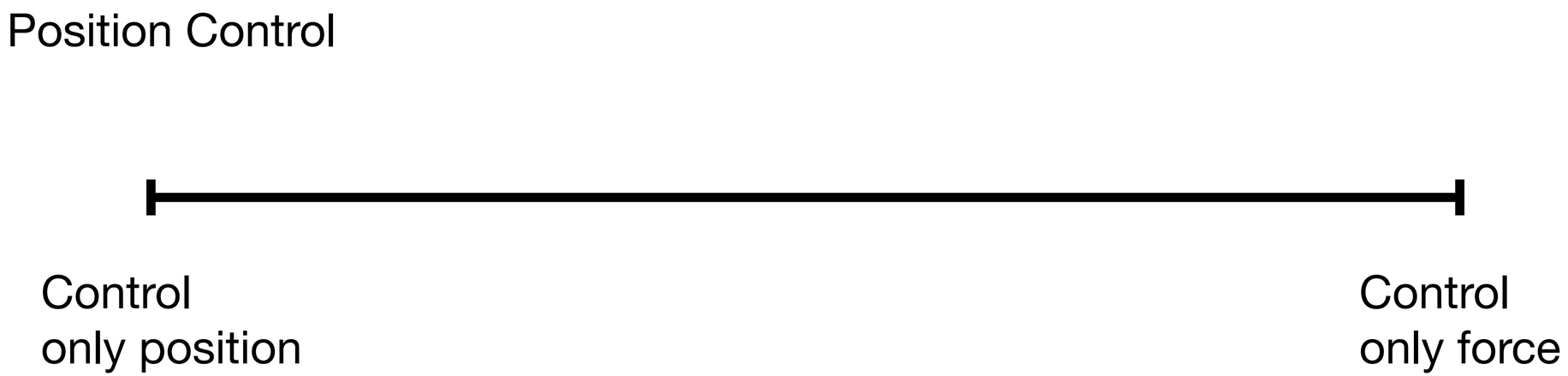
Comparison of Control Strategies

Comparison of Control Strategies

Control
only position

Control
only force

Comparison of Control Strategies



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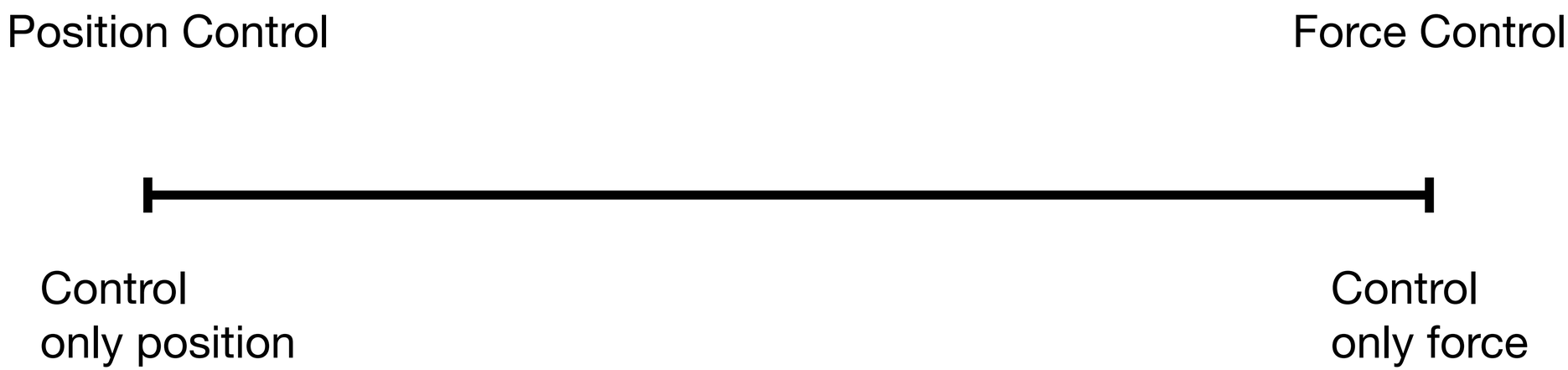

Comparison of Control Strategies

$$Z = \frac{F}{\Delta X}$$

Position Control | Impedance Control | Force Control

Control
only position

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Control only position

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Comparison of Control Strategies

$$Z = \frac{F}{\Delta X}$$

Position Control | Impedance Control | Force Control

Control only position

Control only force

High Impedance

Comparison of Control Strategies

$$Z = \frac{F}{\Delta X}$$

Position Control | Impedance Control | Force Control

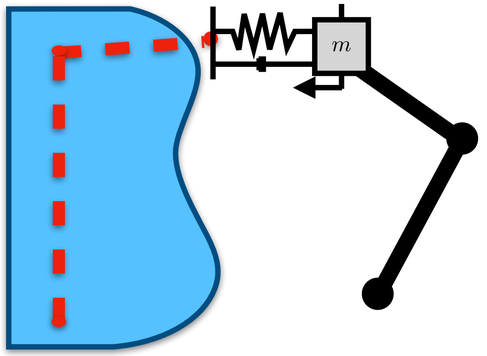
Control only position

Control only force

High Impedance

Low Impedance

Impedance Control:
The great integration of what you have learned



Homogeneous Transformations

Forward Kinematics

Inverse Kinematics

Spring-Mass-Damper System

Impedance Control

Jacobian

PD-Control

Trajectories

Dynamics

We use impedance control for human-robot interaction