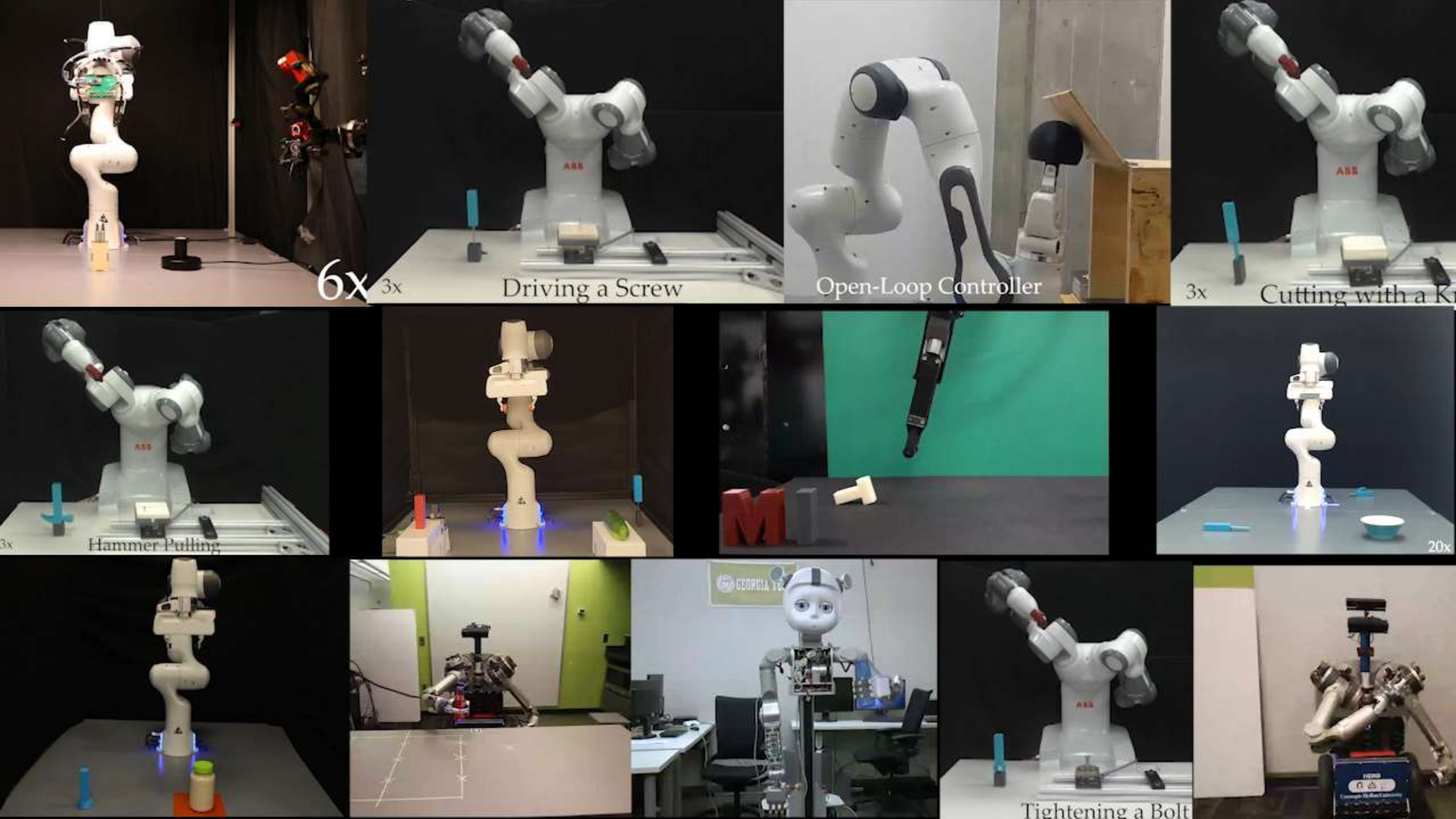

6x
3x
Driving a Screw
Open-Loop Controller
3x
Cutting with a K
3x
Hammer Pulling
20x
Tightening a Bolt

Leveraging Mechanics for Multi-Step Robotic Manipulation Planning

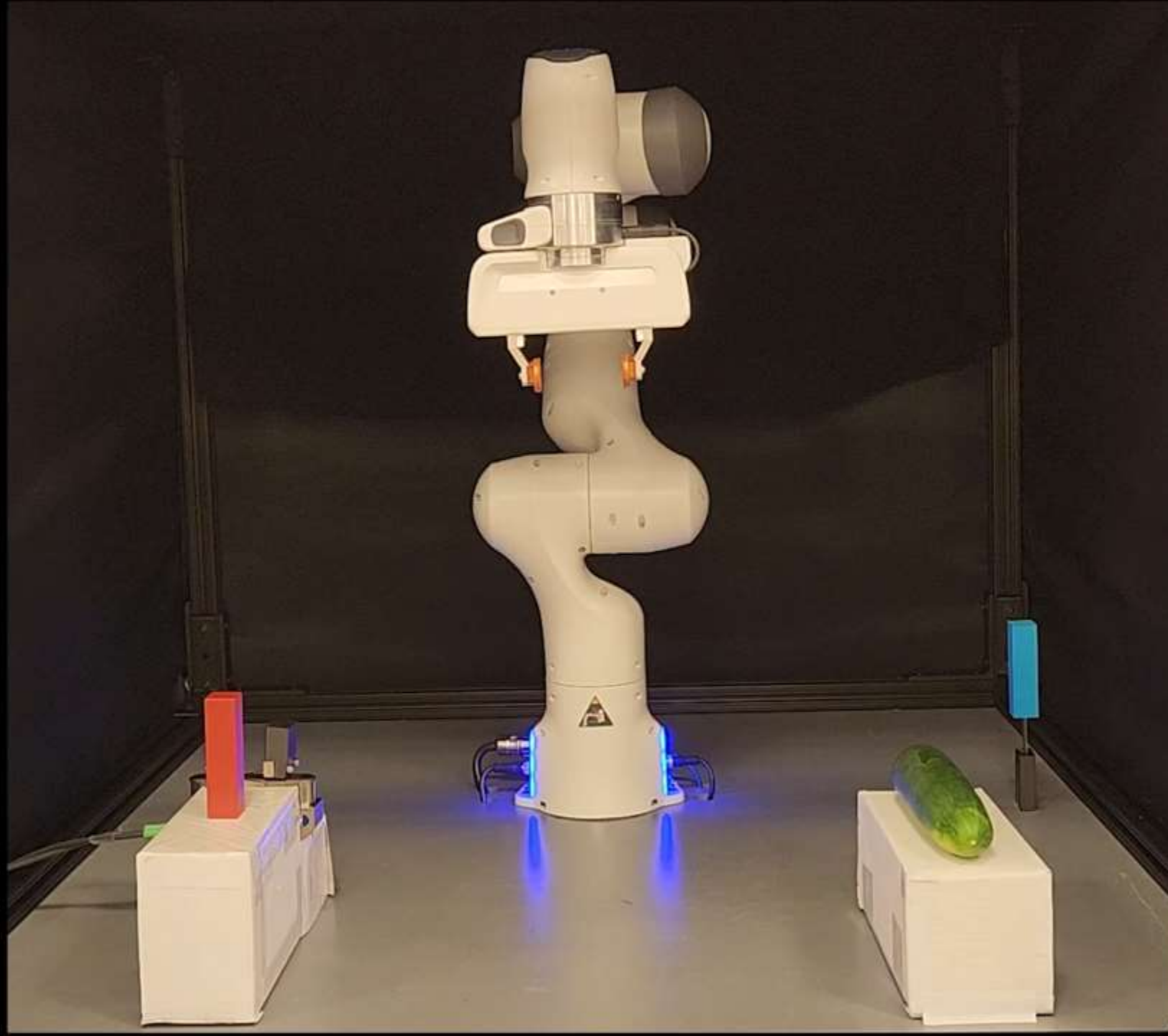
Rachel Holladay

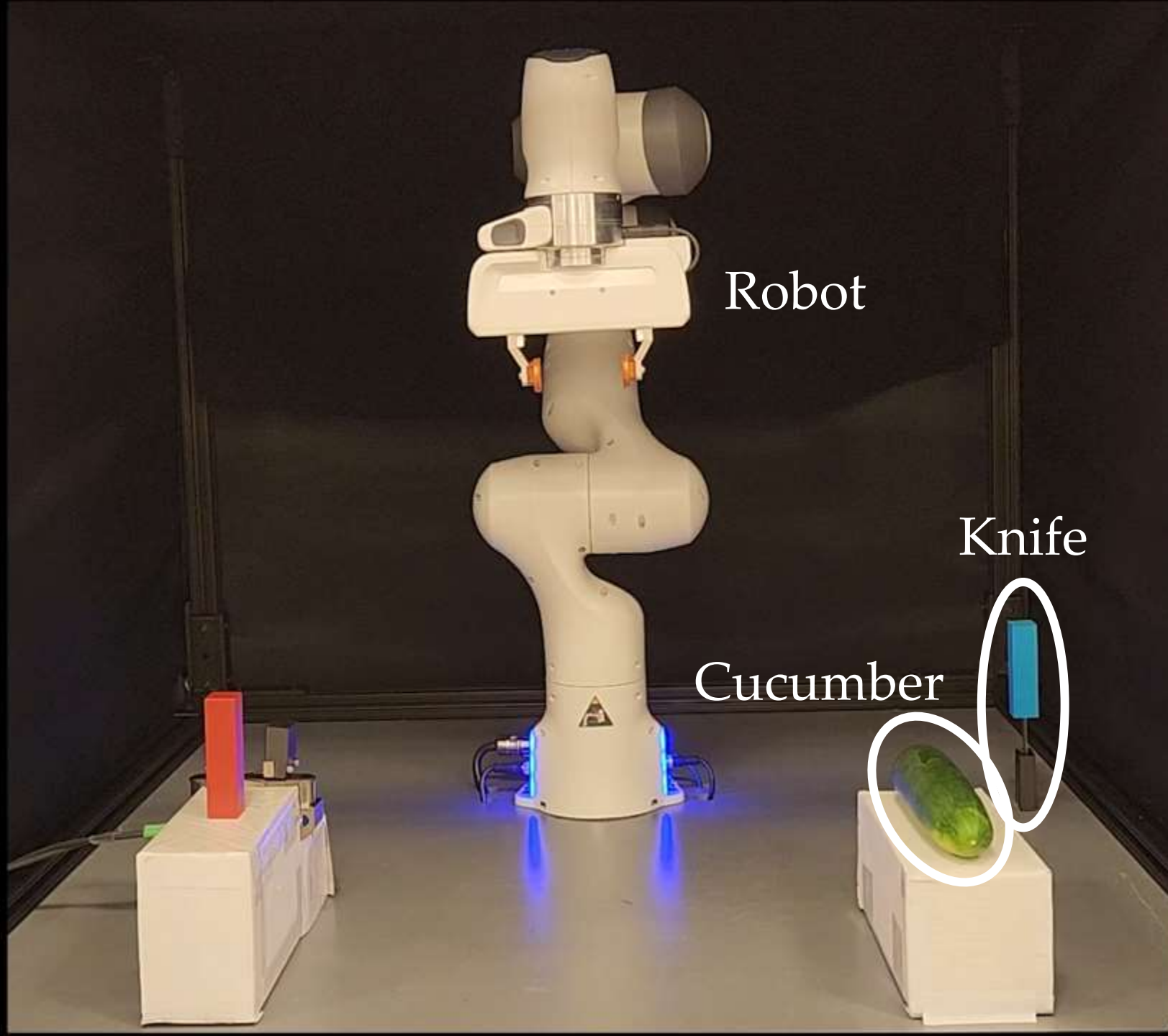
Doctoral Defense
16 August 2024

https://people.csail.mit.edu/rholladay/

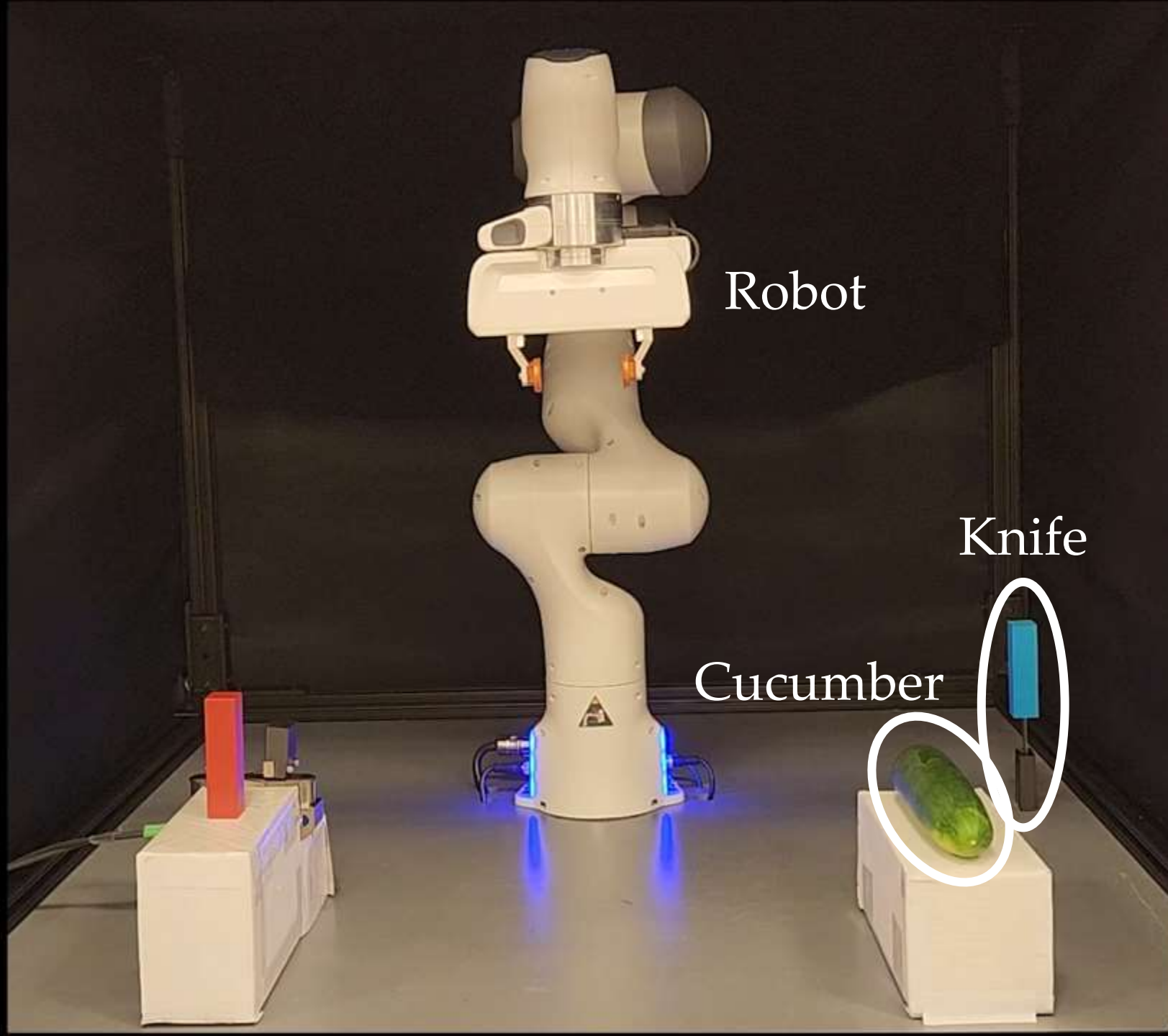



- **chop vegetables**
- saute vegetables
- make sauce sauce
- mix vegetables and sauce



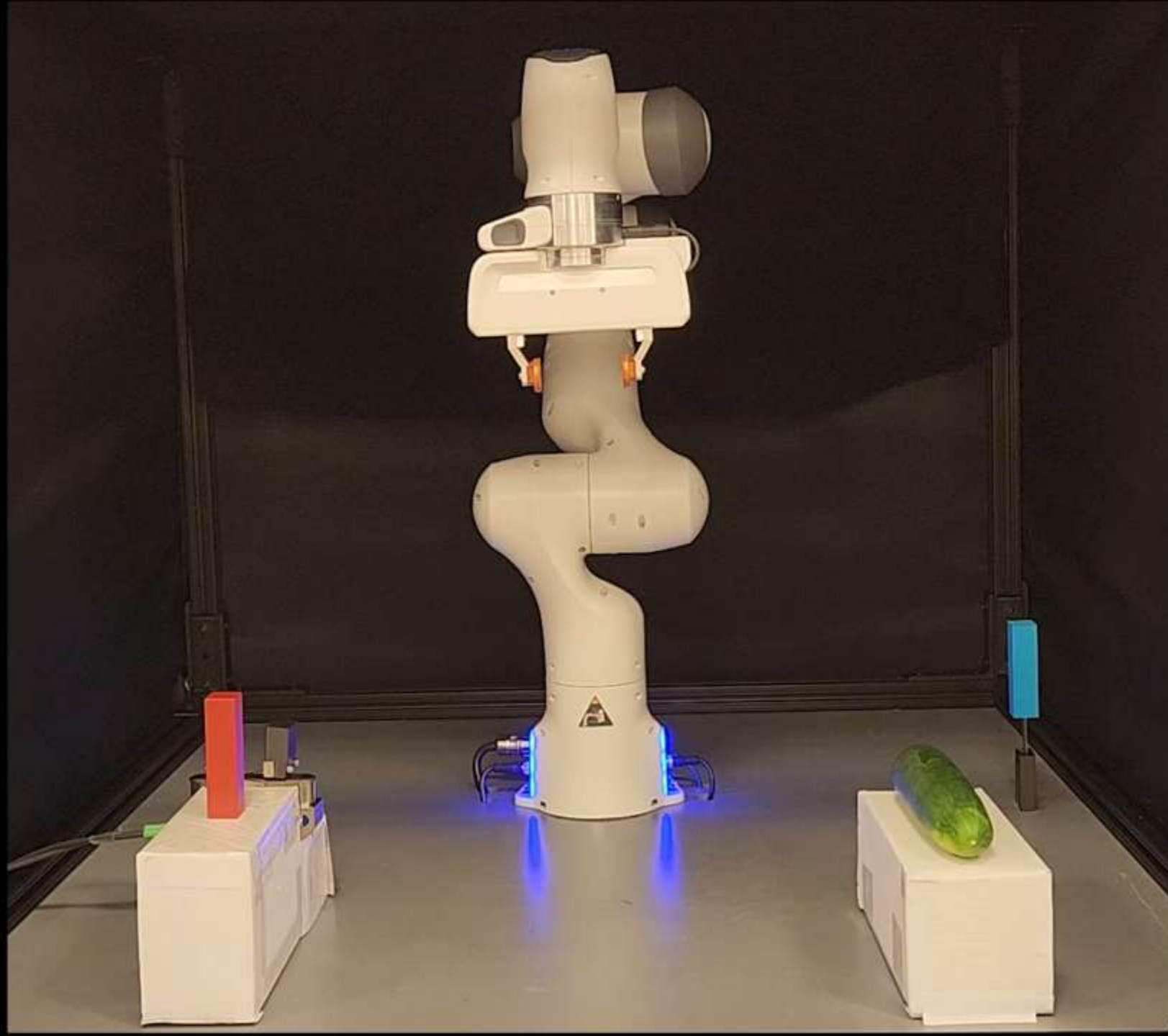

Robot
Knife
Cucumber

How to cut the cucumber?



How to cut the cucumber?

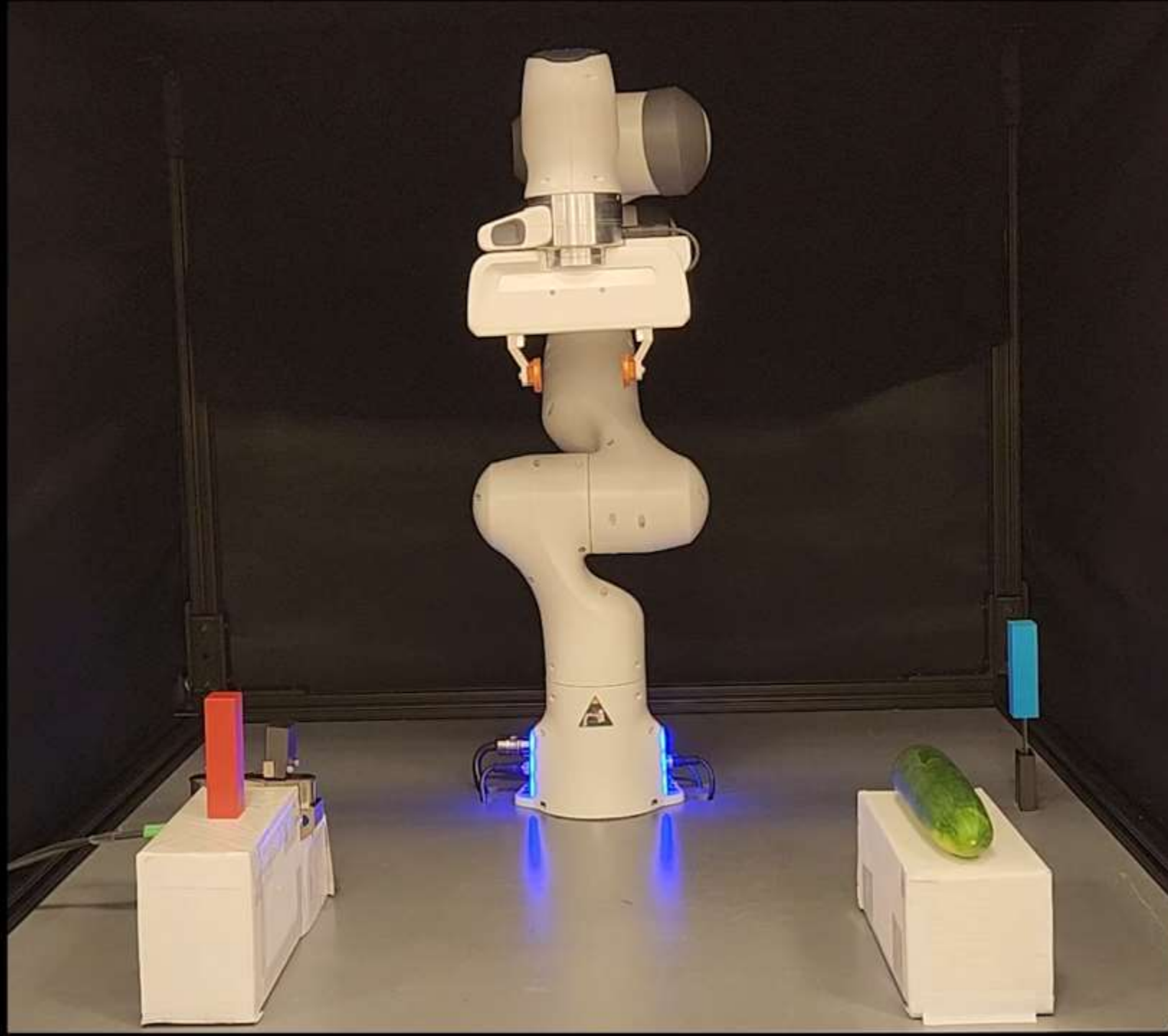
Action Sequence



How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

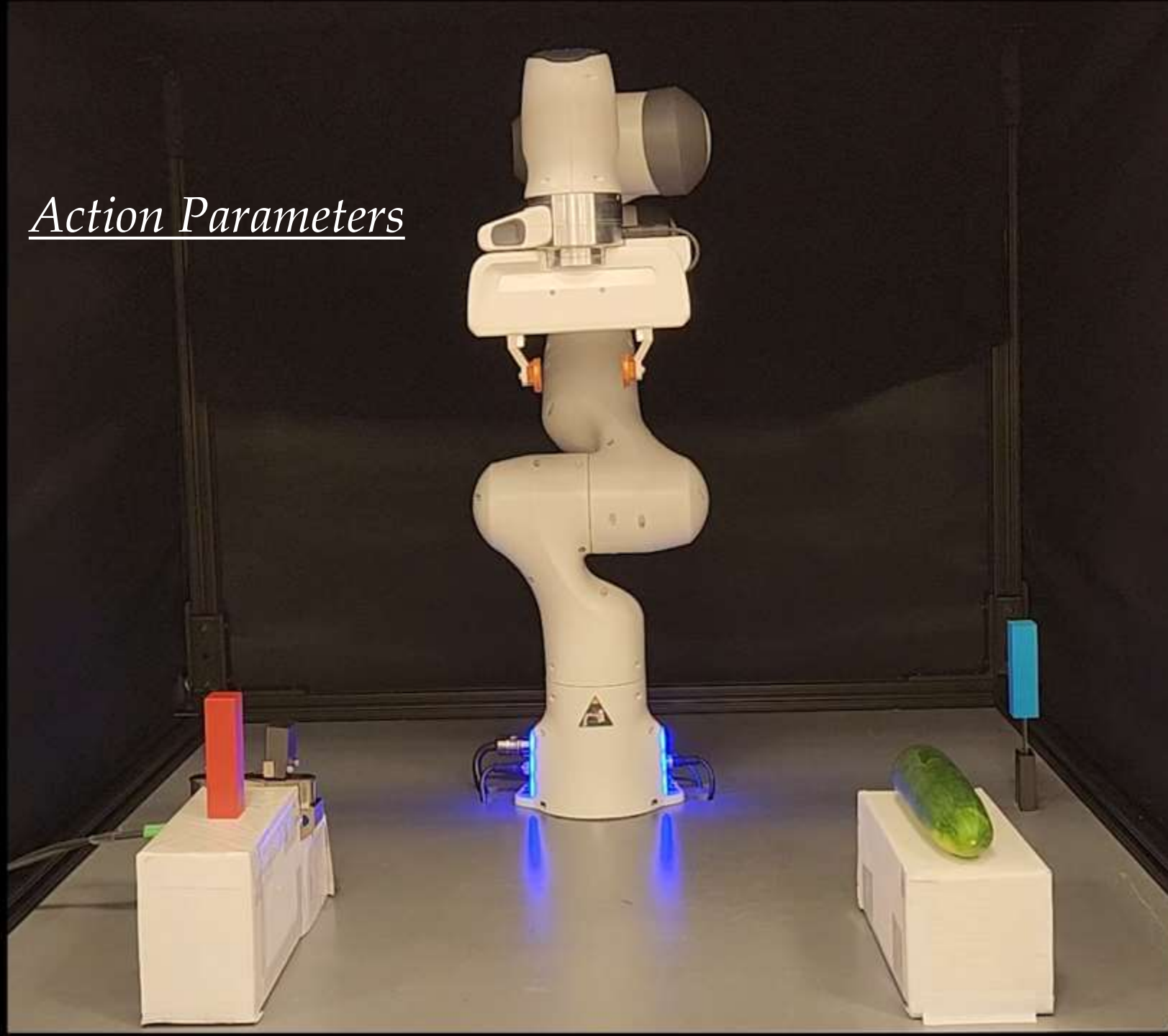


How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters



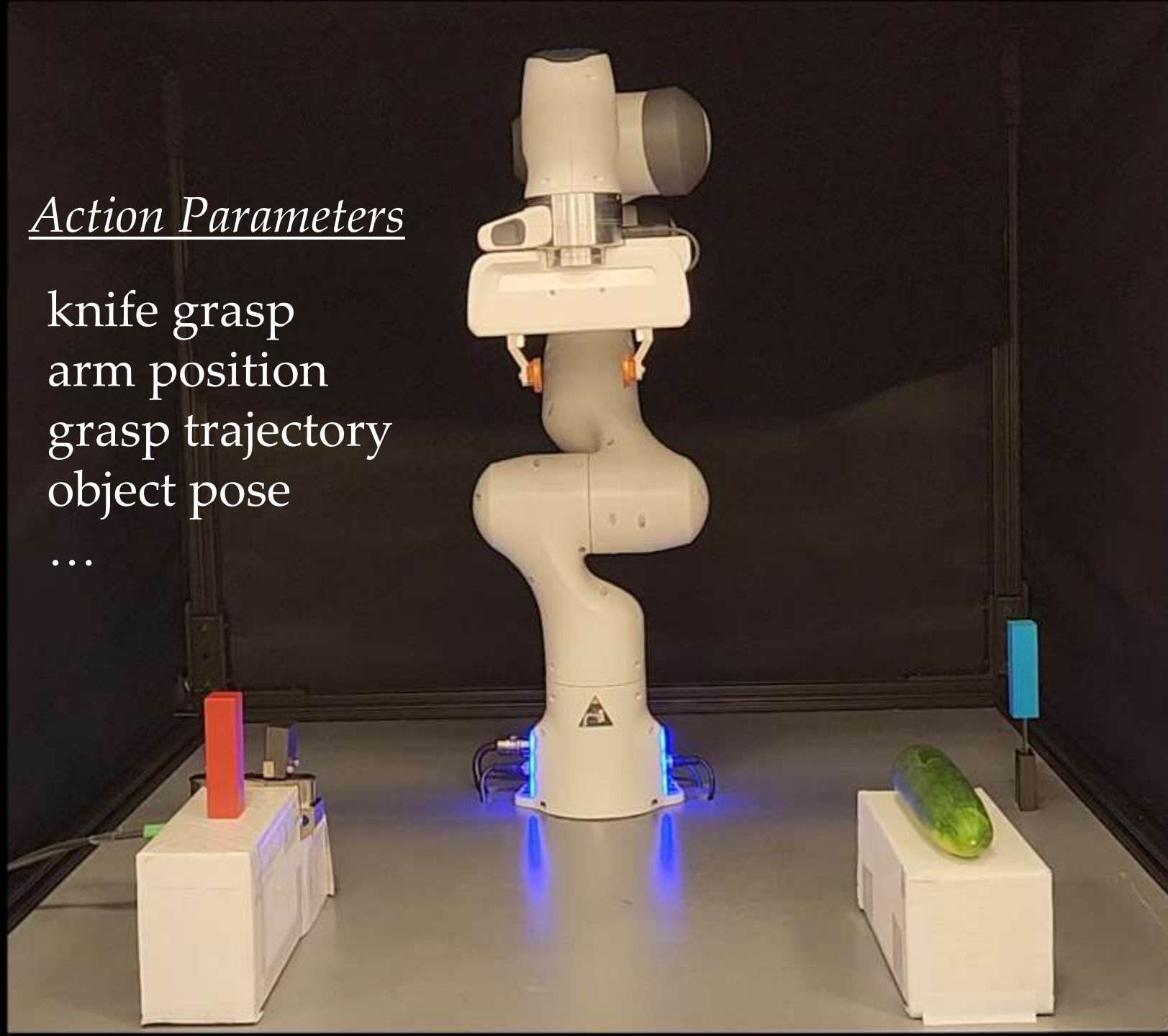
How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

knife grasp
arm position
grasp trajectory
object pose
…



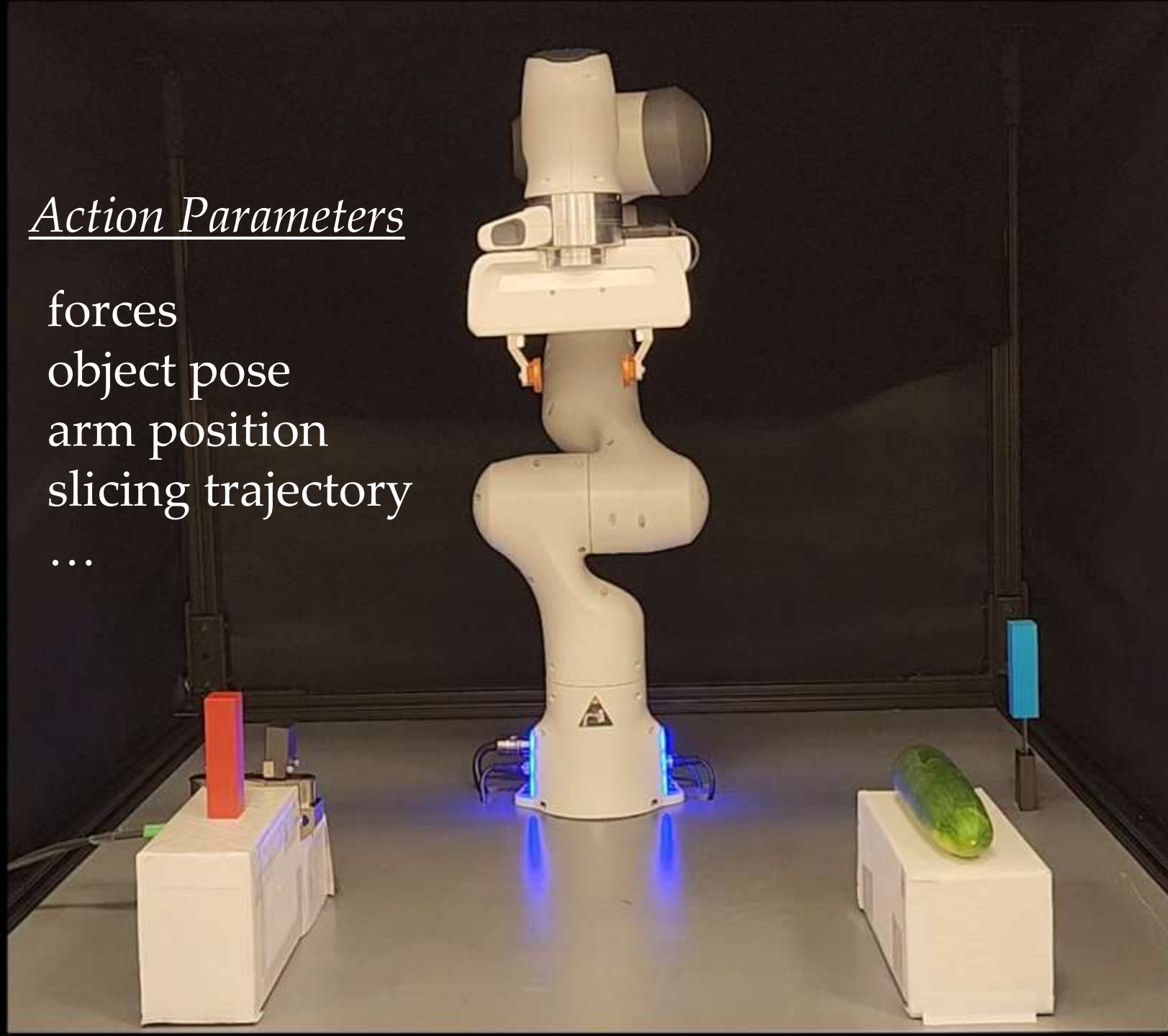
How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

forces
object pose
arm position
slicing trajectory
…



How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

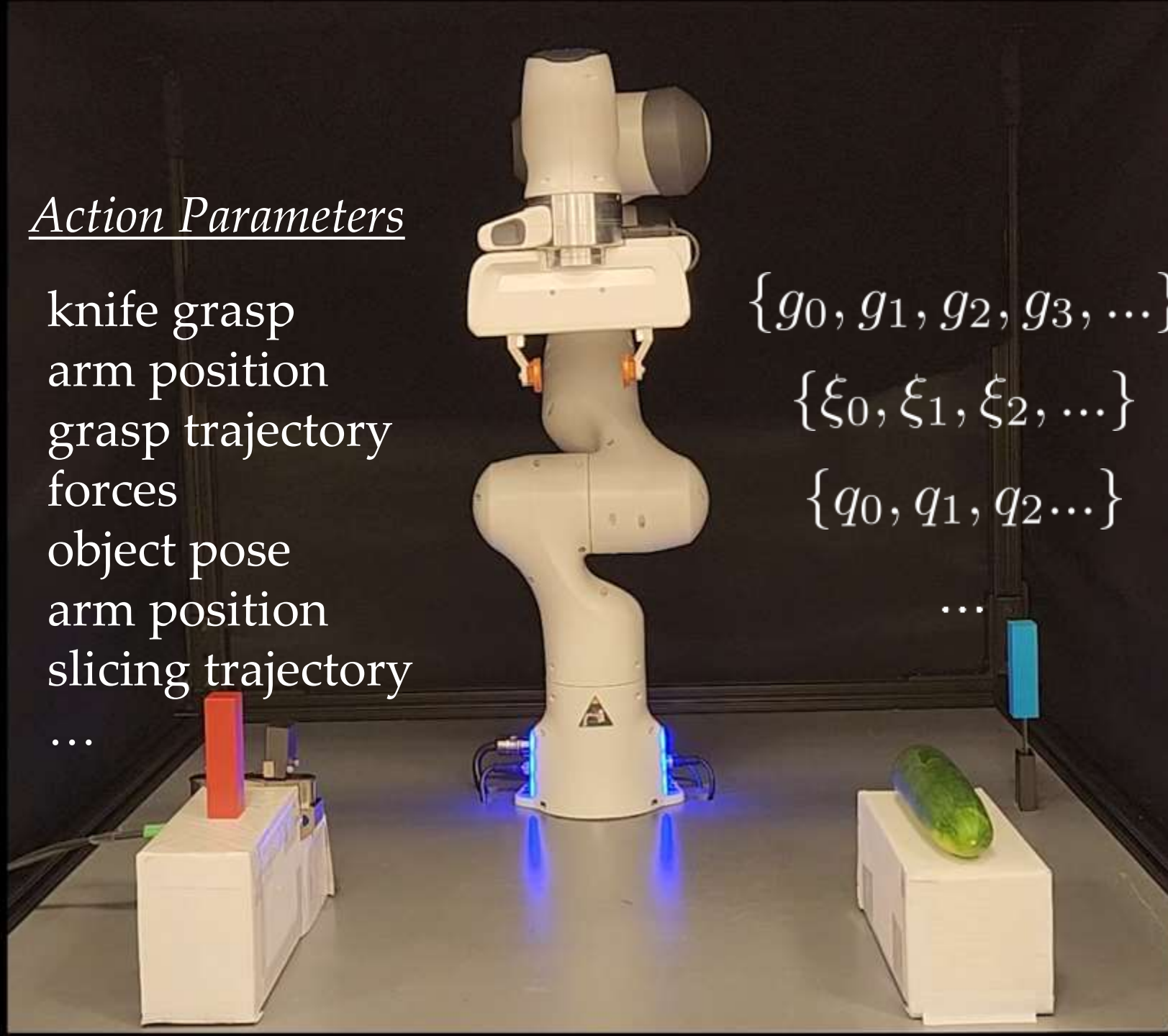
knife grasp
arm position
grasp trajectory
forces
object pose
arm position
slicing trajectory
…

$\{g_0, g_1, g_2, g_3, \cdots\}$

$\{\xi_0, \xi_1, \xi_2, \ldots\}$

$\{q_0, q_1, q_2 \cdots\}$

…



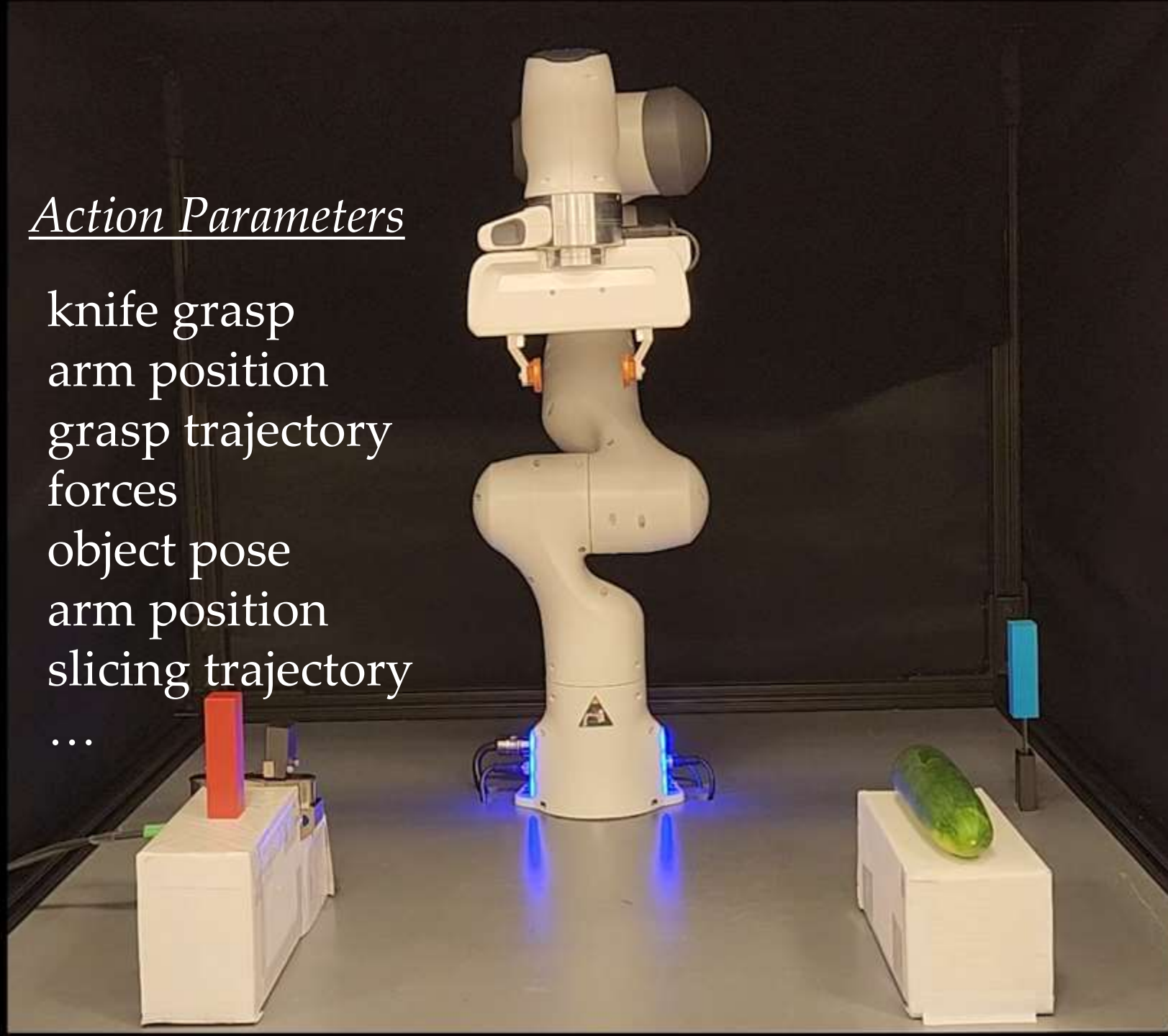
How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

knife grasp
arm position
grasp trajectory
forces
object pose
arm position
slicing trajectory
…



Success?

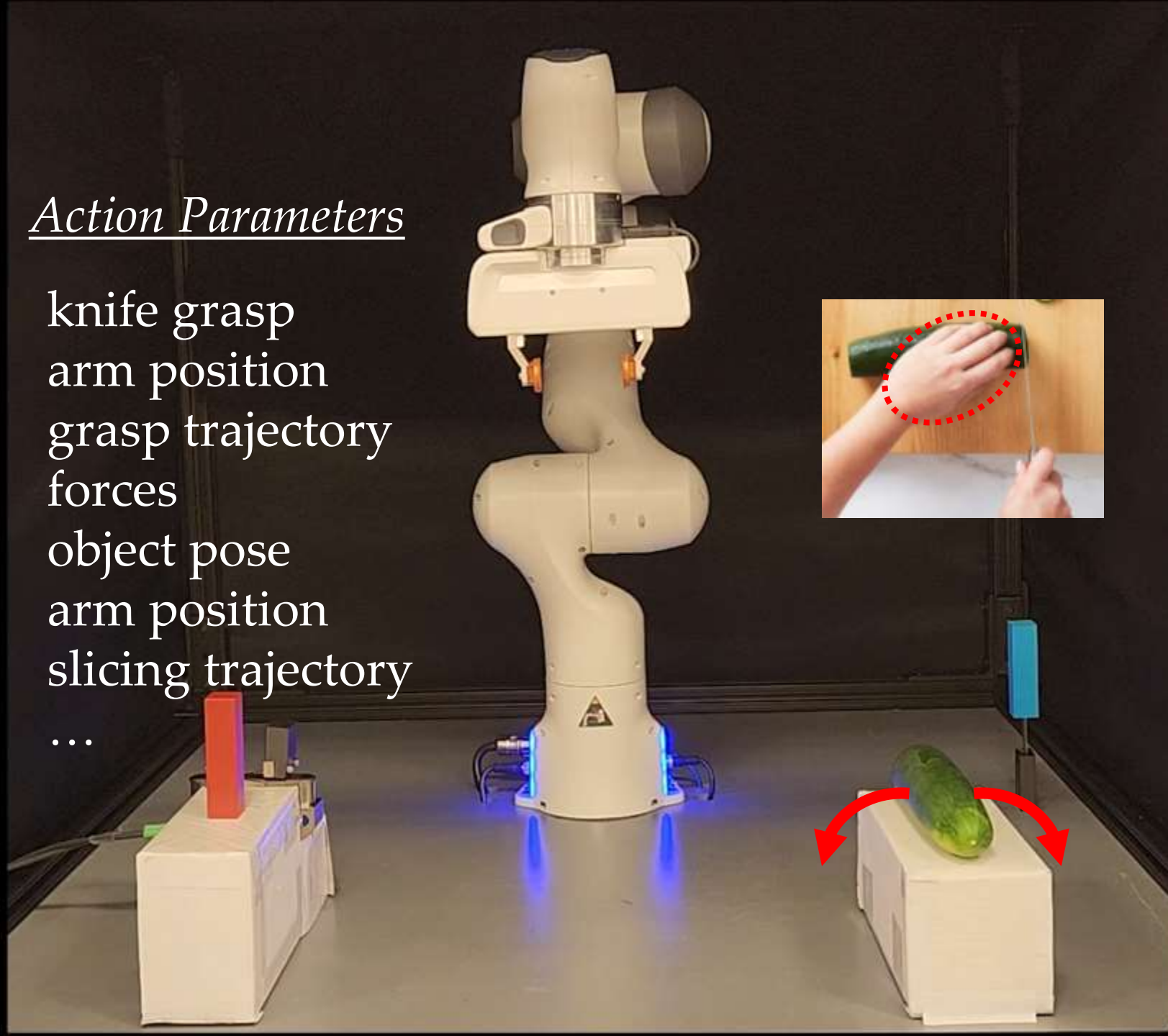
How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

knife grasp
arm position
grasp trajectory
forces
object pose
arm position
slicing trajectory
…



How to cut the cucumber?

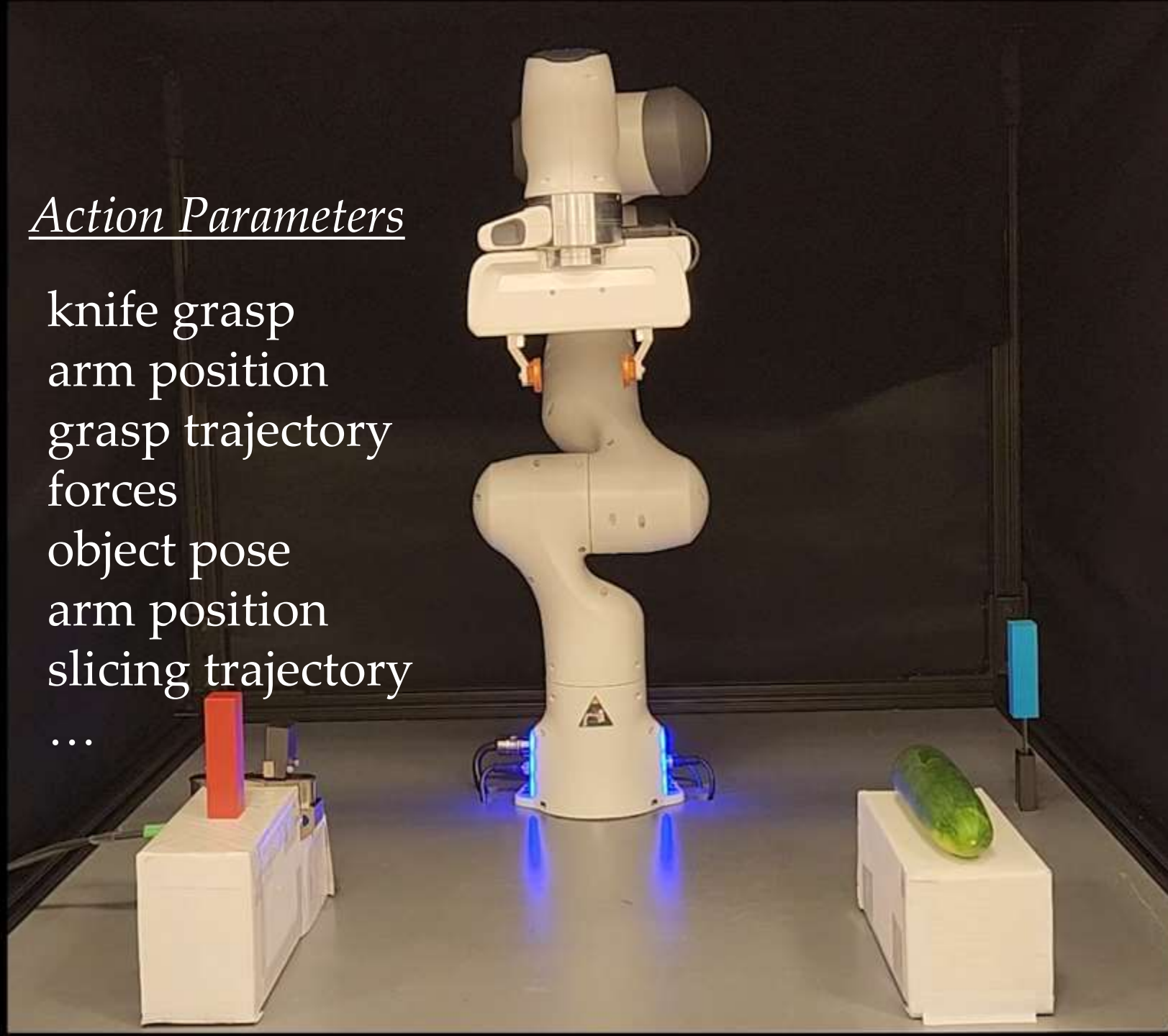
Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

✗ Success

Action Parameters

knife grasp
arm position
grasp trajectory
forces
object pose
arm position
slicing trajectory
…



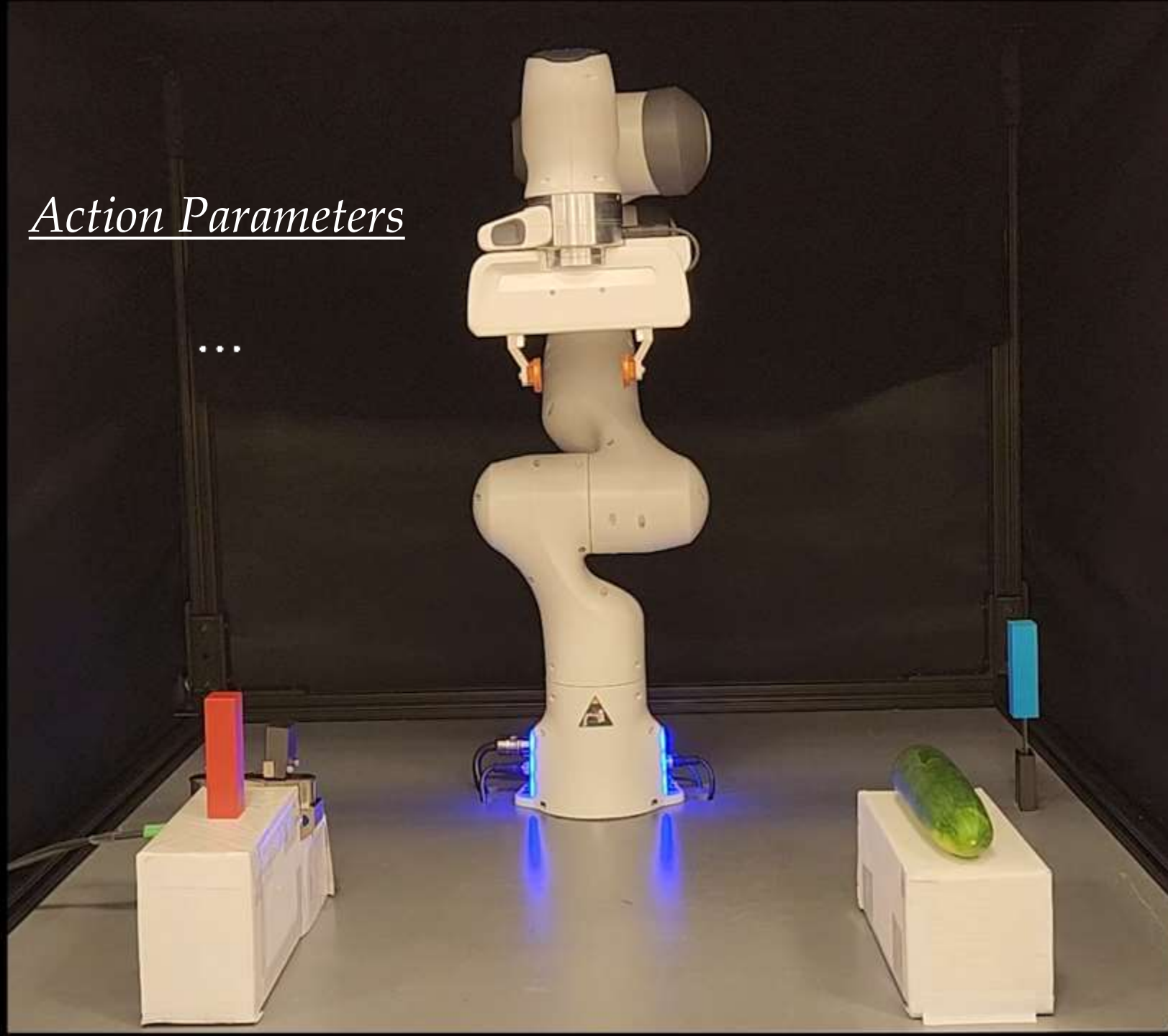
How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

…



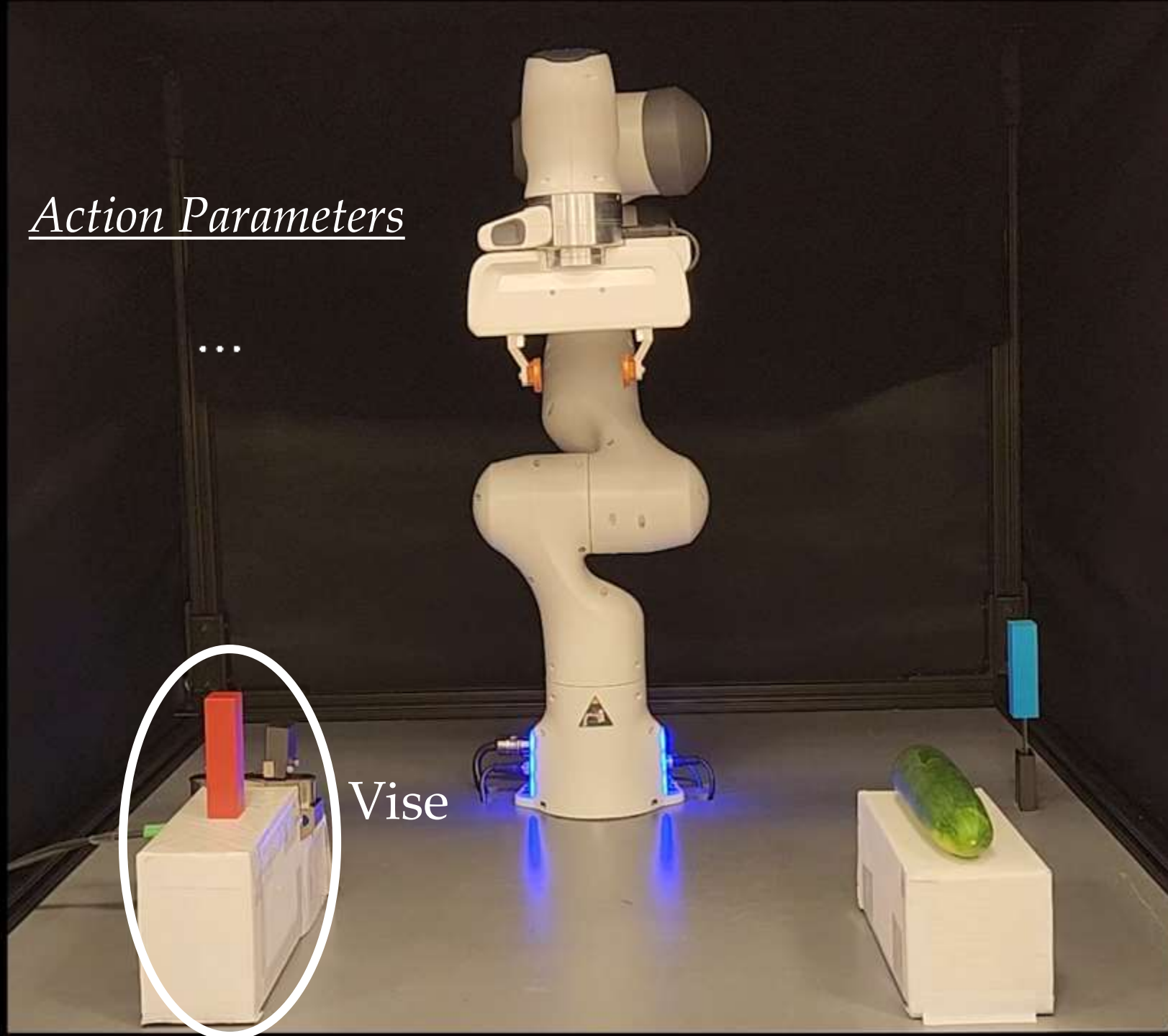
How to cut the cucumber?

Action Sequence

[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

…



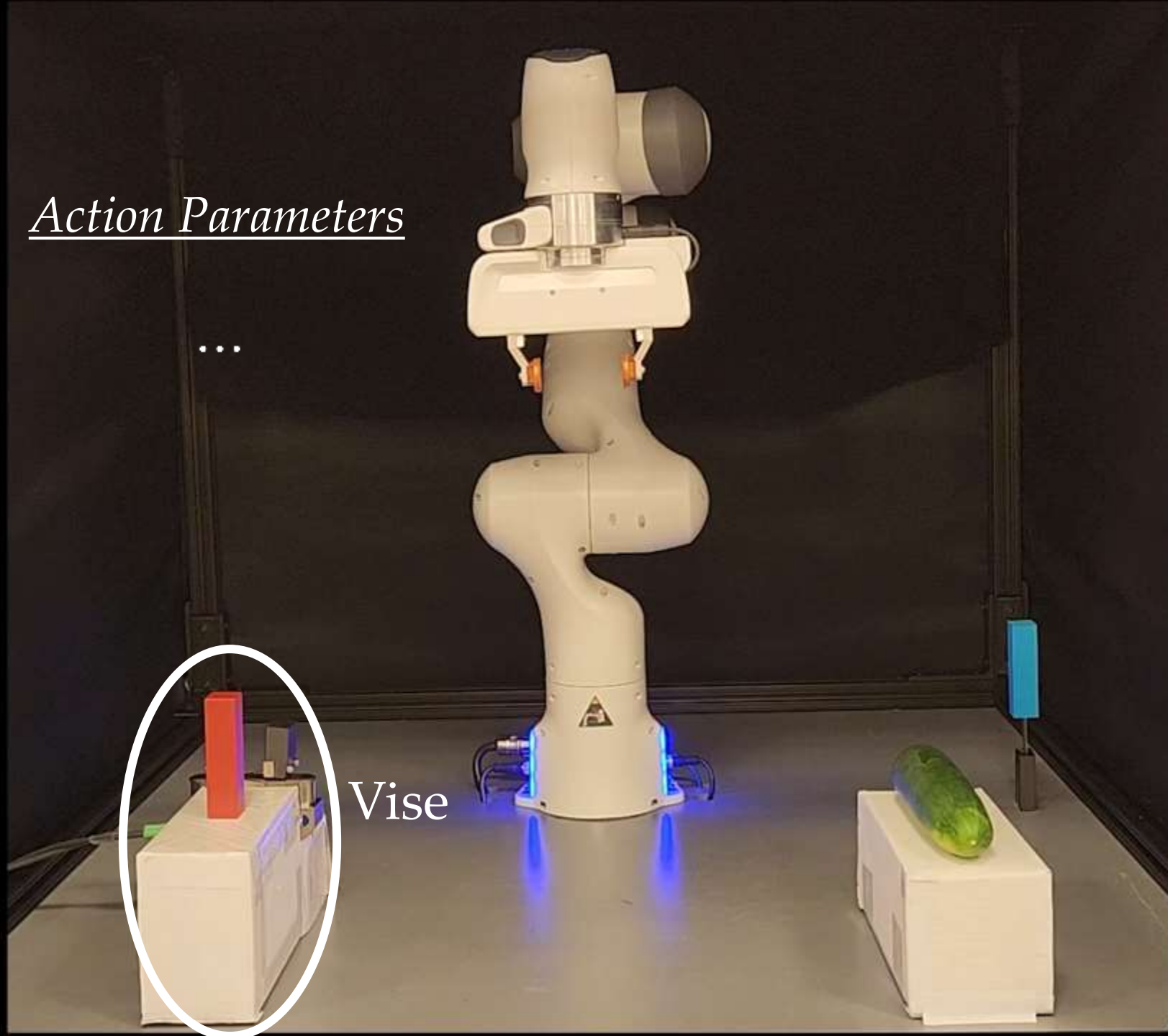
How to cut the cucumber?

Action Sequence

[grasp cucumber]
[place cucumber in vise]
[close vise]
[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

…



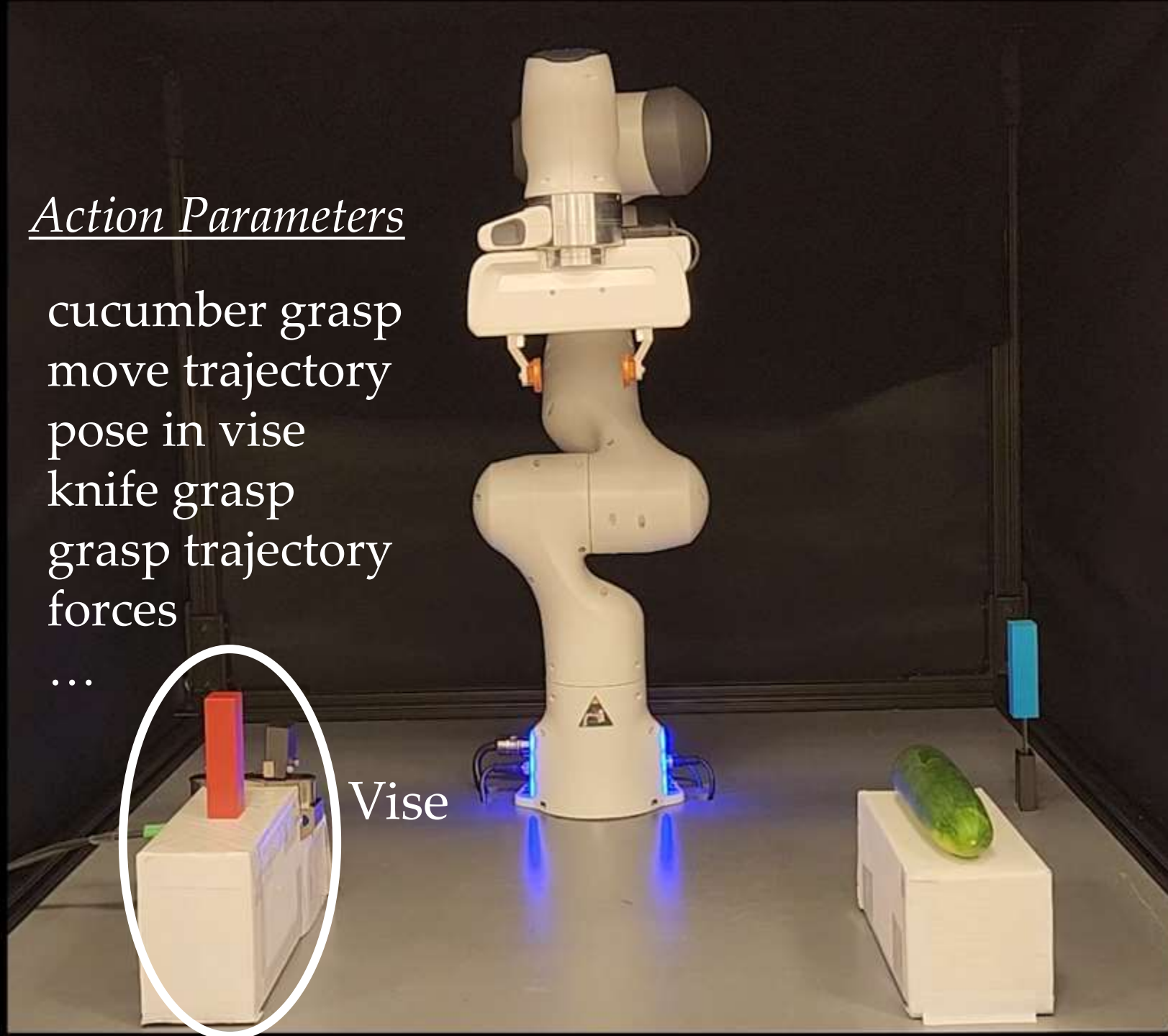
How to cut the cucumber?

Action Sequence

[grasp cucumber]
[place cucumber in vise]
[close vise]
[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

cucumber grasp
move trajectory
pose in vise
knife grasp
grasp trajectory
forces
…



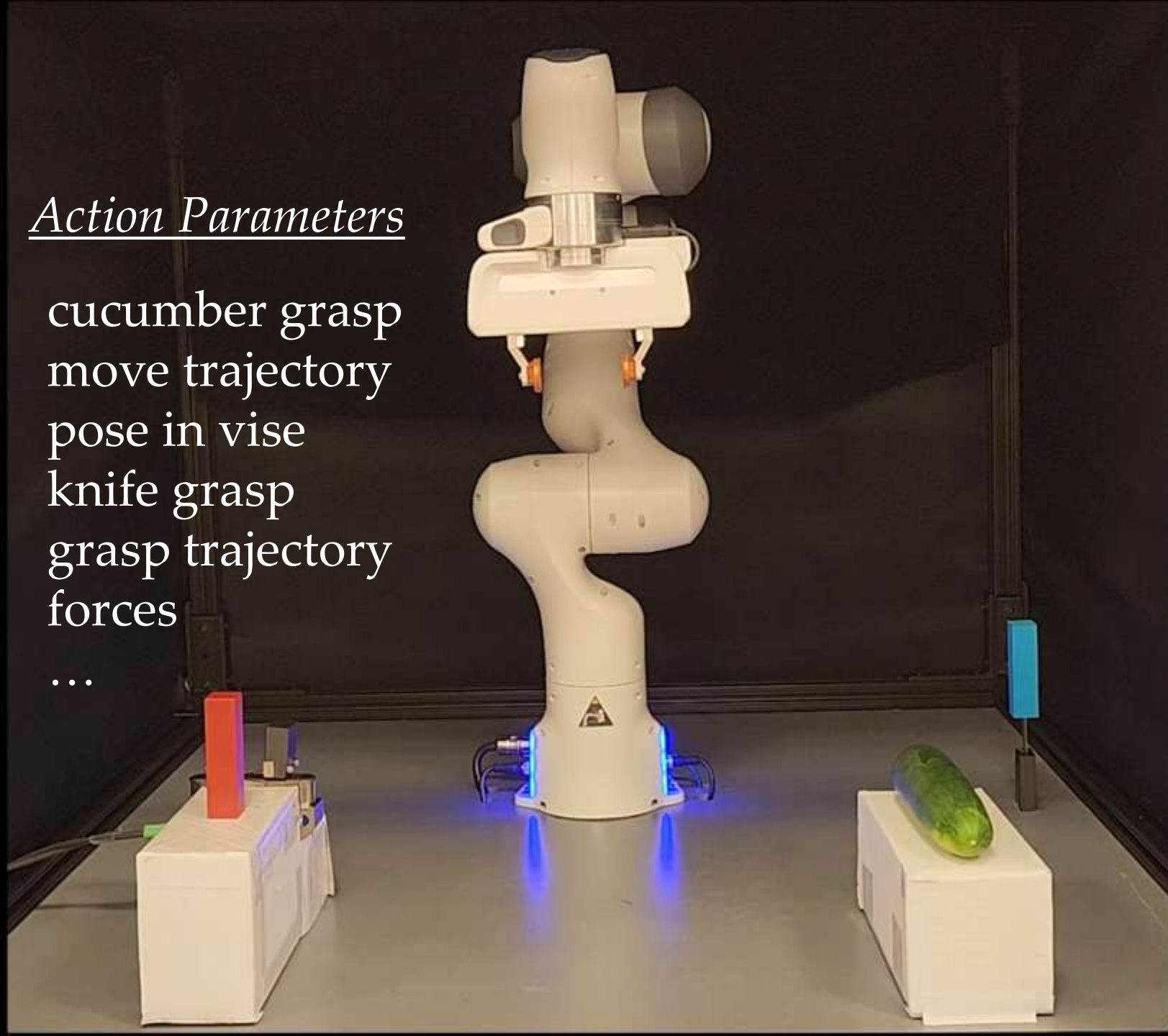
How to cut the cucumber?

Action Sequence

[grasp cucumber]
[place cucumber in vise]
[close vise]
[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

cucumber grasp
move trajectory
pose in vise
knife grasp
grasp trajectory
forces
…



Success?

How to cut the cucumber?

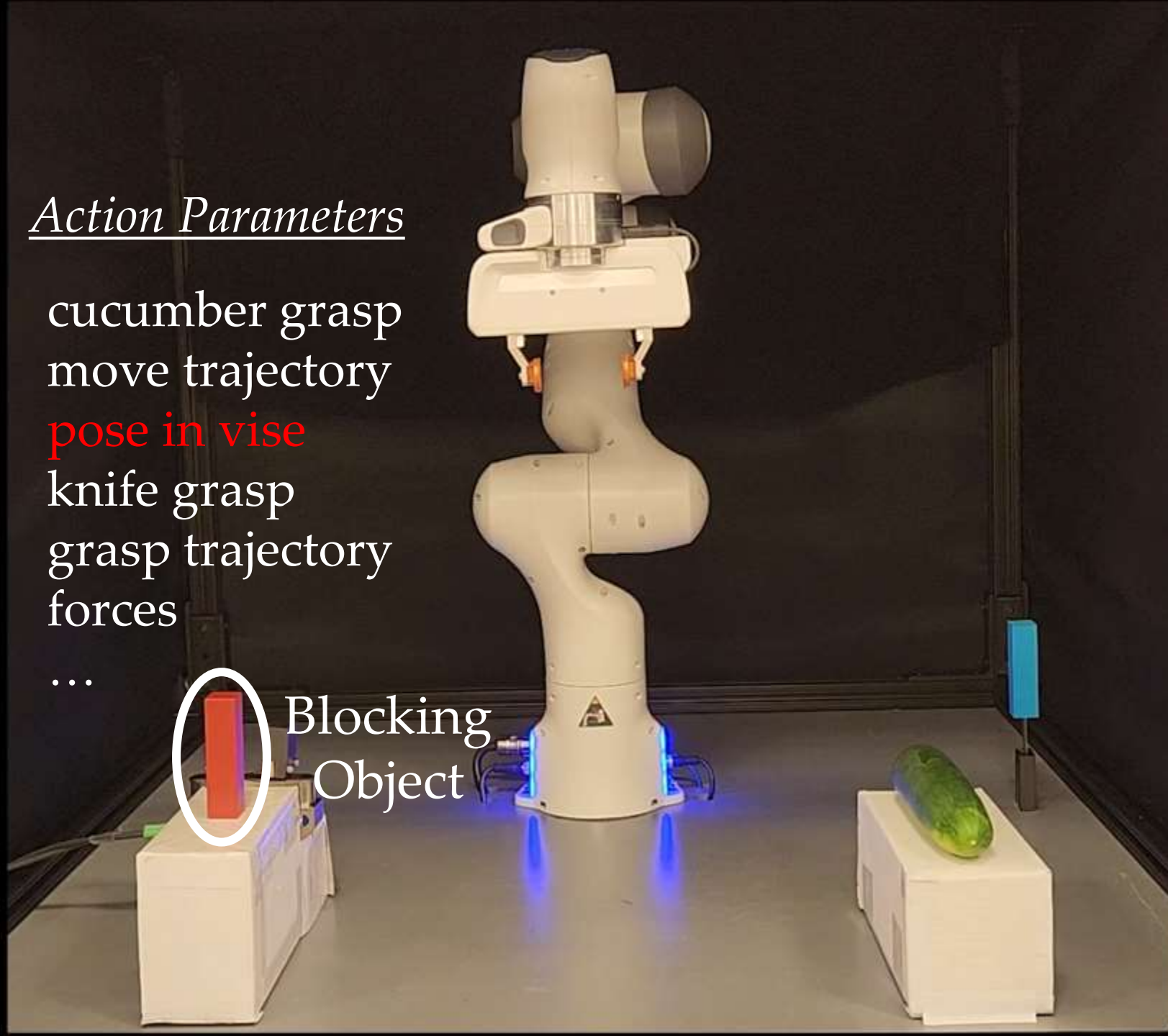
Action Sequence

[grasp cucumber]
[place cucumber in vise]
[close vise]
[grasp knife]
[move knife to cucumber]
[slice cucumber]

✗ Success

Action Parameters

cucumber grasp
move trajectory
pose in vise
knife grasp
grasp trajectory
forces
…



How to cut the cucumber?

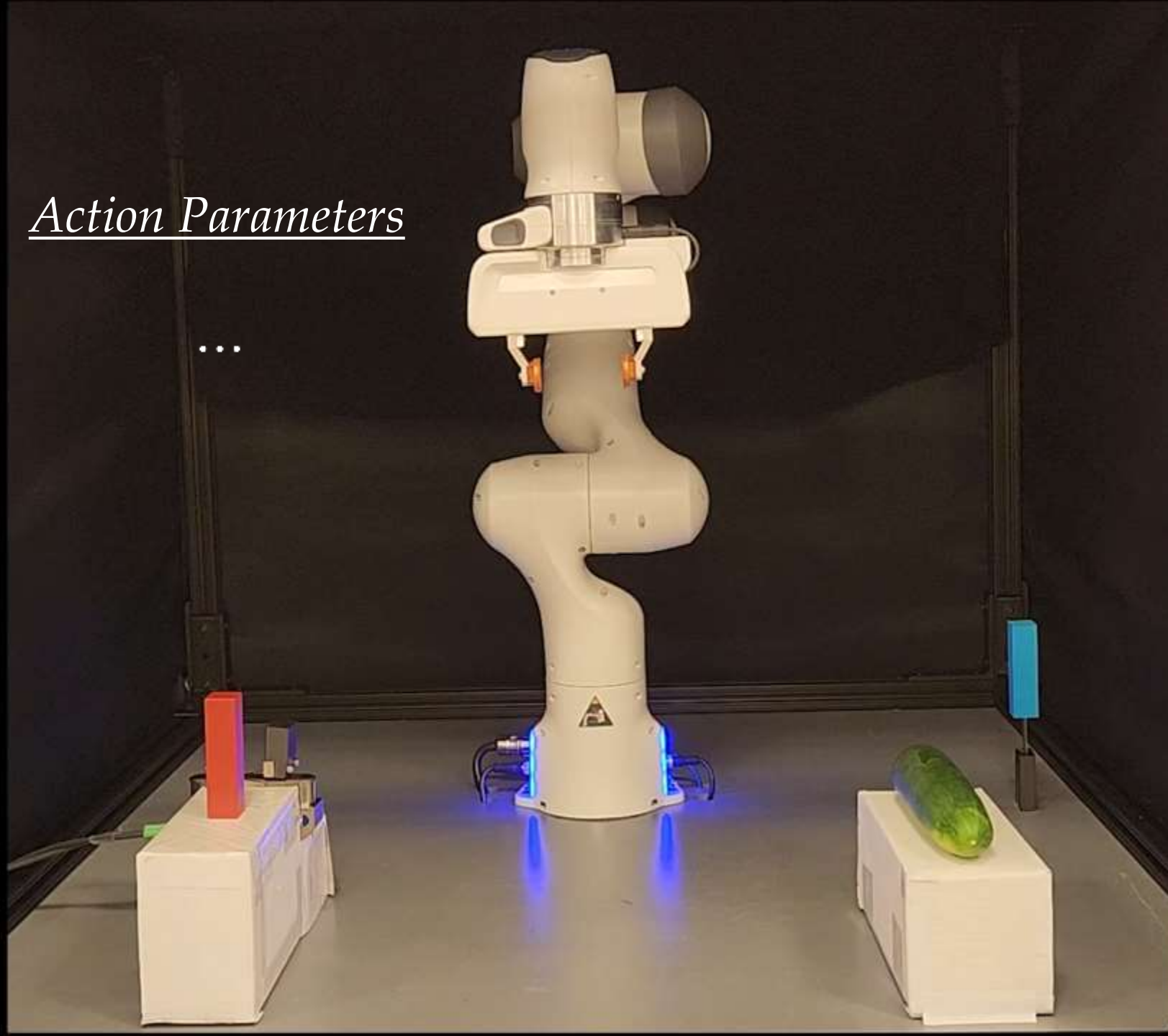
Action Sequence

[grasp cucumber]
[place cucumber in vise]
[close vise]
[grasp knife]
[move knife to cucumber]
[slice cucumber]

✗ Success

Action Parameters

…



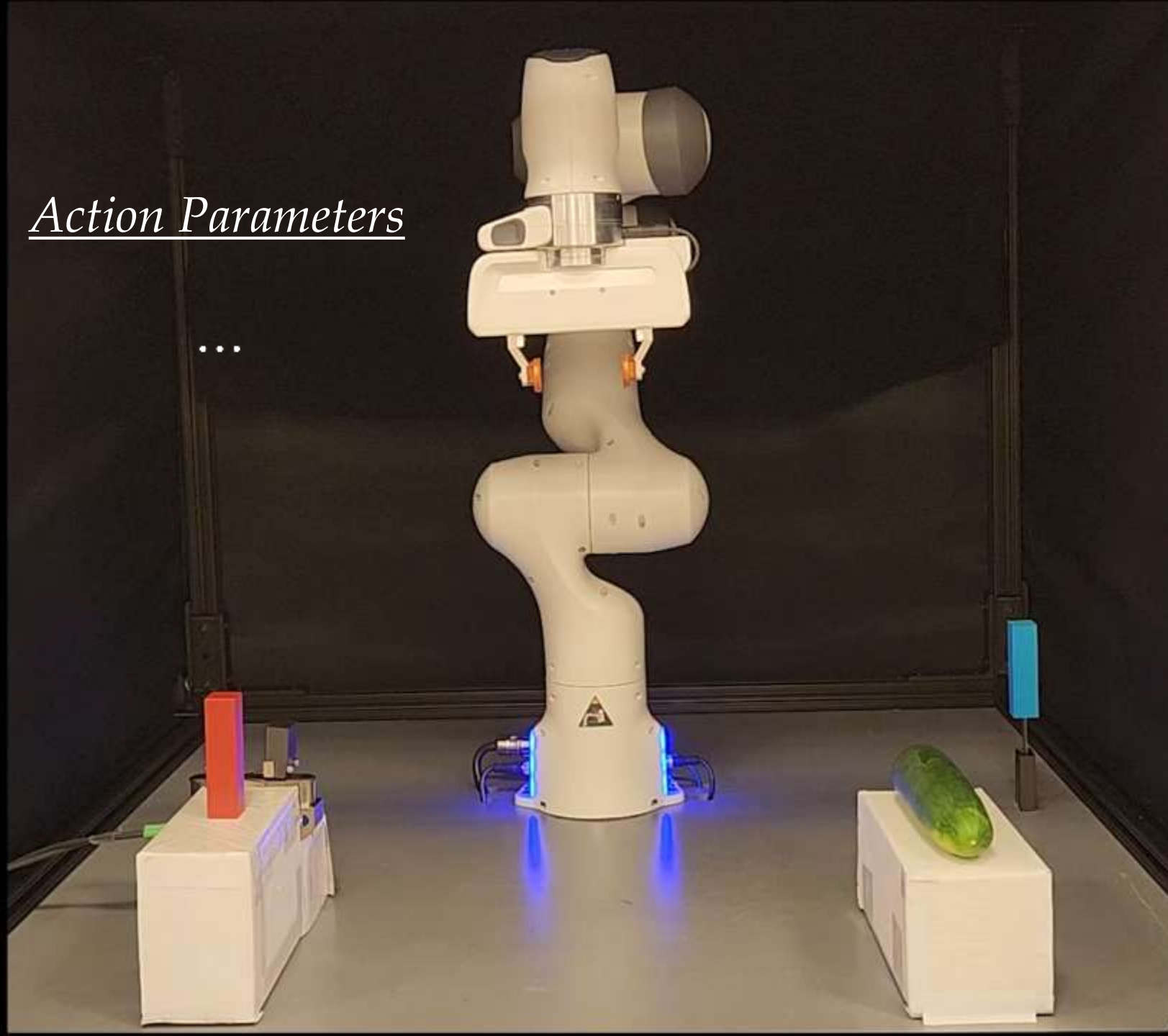
How to cut the cucumber?

Action Sequence

[grasp red block]
[place red block somewhere]
[grasp cucumber]
[place cucumber in vise]
[close vise]
[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

…



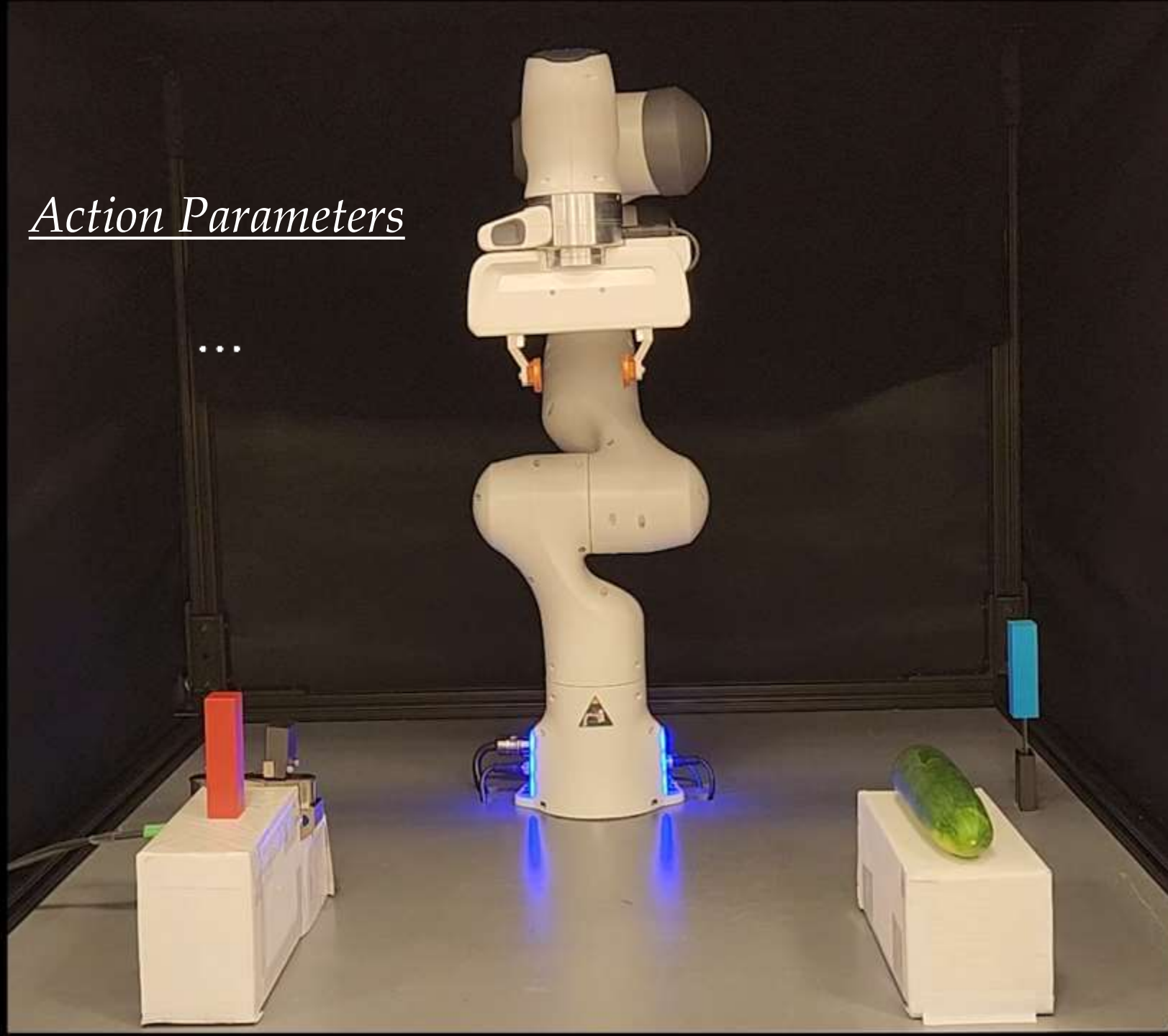
How to cut the cucumber?

Action Sequence

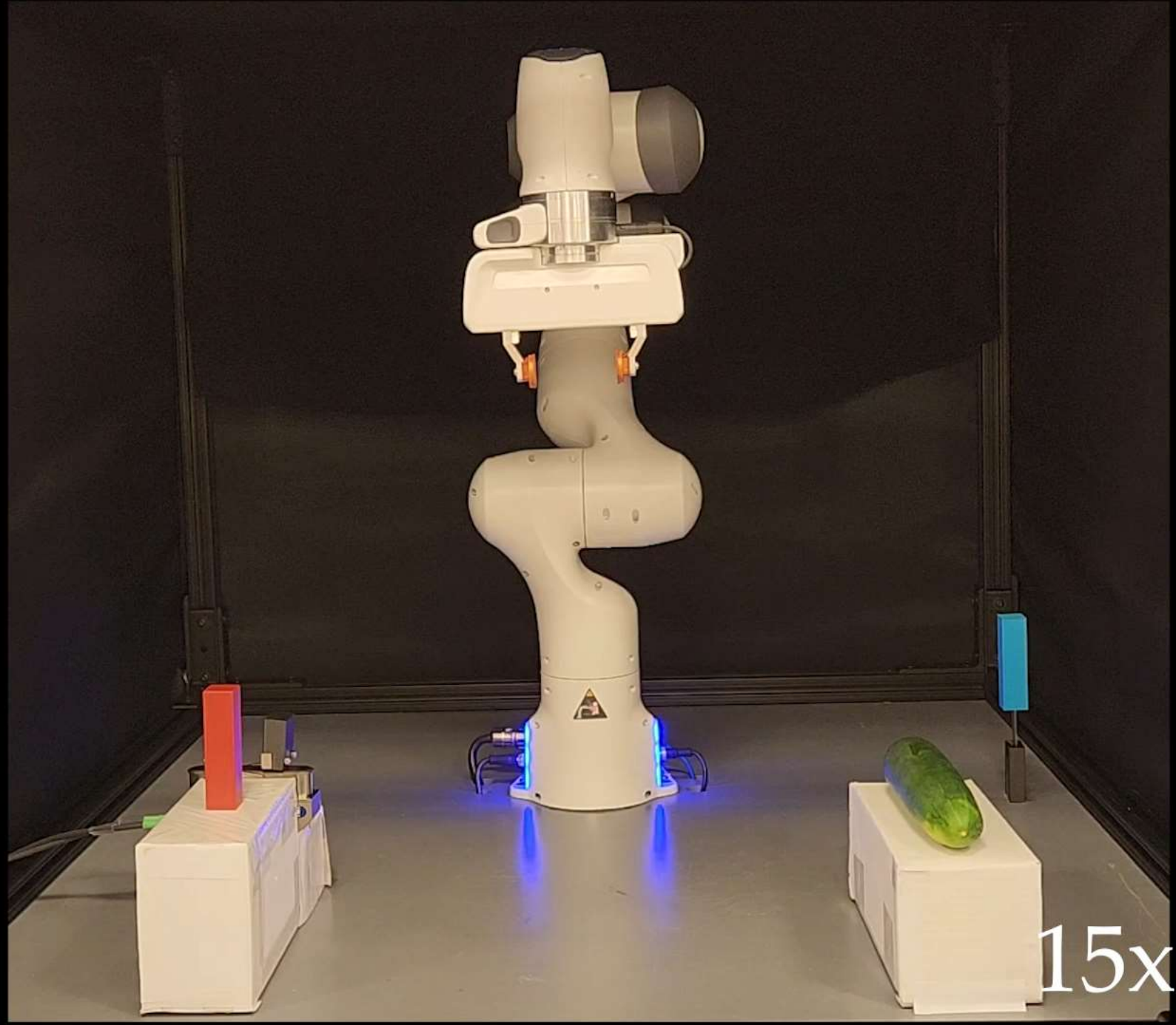
[grasp red block]
[place red block somewhere]
[grasp cucumber]
[place cucumber in vise]
[close vise]
[grasp knife]
[move knife to cucumber]
[slice cucumber]

Action Parameters

…

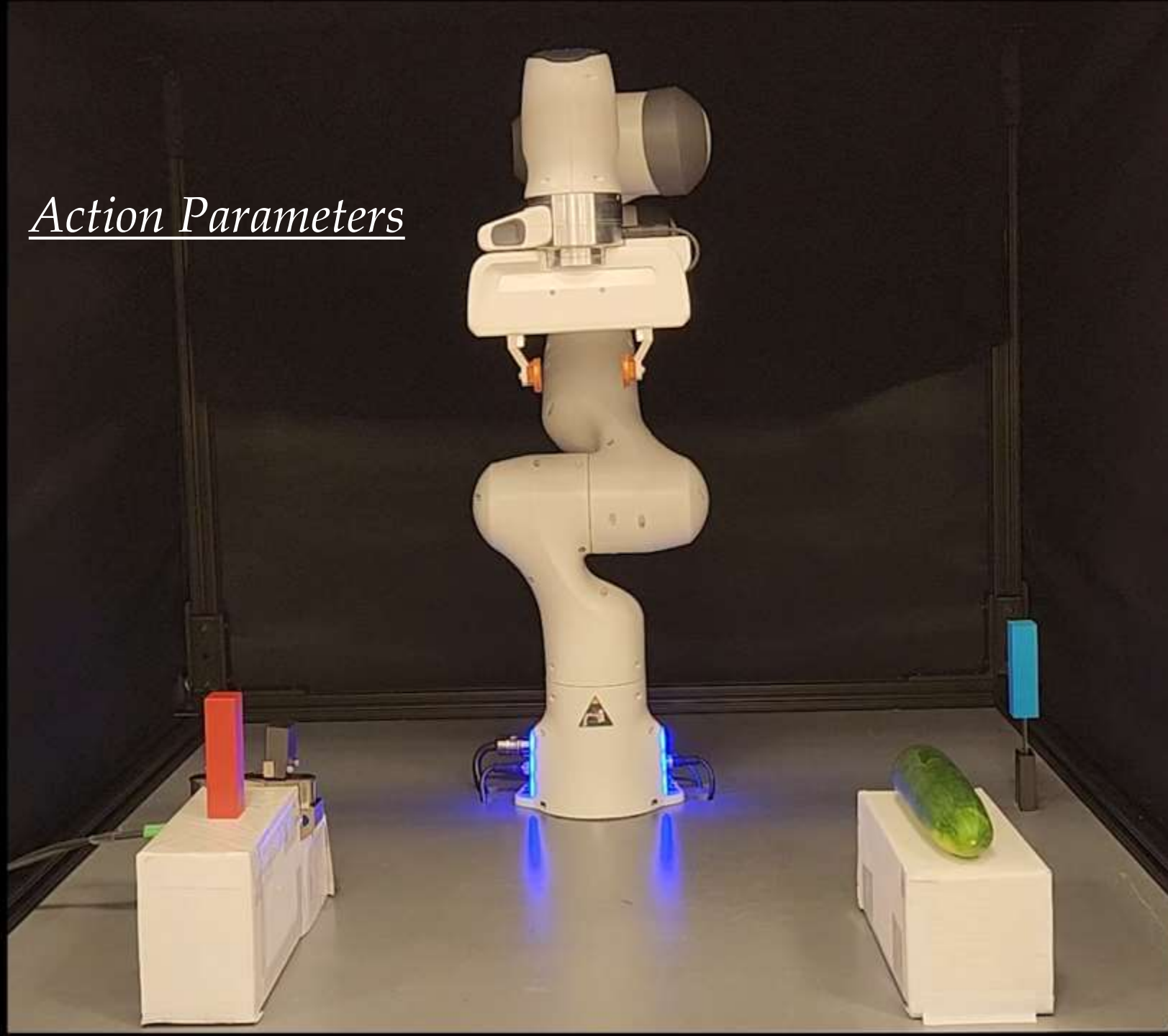


Success?


15x

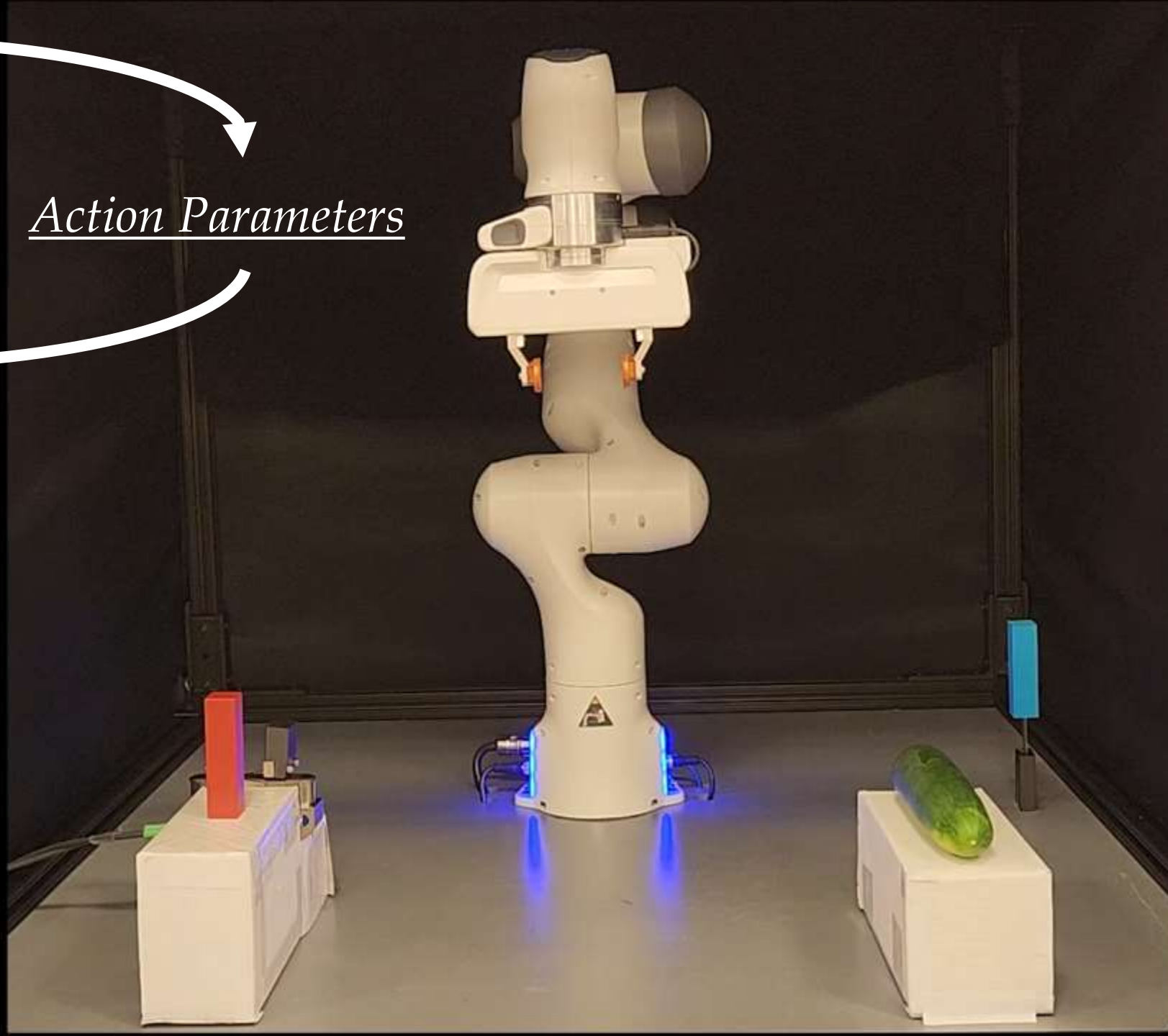
Action Sequence

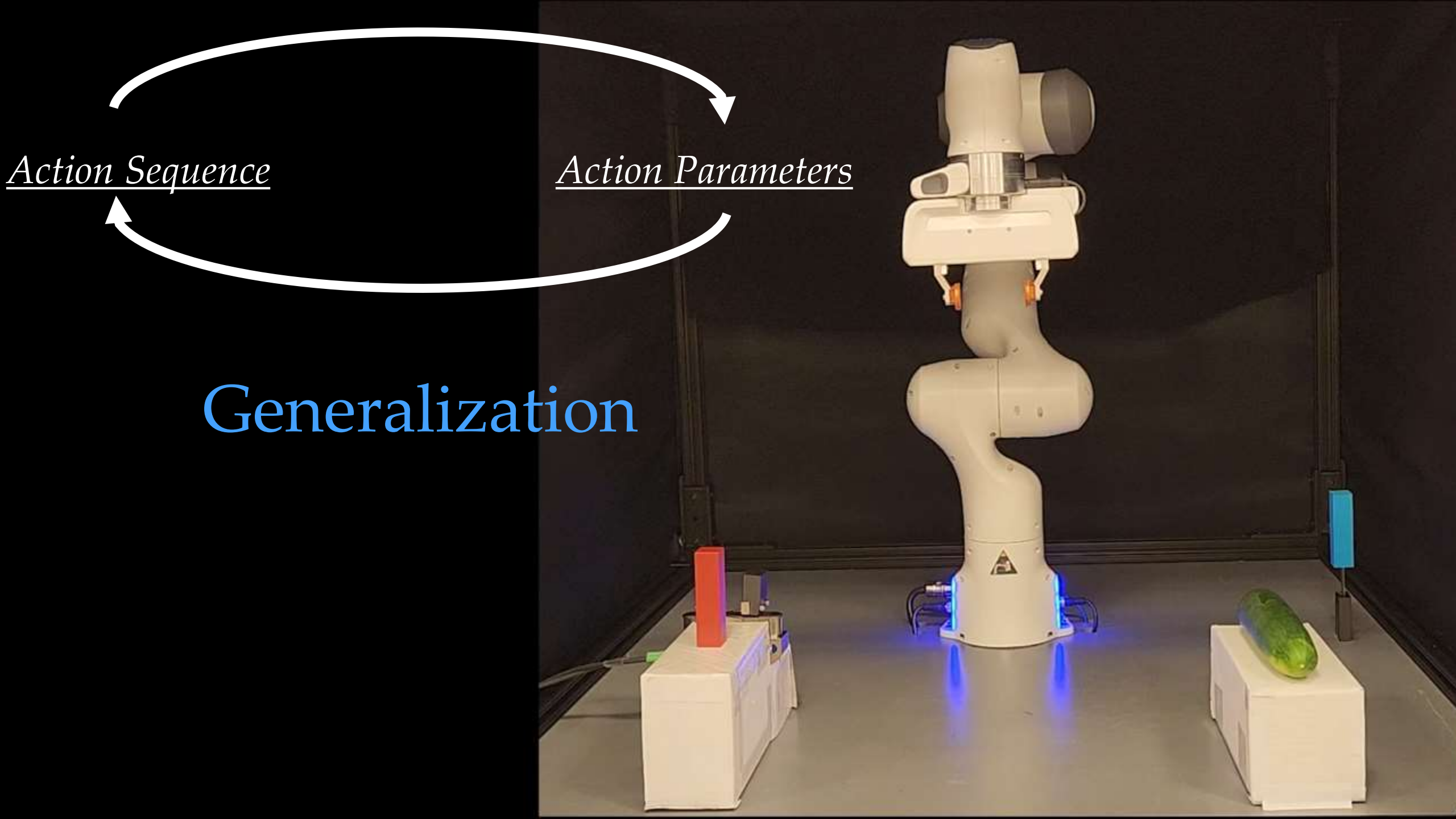
Action Parameters

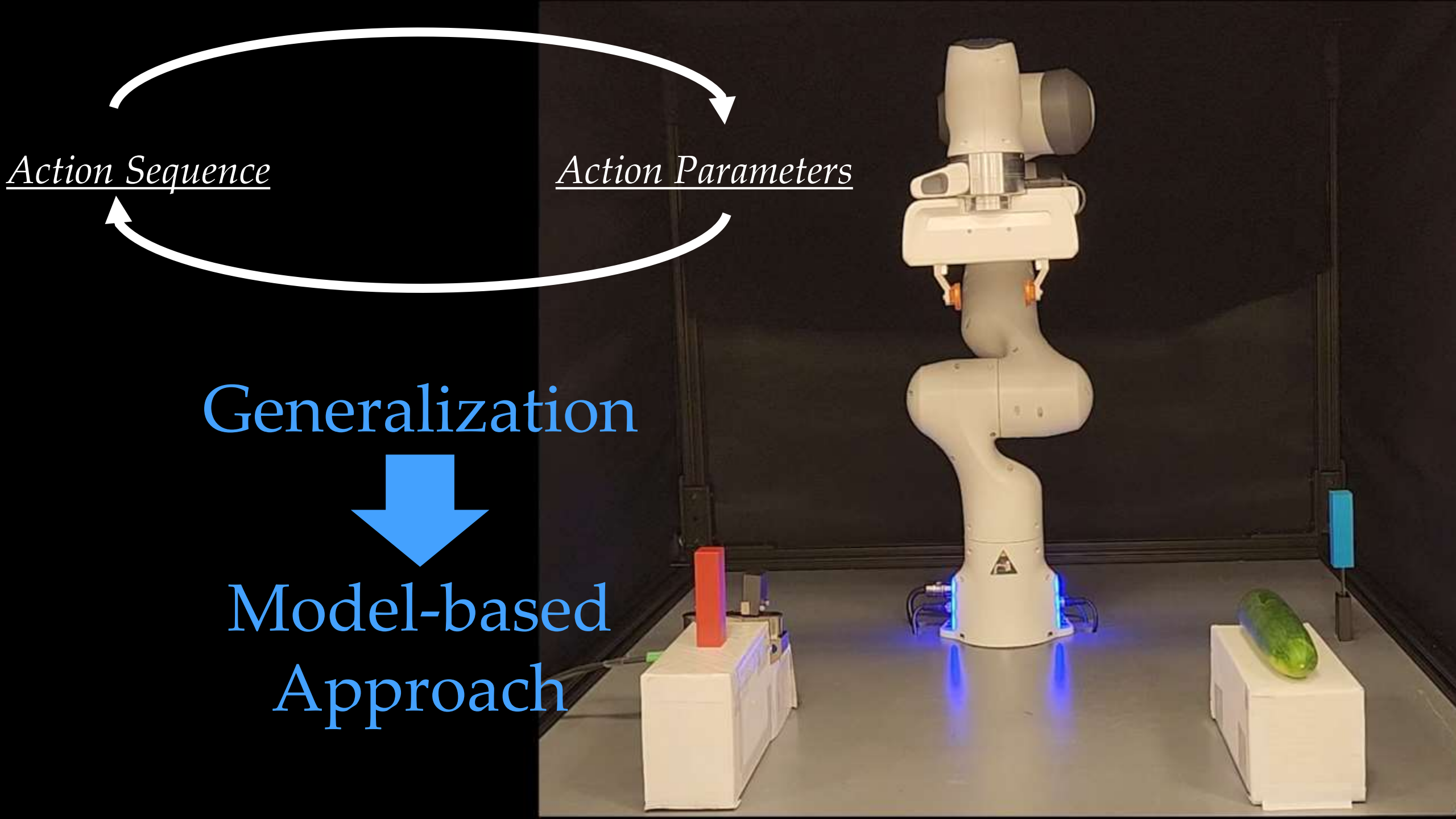


Action Sequence

Action Parameters

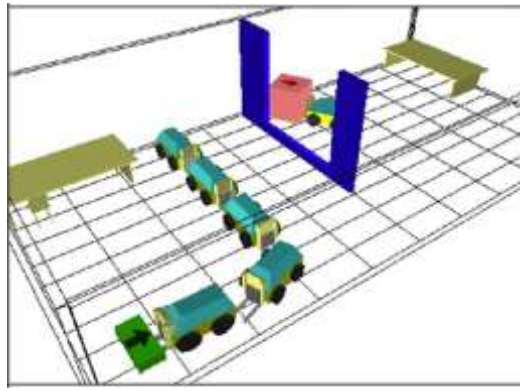



Action Sequence
Action Parameters
Generalization

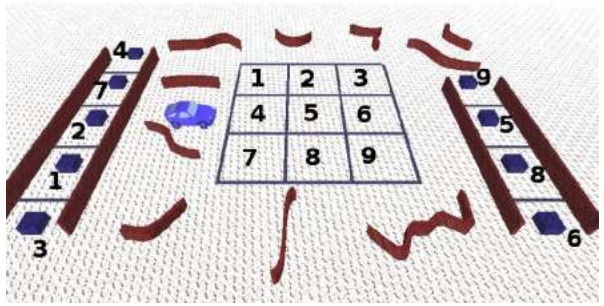

Action Sequence
Action Parameters
Generalization
Model-based
Approach

Task and Motion Planning (TAMP)

Survey Paper: Garrett, Caelan Reed, Rohan Chitnis, Rachel Holladay, Beomjoon Kim, Tom Silver, Leslie Pack Kaelbling, and Tomás Lozano-Pérez. "Integrated task and motion planning." Annual review of control, robotics, and autonomous systems, 2021.

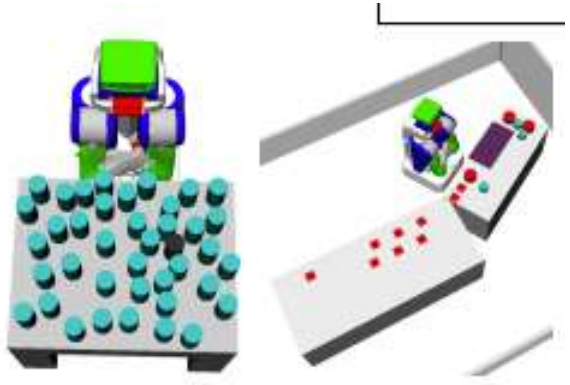


Gravot, et al. (2005)

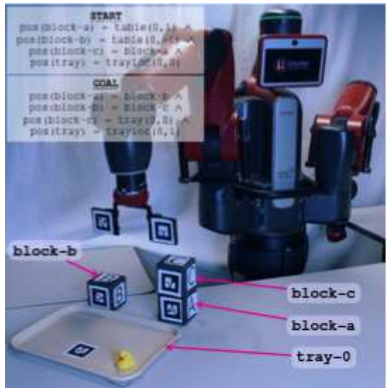


Plaku, Hager (2010)

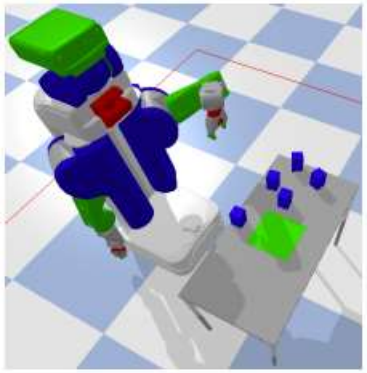
Kaelbling, Lozano-Perez (2013)



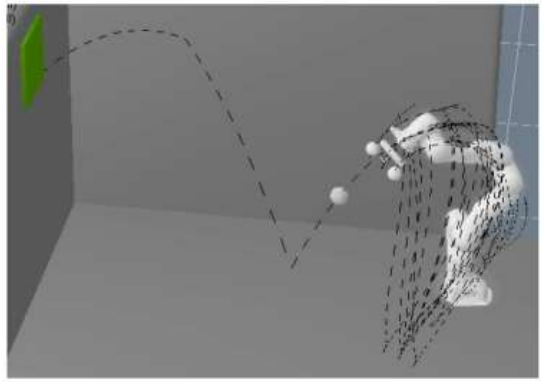
Srivastava et al. (2014)



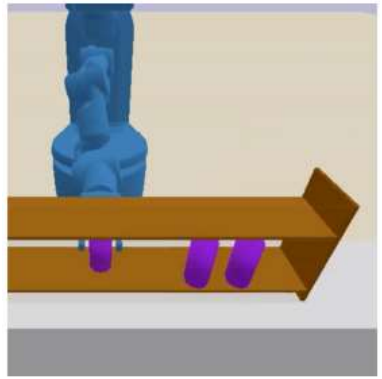
Dantam et al. (2016)



Garrett, et al. (2020)



Toussaint, et al. (2020)*



Silver, et al. (2021)

Reasoning over Geometry

Is a motion collision-free?

Is that placement free?

Reasoning over Geometry

Is the grasp available?

Is an object reachable?

(only)

Reasoning over Geometry

(only)

Reasoning over Geometry






Reasoning over Geometry *and* Physics






Reasoning over Geometry *and* Physics

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

Forceful Manipulation

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

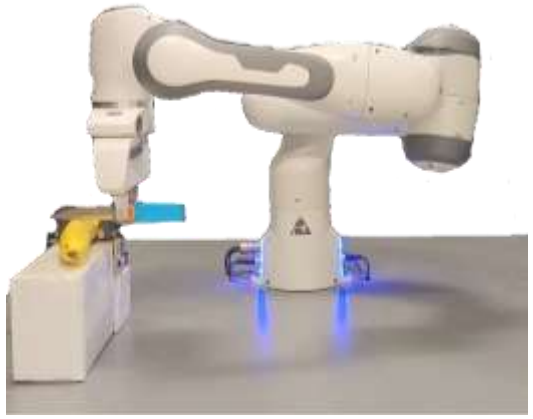
In-Hand Manipulation

Forceful Manipulation

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

In-Hand Manipulation

Forceful Manipulation



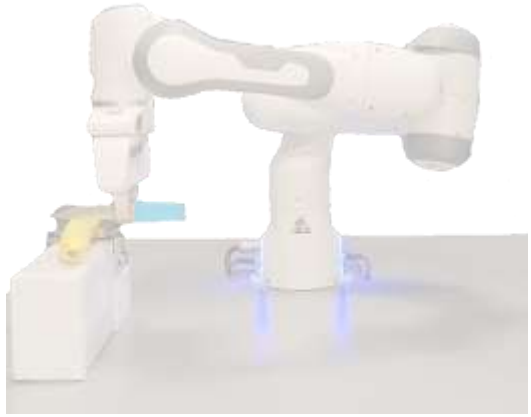
Robust Decision Making

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

In-Hand Manipulation

Guarded Planning

Forceful Manipulation



Robust Decision Making

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

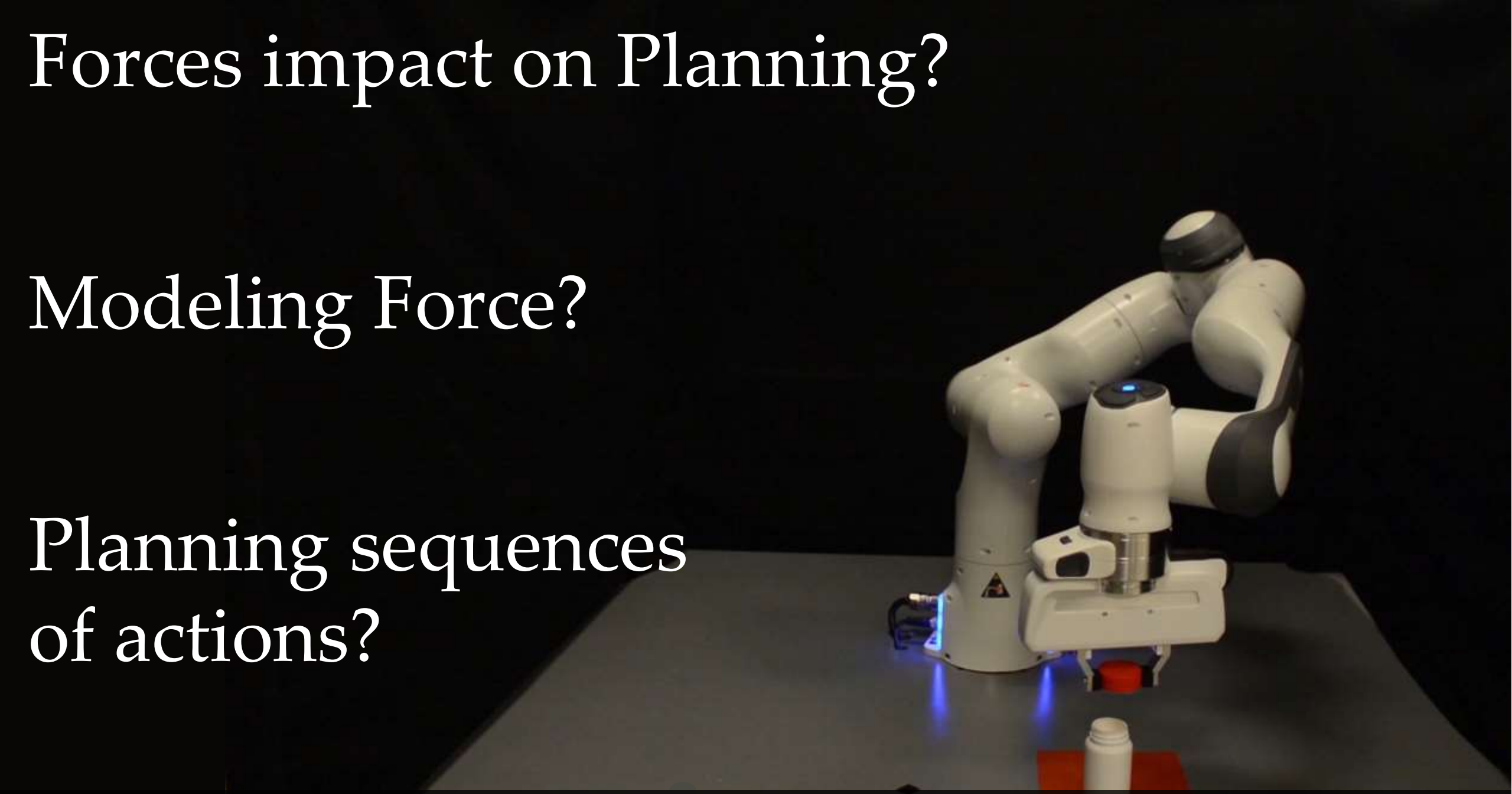
In-Hand Manipulation

Guarded Planning

Forces impact on Planning?

Modeling Force?

Planning sequences of actions?



"Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *ICRA*, 2021.
"Robust Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *IJRR*, 2023.

Opening a Childproof Bottle

Opening a Childproof Bottle

- Push down on the cap

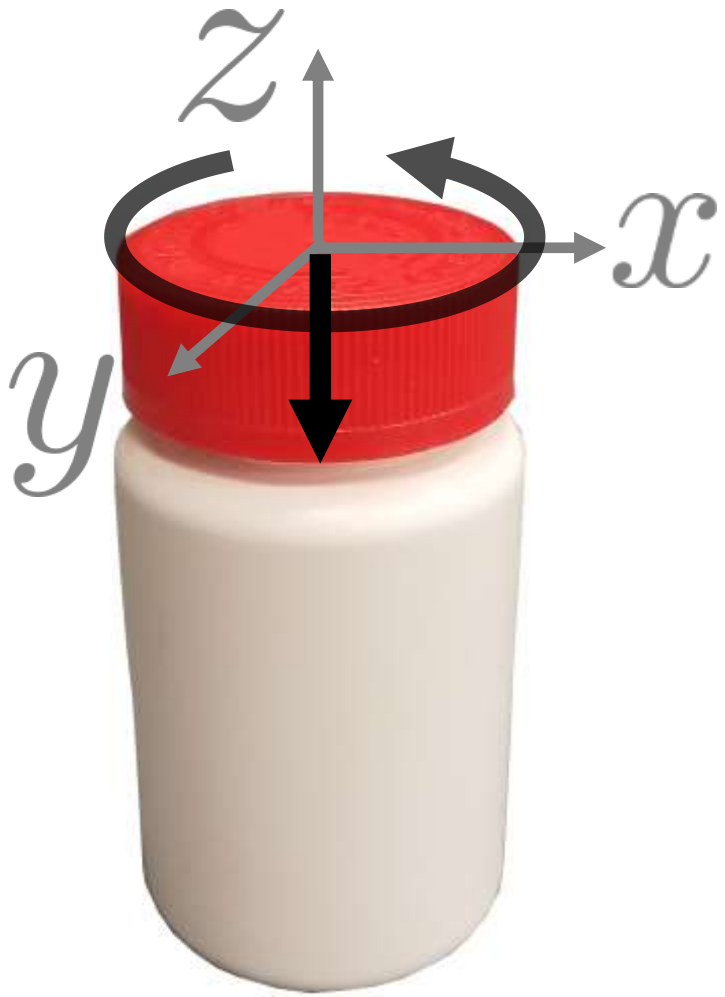
Opening a Childproof Bottle

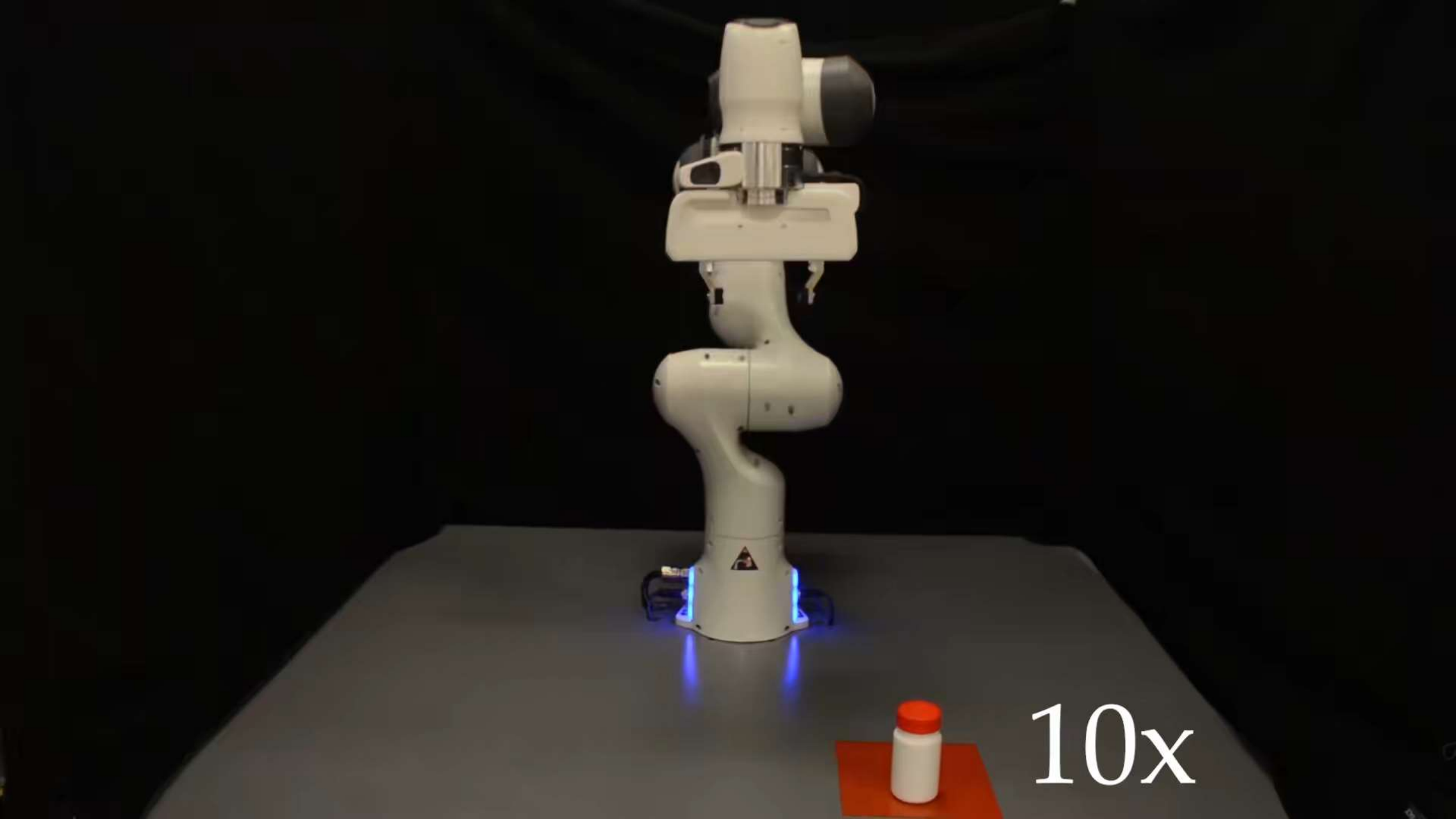
- Push down on the cap
- Twist the cap

Opening a Childproof Bottle

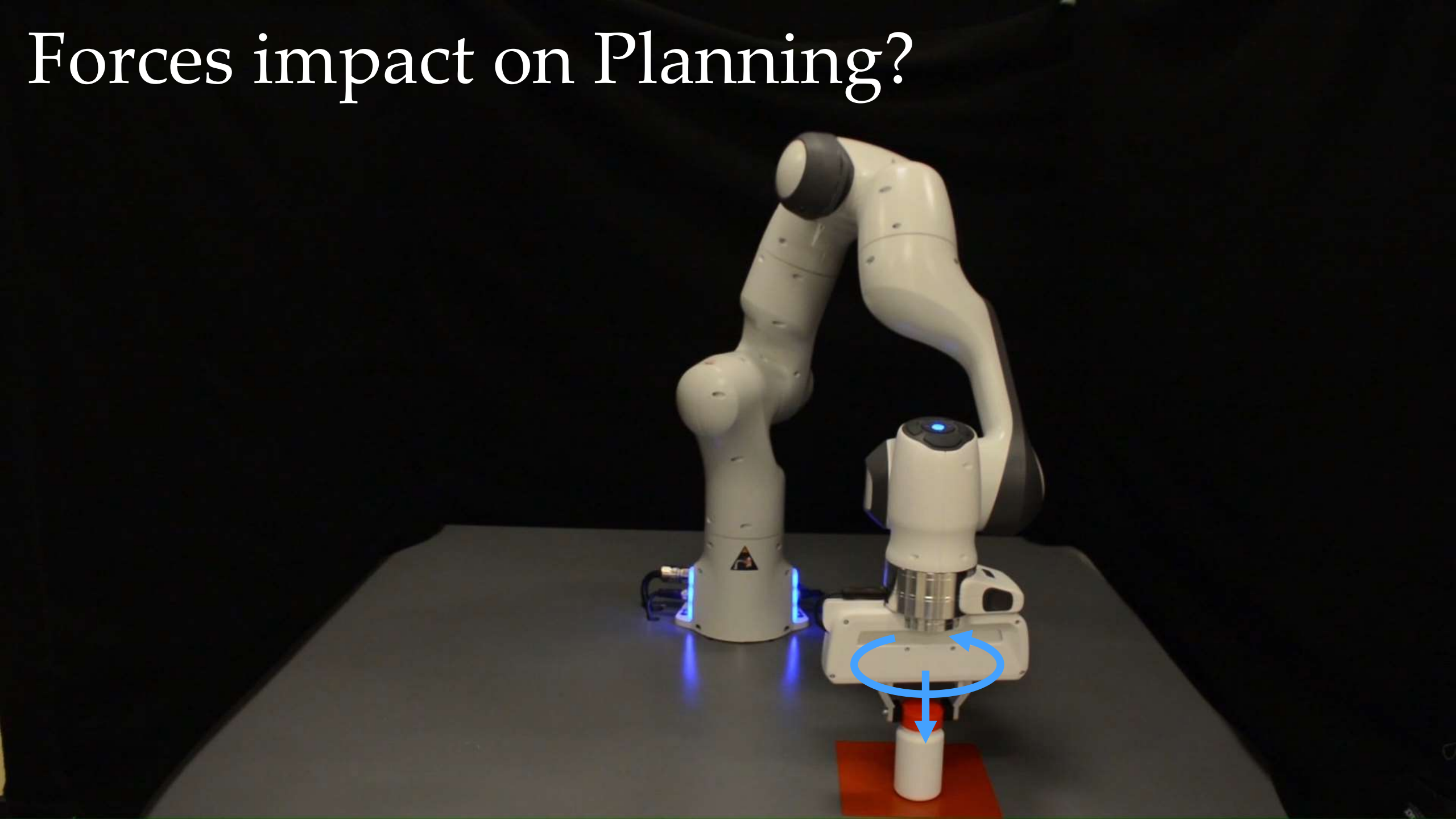
- Push down on the cap
- Twist the cap

$$(0, 0, -f_z, 0, 0, t_z)$$

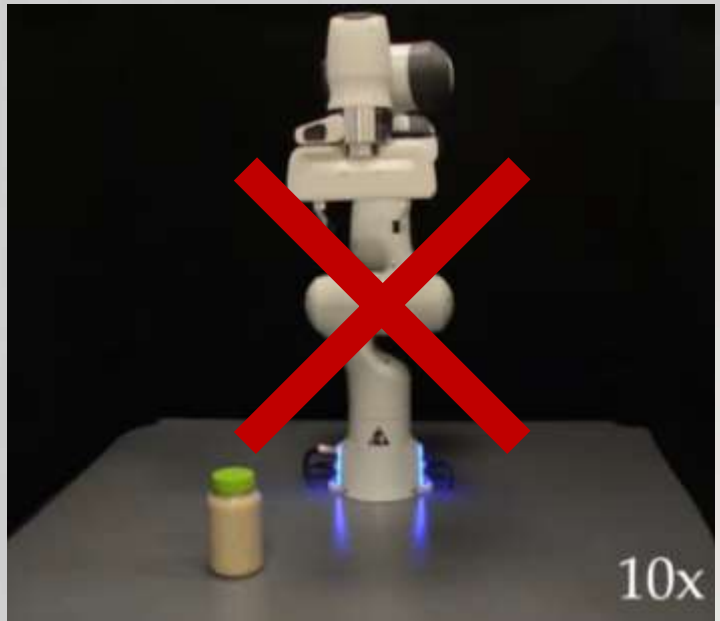



10x

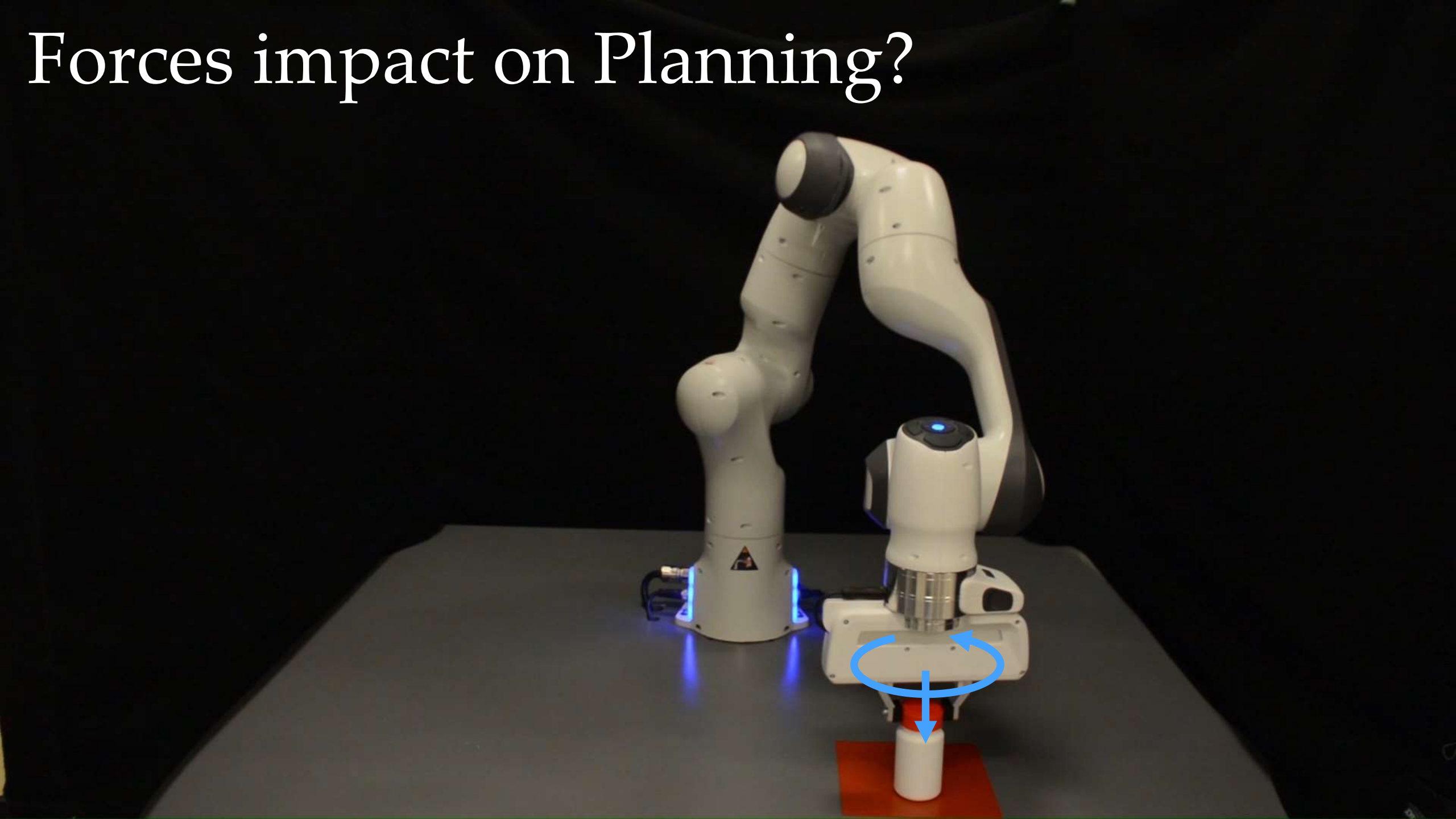
Forces impact on Planning?



Forces impact on Planning?

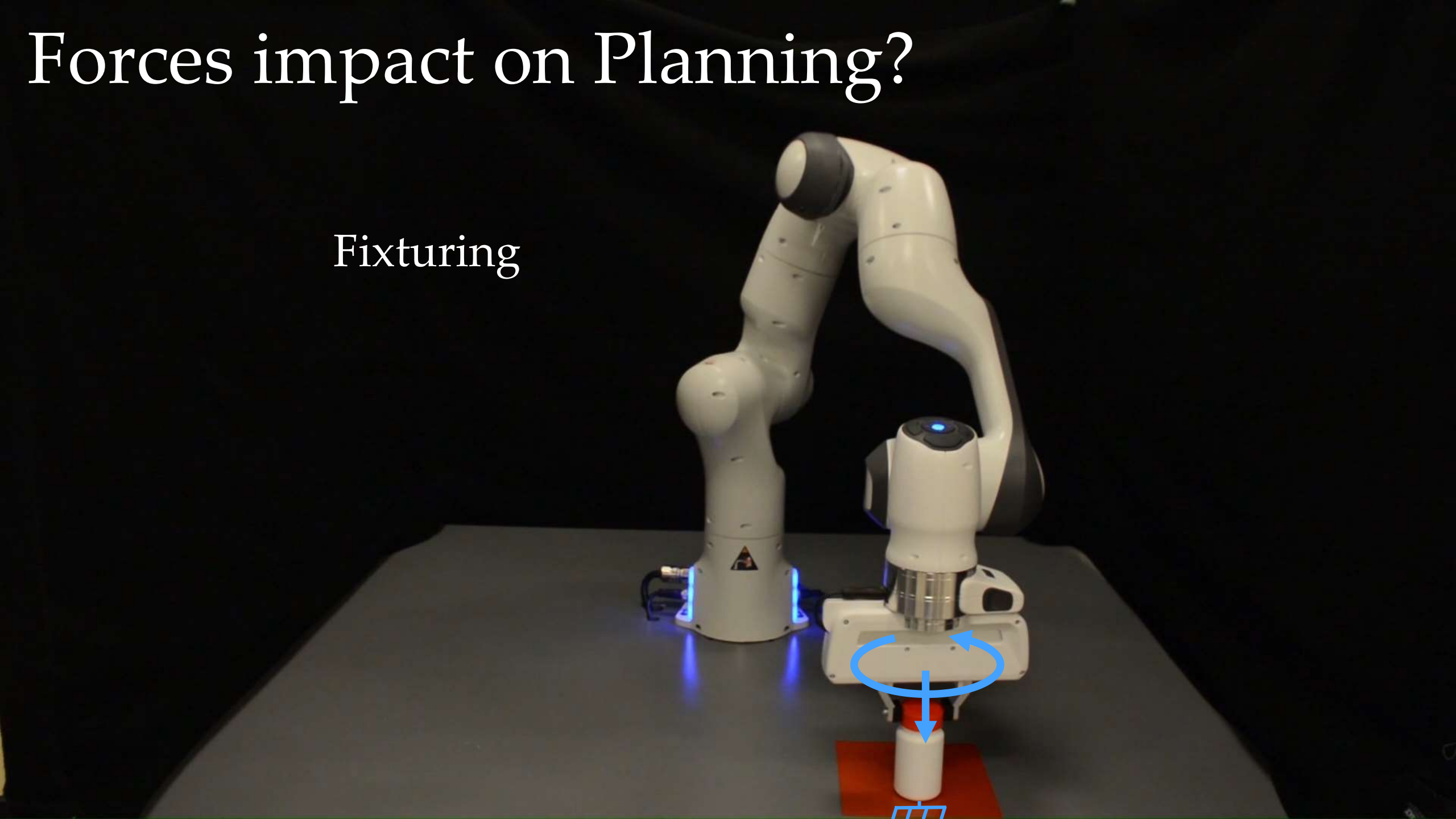


Forces impact on Planning?



Forces impact on Planning?

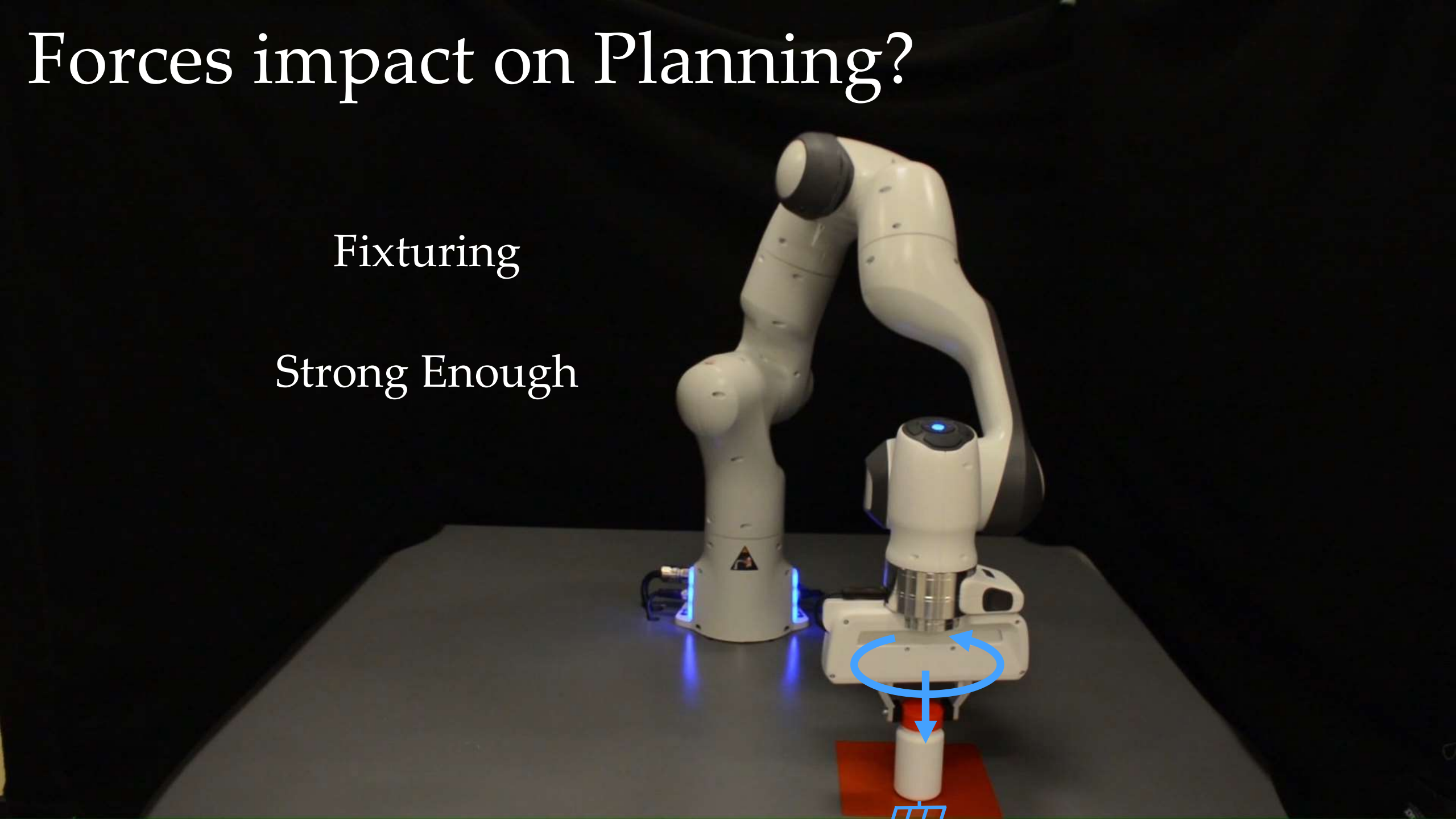
Fixturing

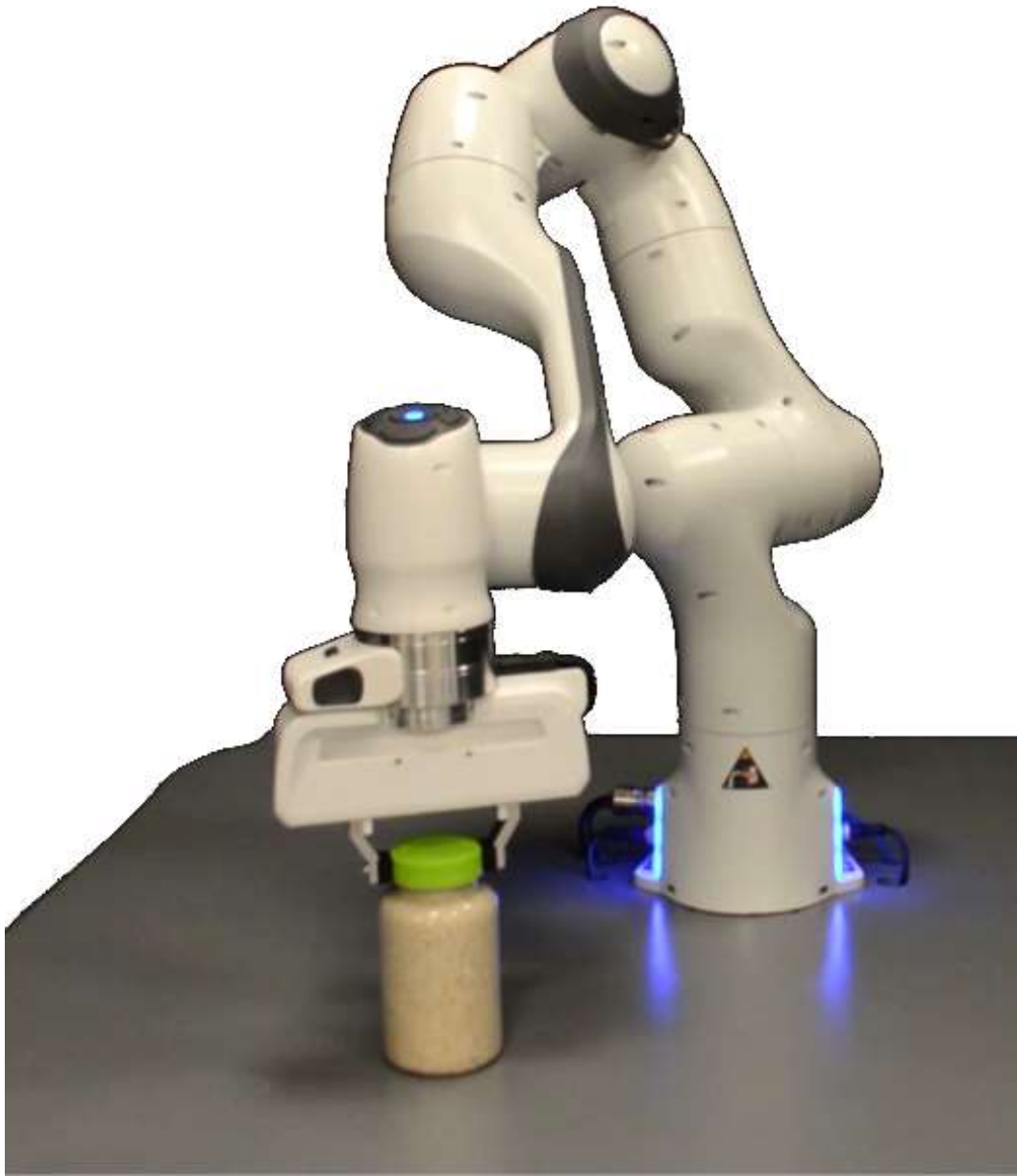


Forces impact on Planning?

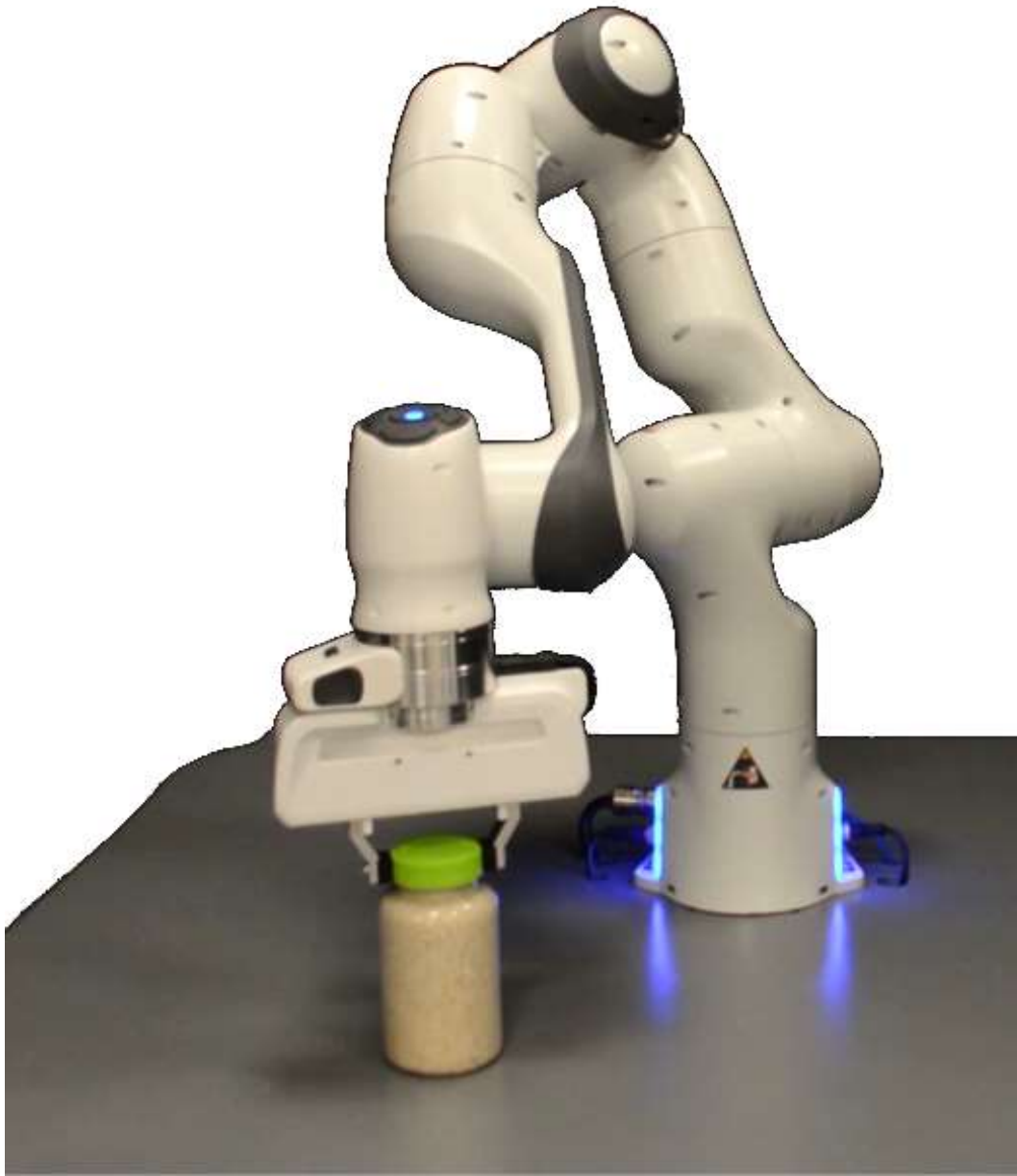
Fixturing

Strong Enough

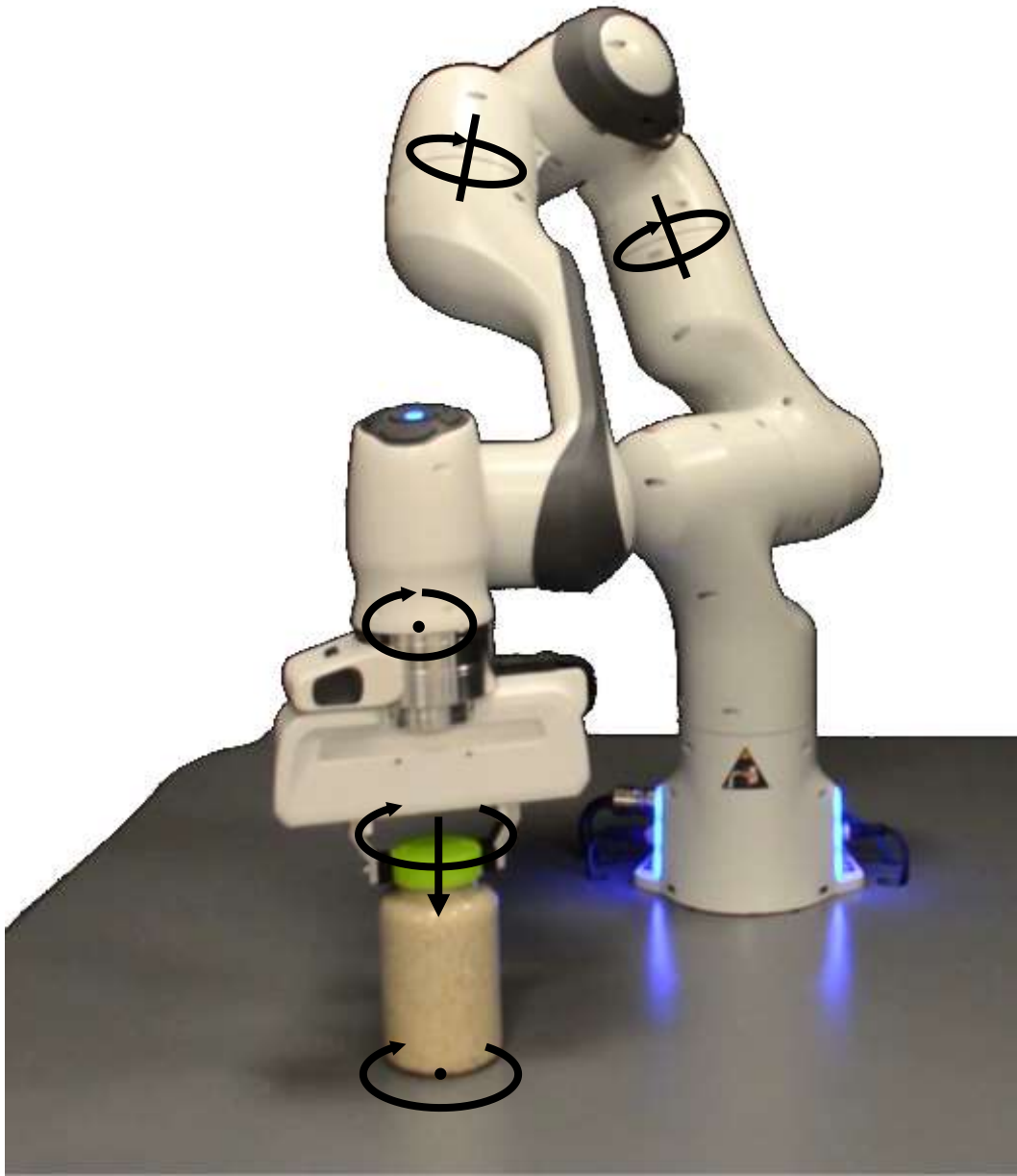




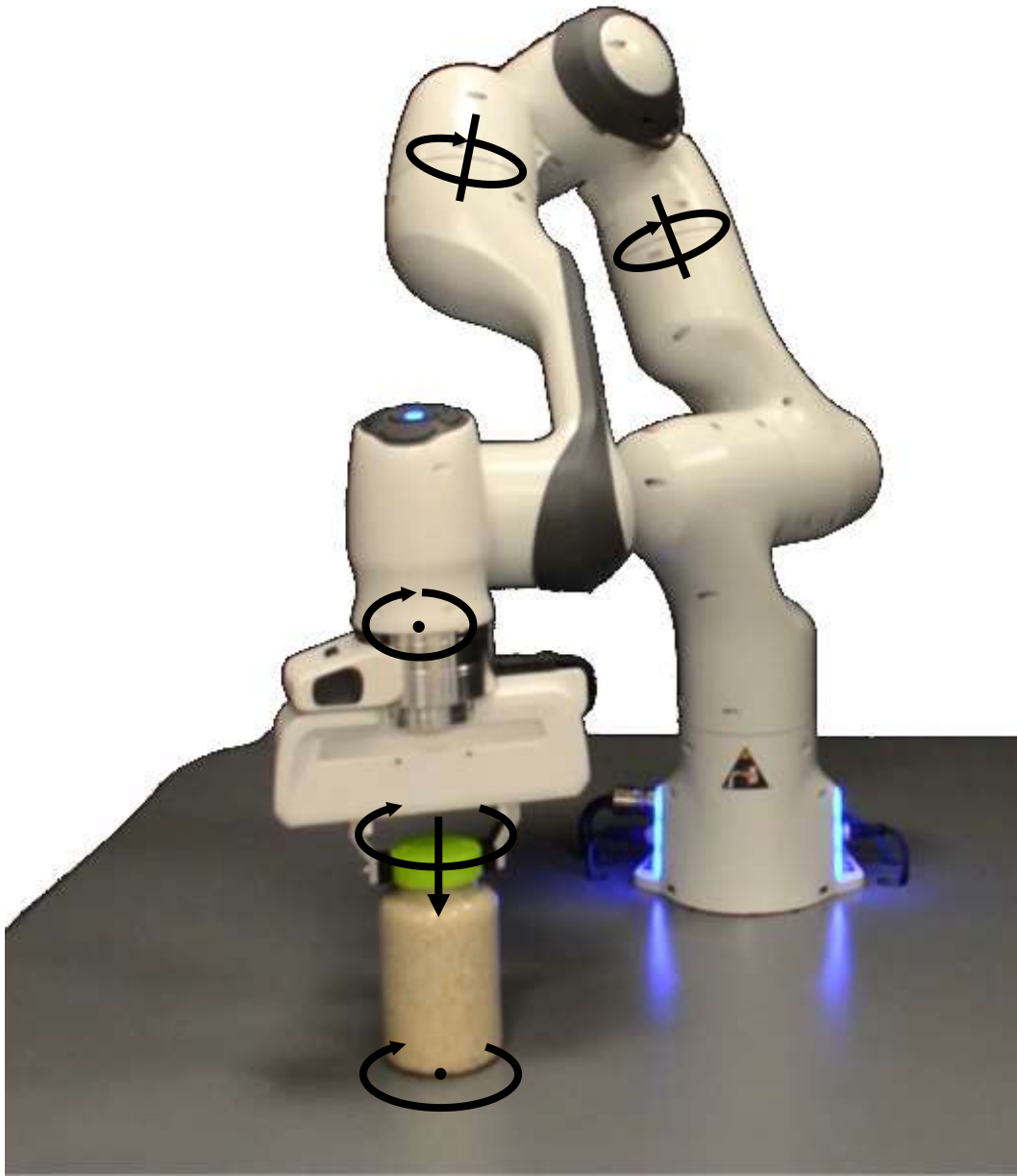
Kinematic Chain

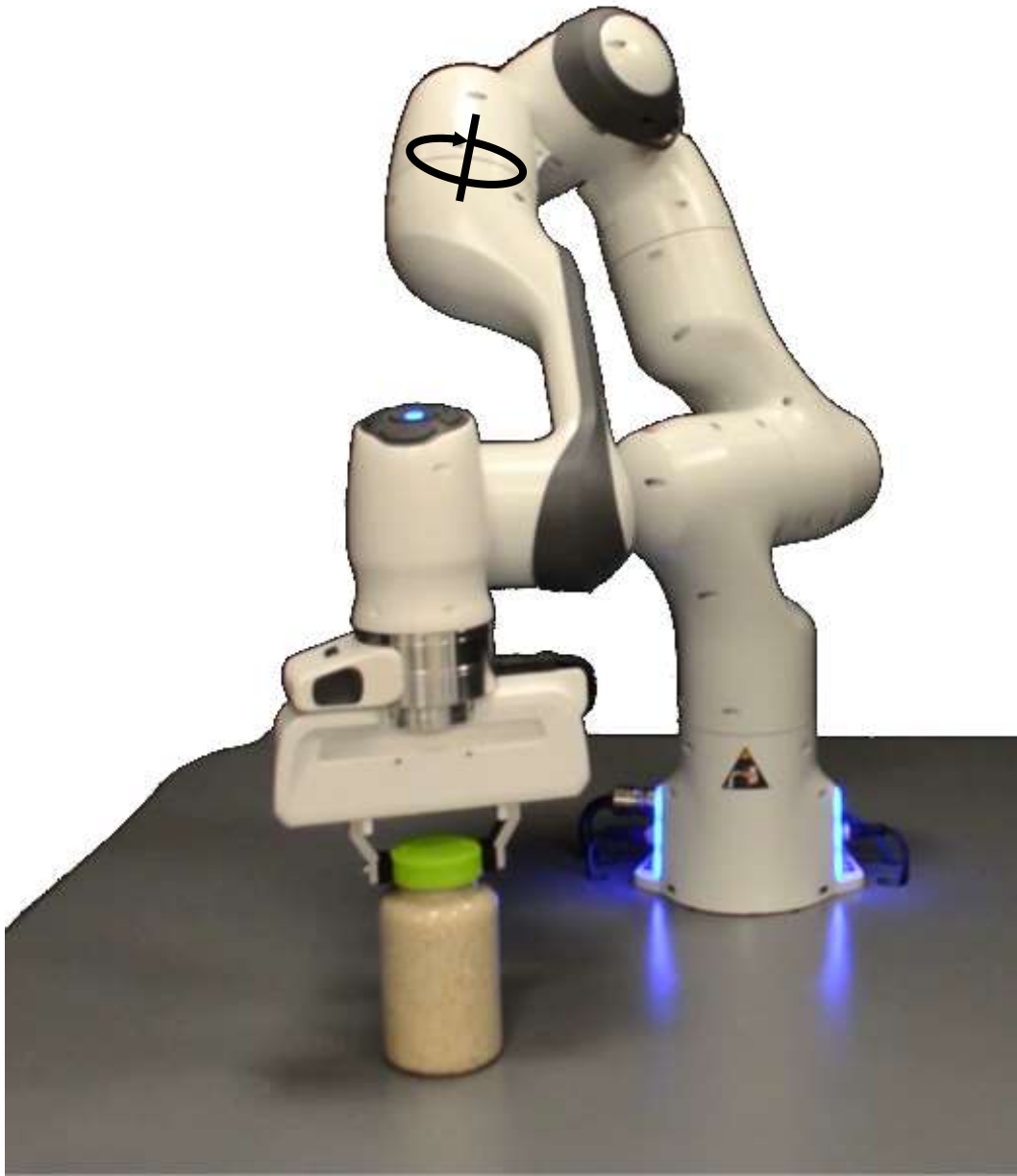


Kinematic Chain

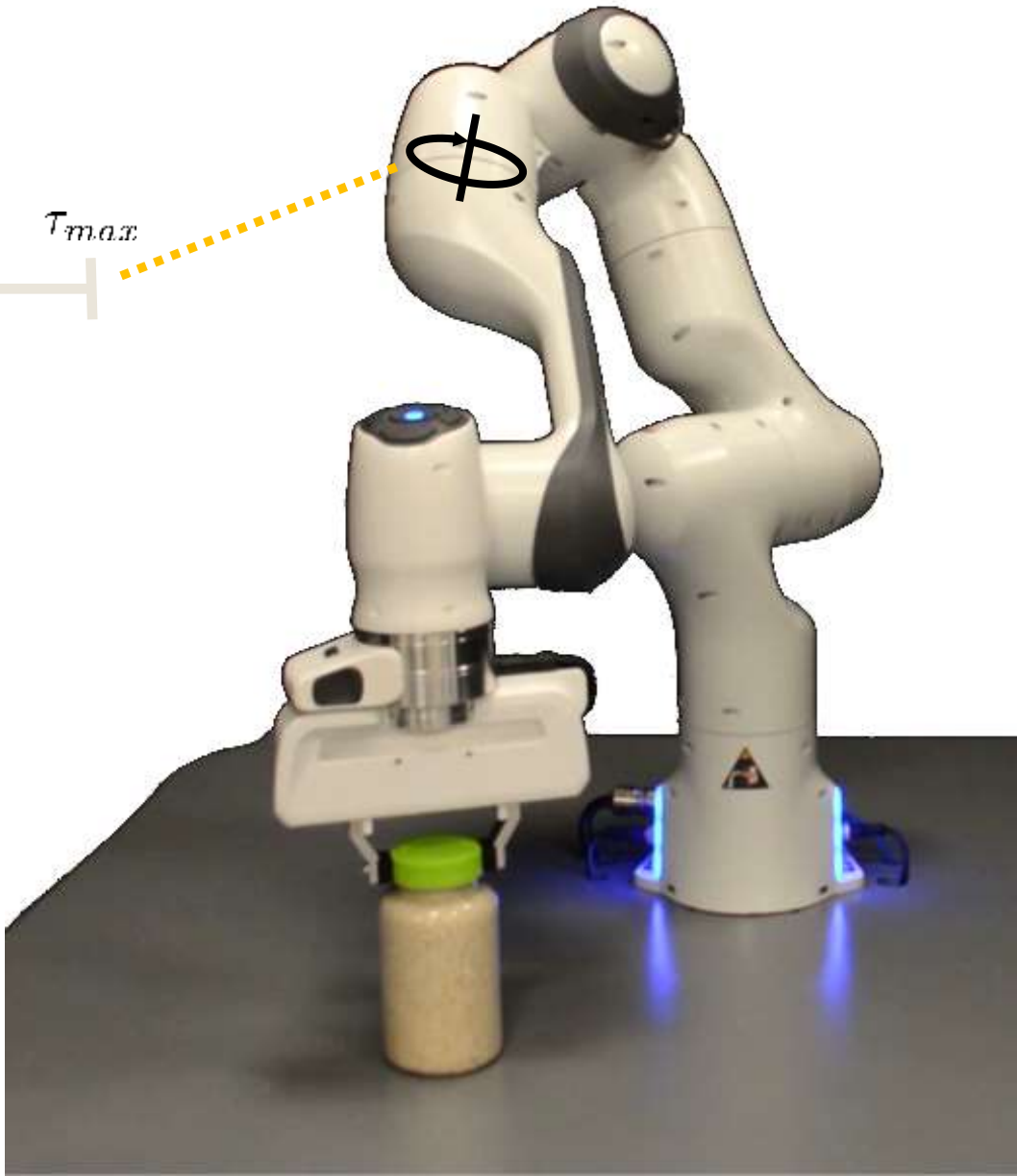


Forceful Kinematic Chain

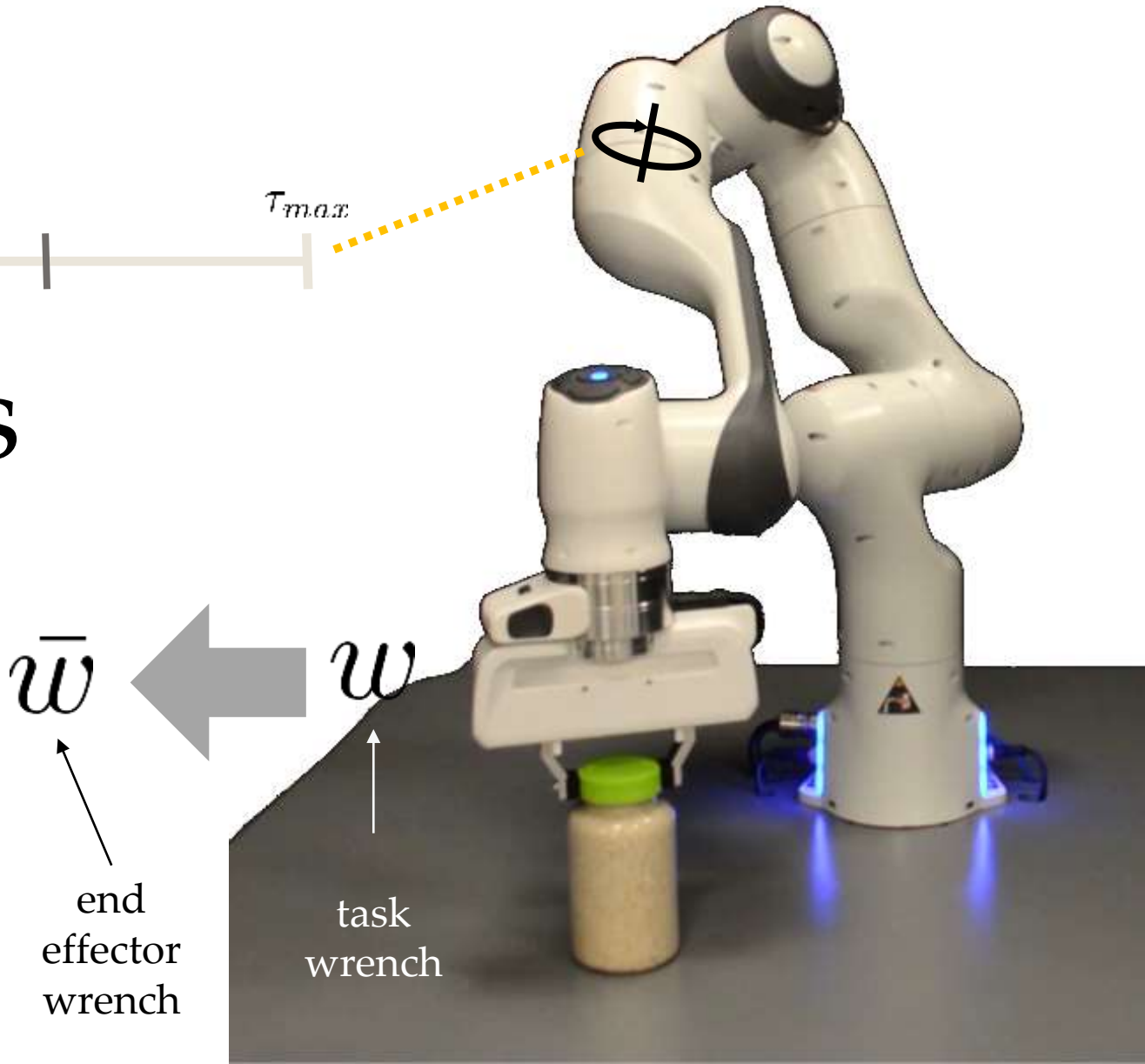




Torque Limits



Torque Limits



Torque Limits

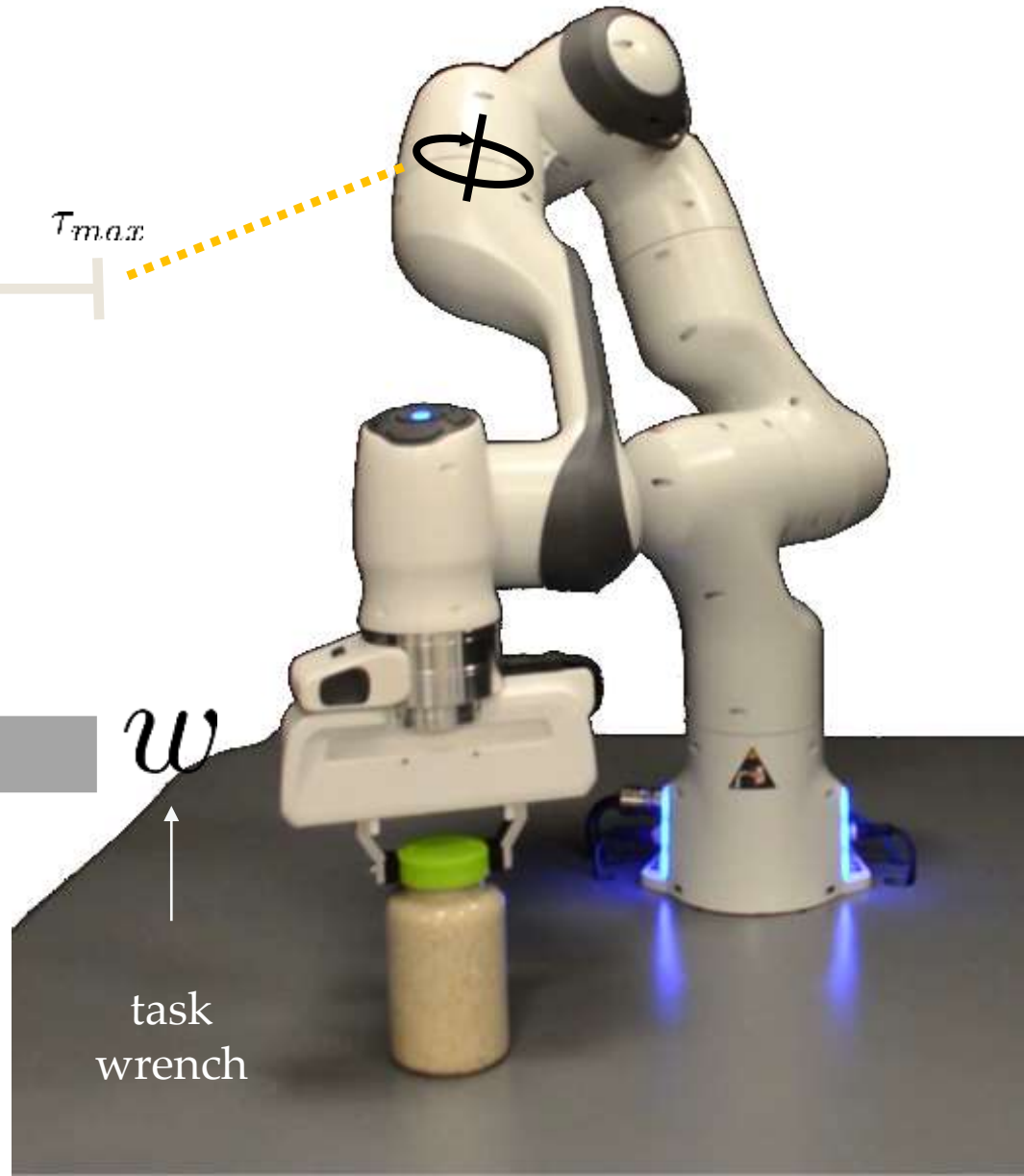
τ_{min} τ_{max}

τ $\bar{w}$ w

joint torques

end effector wrench

task wrench



Torque Limits

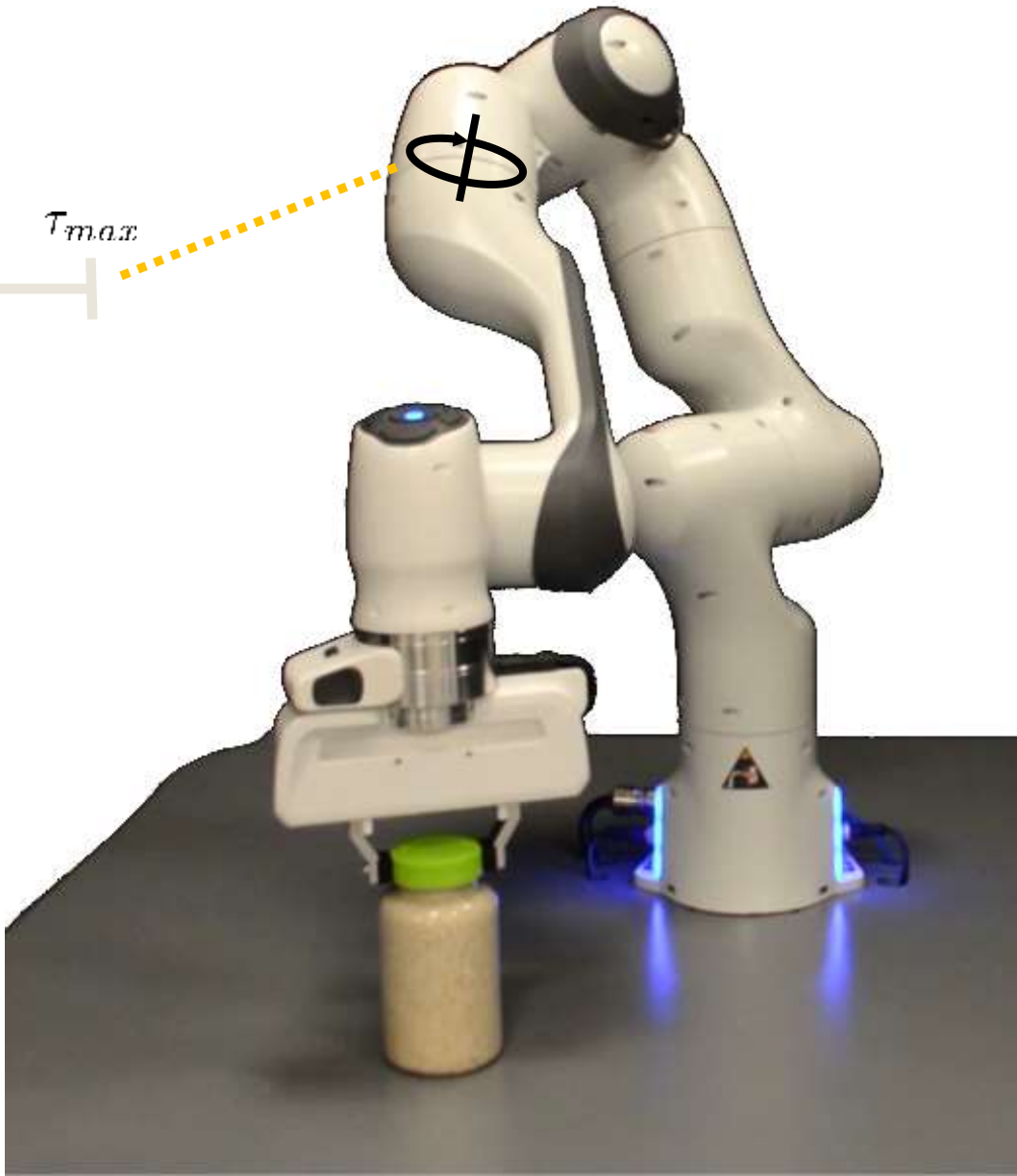
$$\tau = J_m^T(q)\bar{w}$$

joint torques

manipulator jacobian

joint angles

end effector wrench



Torque Limits

$$\tau_{lim} > \tau = J_m^T(q)\bar{w}$$

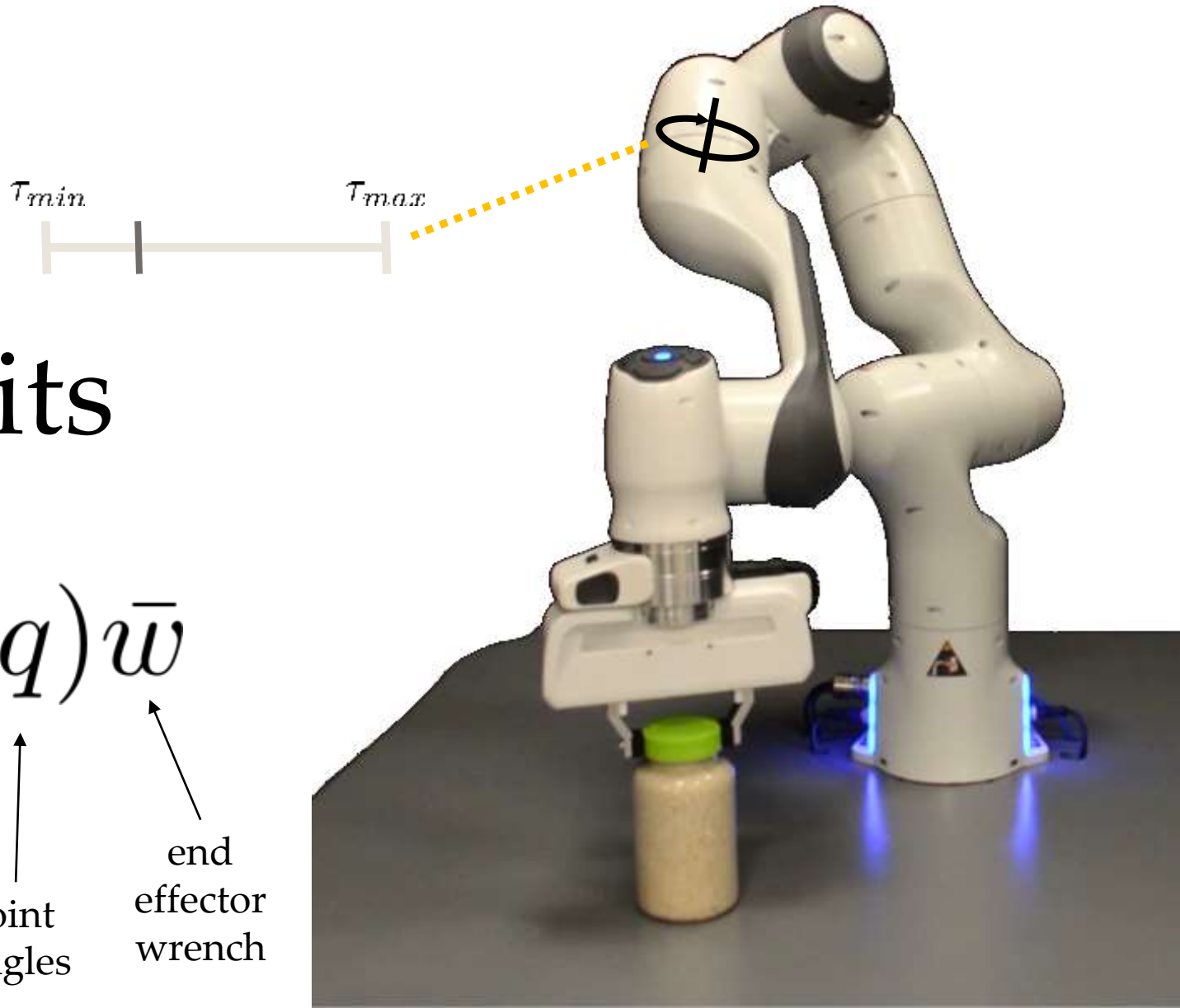
torque limits

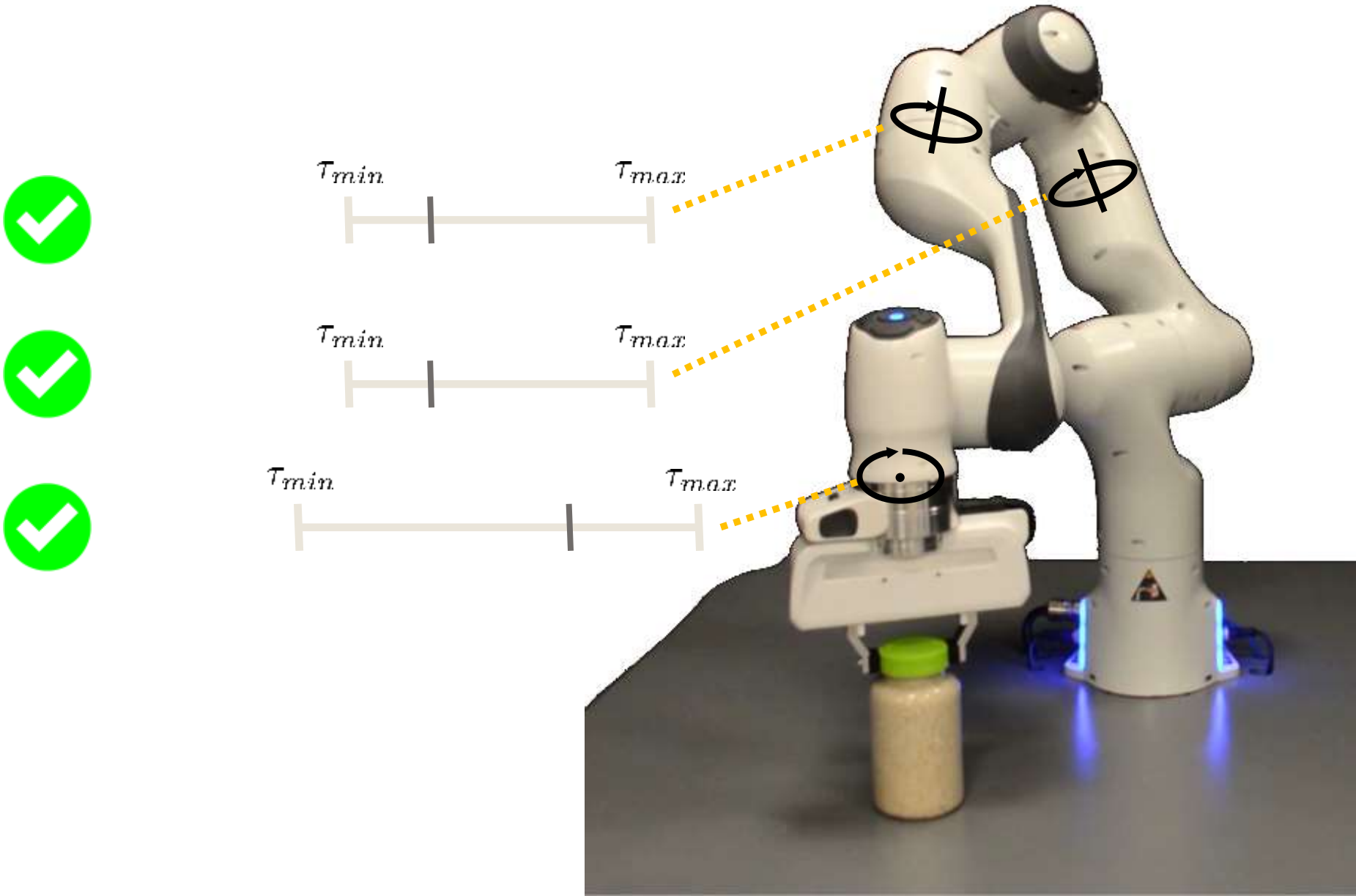
joint torques

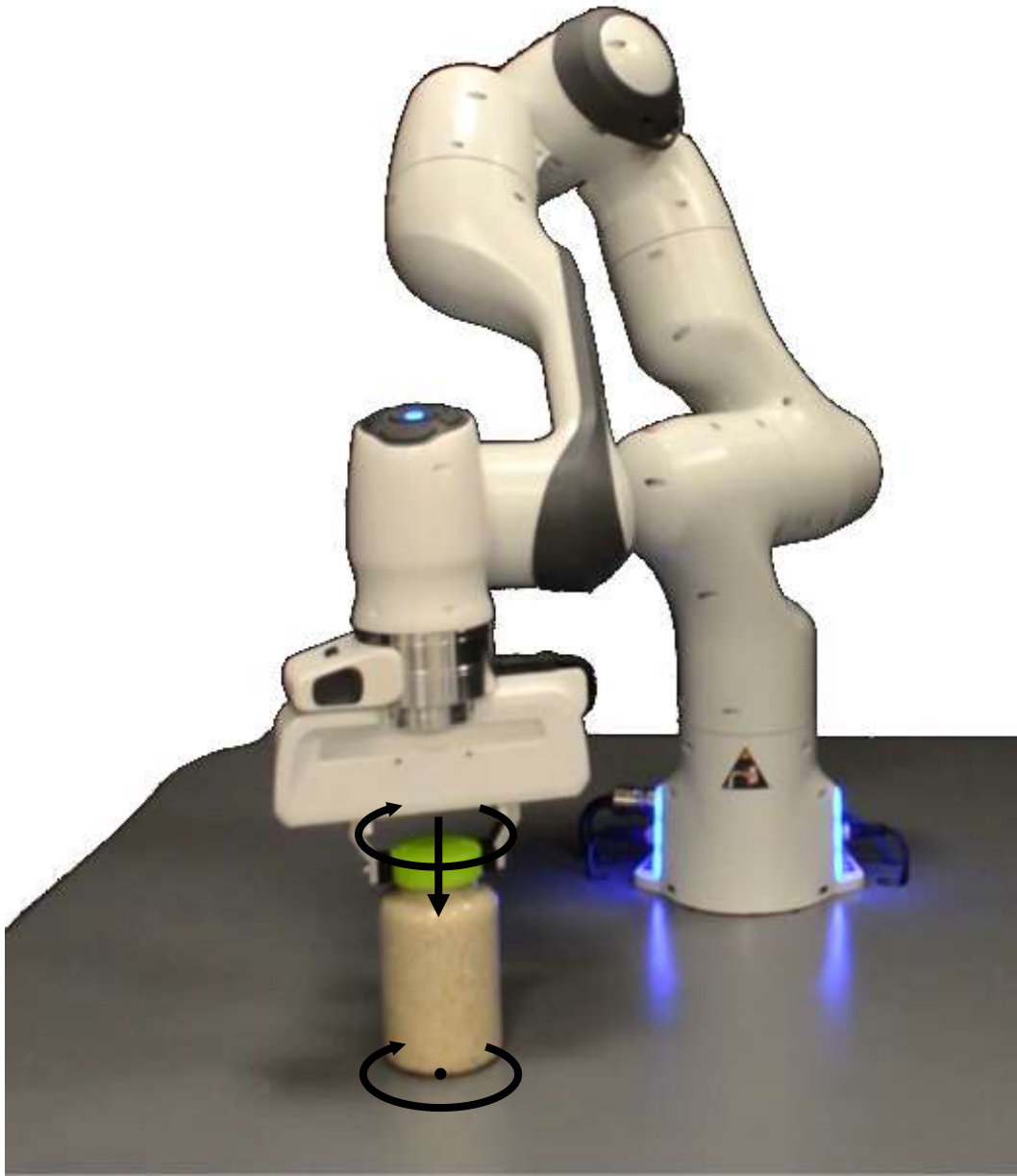
manipulator jacobian

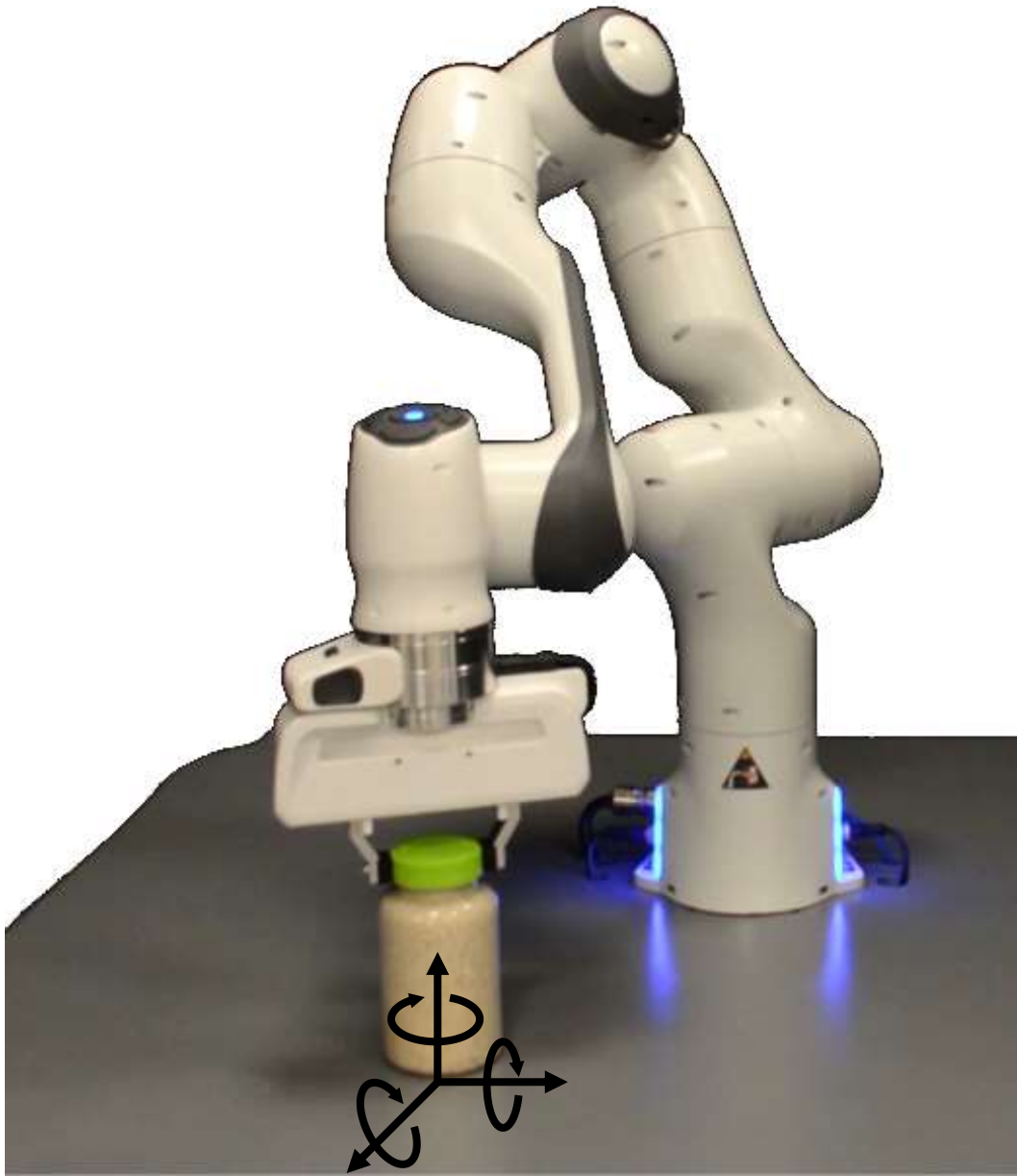
joint angles

end effector wrench

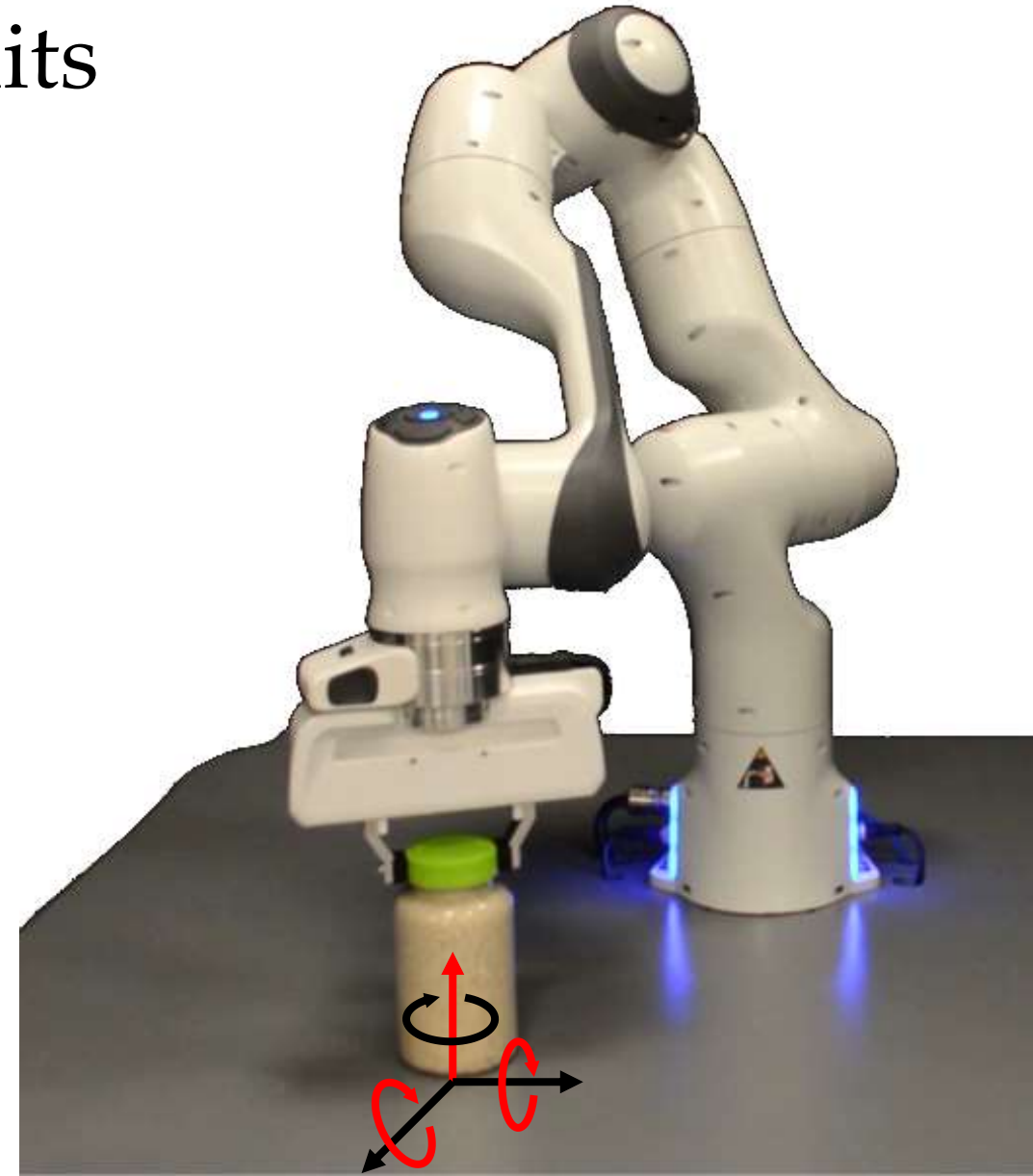



τ_{min}
τ_{max}
τ_{min}
τ_{max}
τ_{min}
τ_{max}

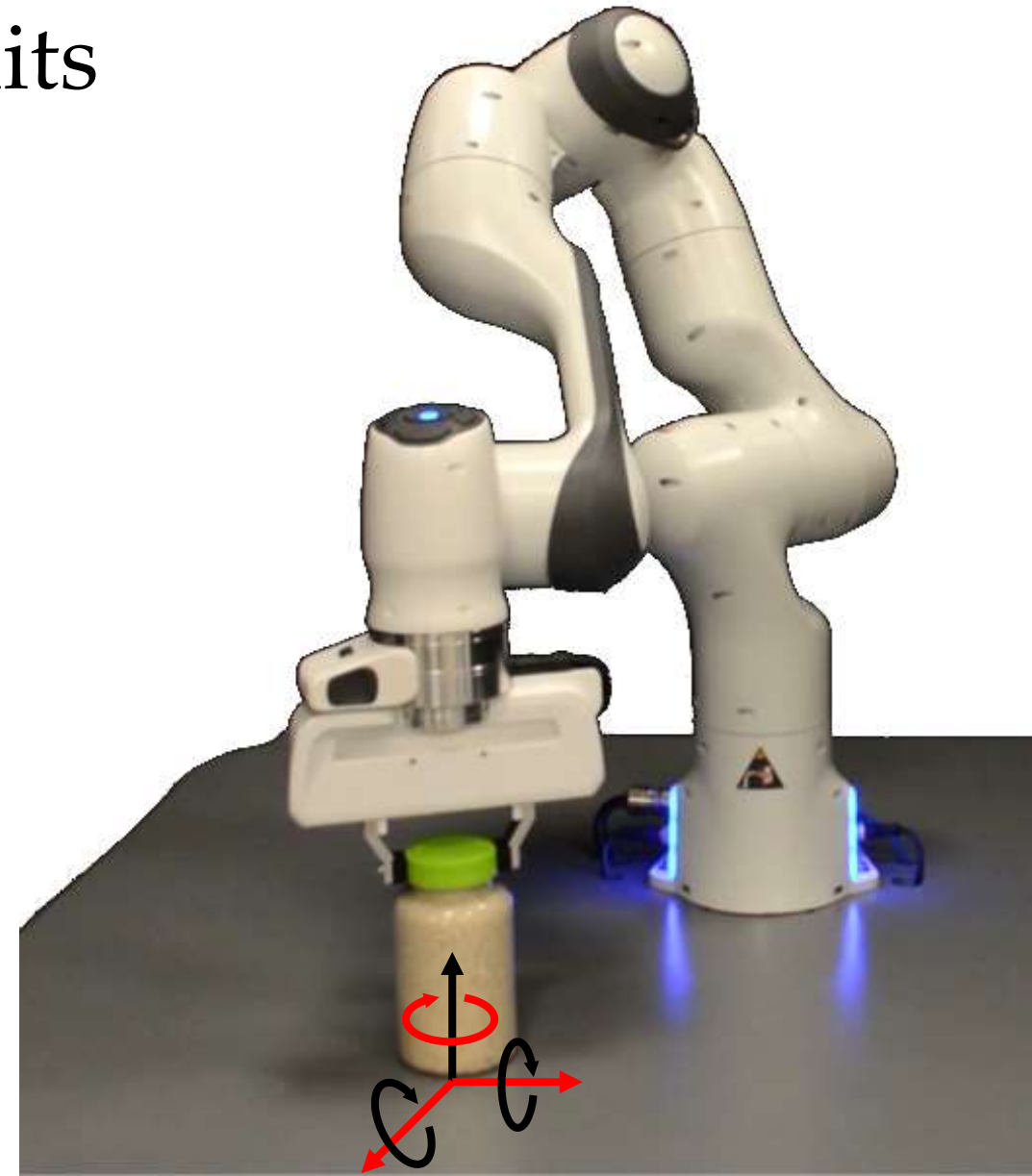




Kinematics: Non-Penetration Limits



Kinematics: Non-Penetration Limits



Kinematics: Non-Penetration Limits

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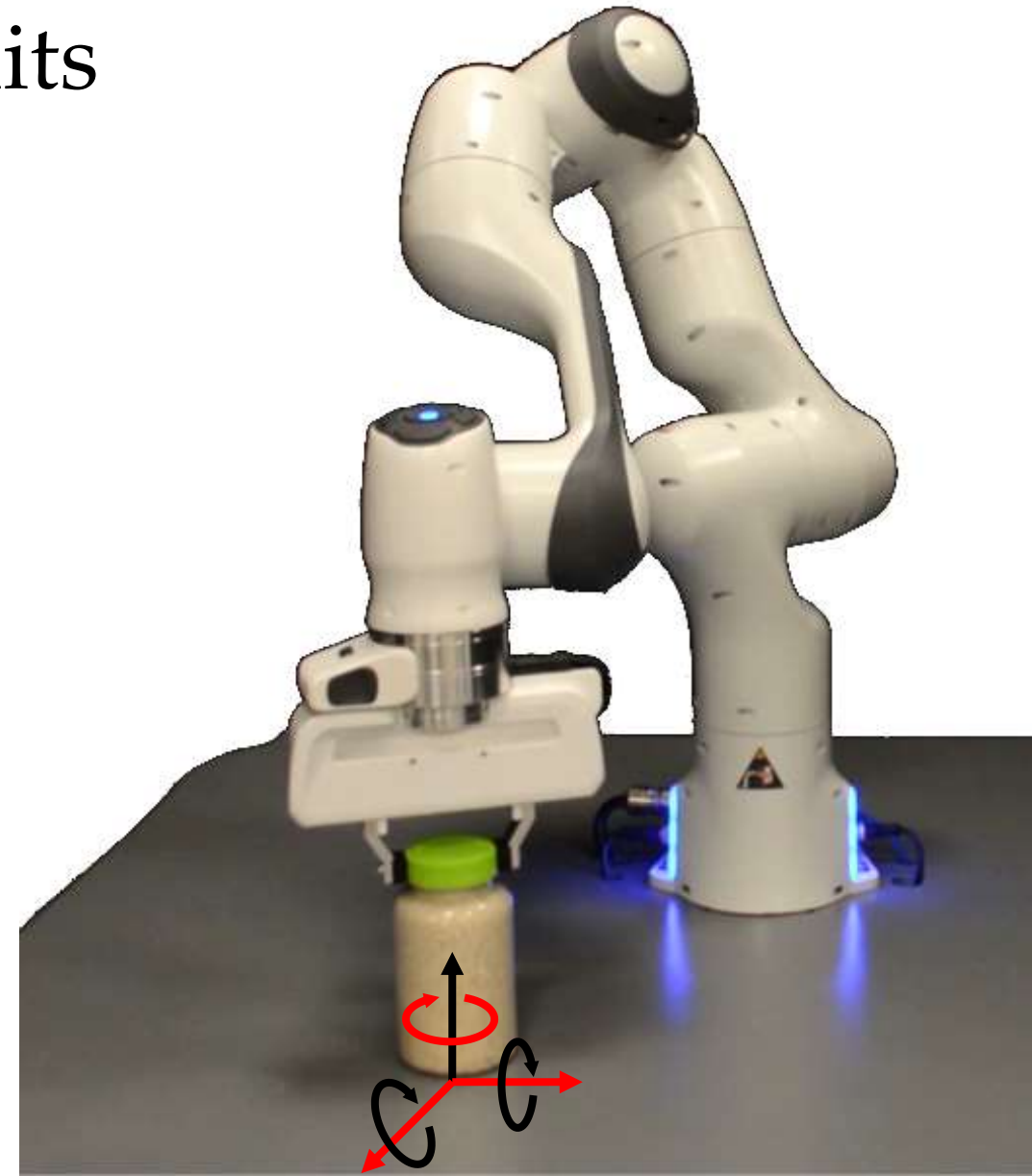
Friction:



Kinematics: Non-Penetration Limits

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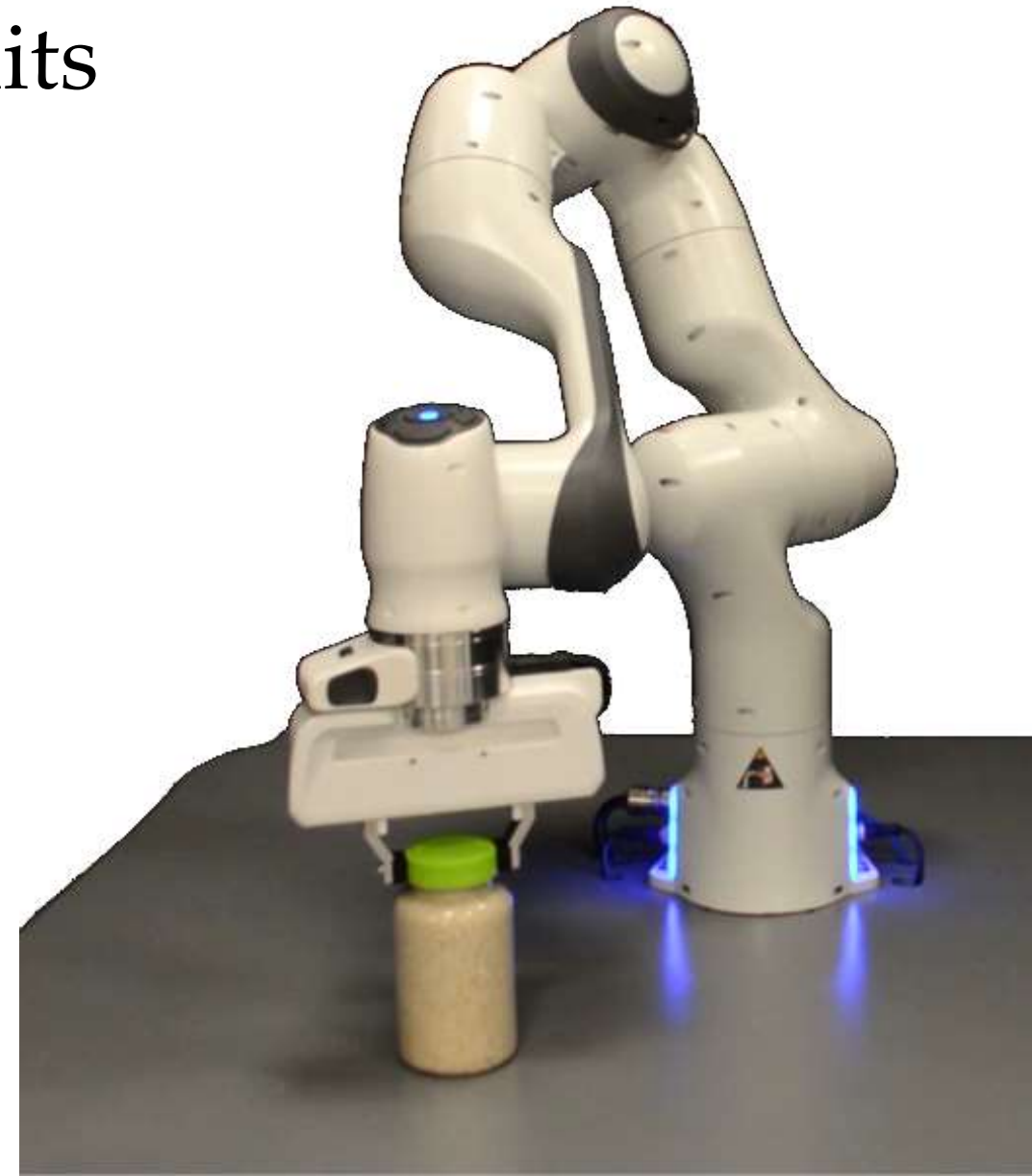
Friction: Limit Surface



Kinematics: Non-Penetration Limits

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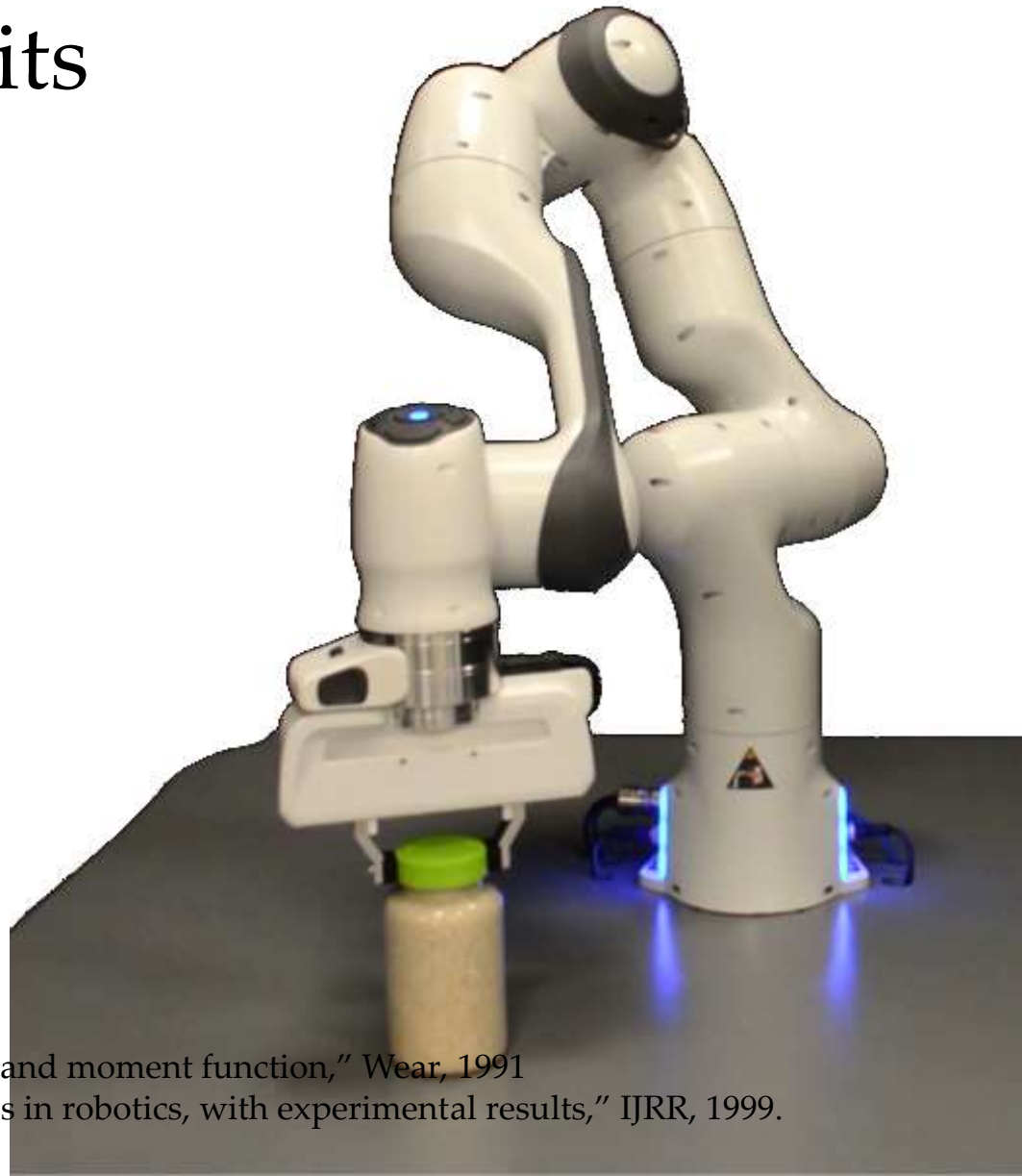
Friction: Limit Surface

Ellipsoidal Approximation

Generalized Friction Cone



S. Goyal, A. Ruina, and J. Papadopoulos, “Planar sliding with dry friction part 1. limit surface and moment function,” Wear, 1991
N. Xydas and I. Kao, “Modeling of contact mechanics and friction limit surfaces for soft fingers in robotics, with experimental results,” IJRR, 1999.
Erdmann, Michael. "On a representation of friction in configuration space." *IJRR*, 1994.

Kinematics: Non-Penetration Limits

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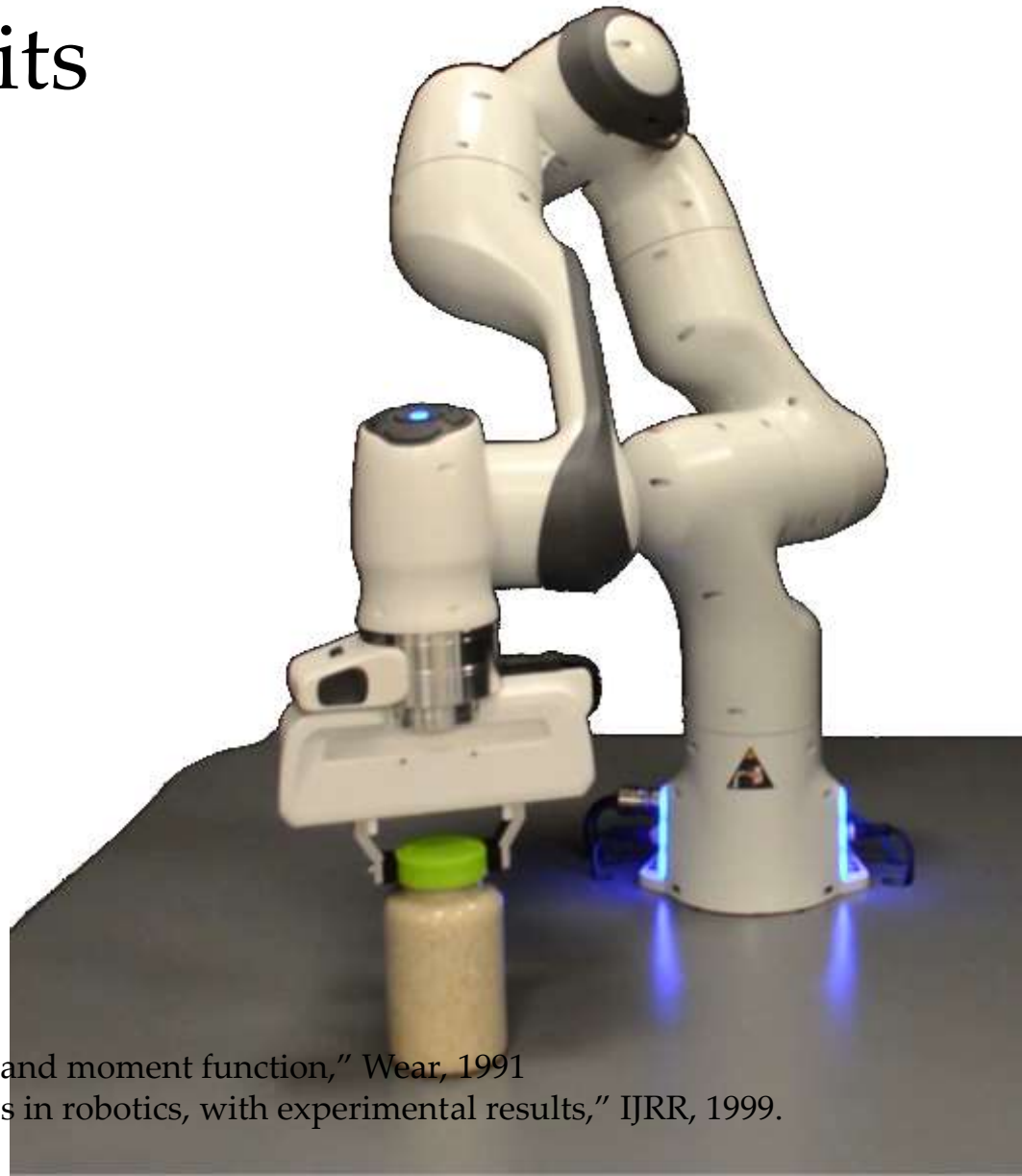
Friction: Limit Surface

Ellipsoidal Approximation

Generalized Friction Cone



S. Goyal, A. Ruina, and J. Papadopoulos, “Planar sliding with dry friction part 1. limit surface and moment function,” Wear, 1991
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Kinematics: Non-Penetration Limits

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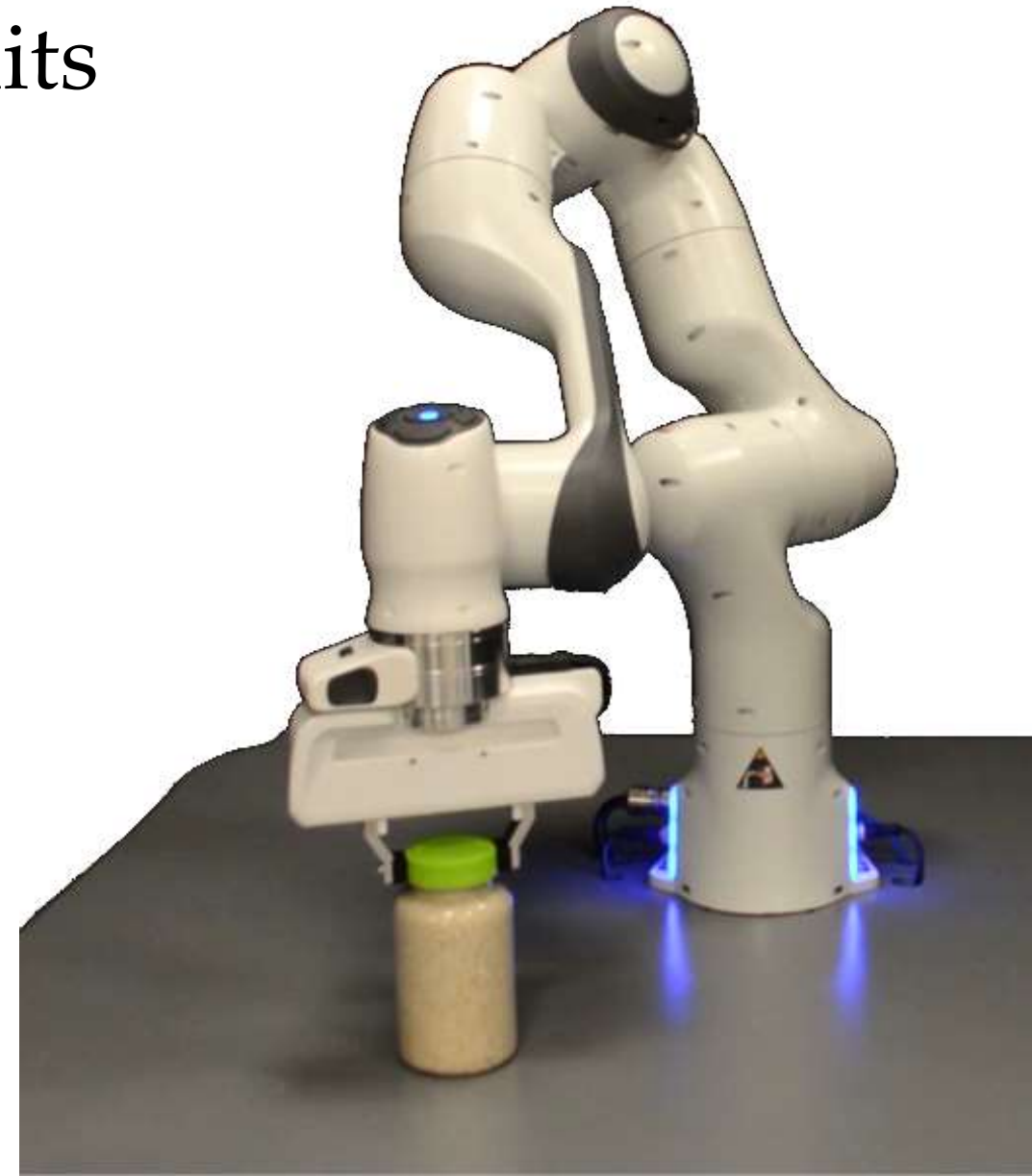
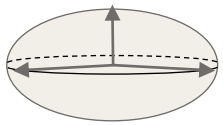
Friction: Limit Surface

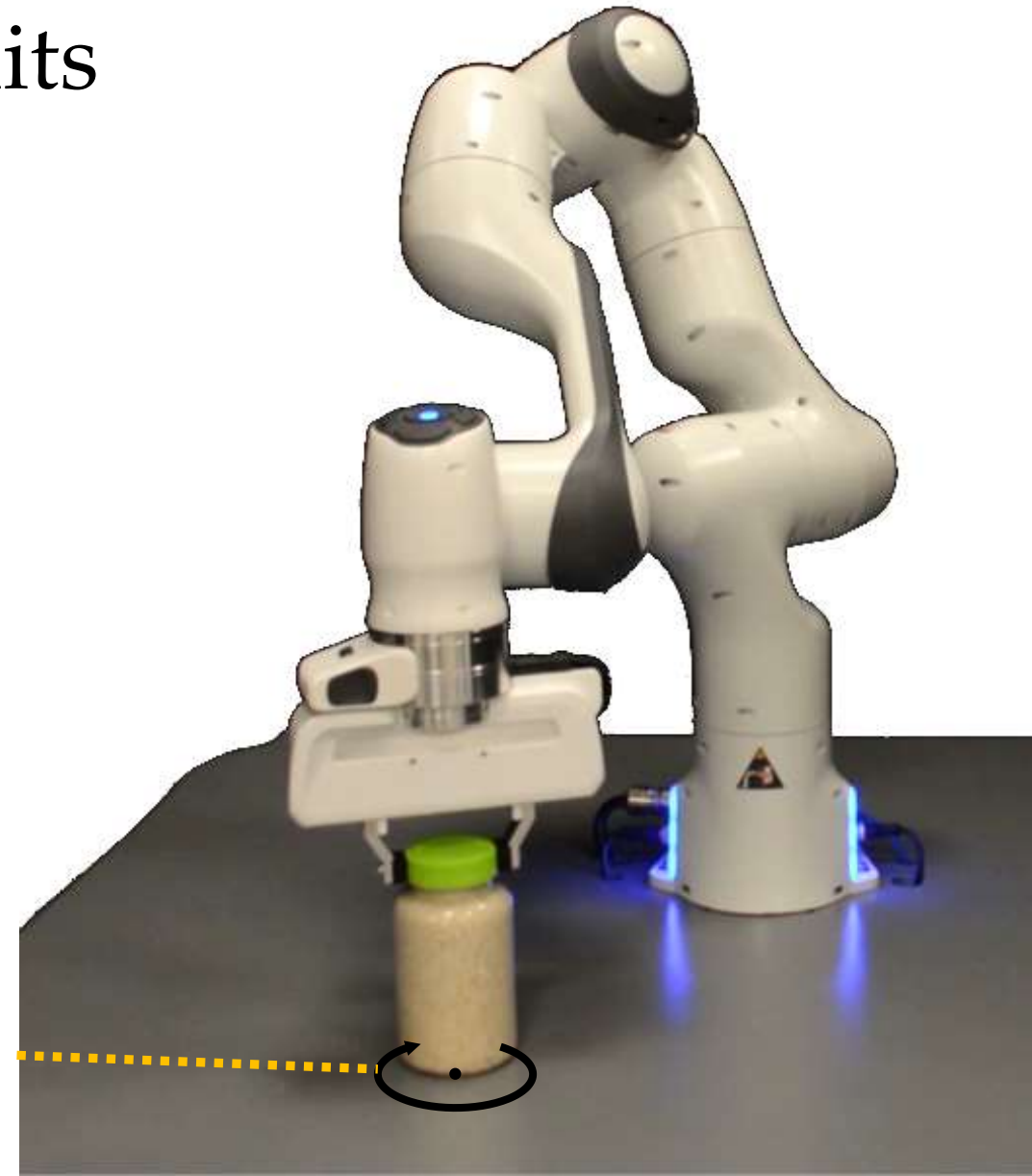


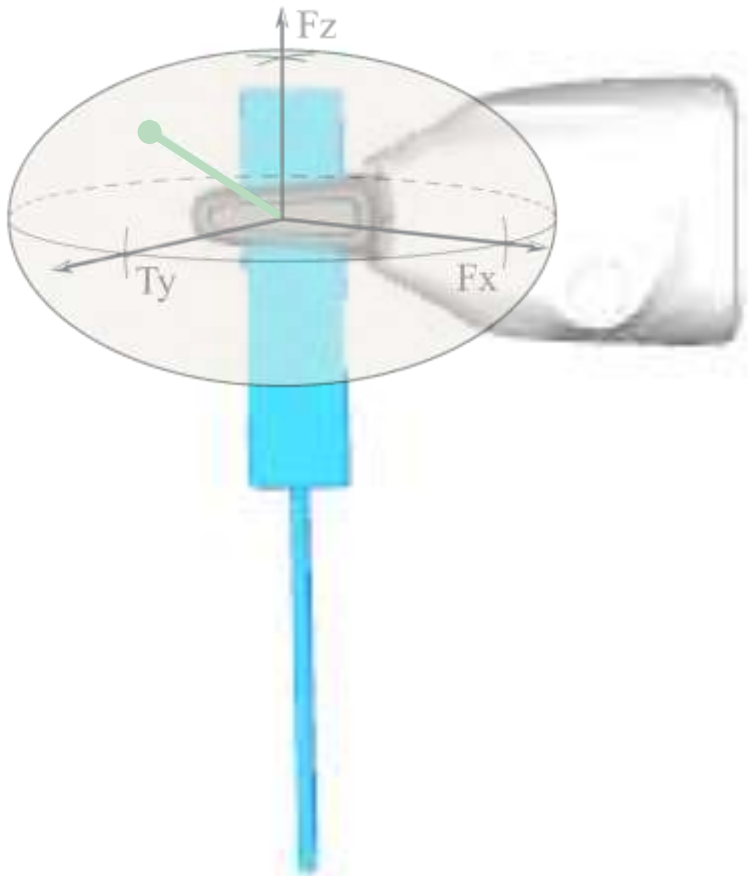
Kinematics: Non-Penetration Limits

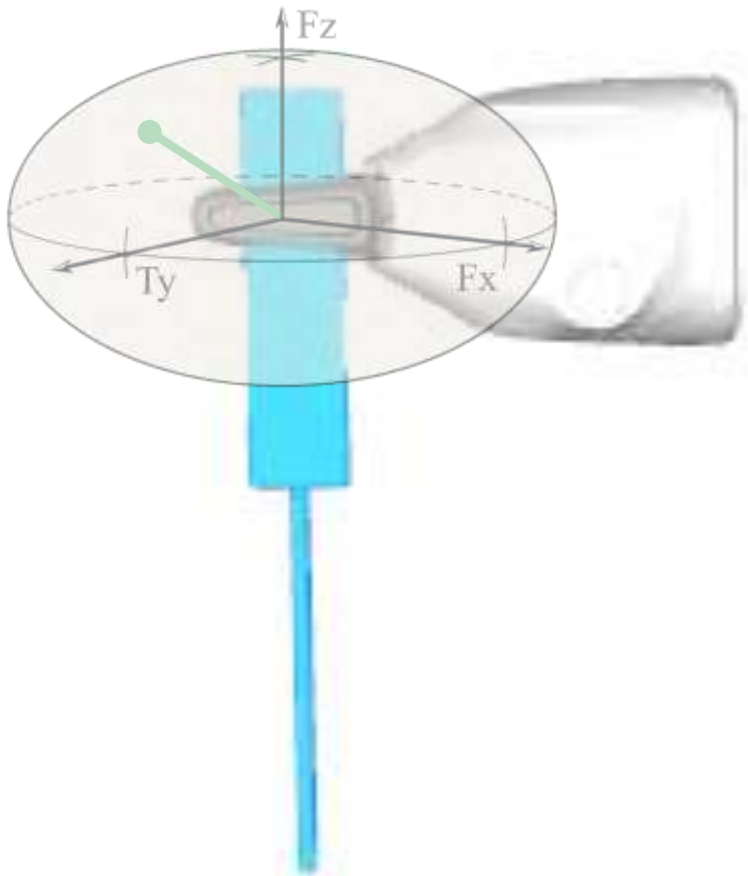
+

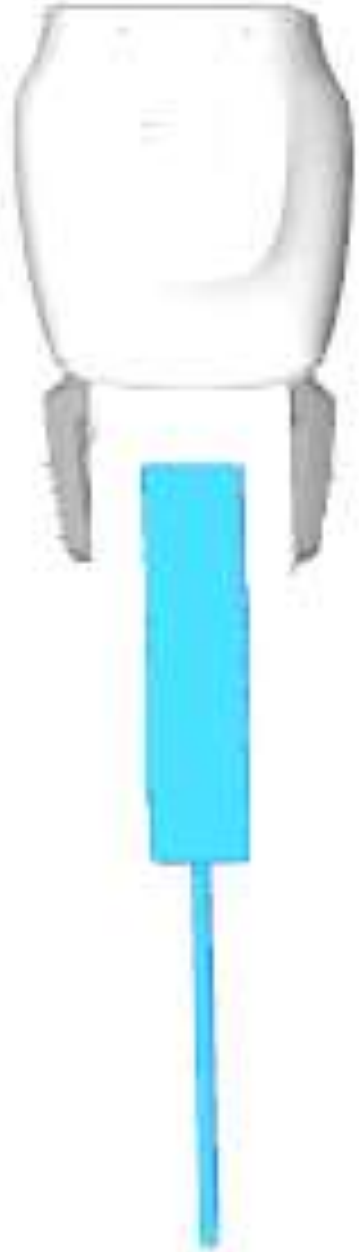
Friction: Limit Surface

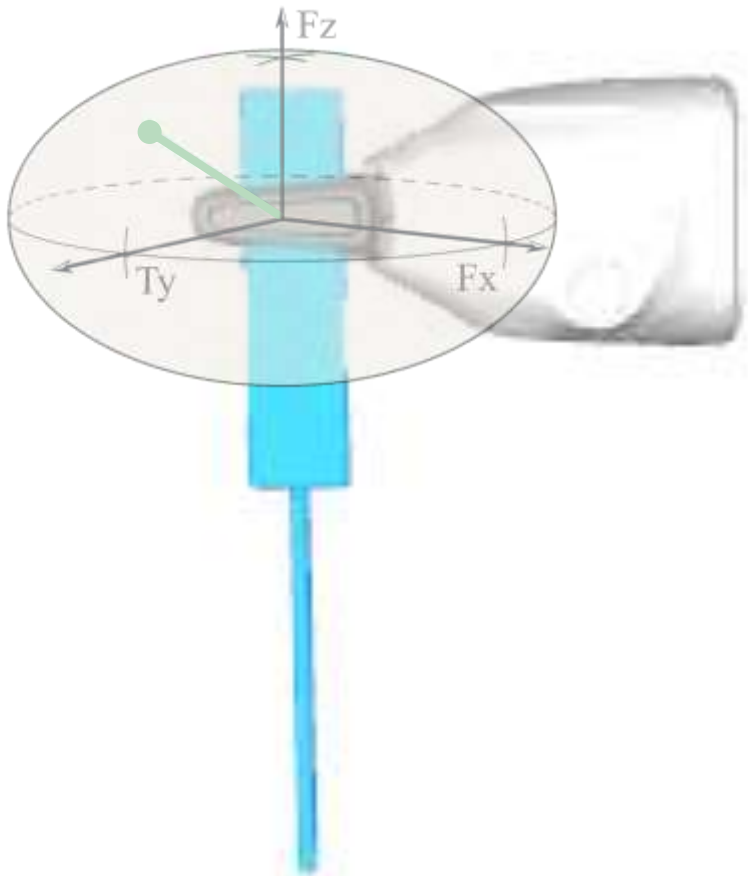





Fz
Ty
Fx


Fz
Ty
Fx




Fz
Ty
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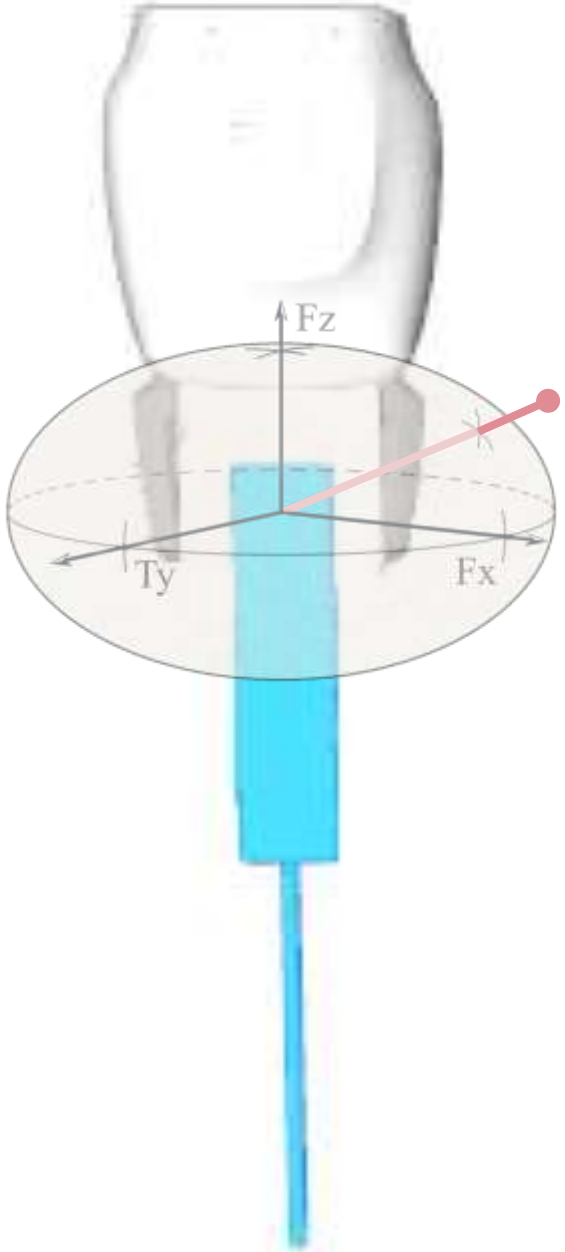
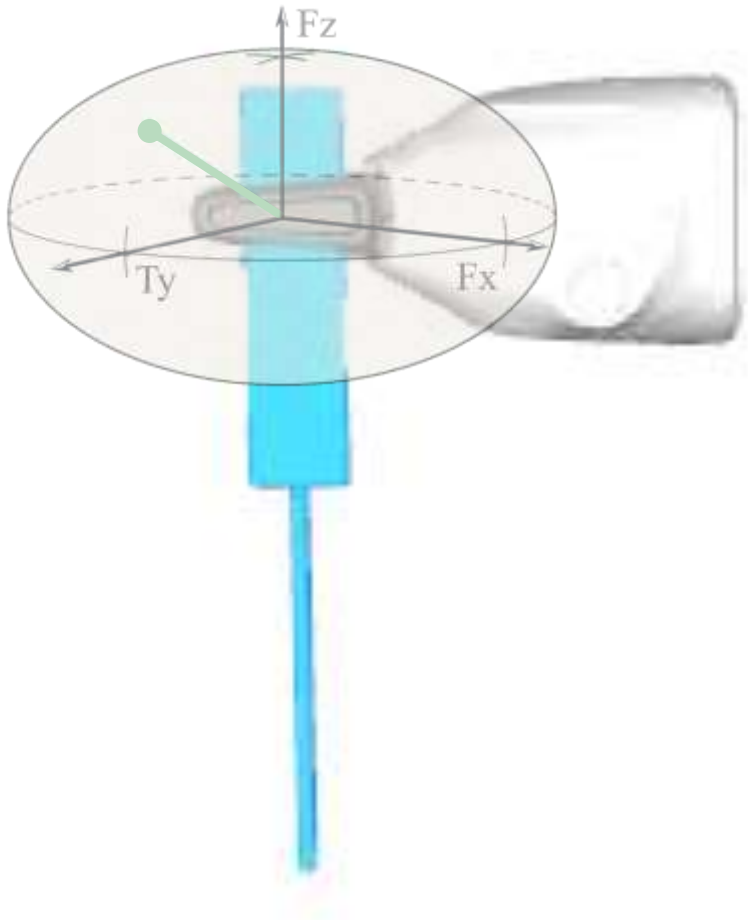
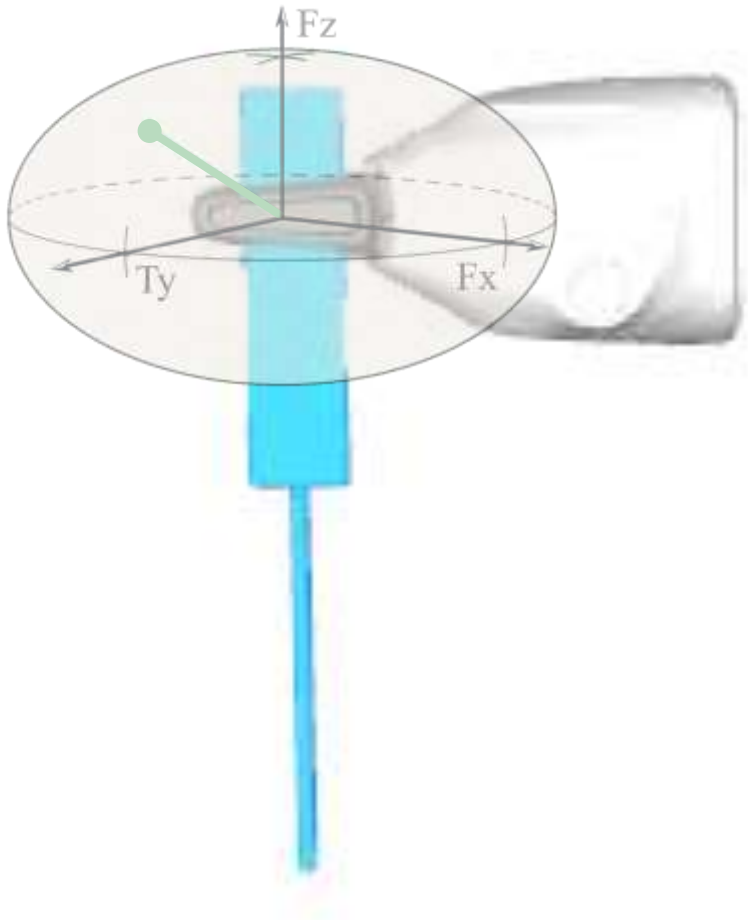

Fz
Ty
Fx

Limit Surface



$$w = (f_x, f_z, t_y)$$

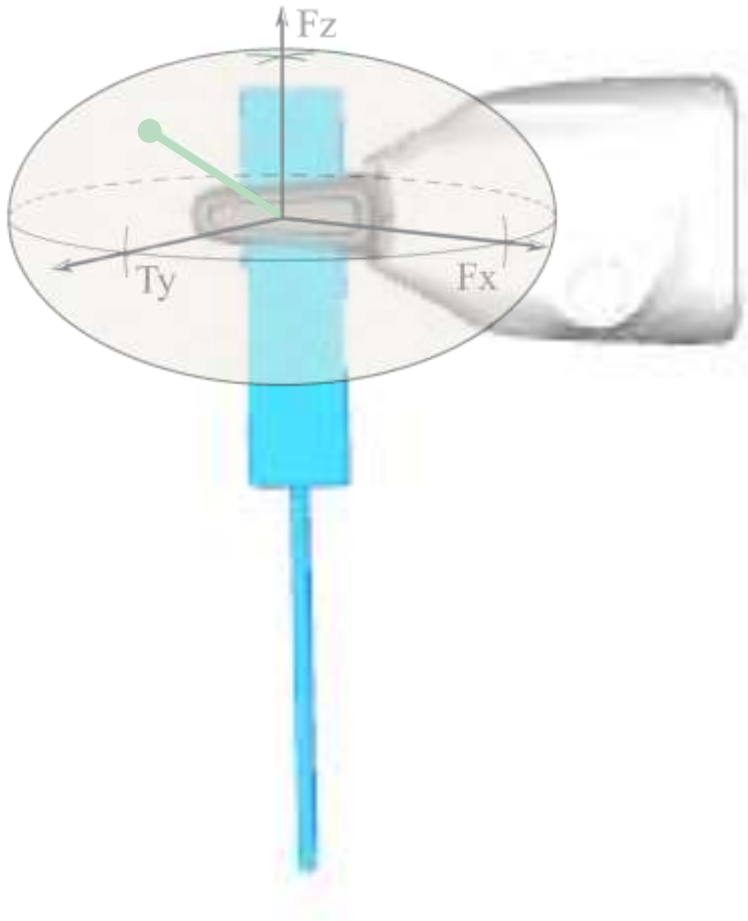
Limit Surface



$$w = (f_x, f_z, t_y)$$

$$w^T A w = 1$$

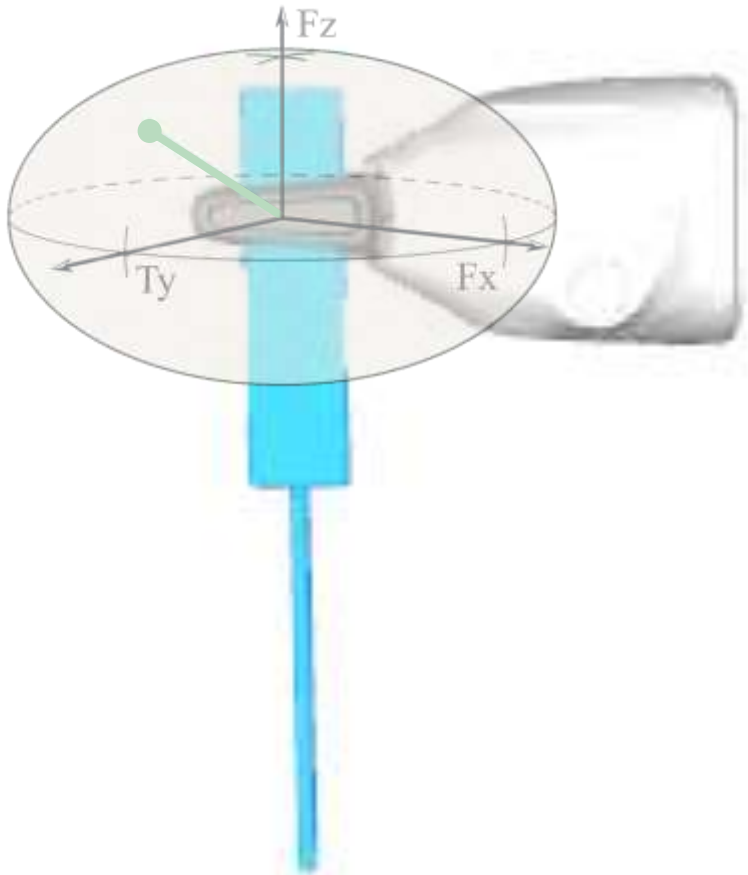
Limit Surface

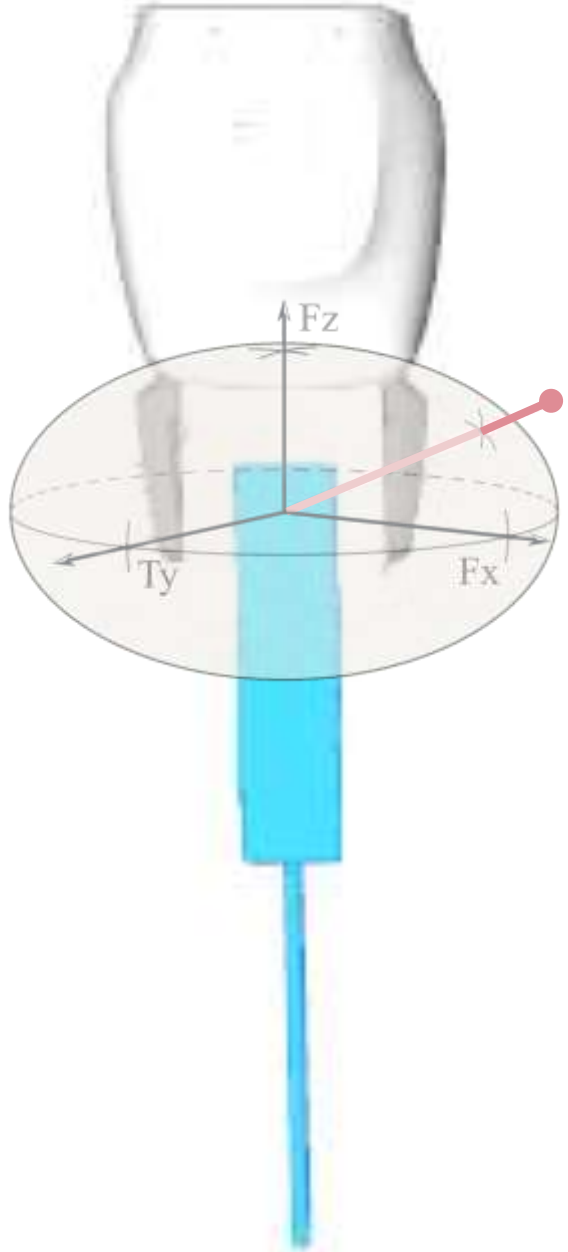


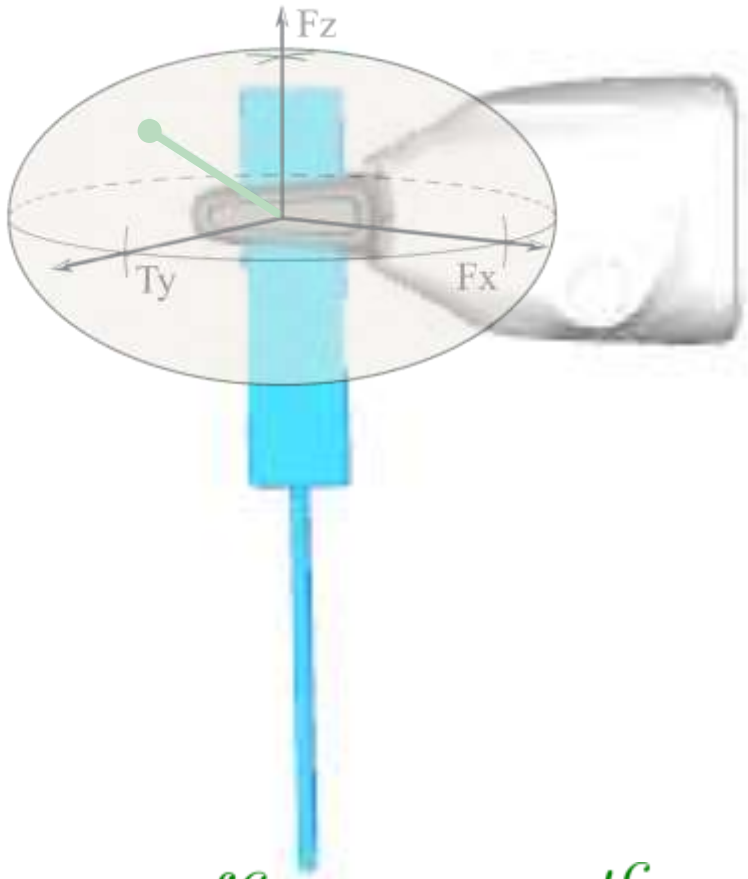
$$w = (f_x, f_z, t_y)$$

$$w^T A w = 1$$

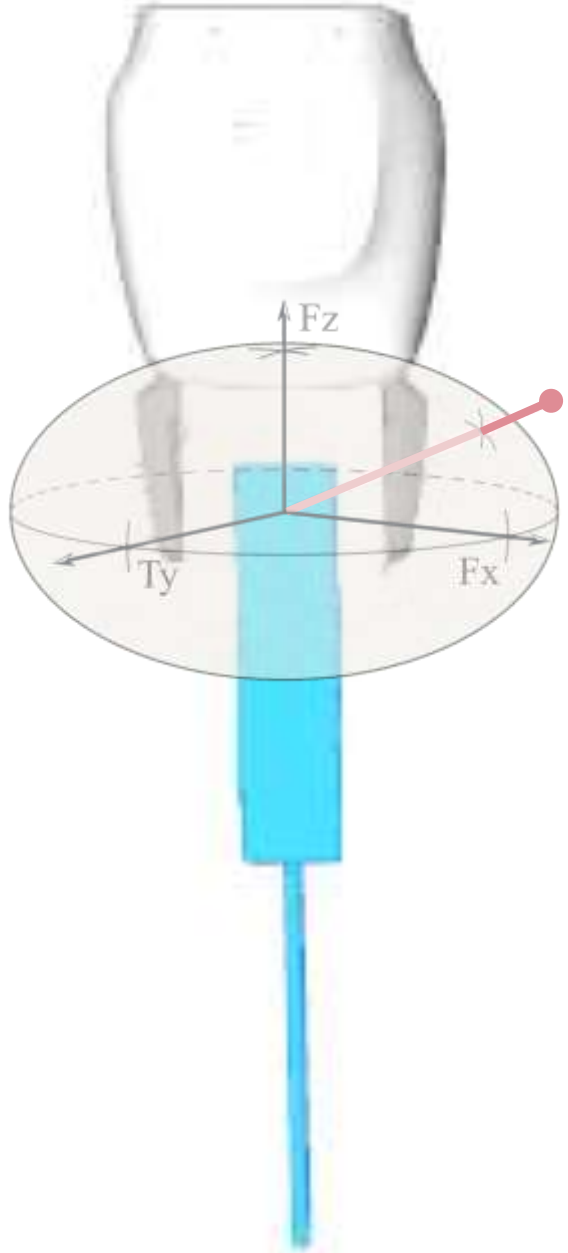
$$A = \begin{bmatrix} \frac{1}{(N\mu)^2} & & 0 \\ & \frac{1}{(N\mu)^2} & \\ 0 & & \frac{1}{(N\mu)^2(rc)^2} \end{bmatrix}$$


Fz
Ty
Fx


Fz
Ty
Fx



$$\frac{f_x^c}{(N\mu)^2} + \frac{f_z^c}{(N\mu)^2} + \frac{t_y^c}{(N\mu)^2(rc)^2} < 1$$

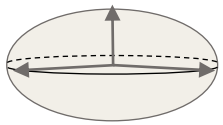


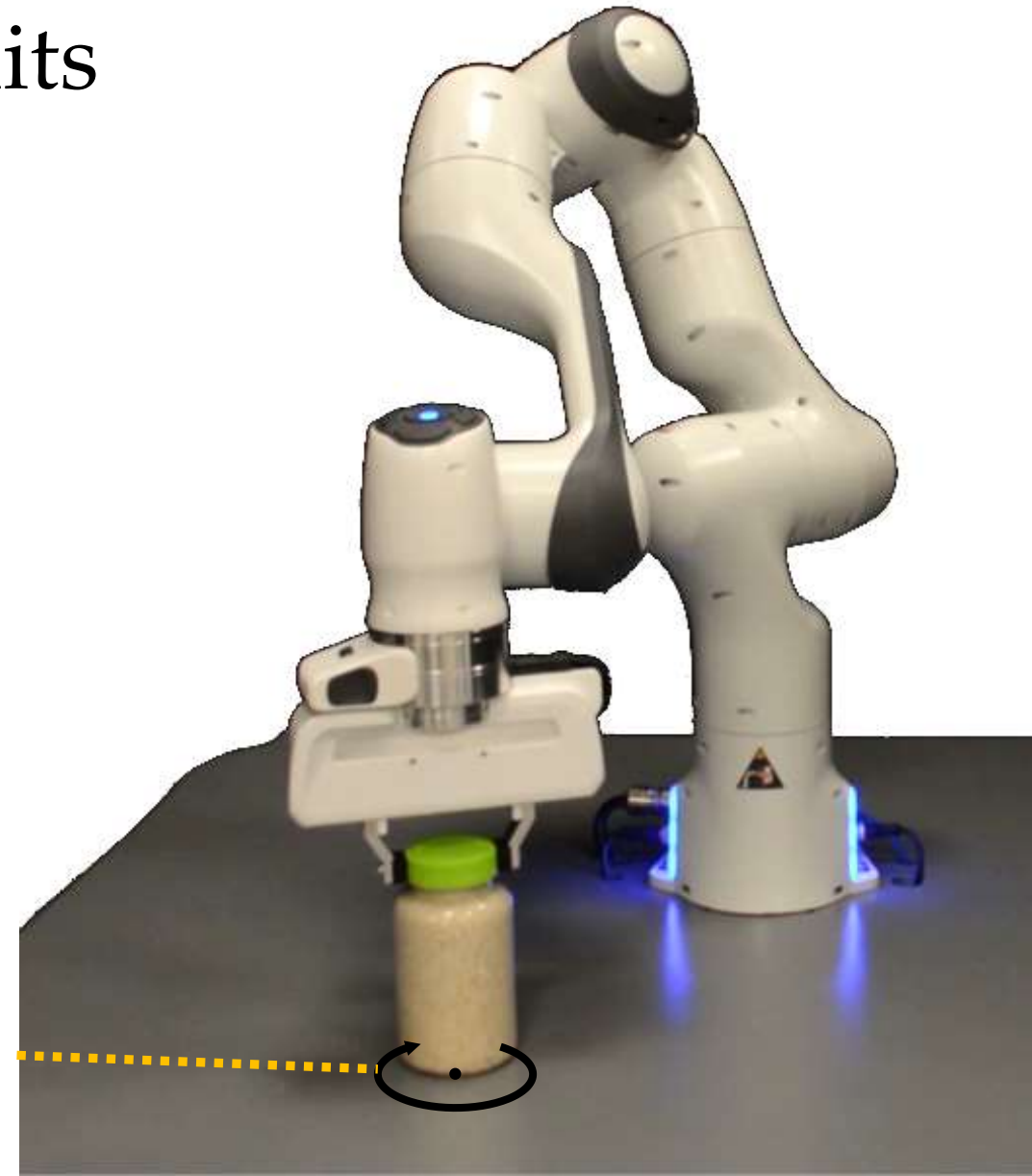
$$\frac{f_x^c}{(N\mu)^2} + \frac{f_z^c}{(N\mu)^2} + \frac{t_y^c}{(N\mu)^2(rc)^2} > 1$$

Kinematics: Non-Penetration Limits

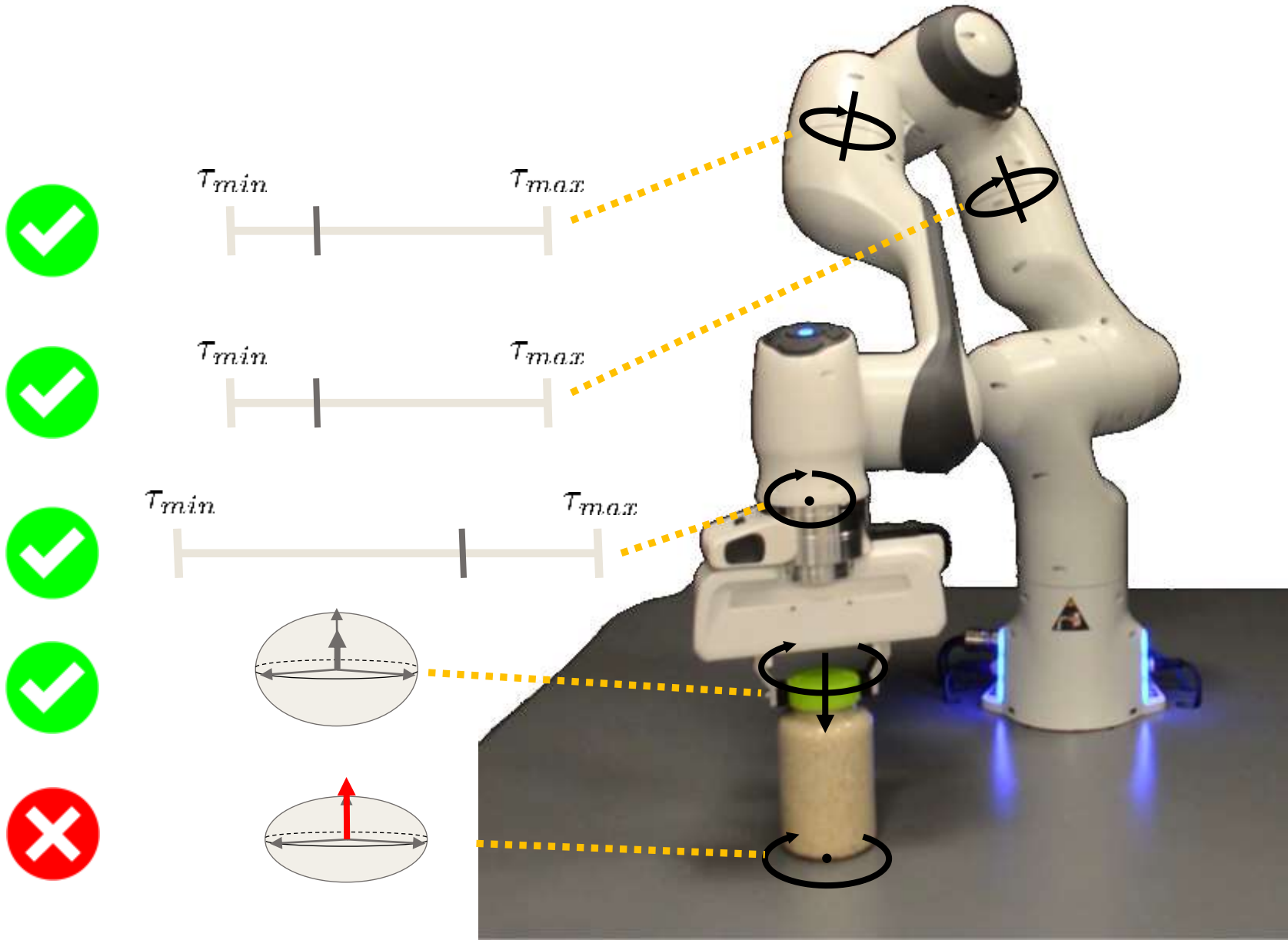
+

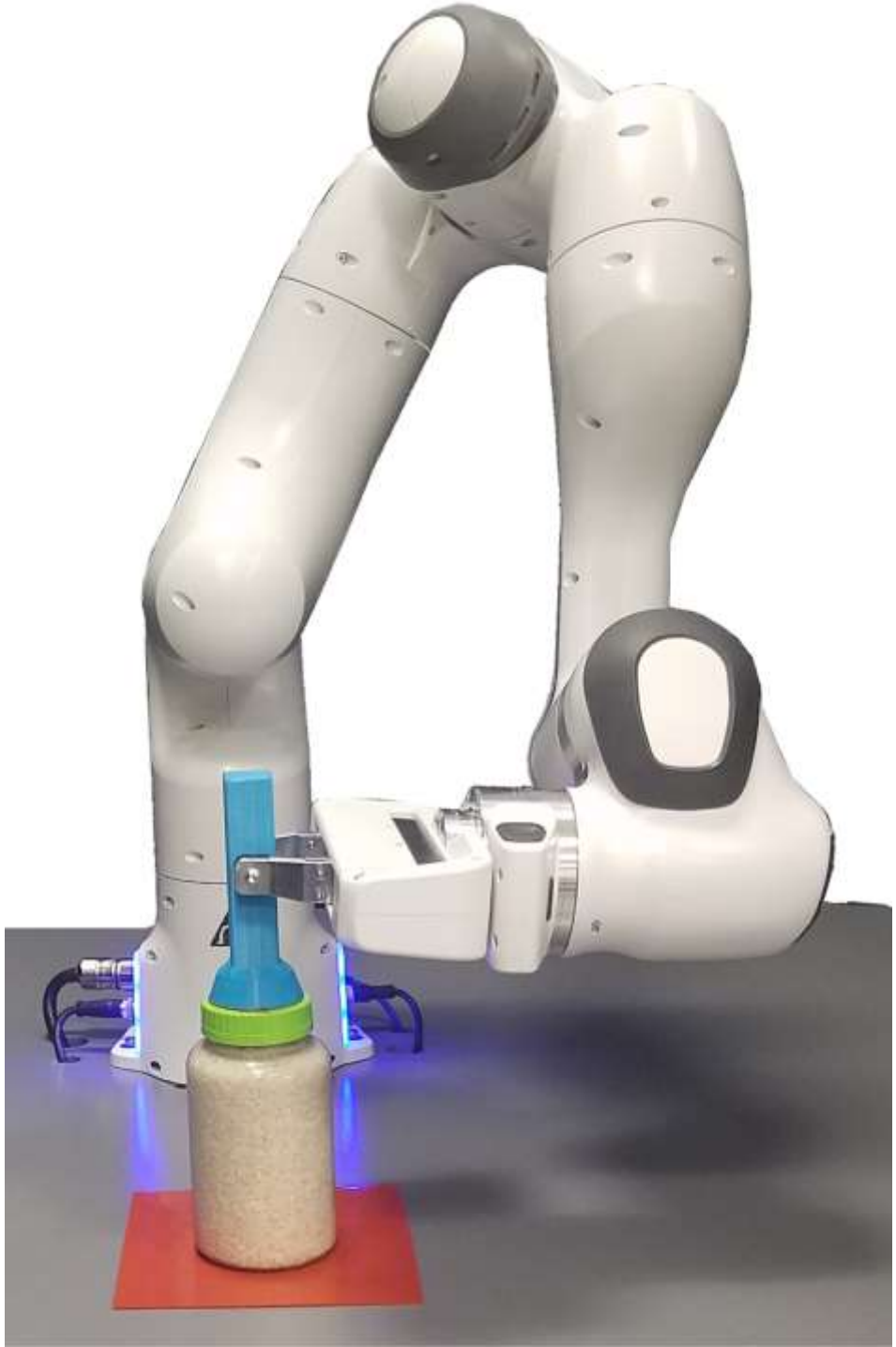
Friction: Limit Surface

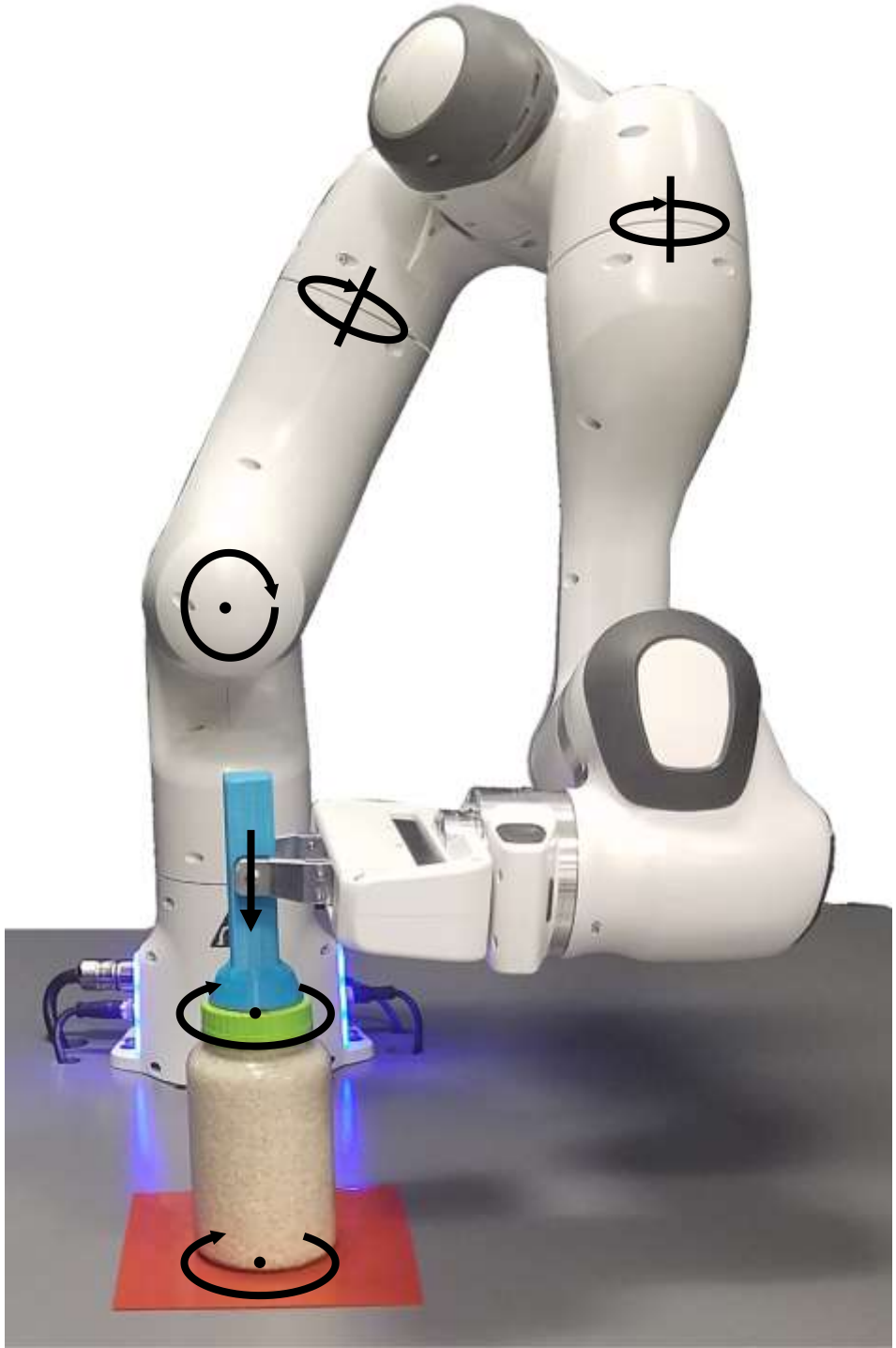


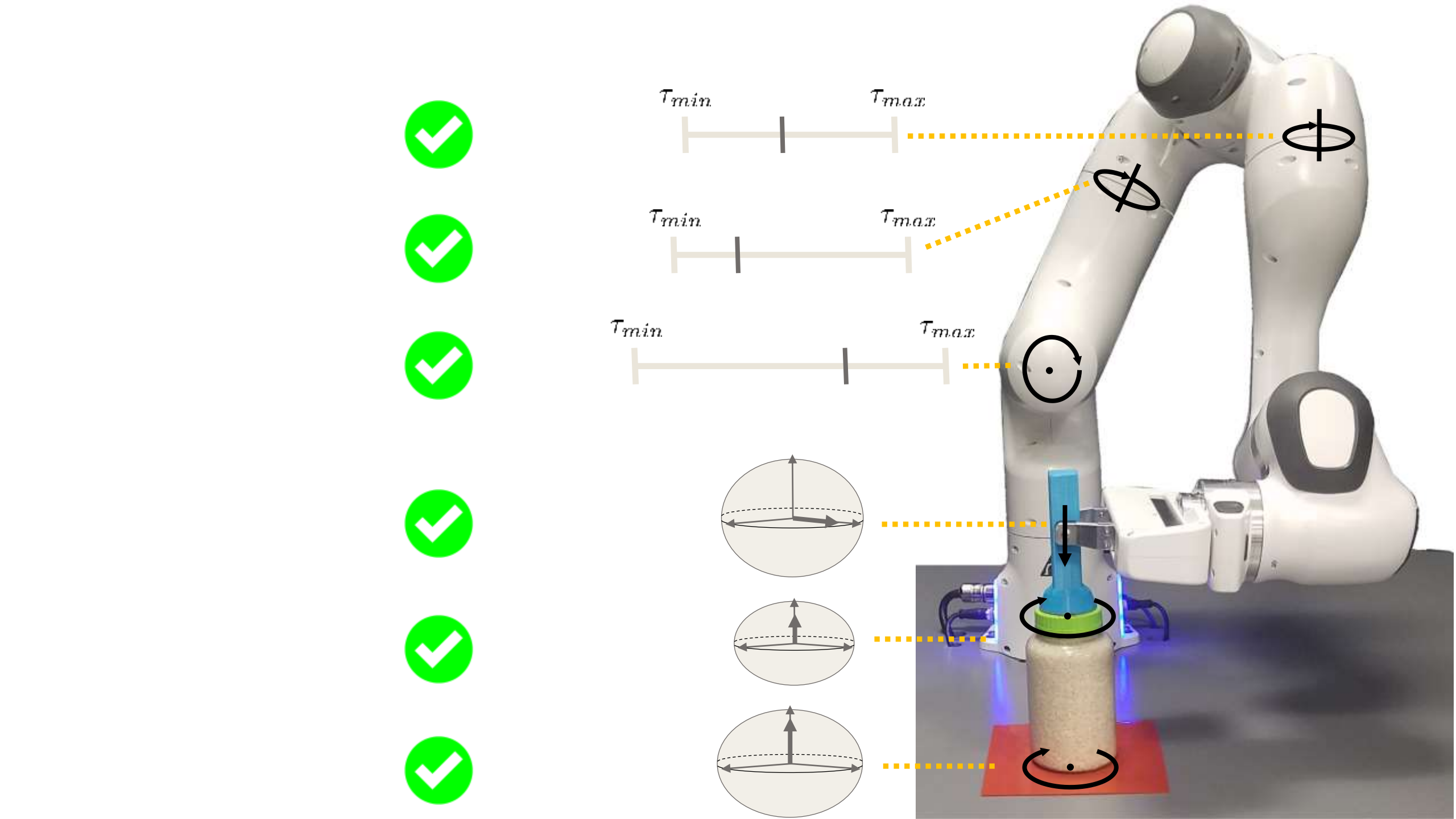


Forceful Kinematic Chain







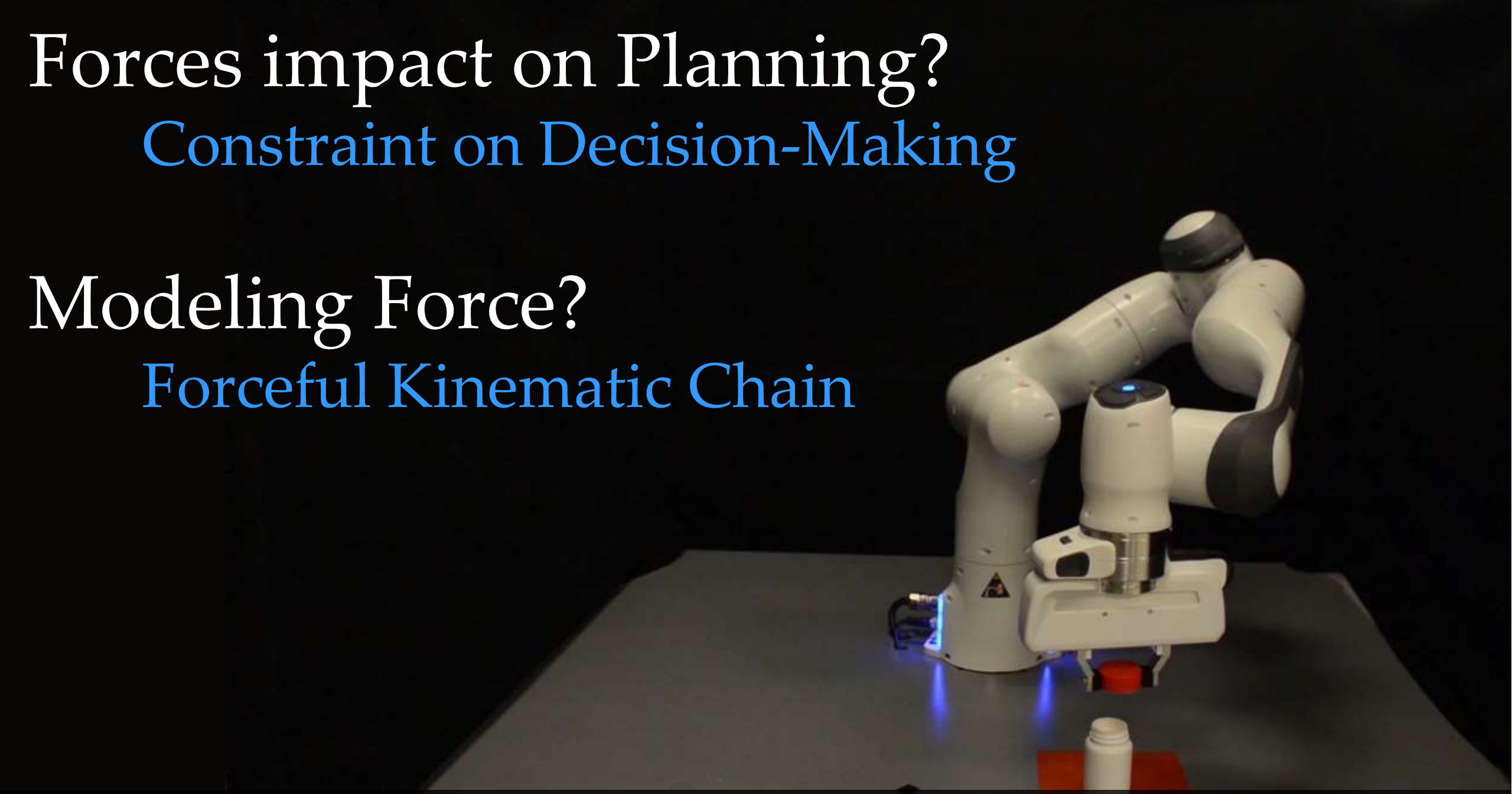

τ_{min}
τ_{max}
τ_{min}
τ_{max}
τ_{min}
τ_{max}

Forces impact on Planning?

Constraint on Decision-Making

Modeling Force?

Forceful Kinematic Chain



"Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *ICRA*, 2021.
"Robust Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *IJRR*, 2023.

Forces impact on Planning?

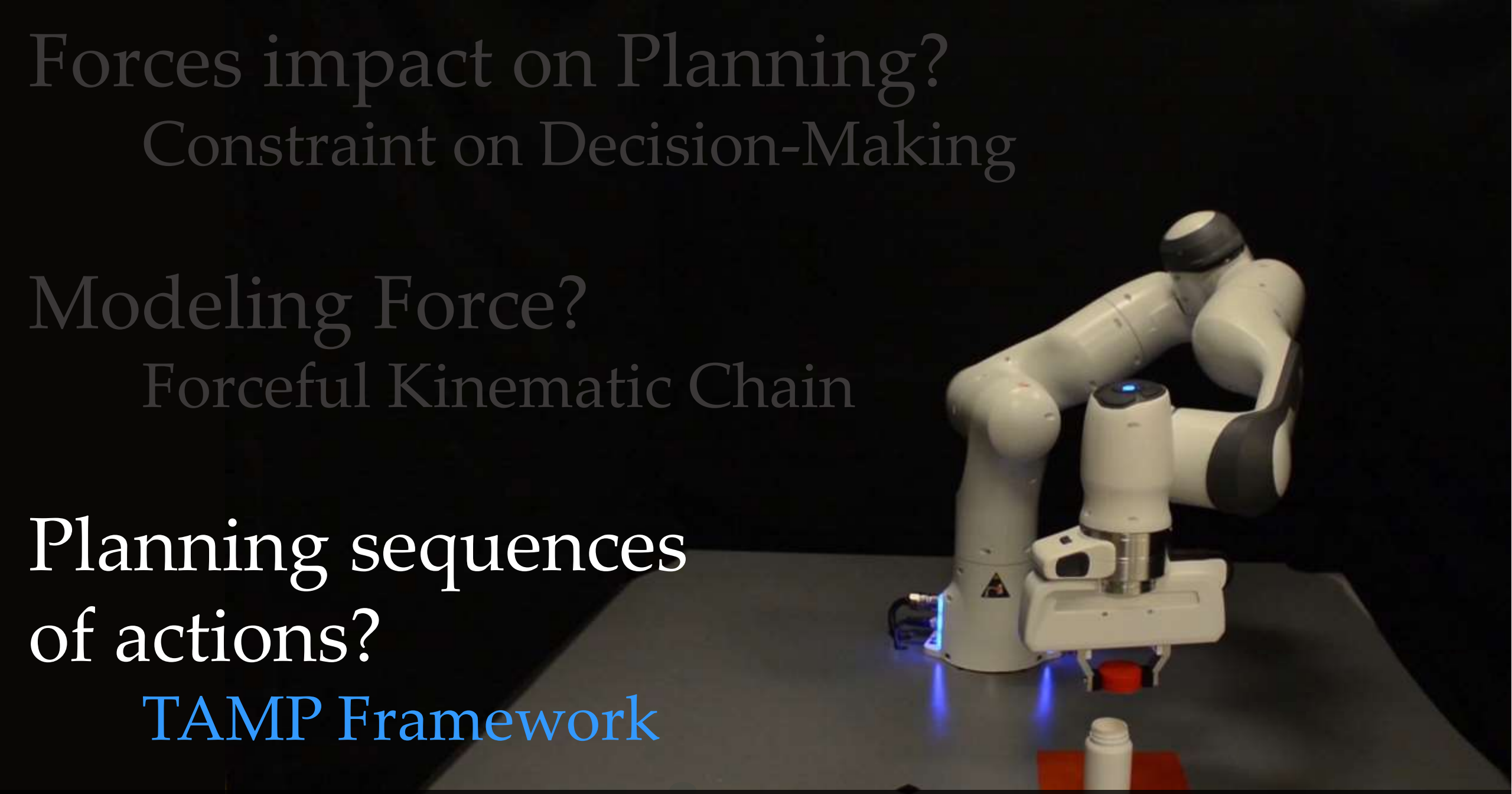
Constraint on Decision-Making

Modeling Force?

Forceful Kinematic Chain

Planning sequences of actions?

TAMP Framework



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"Robust Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *IJRR*, 2023.

Action Definition

Action Definition

`Controller`

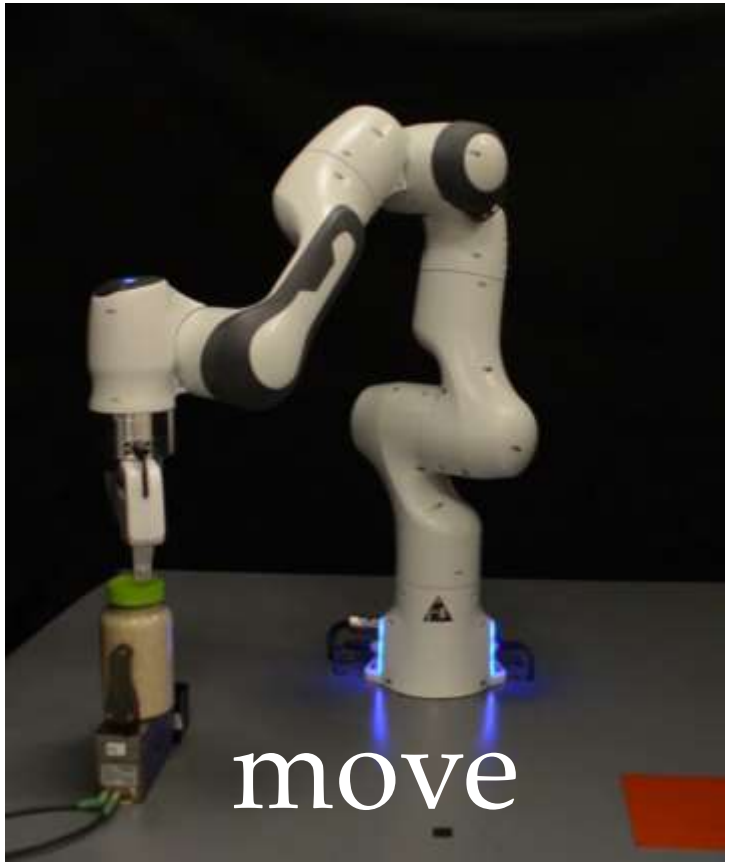
Action Definition

Controller
Preconditions
Effects

Action Definition

Controller
Preconditions
Effects

Controller
Preconditions
Effects



Controller
Preconditions
Effects

Action Definition

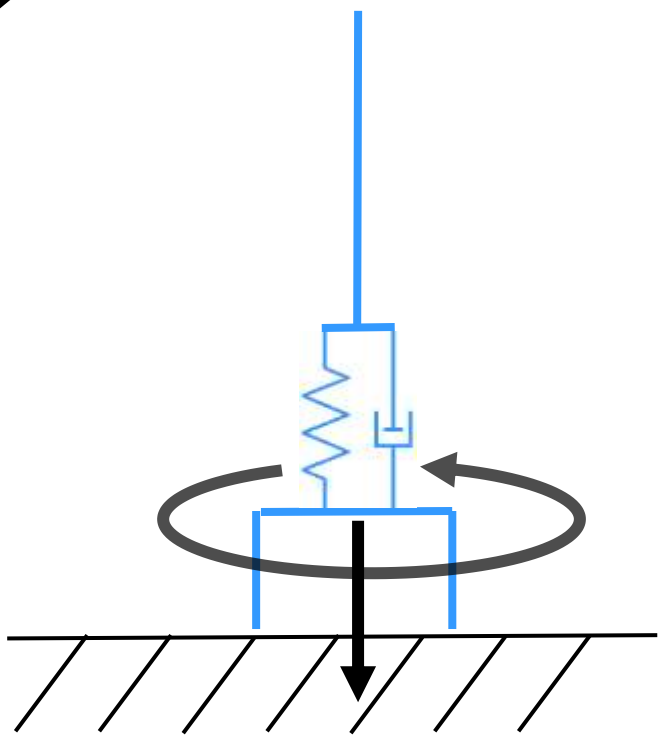
Controller
Preconditions
Effects

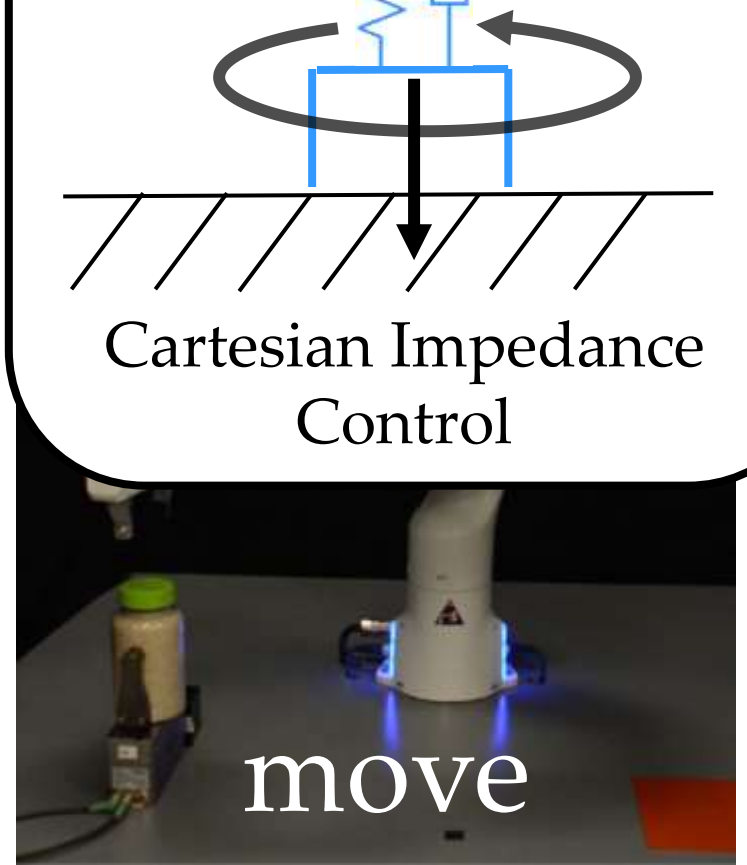
Controller
Preconditions
Effects

Controller
Preconditions
Effects

Action Definition

Controller
Preconditions
Effects





Controller
Preconditions
Effects

Action Definition

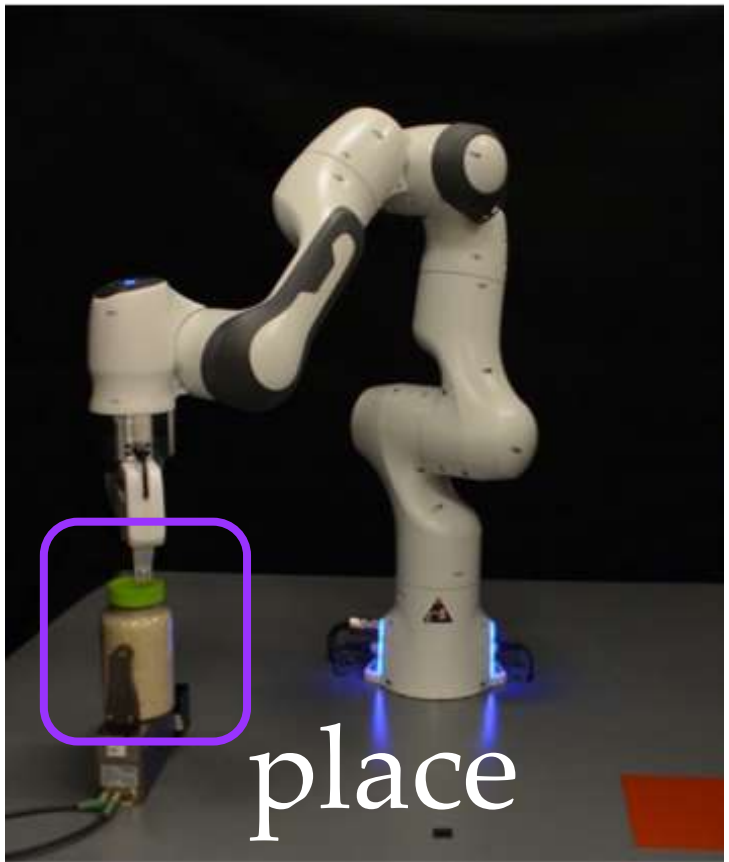
Controller
Preconditions
Effects

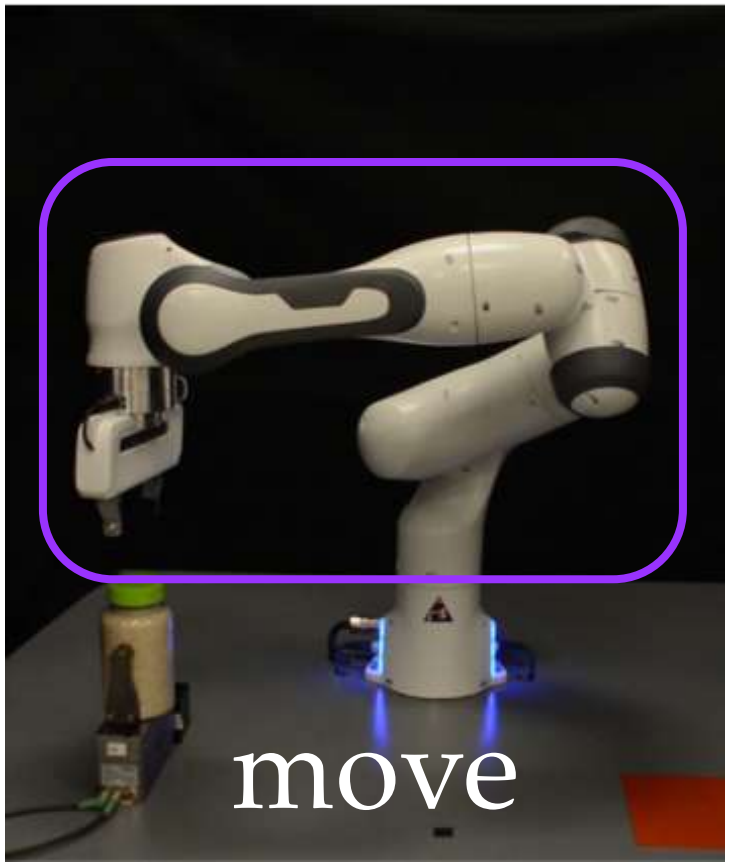
Controller
Preconditions
Effects

Controller
Preconditions
Effects

Find a sequence of actions and the parameters of those actions, subject to constraints

Find a sequence of actions and the parameters of those actions, subject to constraints



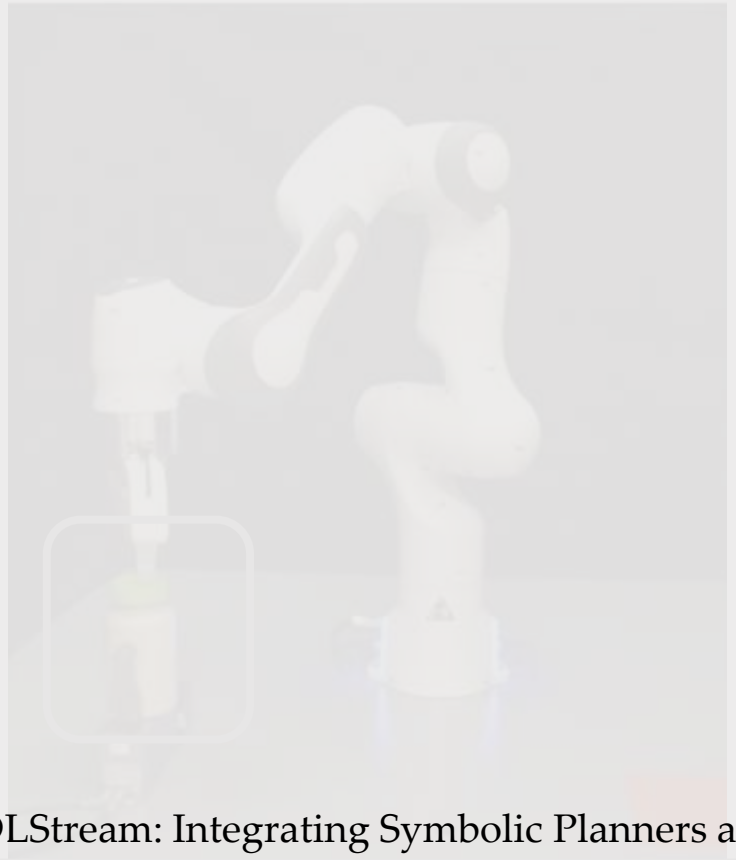


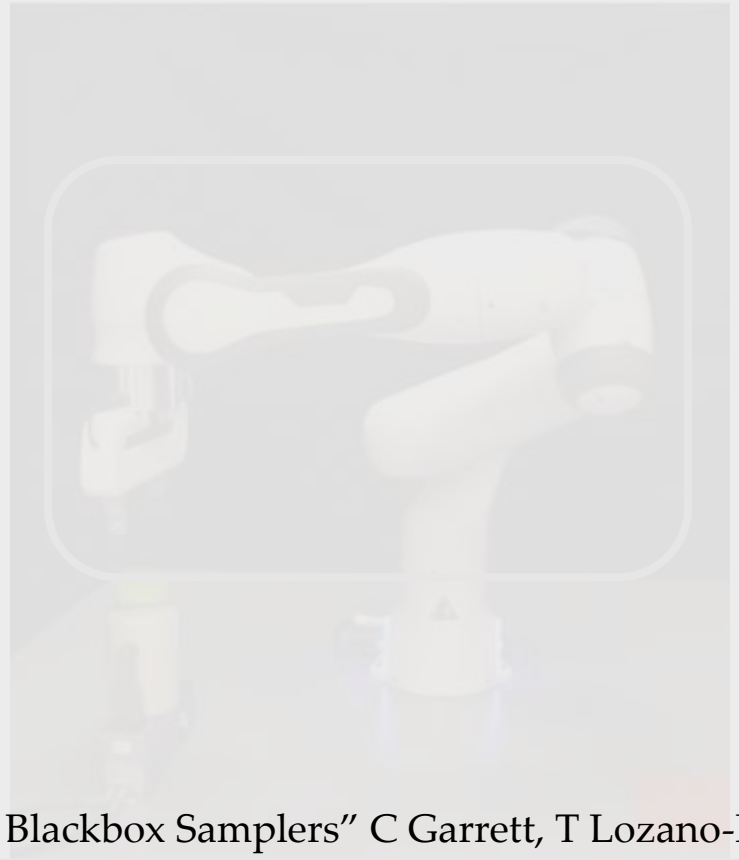
Find a sequence of actions and the parameters of those actions, subject to constraints

TAMP Framework: PDDLStream

Find a sequence of actions and parameters of those actions, subject to constraints

place move pushtwist

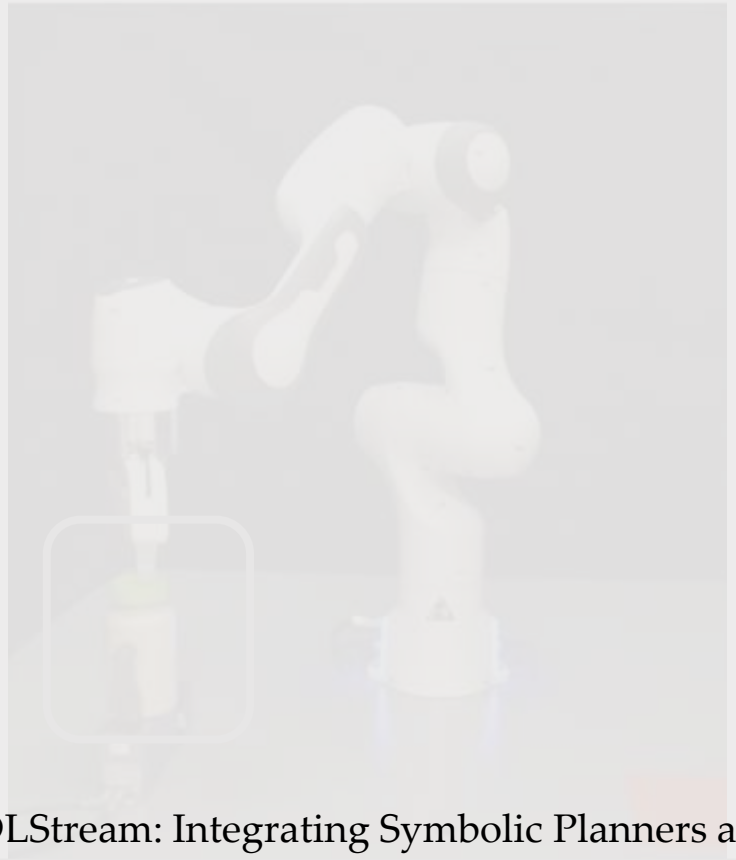


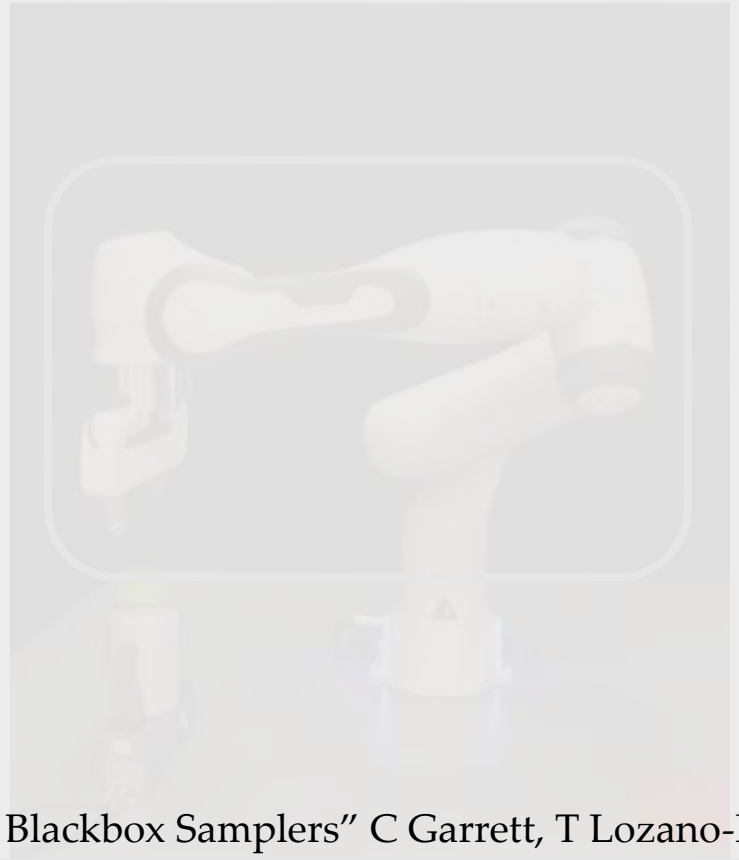


"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream

Streams





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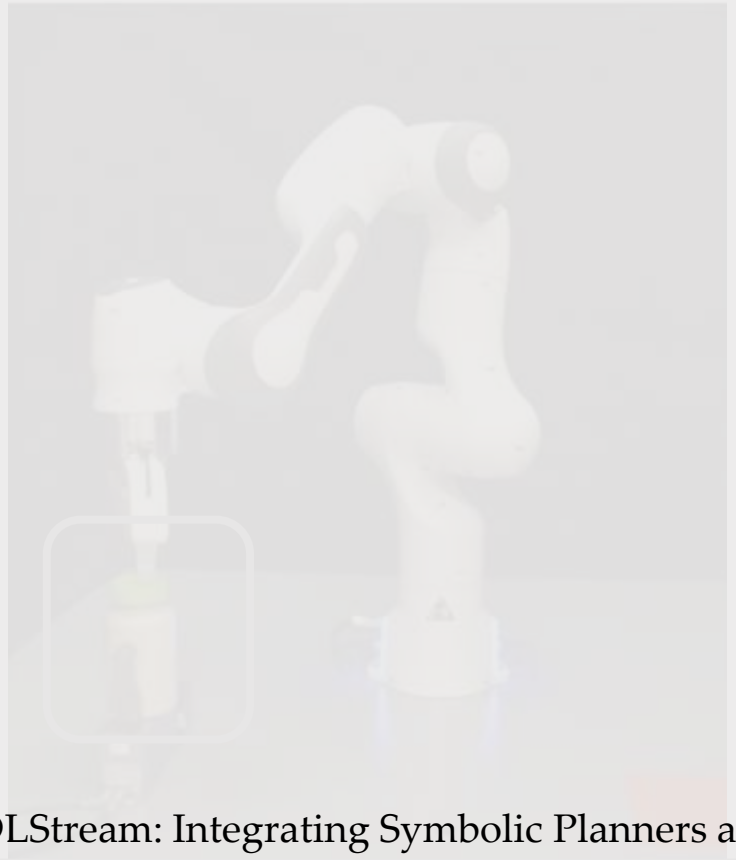
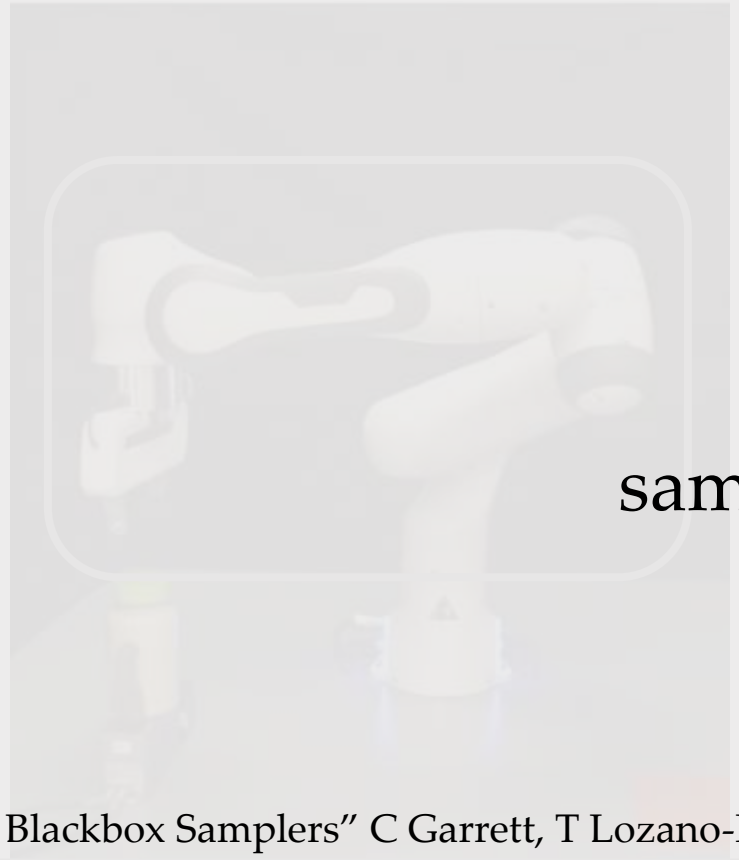
TAMP Framework: PDDLStream

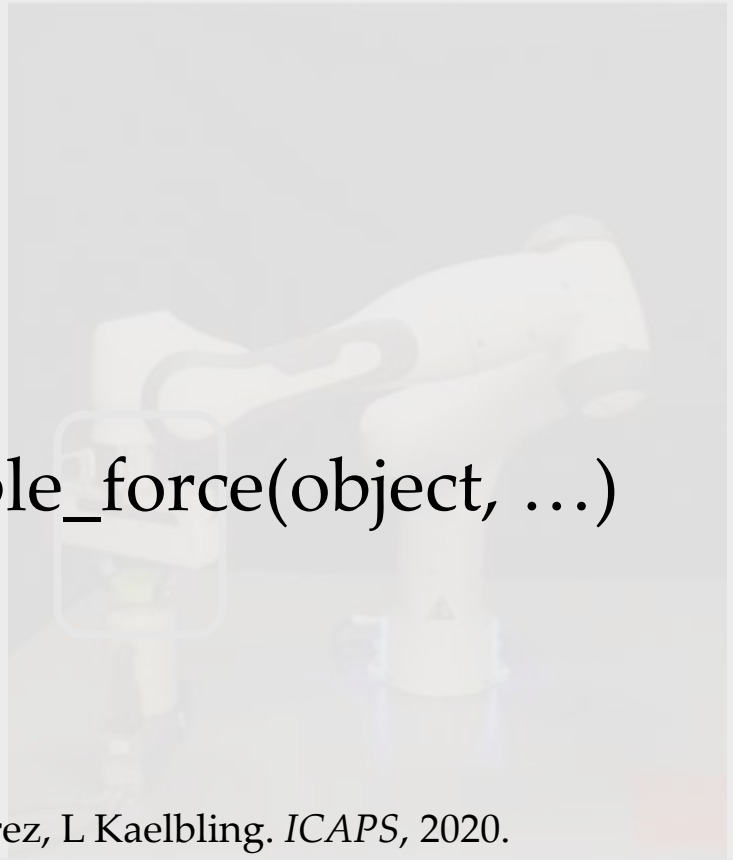
sample_grasp(object)

Streams





sample_force(object, …)



"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream

sample_grasp(object)

Streams

plan_impedance(arm, …)

sample_force(object, …)

plan_motion(arm, q_{start}, q_{goal})

"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream

sample_grasp(object)

check_collision_free(path)

Streams

plan_impedance(arm, …)

check_forceful_kinematic_chain(chain, wrench, …)

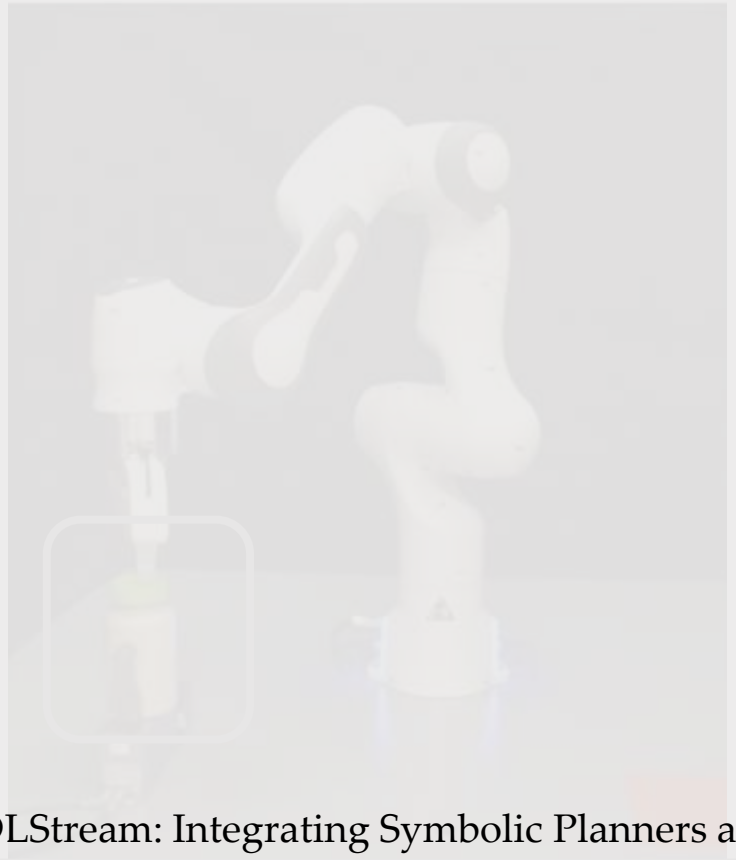
sample_force(object, …)

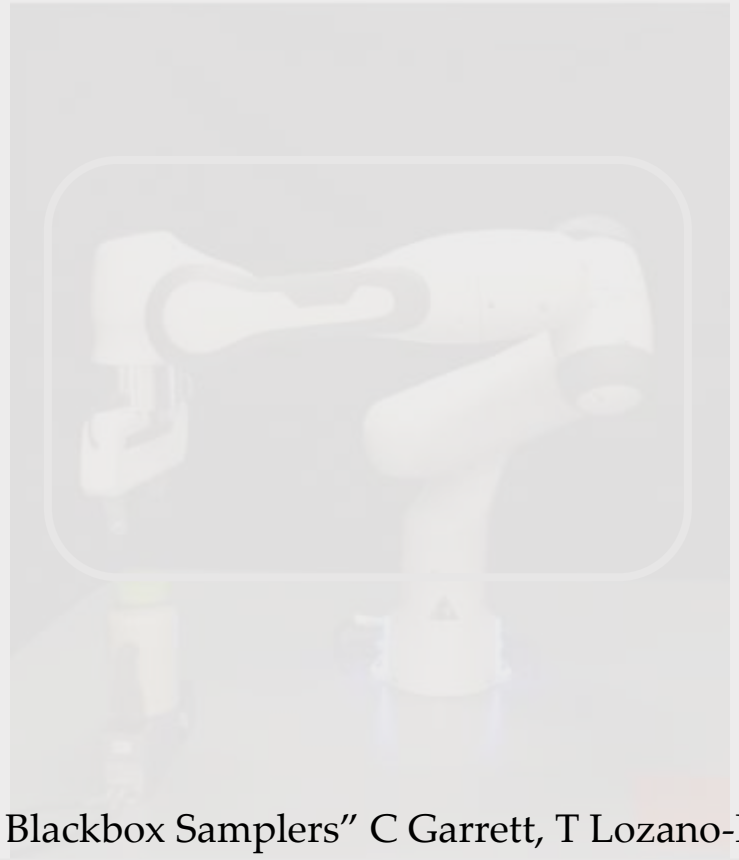
plan_motion(arm, q_{start}, q_{goal})

"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream

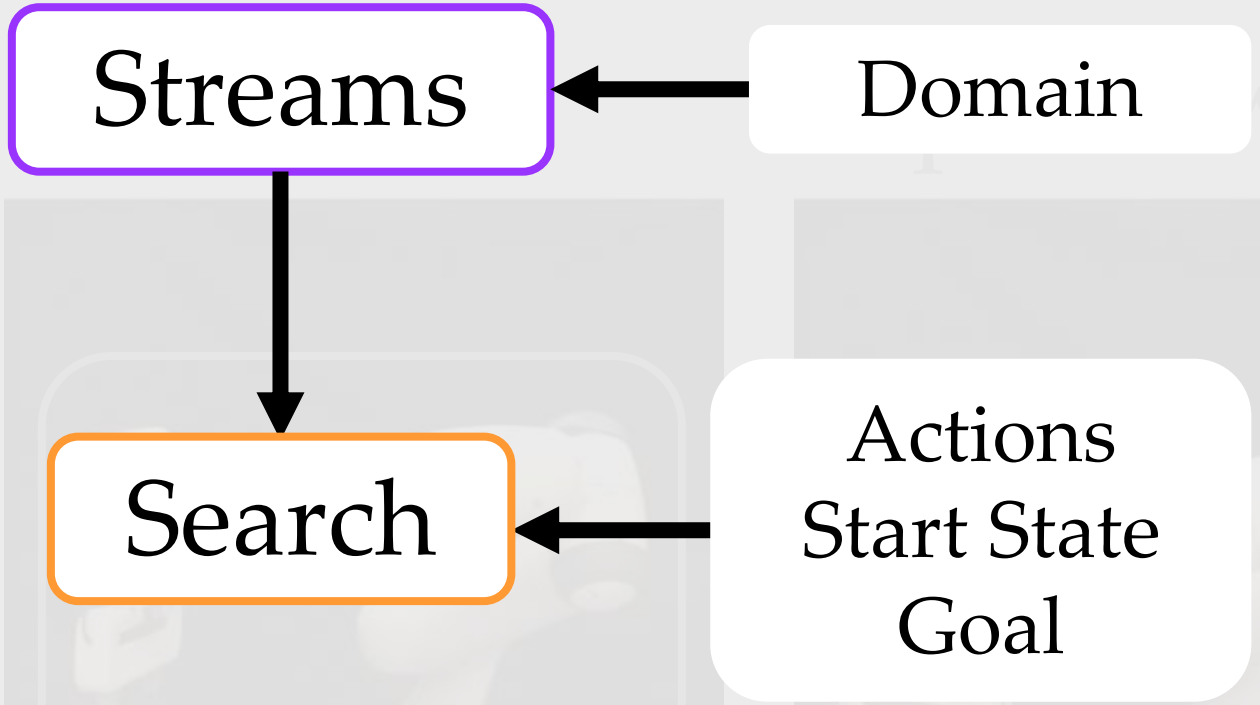
Streams ← Domain





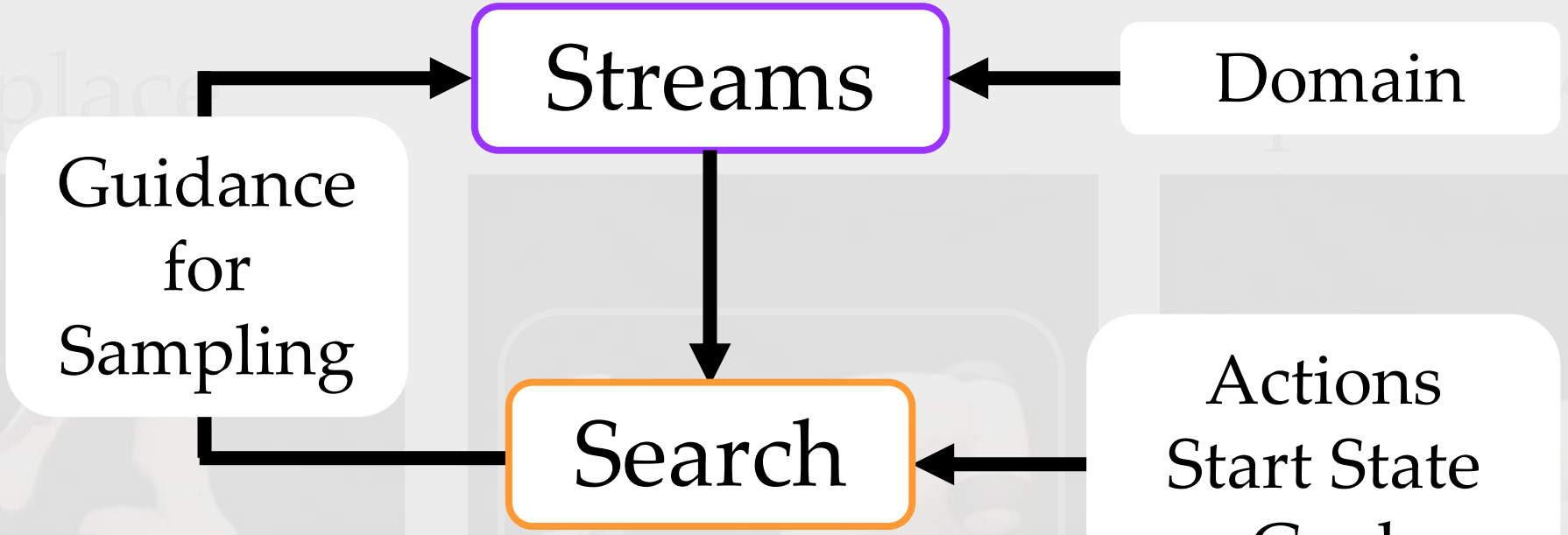
"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream



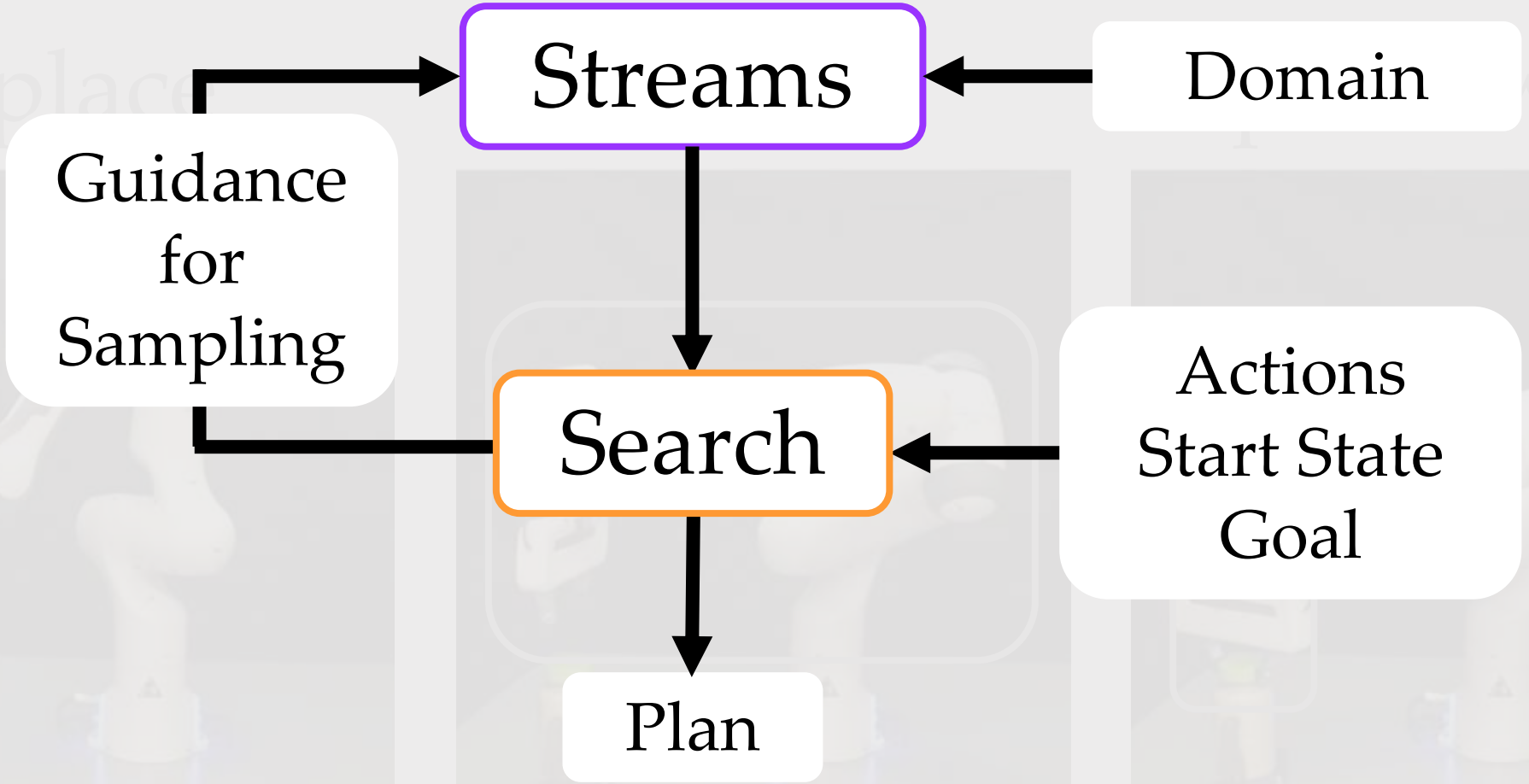
"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream

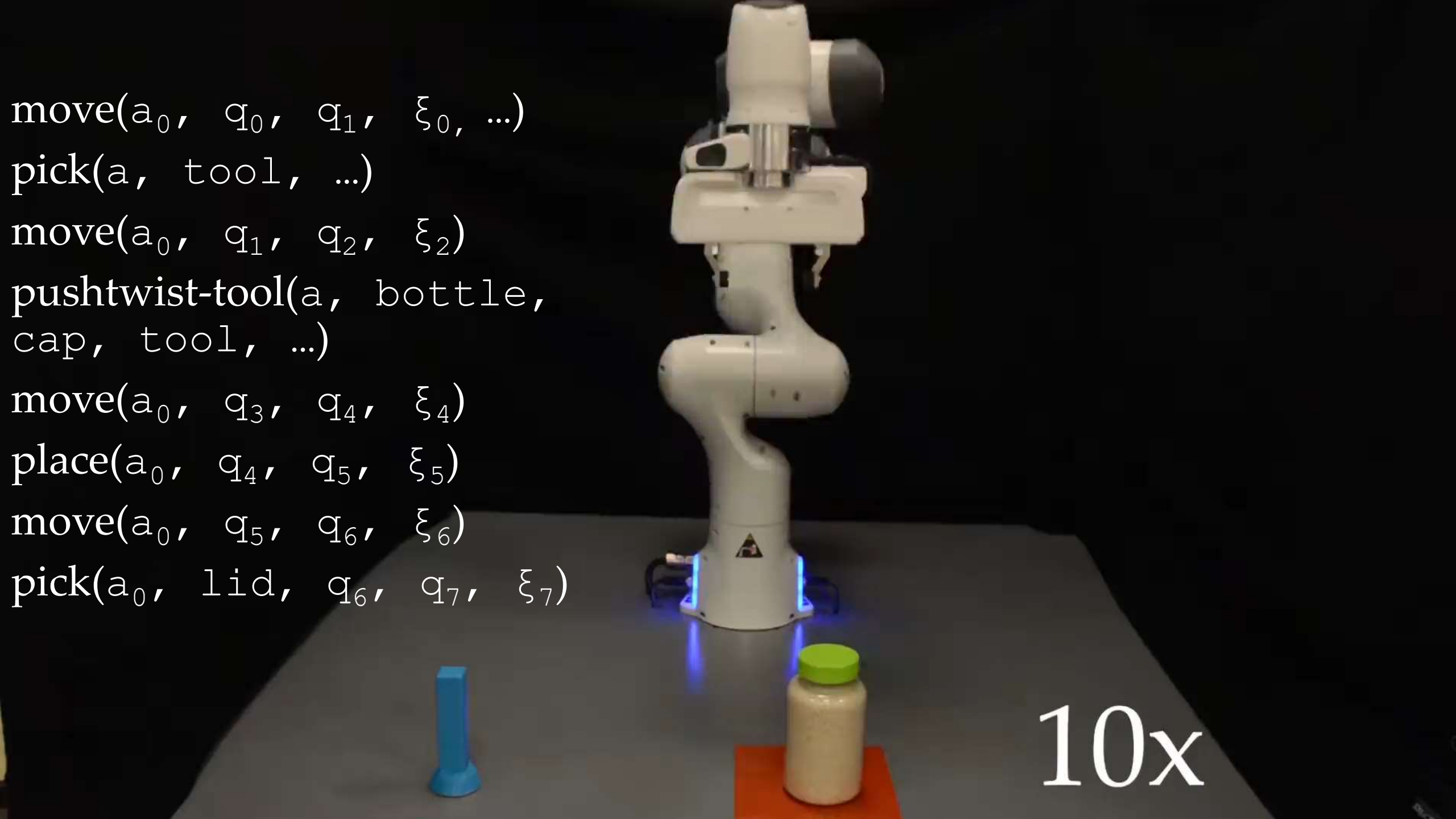


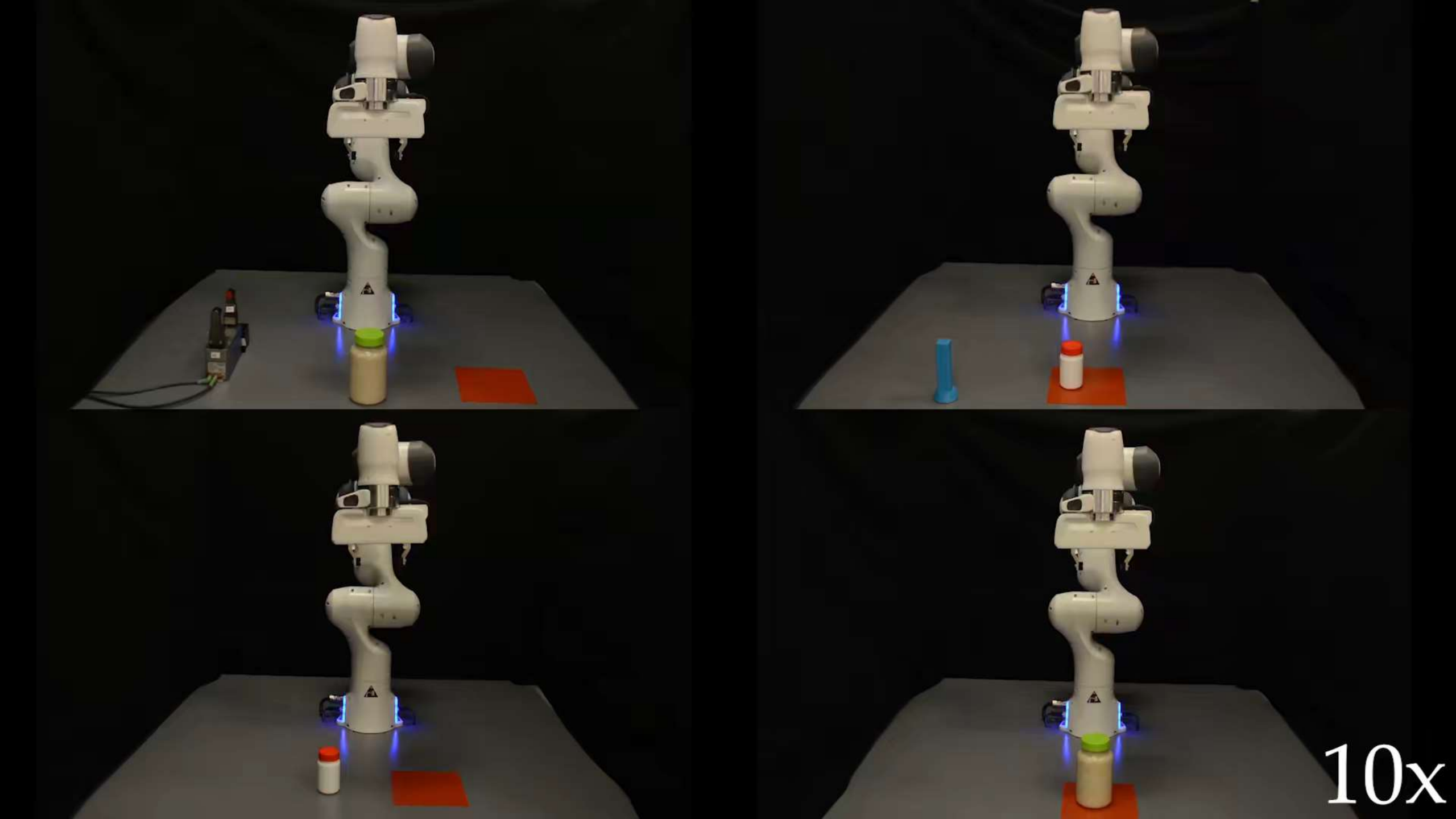
"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream

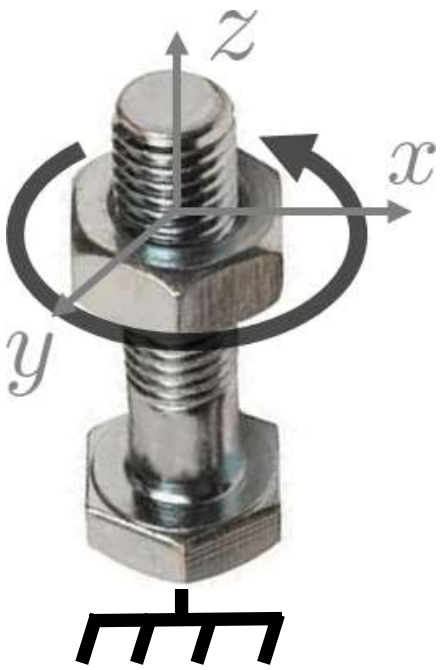


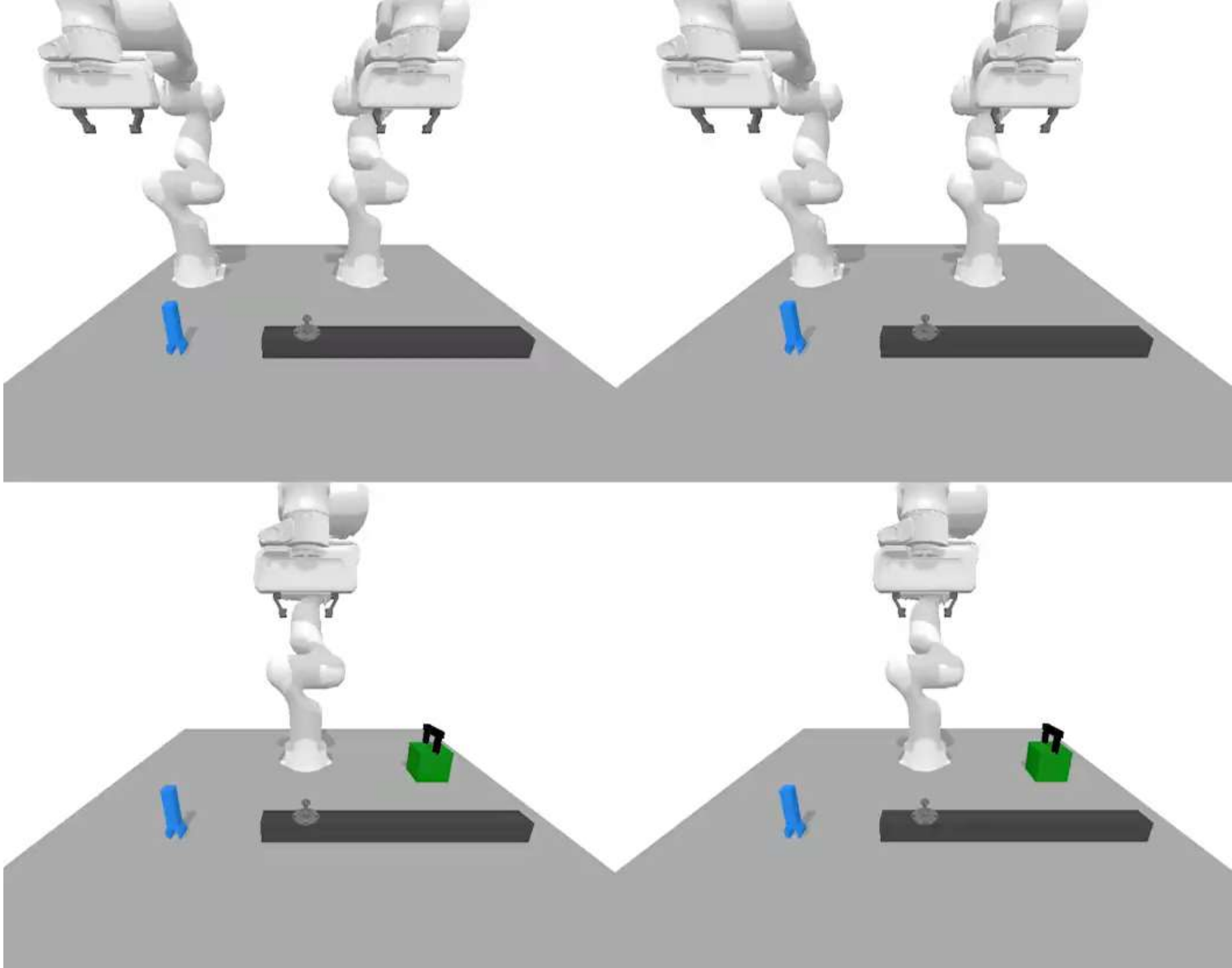
"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.


move(a_0, q_0, q_1, ξ_0, …)
pick(a, tool, …)
move(a_0, q_1, q_2, ξ_2)
pushtwist-tool(a, bottle, cap, tool, …)
move(a_0, q_3, q_4, ξ_4)
place(a_0, q_4, q_5, ξ_5)
move(a_0, q_5, q_6, ξ_6)
pick(a_0, lid, q_6, q_7, ξ_7)
10x


10x

Nut Twisting





Forces impact on Planning?

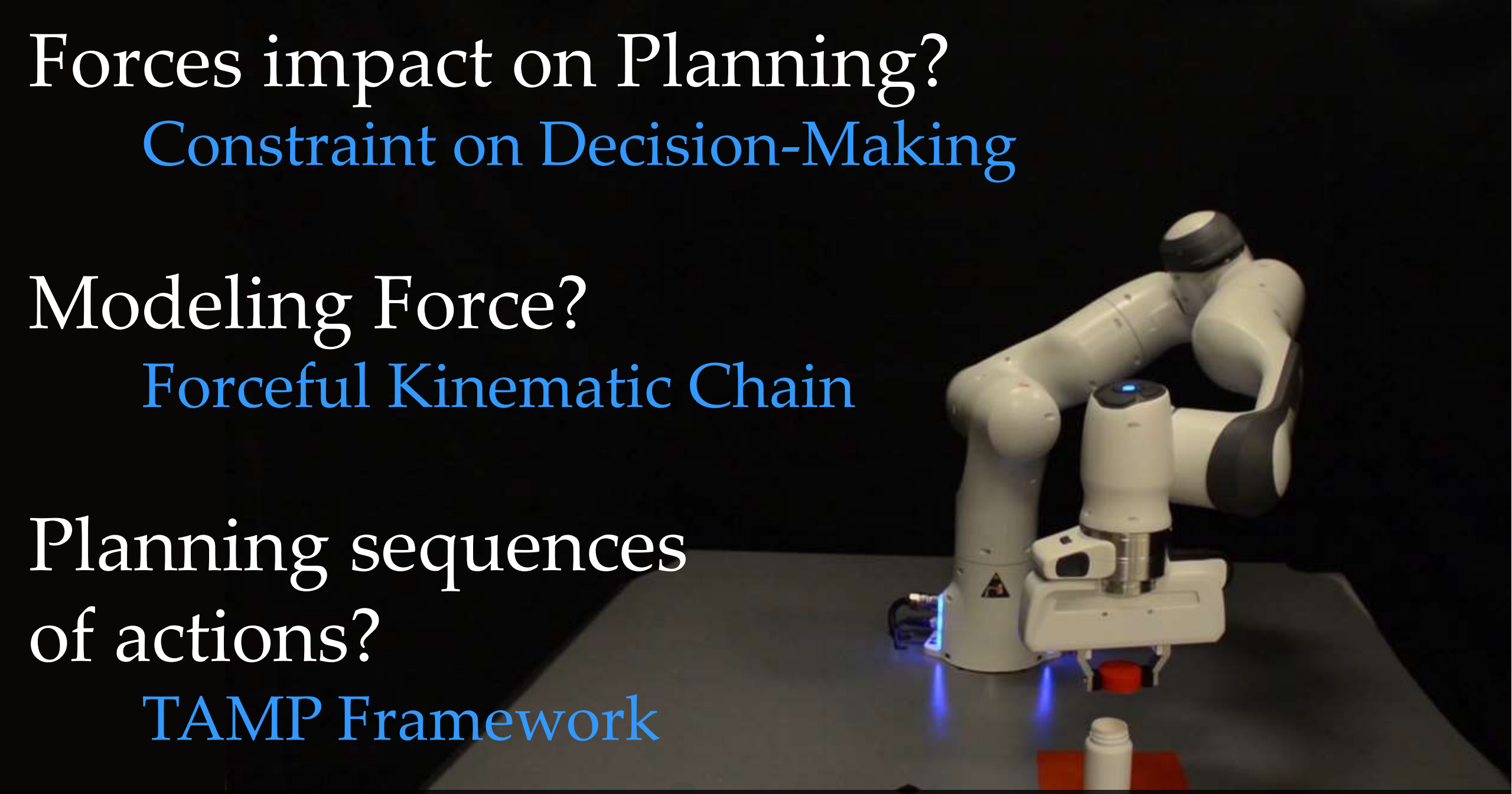
Constraint on Decision-Making

Modeling Force?

Forceful Kinematic Chain

Planning sequences of actions?

TAMP Framework



"Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *ICRA*, 2021.
"Robust Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *IJRR*, 2023.

TAMP Framework: PDDLStream

sample_grasp(object)

check_collision_free(path)

Streams

plan_impedance(arm, …)

check_forceful_kinematic_chain(chain, wrench, …)

sample_force(object, …)

plan_motion(arm, q_{start}, q_{goal})

"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

TAMP Framework: PDDLStream

sample_grasp(object)

check_collision_free(path)

Streams

plan_impedance(arm, …)

check_forceful_kinematic_chain(chain, wrench, …)

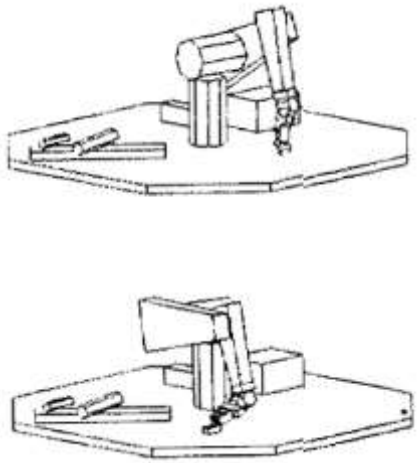
regrasp(object, $grasp_{start}$, $grasp_{goal}$)

sample_force(object, …)

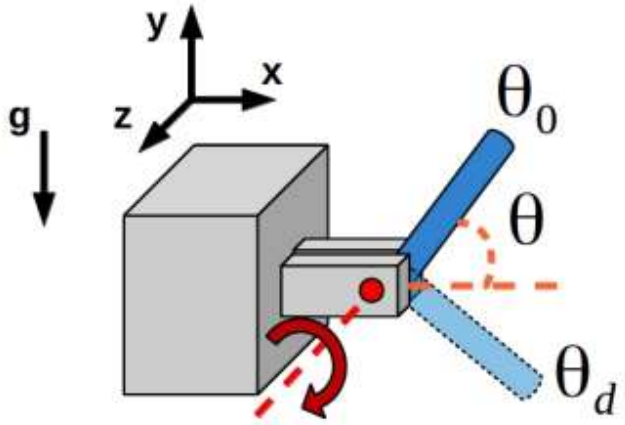
plan_motion(arm, q_{start}, q_{goal})

"PDDLStream: Integrating Symbolic Planners and Blackbox Samplers" C Garrett, T Lozano-Pérez, L Kaelbling. *ICAPS*, 2020.

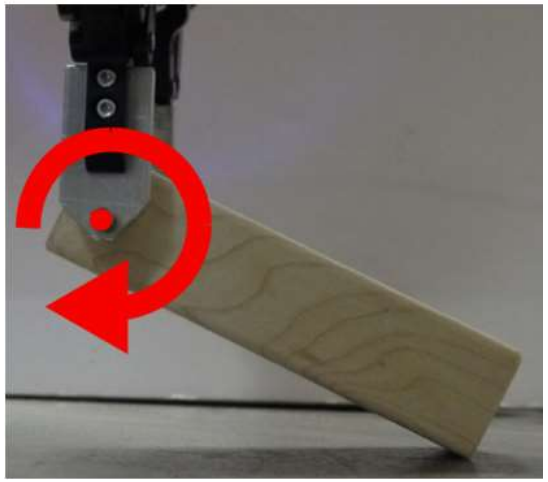

M



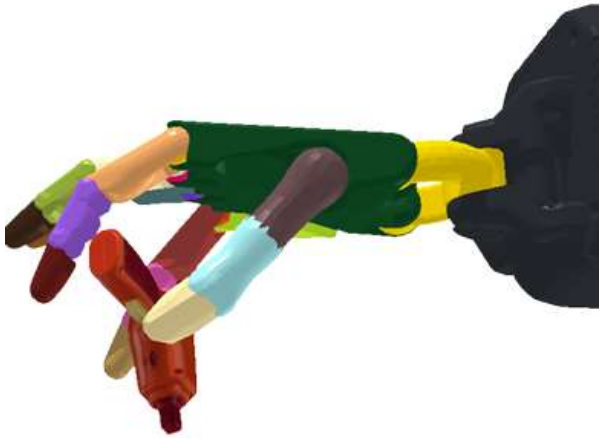
[Tournassoud, Lozano-Pérez, Mazer 1987]



[Vina, Karayiannidis, Smith Kragic, 2016]

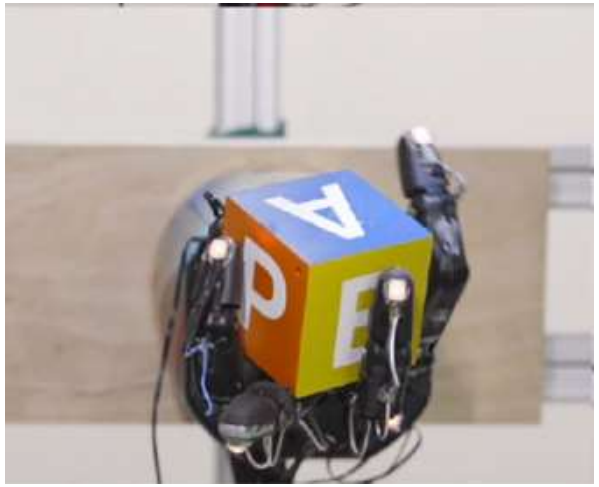


[A. Holladay, Paolini, Mason 2015]



[Chen, Xu, Agrawal 2022]

[Shi, Woodruff, Lynch 2015]



[OpenAI 2020]

[Hou, Jia, Johnson, Mason 2020]

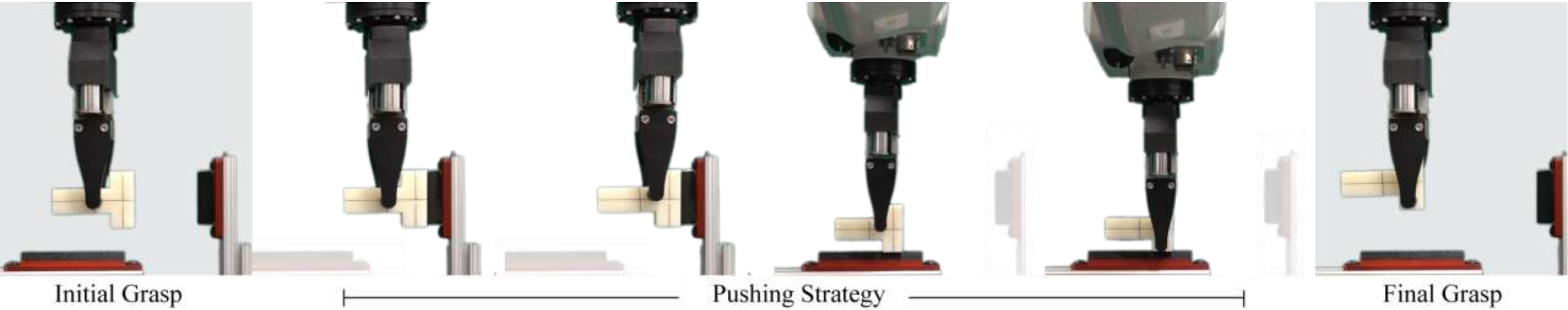
[Cruciani, Hang, Smith, Kragic 2019]

Initial Grasp

Final Grasp

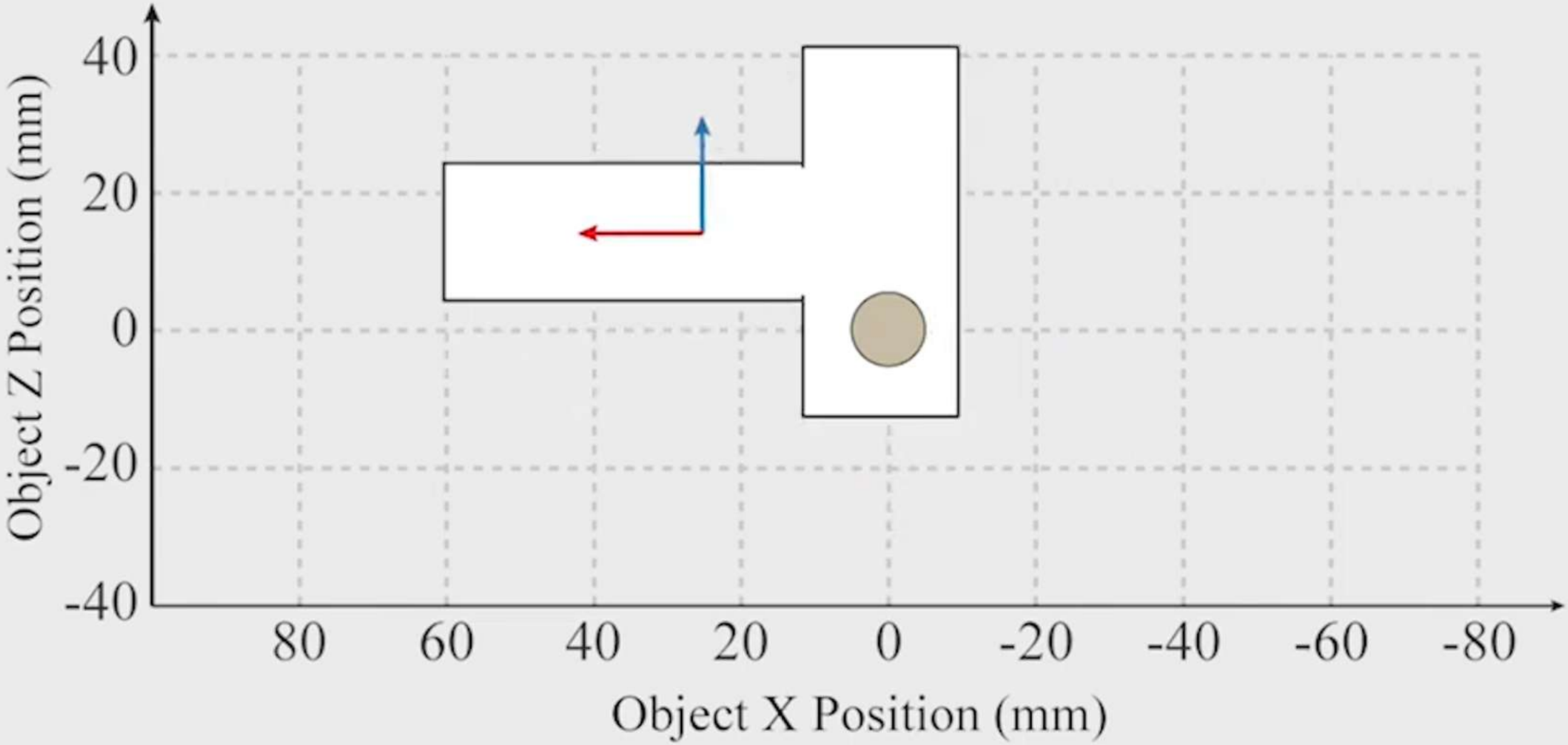
Initial Grasp

Final Grasp



Output: Sequence of Continuous Pushes

Feasible Motions?



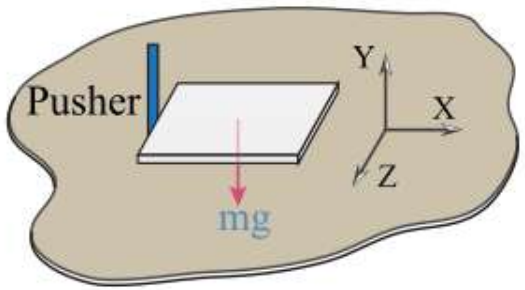
Motion Cone

the set of feasible motions that a rigid body can follow under the action of a frictional push

"Mechanics and Planning of Manipulator Pushing Operations". Matthew Mason. *IJRR*, 1986.

Motion Cone

the set of feasible motions that a rigid body can follow under the action of a frictional push



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Motion Cone

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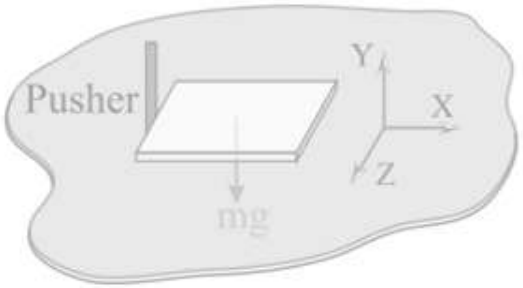
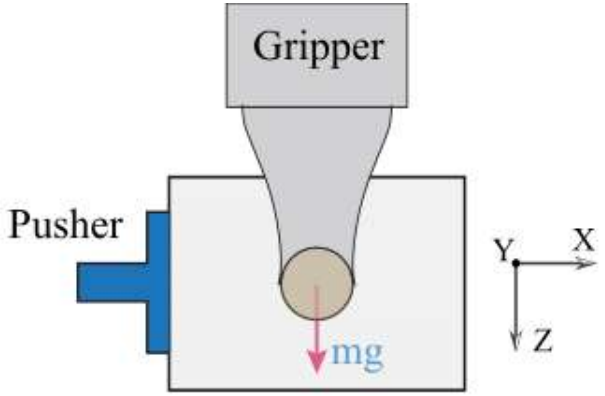
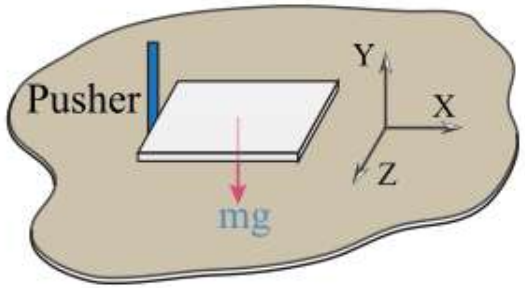


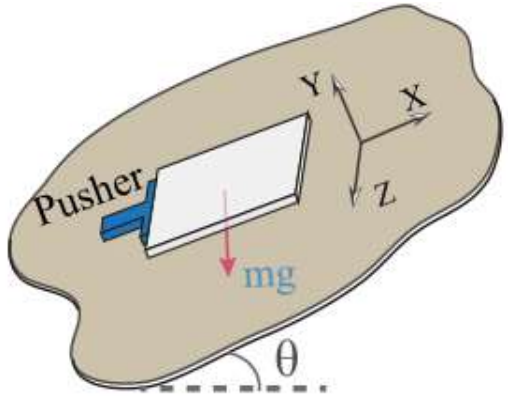


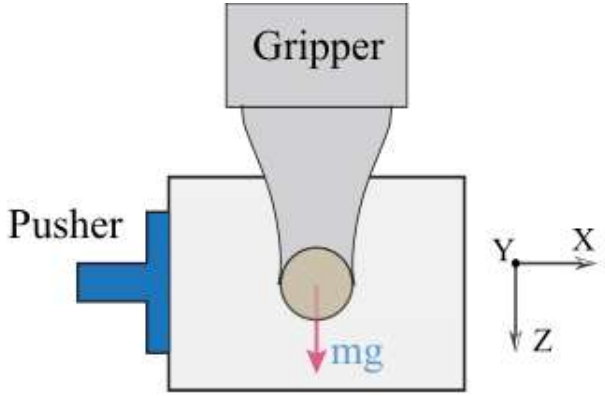
Extending the

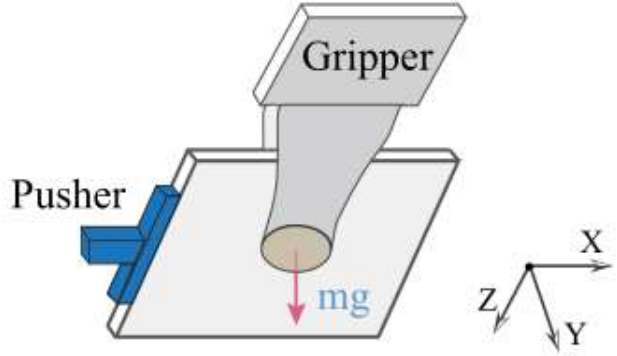
Motion Cone

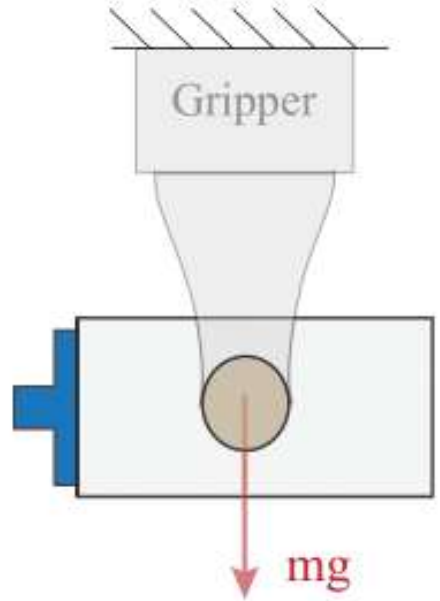
the set of feasible motions that a rigid body can follow under the action of a frictional push

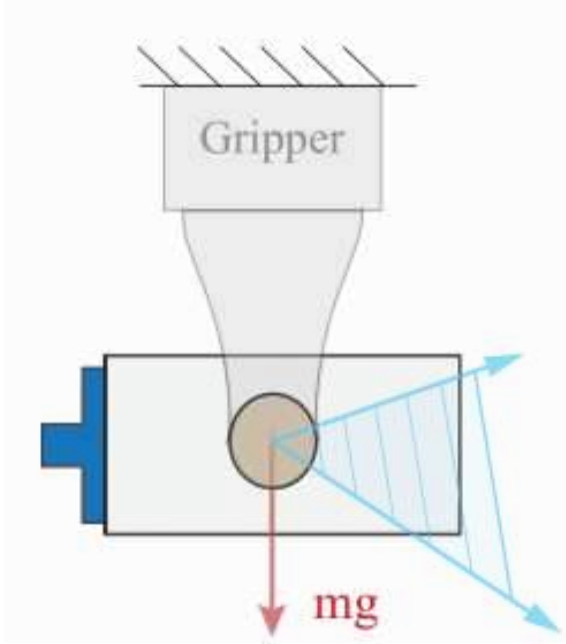




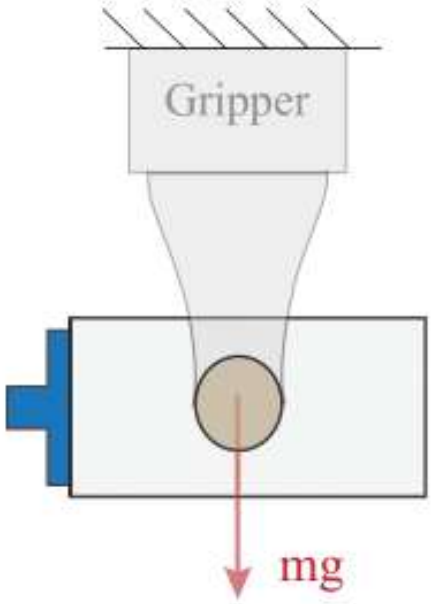


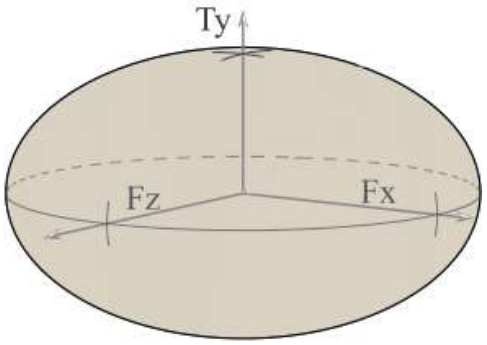



Gripper
mg

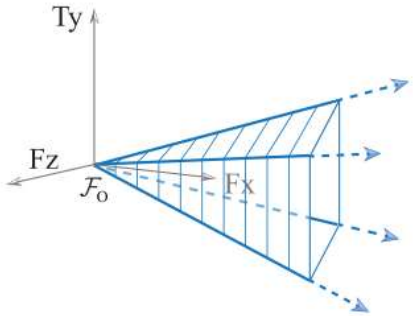


Motion Cone

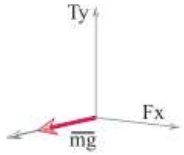




Frictional Support

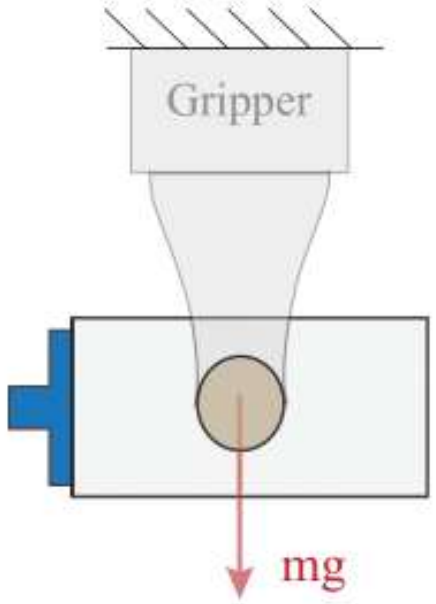


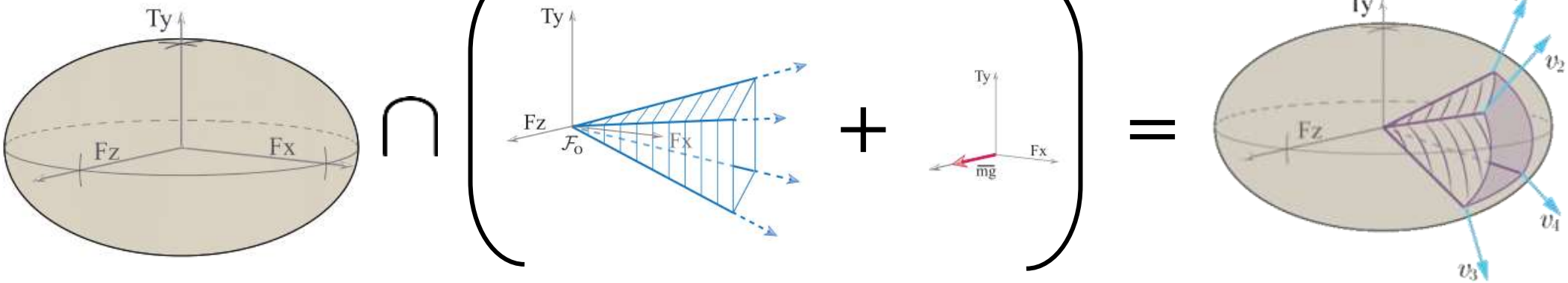
Pushing Force



Gravity

Erdmann (1994). Goyal, Ruina, and Papadopoulos (1991). Xydas and Kao (1999)

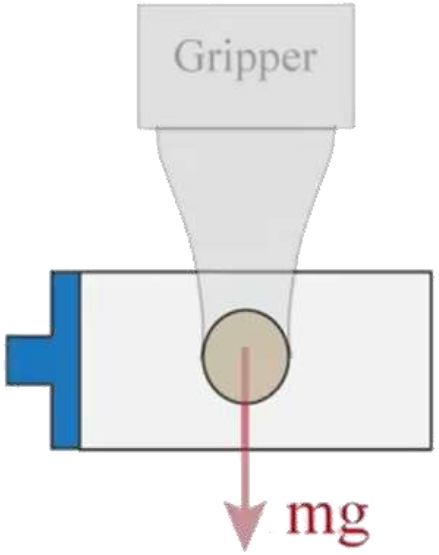


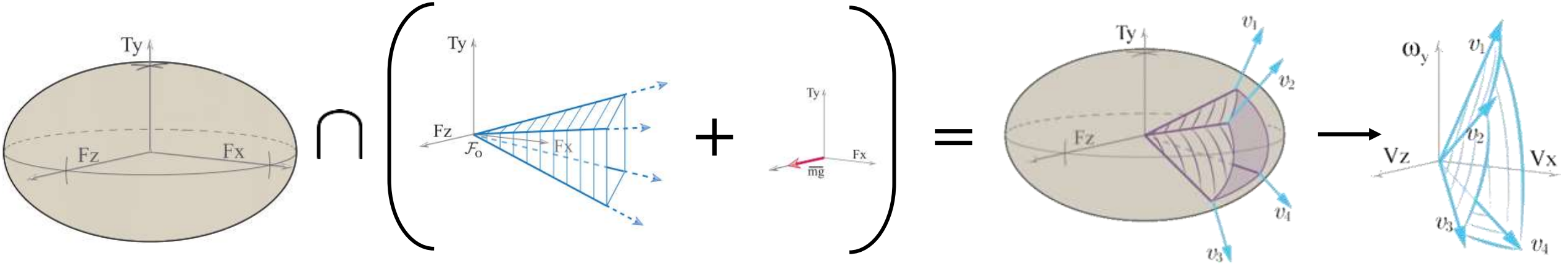


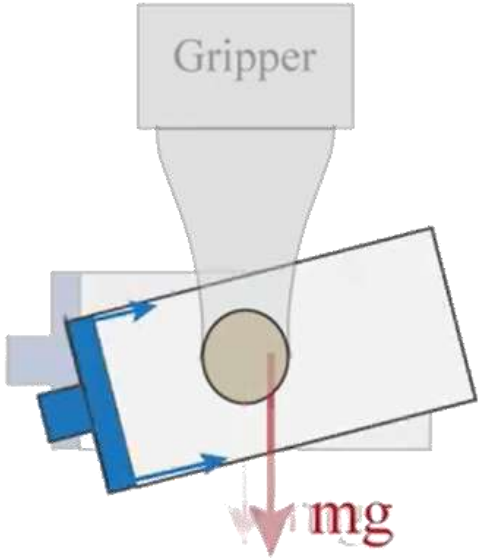
Frictional Support

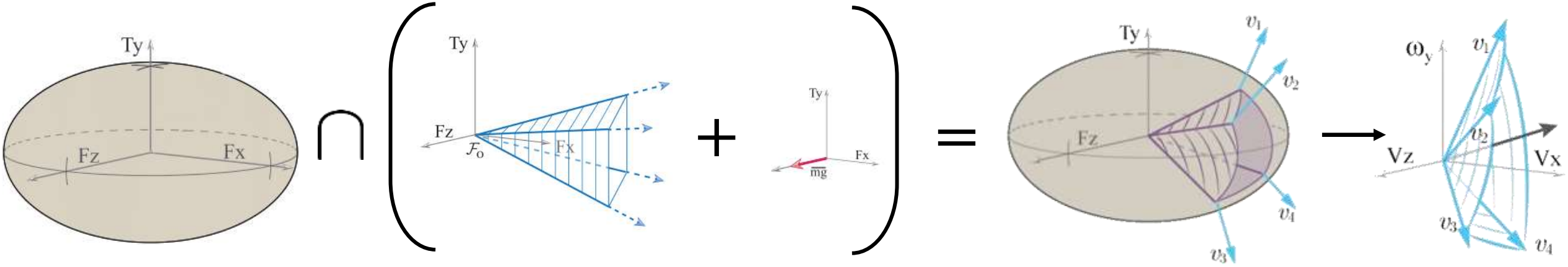
Pushing Force

Gravity


Gripper
mg


Ty
Fz
Fx
Ty
Fz
$\mathcal{F}_o$
Fx
Ty
Fx
mg
Ty
Fz
v_1
v_2
v_3
v_4
ω_y
v_1
v_2
v_3
v_4
Vz
Vx


Gripper
mg


Ty
Fz
Fx
Ty
Fz
$\mathcal{F}_o$
Fx
Ty
Fx
mg
Ty
Fz
v_1
v_2
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v_4
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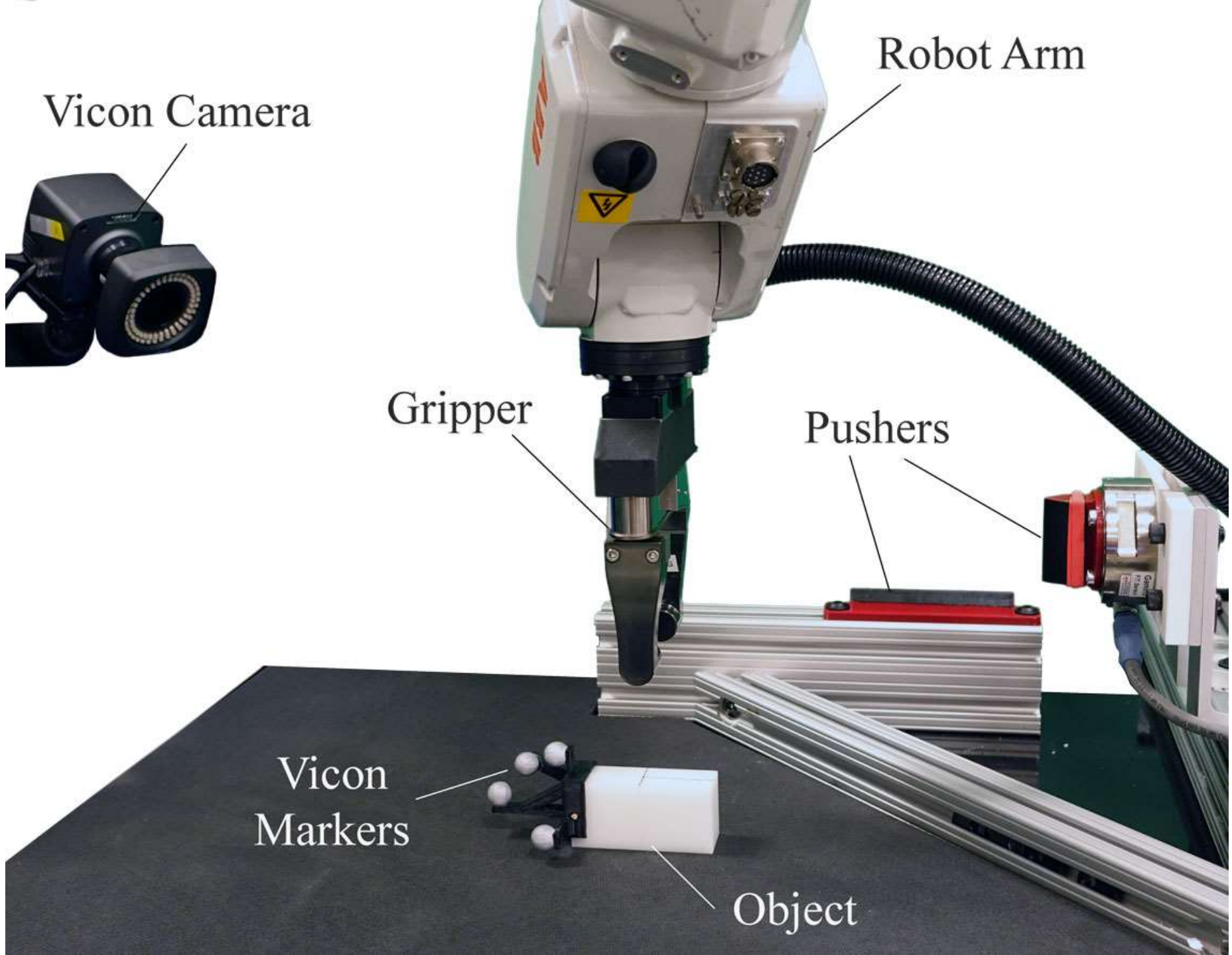
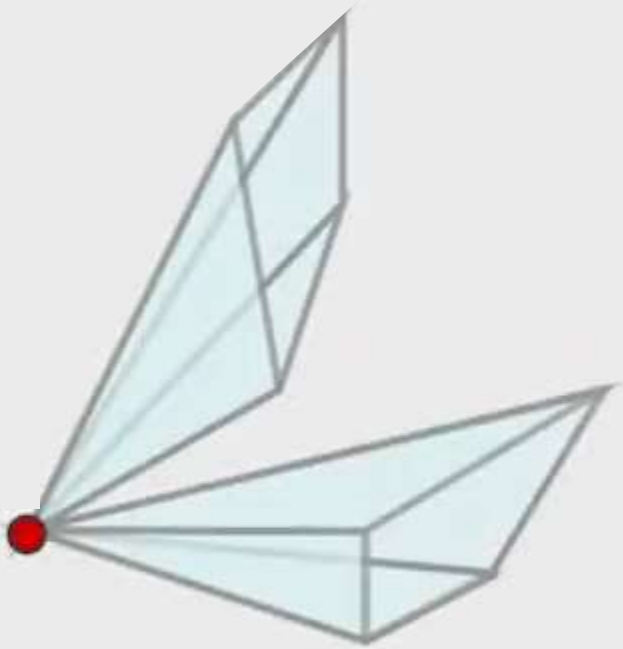
v_1
v_2
Vz
Vx
v_3
v_4


Vicon Camera
Robot Arm
Gripper
Pushers
Vicon
Markers
Object

Initial Grasp

Initial Grasp

Initial Grasp



Final Grasp

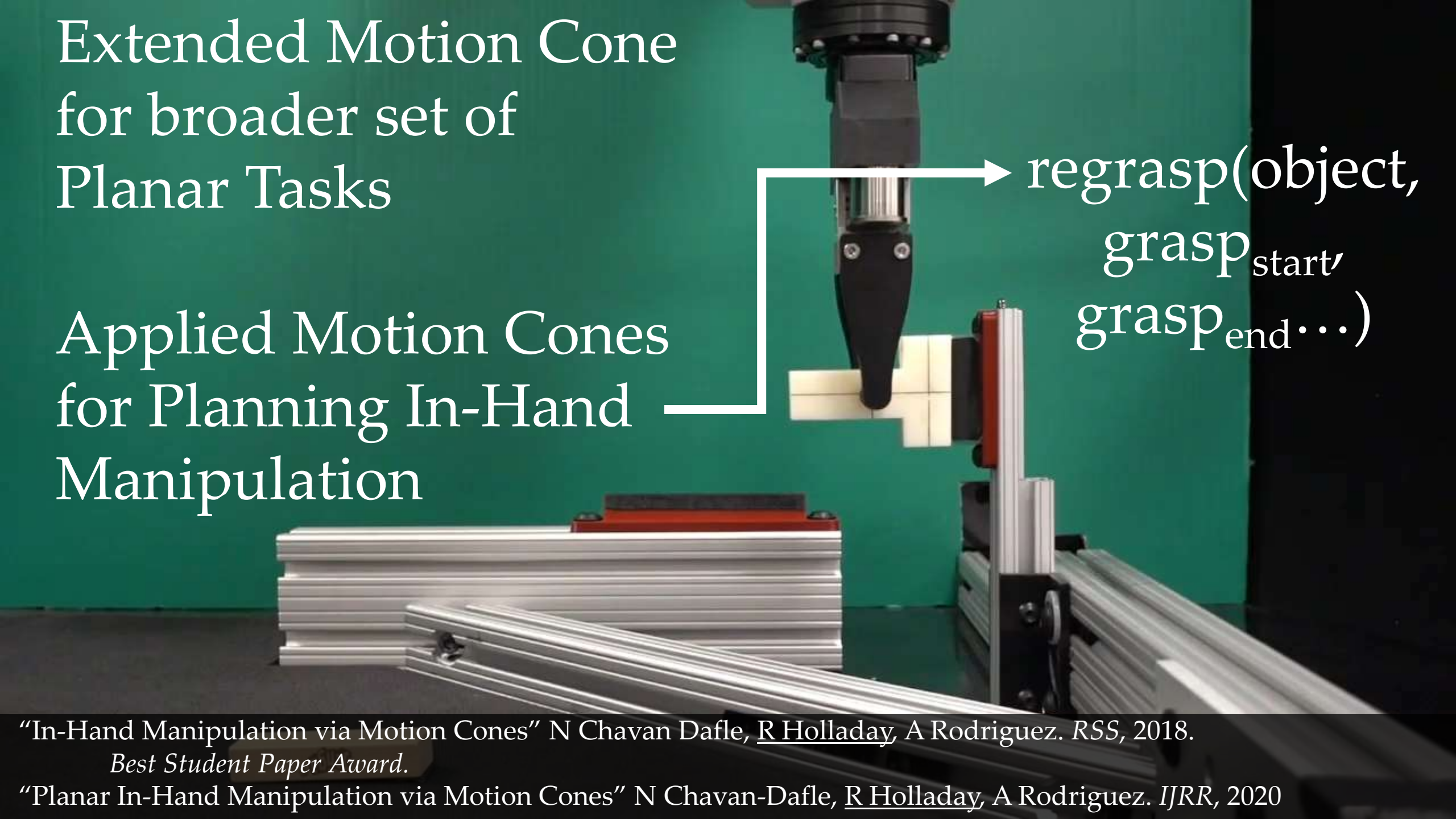
Extended Motion Cone for broader set of Planar Tasks

"In-Hand Manipulation via Motion Cones" N Chavan Dafle, R Holladay, A Rodriguez. *RSS*, 2018.
Best Student Paper Award.
"Planar In-Hand Manipulation via Motion Cones" N Chavan-Dafle, R Holladay, A Rodriguez. *IJRR*, 2020

Extended Motion Cone for broader set of Planar Tasks

Applied Motion Cones for Planning In-Hand Manipulation

"In-Hand Manipulation via Motion Cones" N Chavan Dafle, R Holladay, A Rodriguez. *RSS*, 2018.
Best Student Paper Award.
"Planar In-Hand Manipulation via Motion Cones" N Chavan-Dafle, R Holladay, A Rodriguez. *IJRR*, 2020



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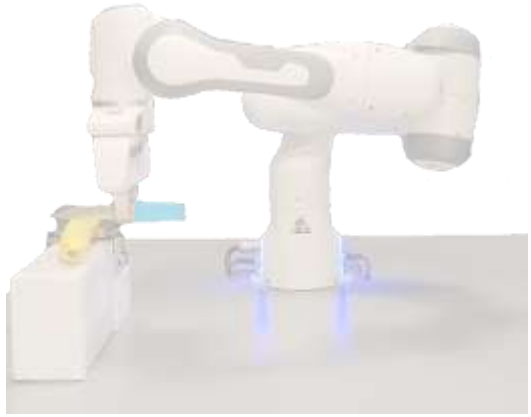
Forceful Manipulation



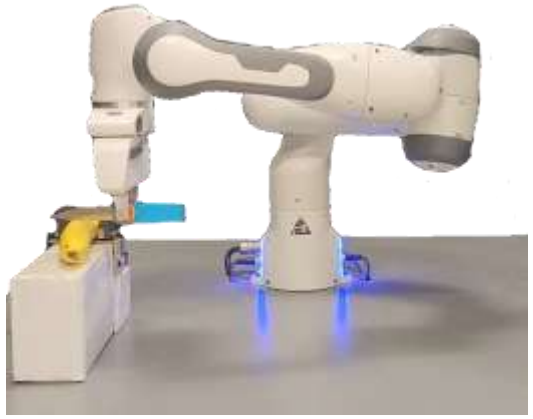
Robust Decision Making

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

In-Hand Manipulation

Guarded Planning

Forceful Manipulation



Robust Decision Making

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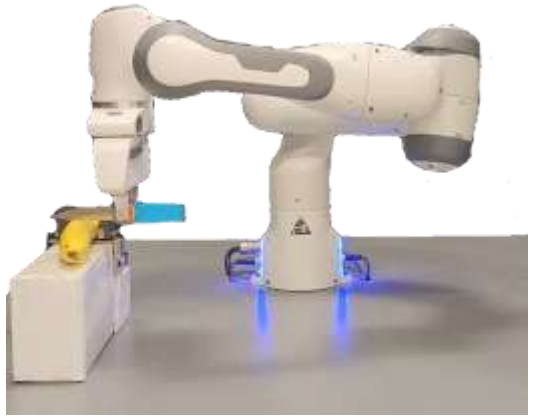

Robust Decision Making

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

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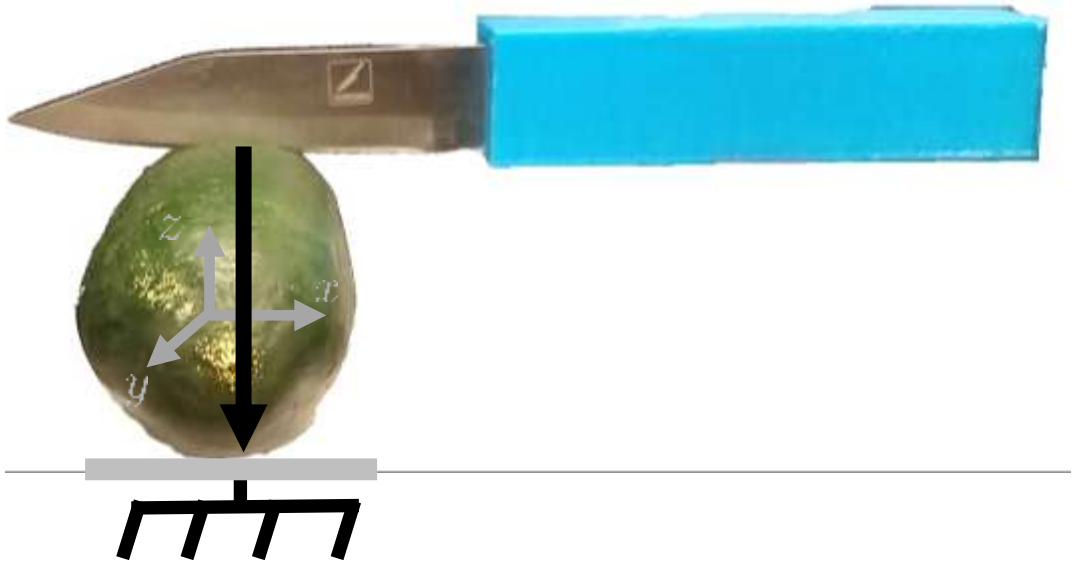
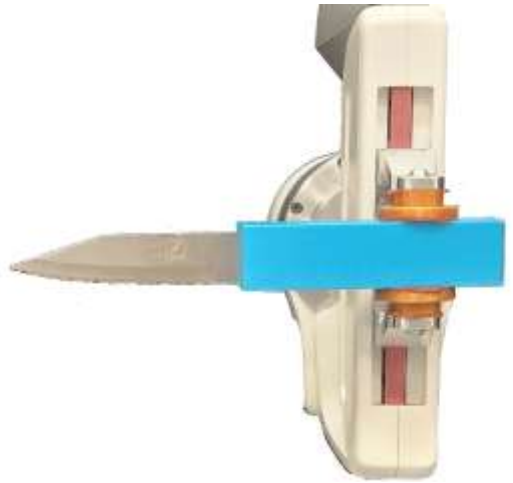
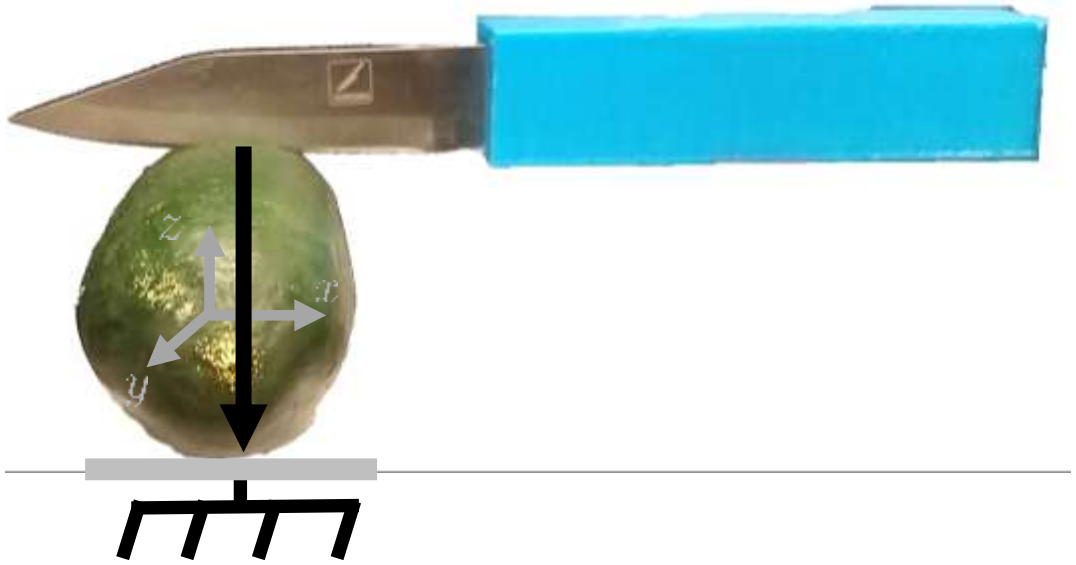
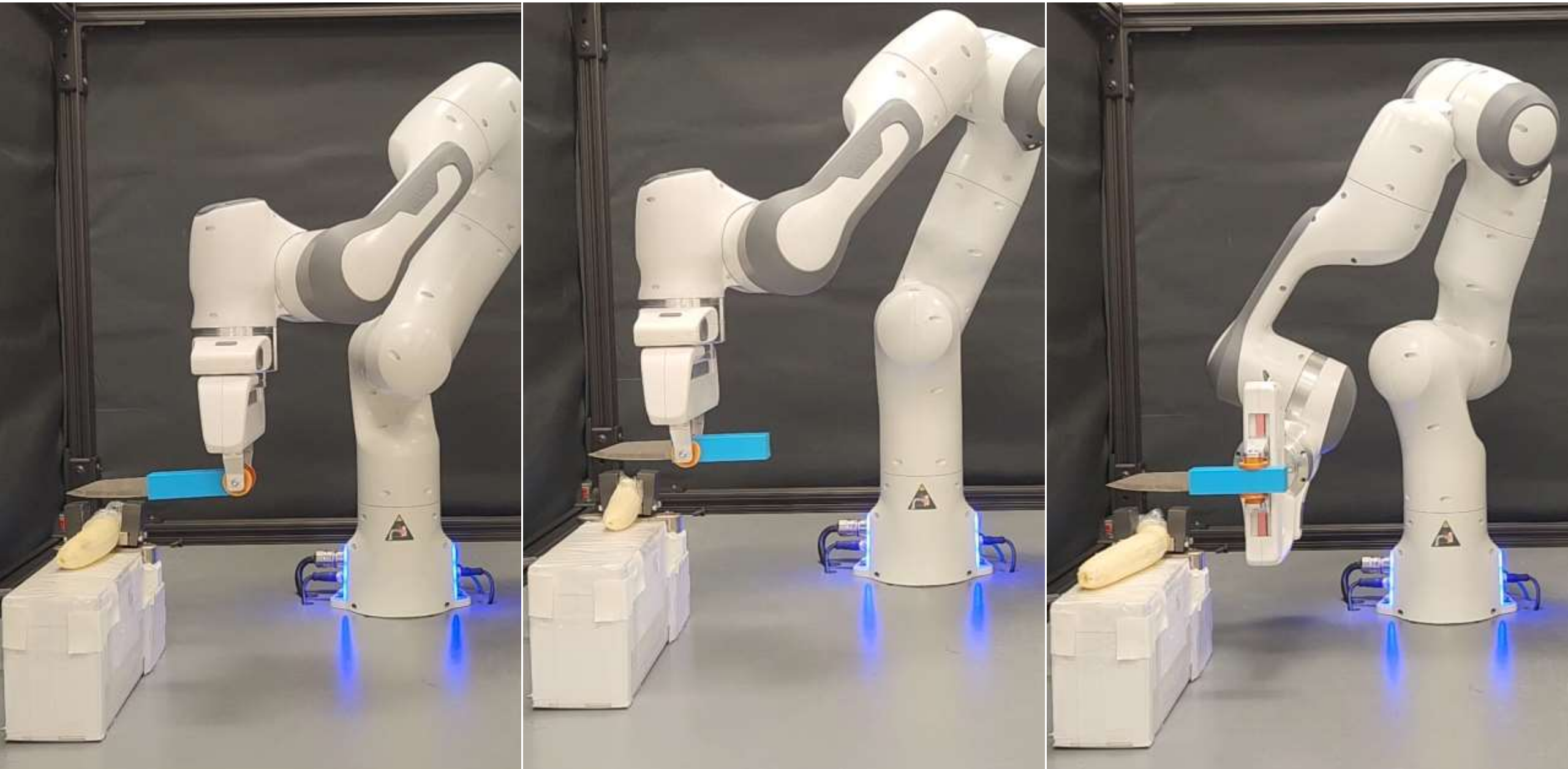
Guarded Planning


z
x
y

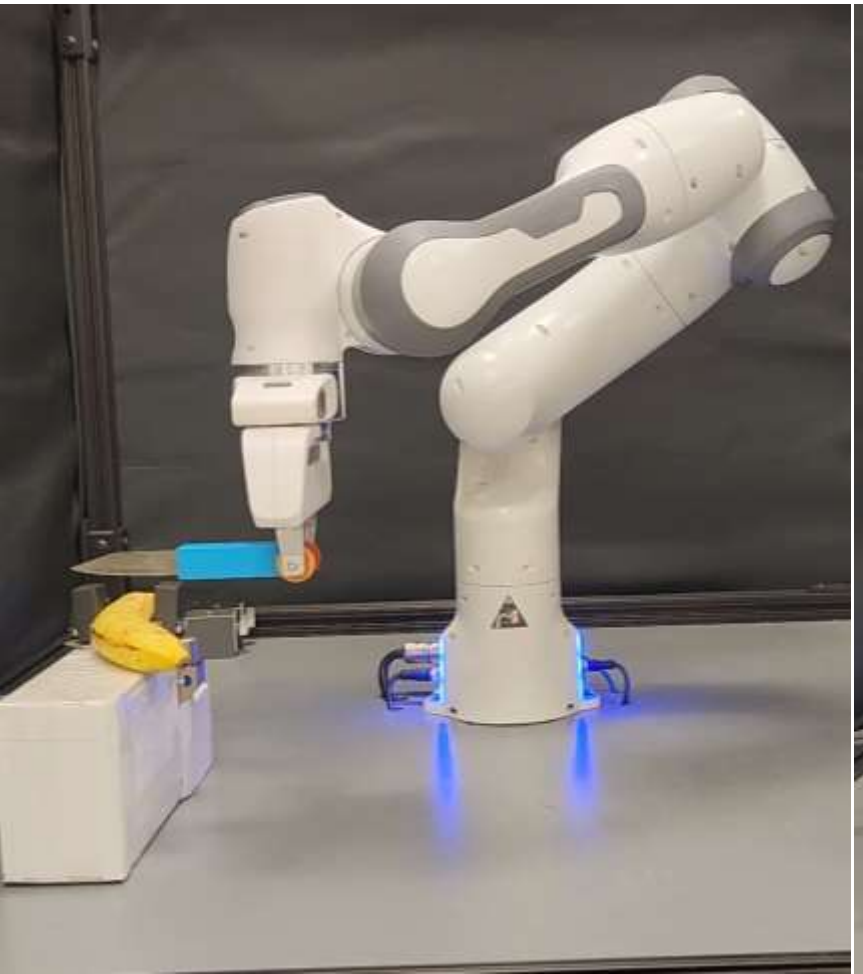
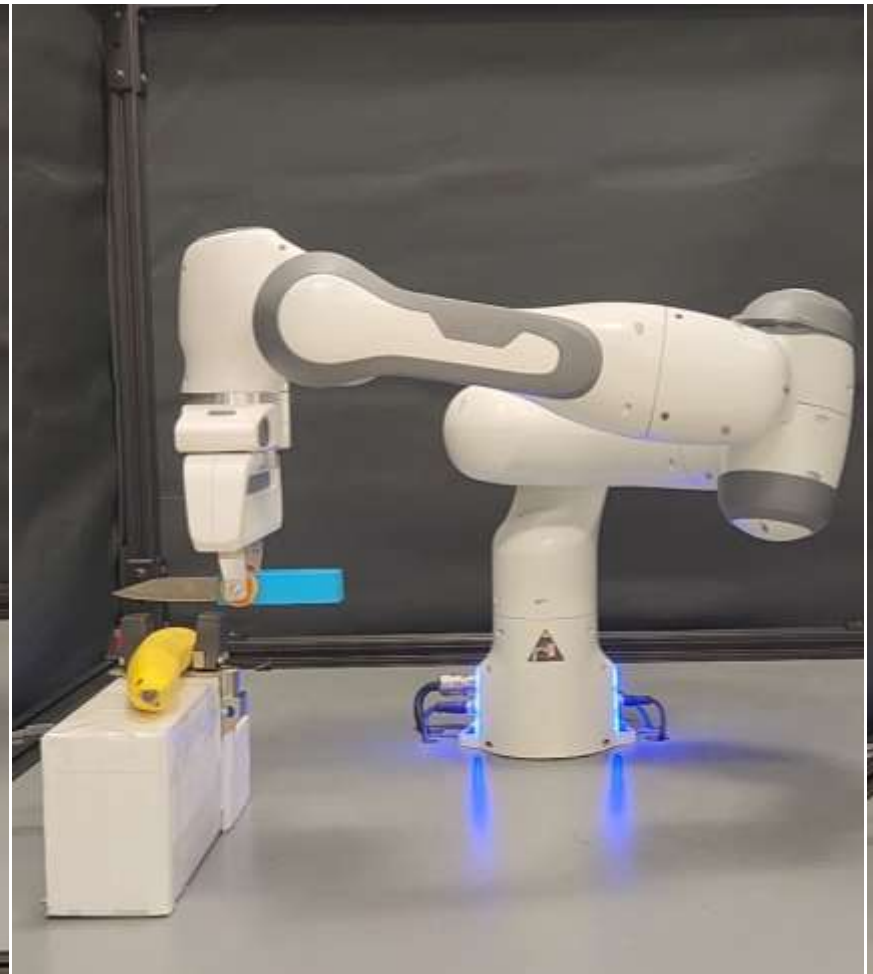
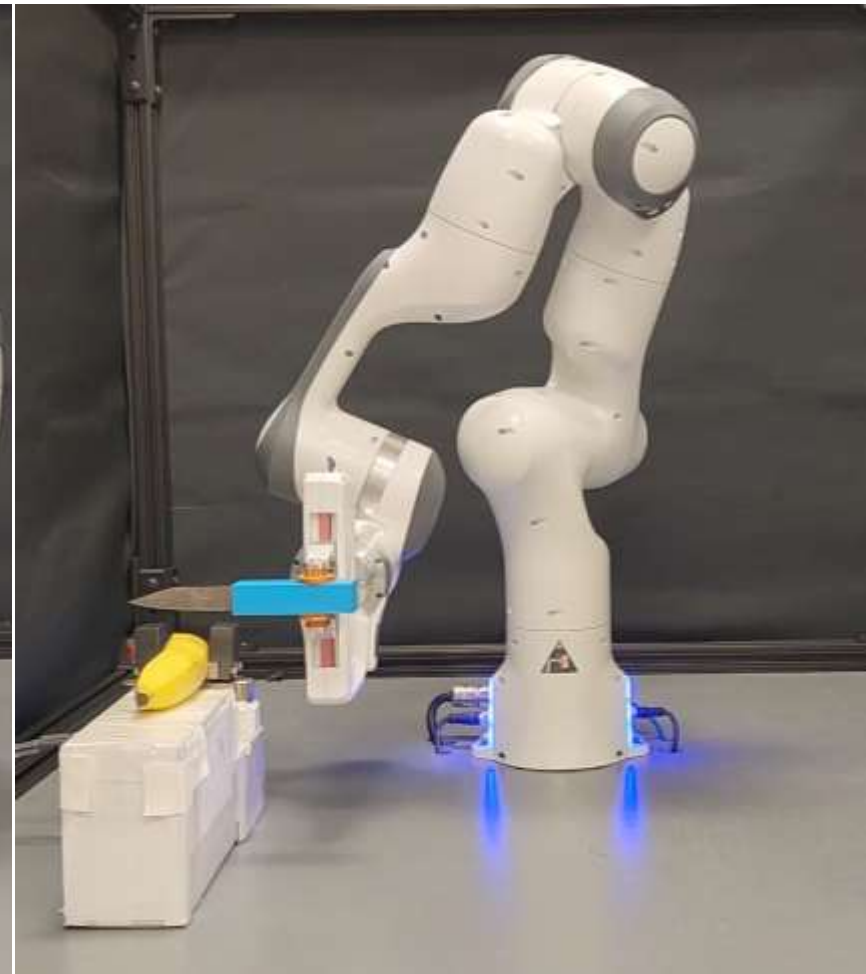



z
x
y

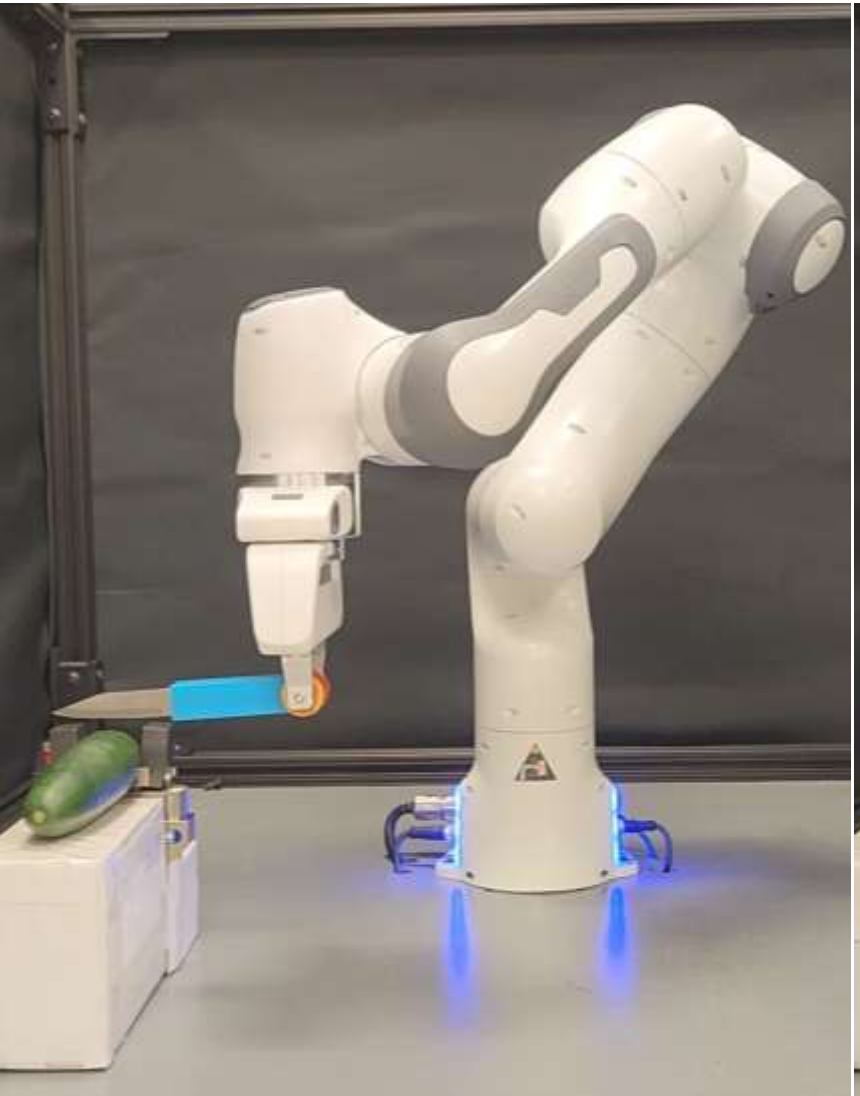
Peeled Banana

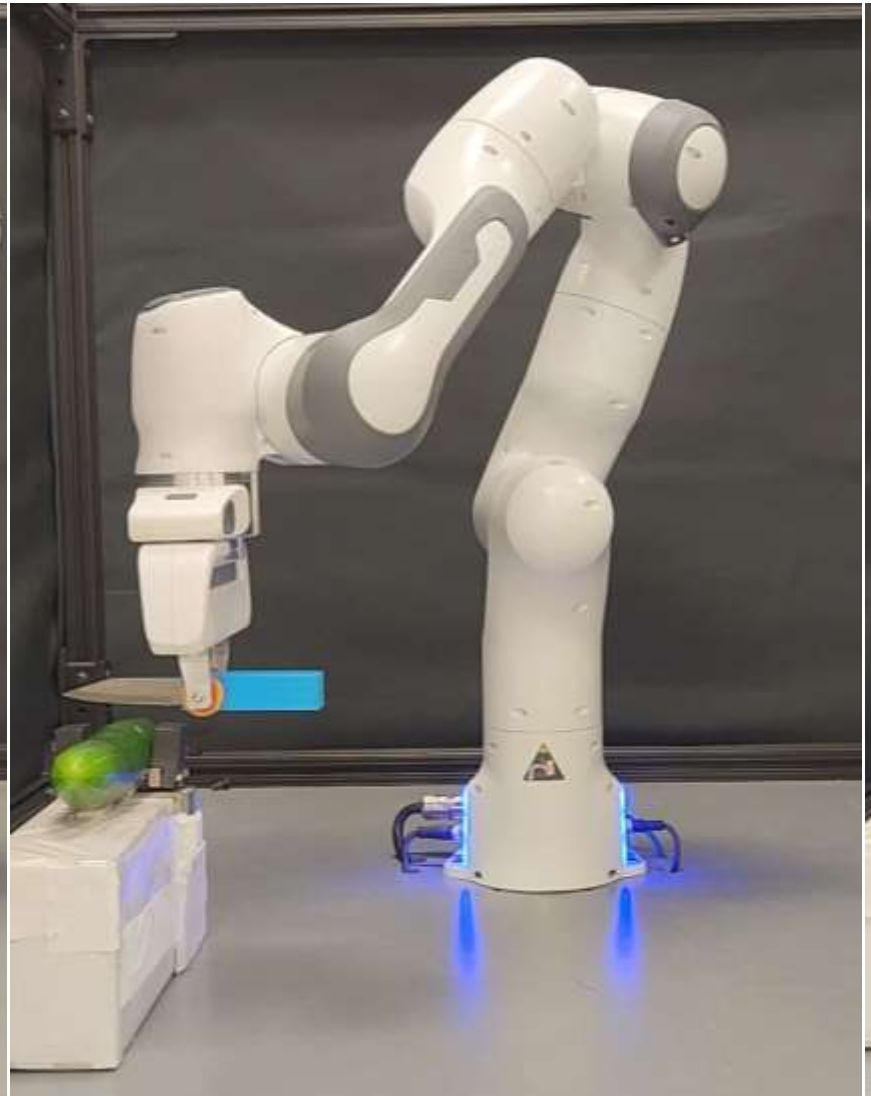


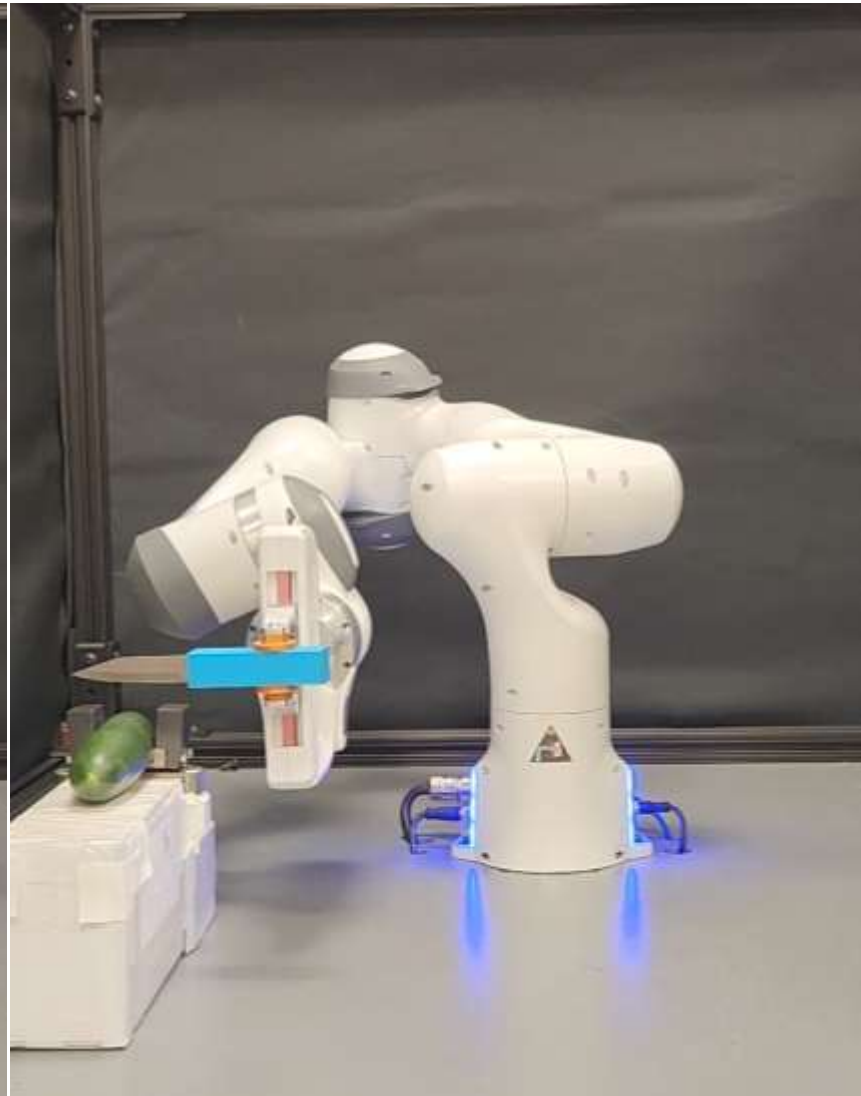
Unpeeled Banana

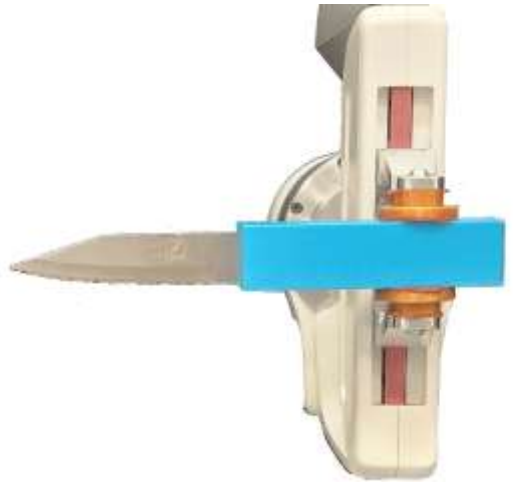




Cucumber

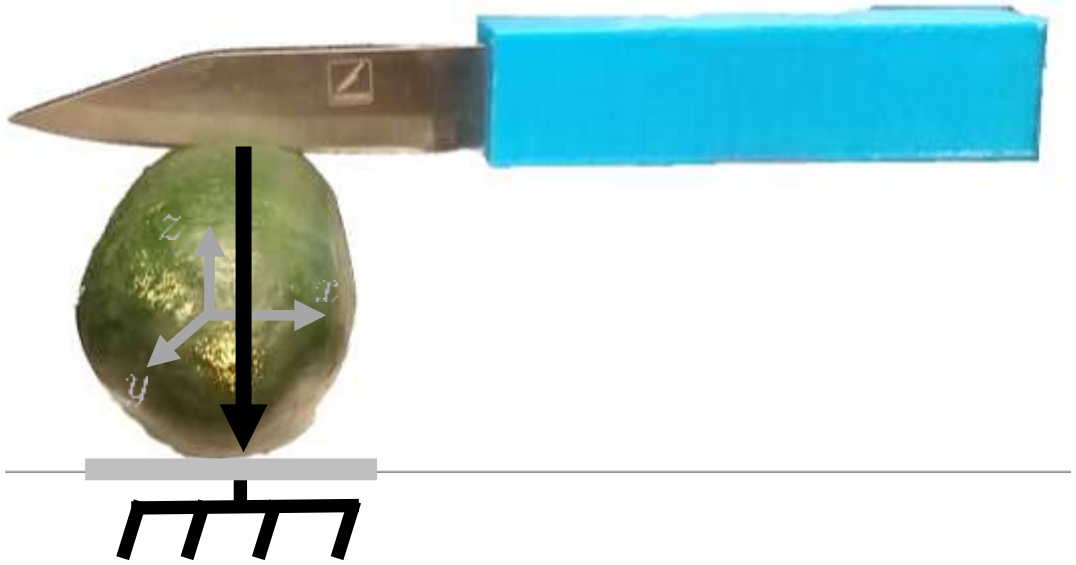


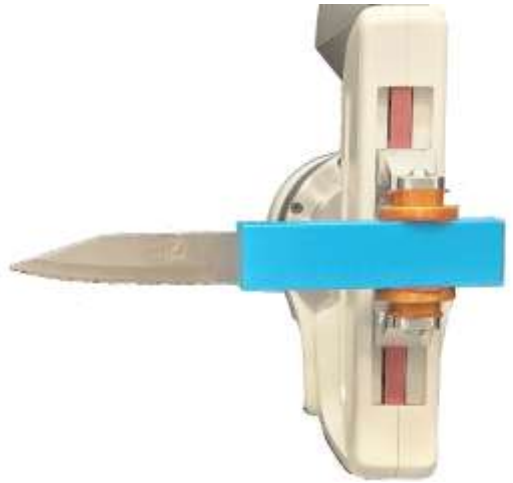




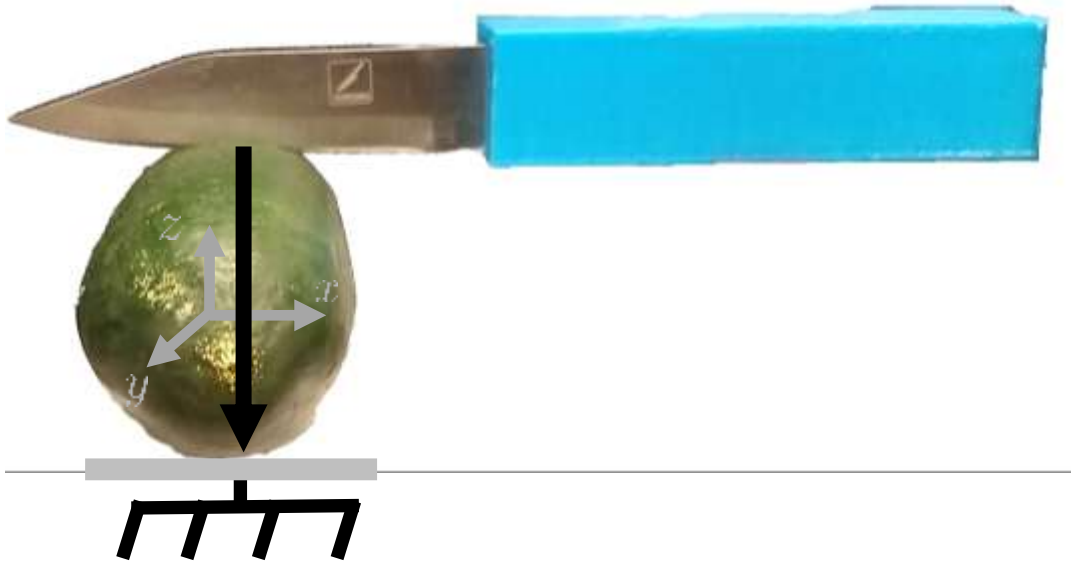


Best?





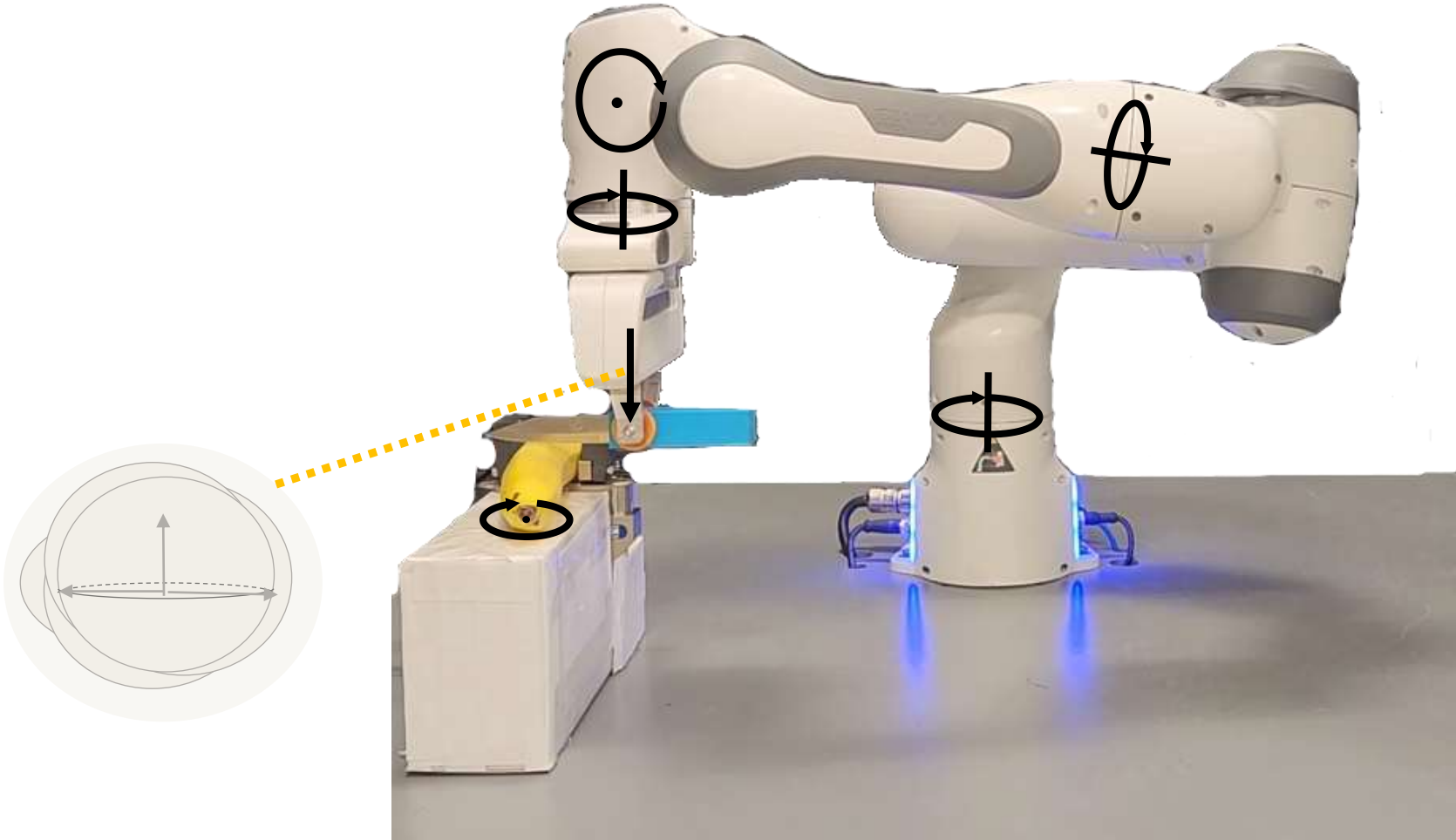
Be t?





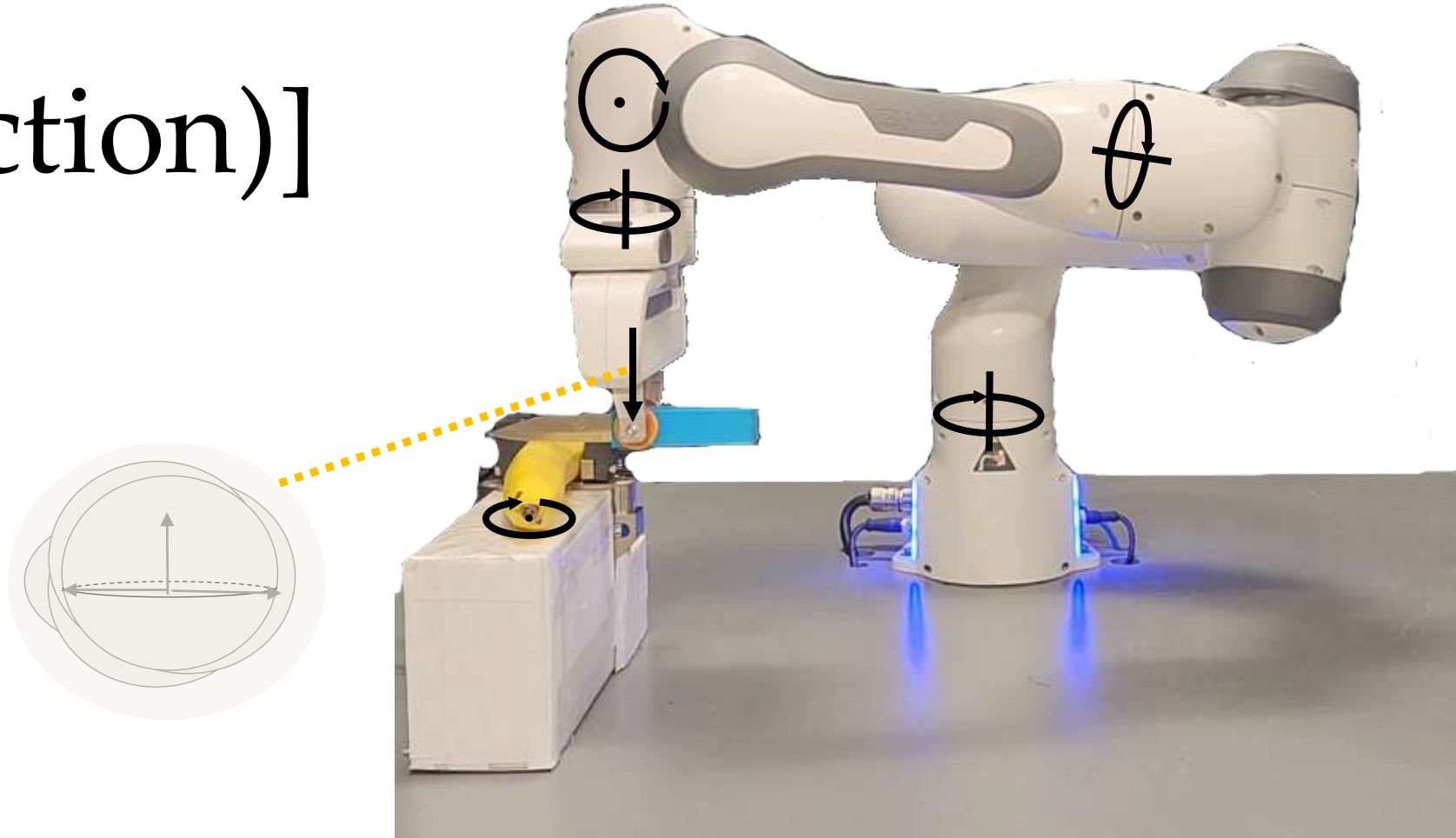
Balancing Constraints and Robustness?

Robust to Variations in the Physical Parameters



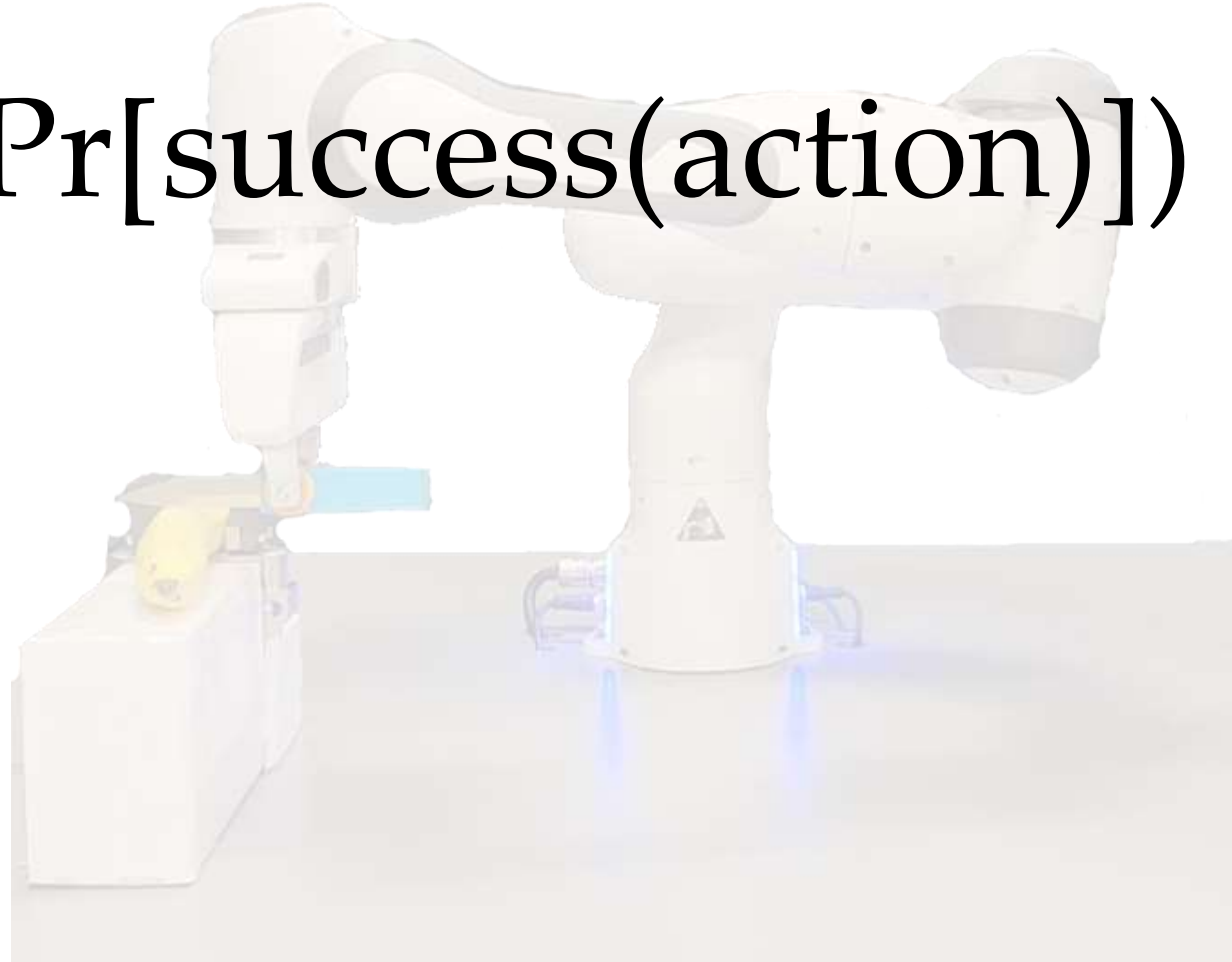
Robust to Variations in the Physical Parameters

Pr[success(action)]



Robust to Variations in the Physical Parameters via Cost-Sensitive Planning

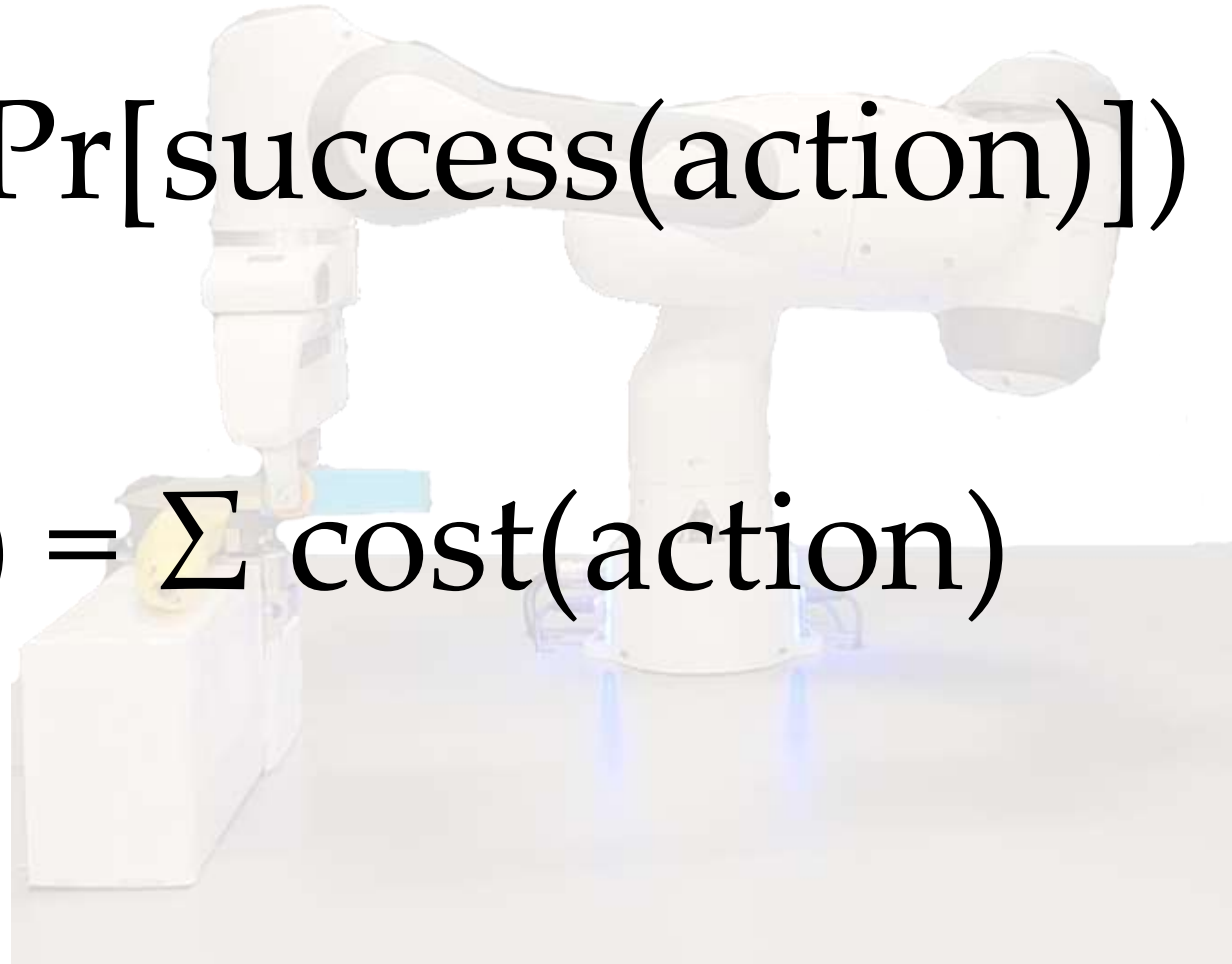
$$\text{cost}(\text{action}) = -\log(\Pr[\text{success}(\text{action})])$$



Robust to Variations in the Physical Parameters via Cost-Sensitive Planning

$$\text{cost}(\text{action}) = -\log(\Pr[\text{success}(\text{action})])$$

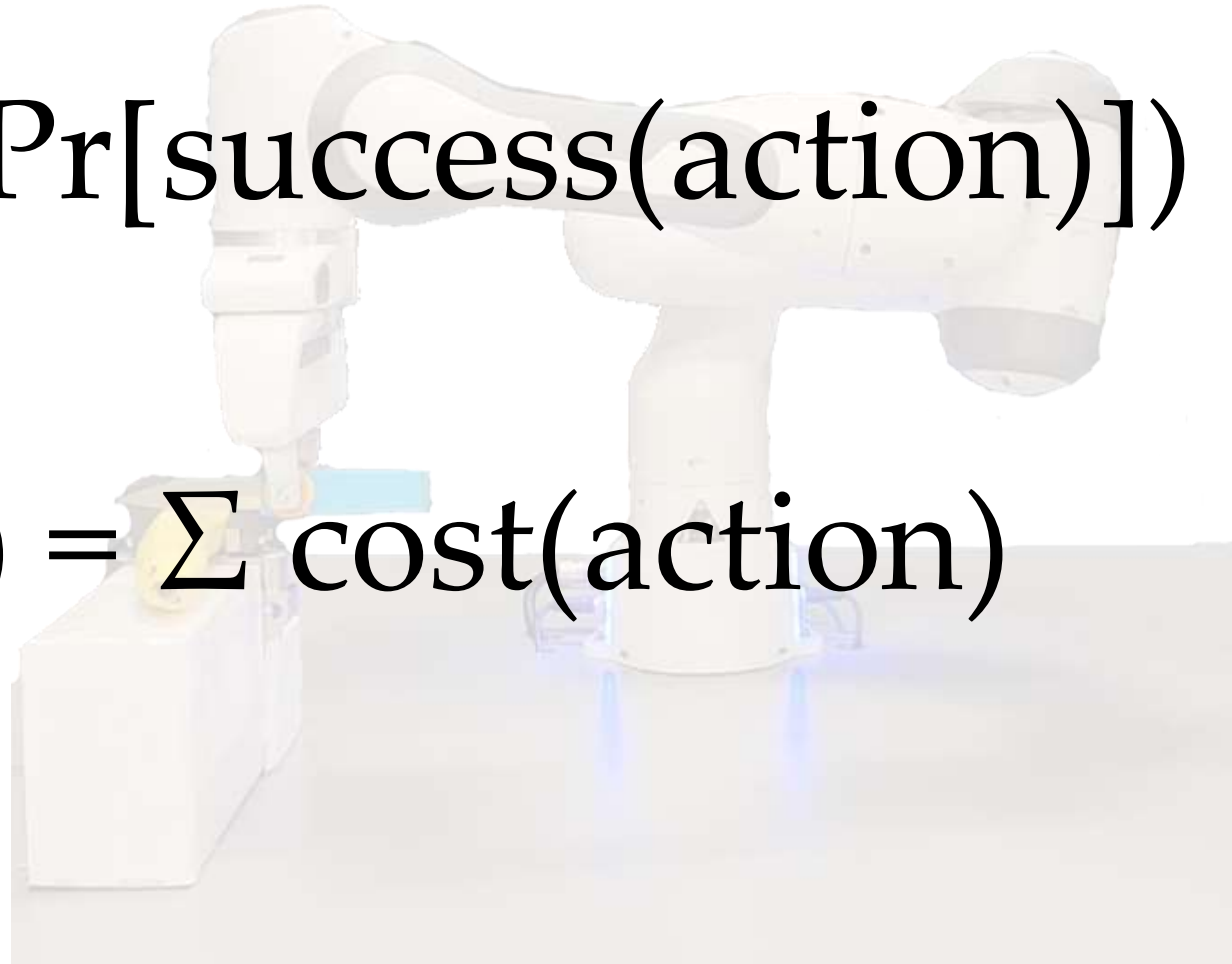
$$\text{cost}(\text{plan}) = \Sigma\ \text{cost}(\text{action})$$



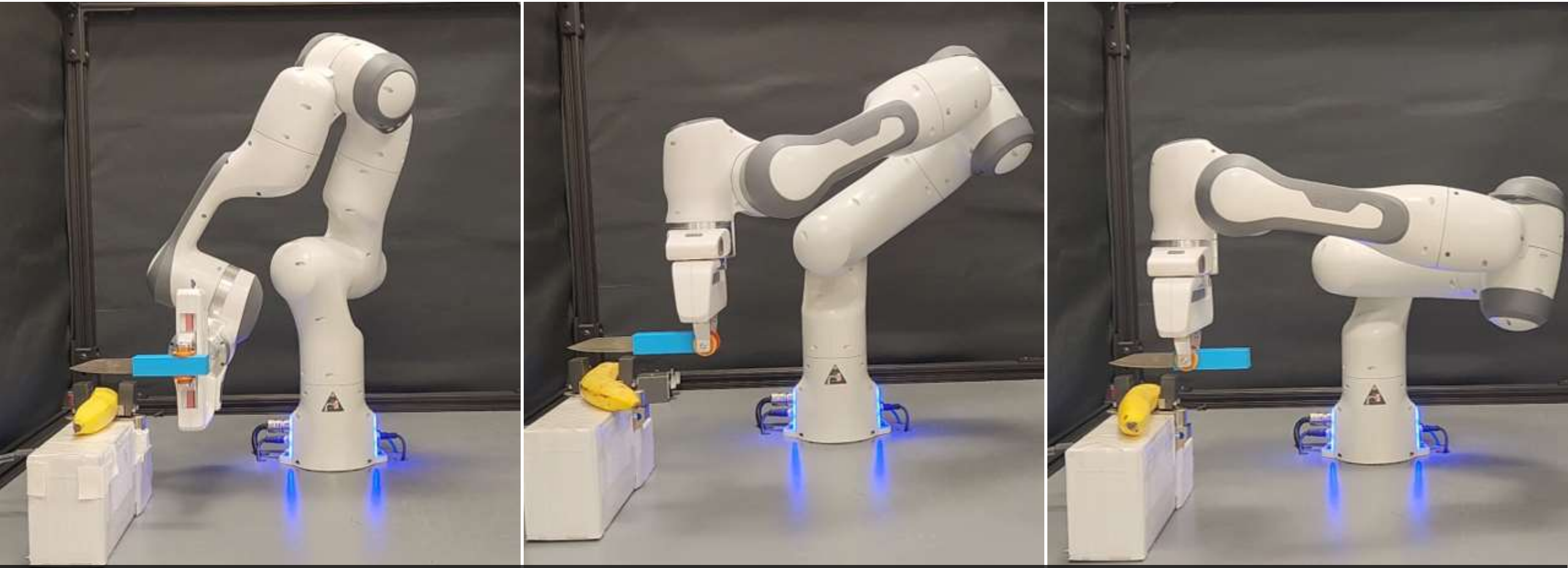
Robust to Variations in the Physical Parameters via Cost-Sensitive Planning

$$\text{cost}(\text{action}) = -\log(\Pr[\text{success}(\text{action})])$$

$$c_{max} \overset{?}{>} \text{cost}(\text{plan}) = \Sigma\, \text{cost}(\text{action})$$

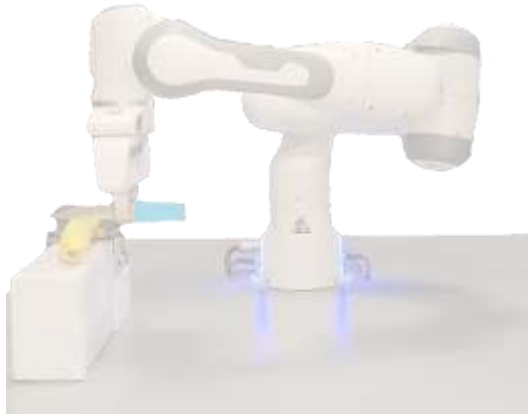


Enable Reasoning Over Robust Choices in the Context of Competing Constraints



"Robust Planning for Multi-stage Forceful Manipulation" R Holladay, T Lozano-Pérez, A Rodriguez. *IJRR*, 2023.

Forceful Manipulation



Robust Decision Making

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Multi-Step Manipulation Tasks

In-Hand Manipulation

Guarded Planning

Action Space

move(q_s, q_g, …)

place(obj, p_0, ..)

pushtwist(obj, w, …)

regrasp(obj, g_s, g_g, …)

.

.

.

Special Thanks to Xiaolin Fang

Action Space

move(q_s, q_g, …)

place(obj, p_0, ..)

pushtwist(obj, w, …)

regrasp(obj, g_s, g_g, …)

.

.

.

Action Space

move(q_s, q_g, …)

place(obj, p_0, ..)

pushtwist(obj, w, …)

regrasp(obj, g_s, g_g, …)

dnp_move(obj, p_s, P_g, …)

.

.

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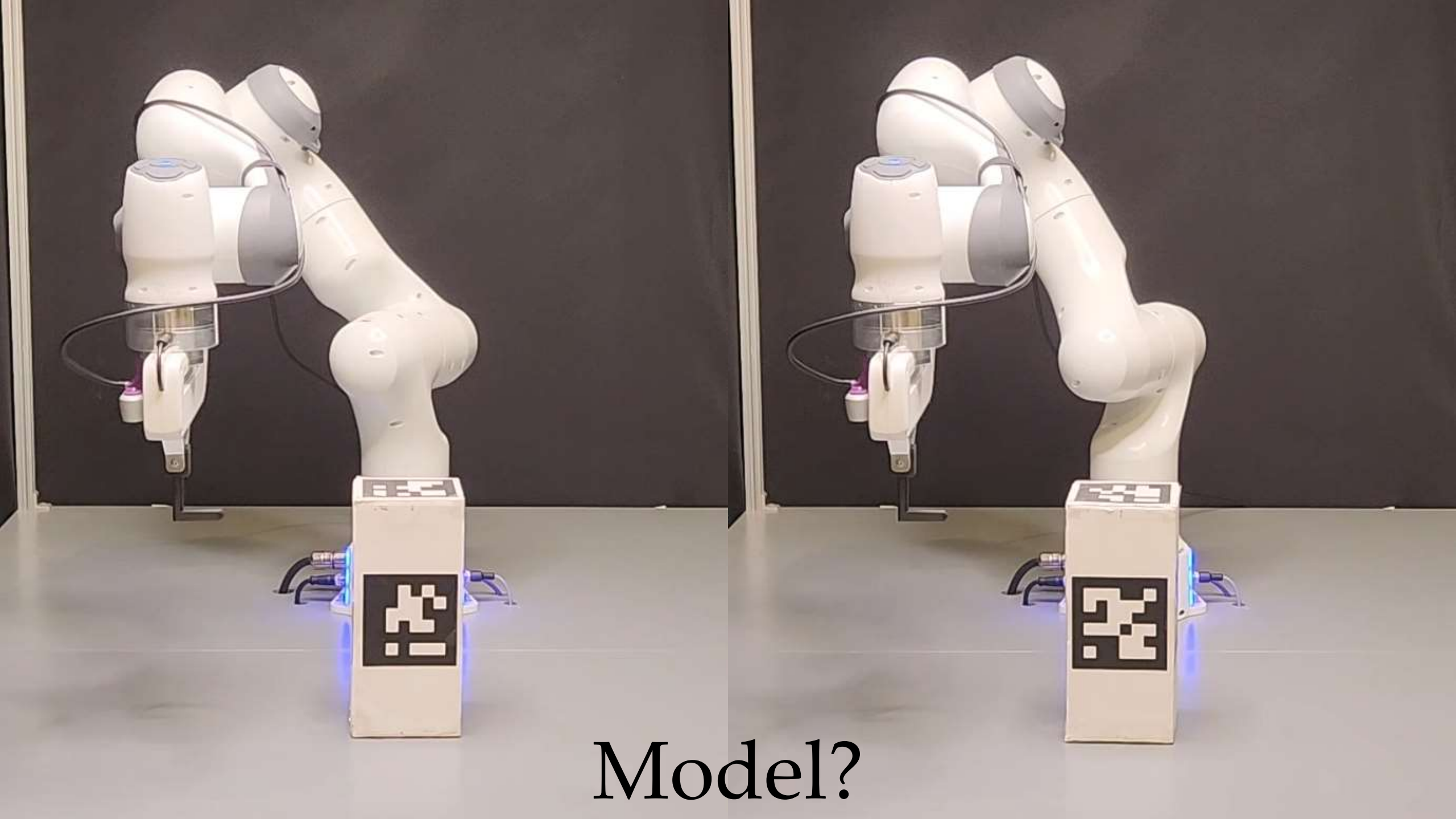
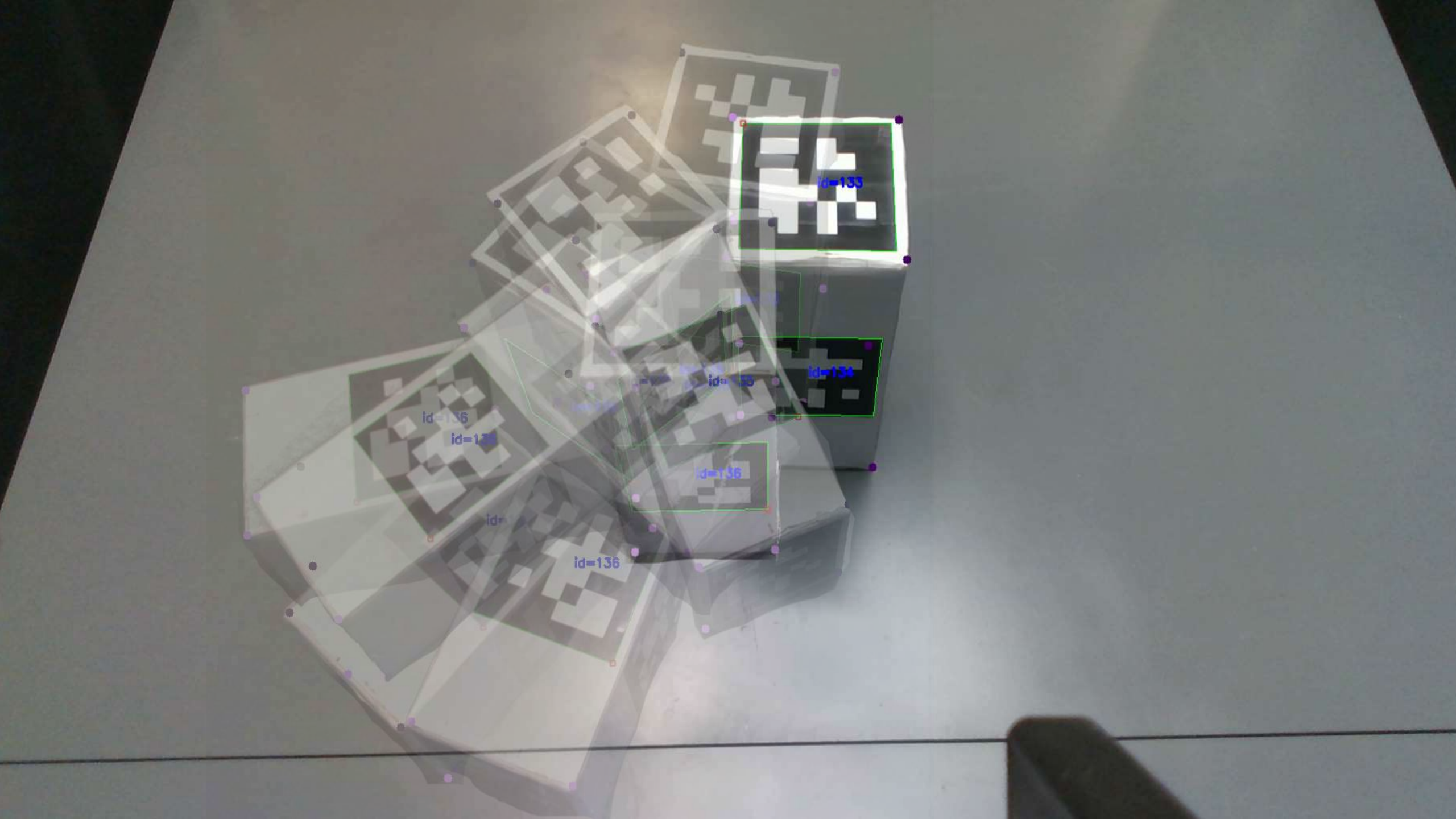

Model?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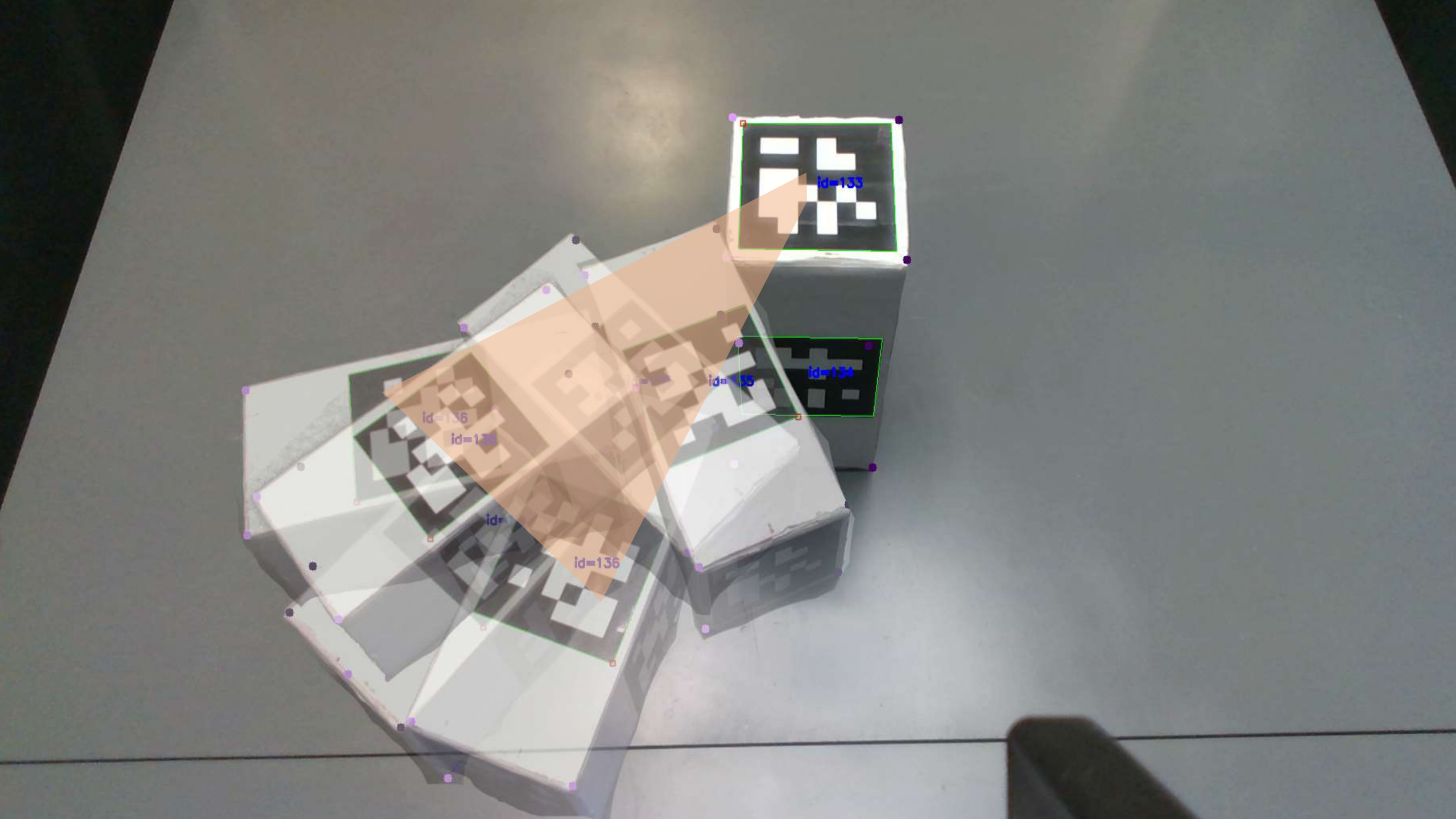
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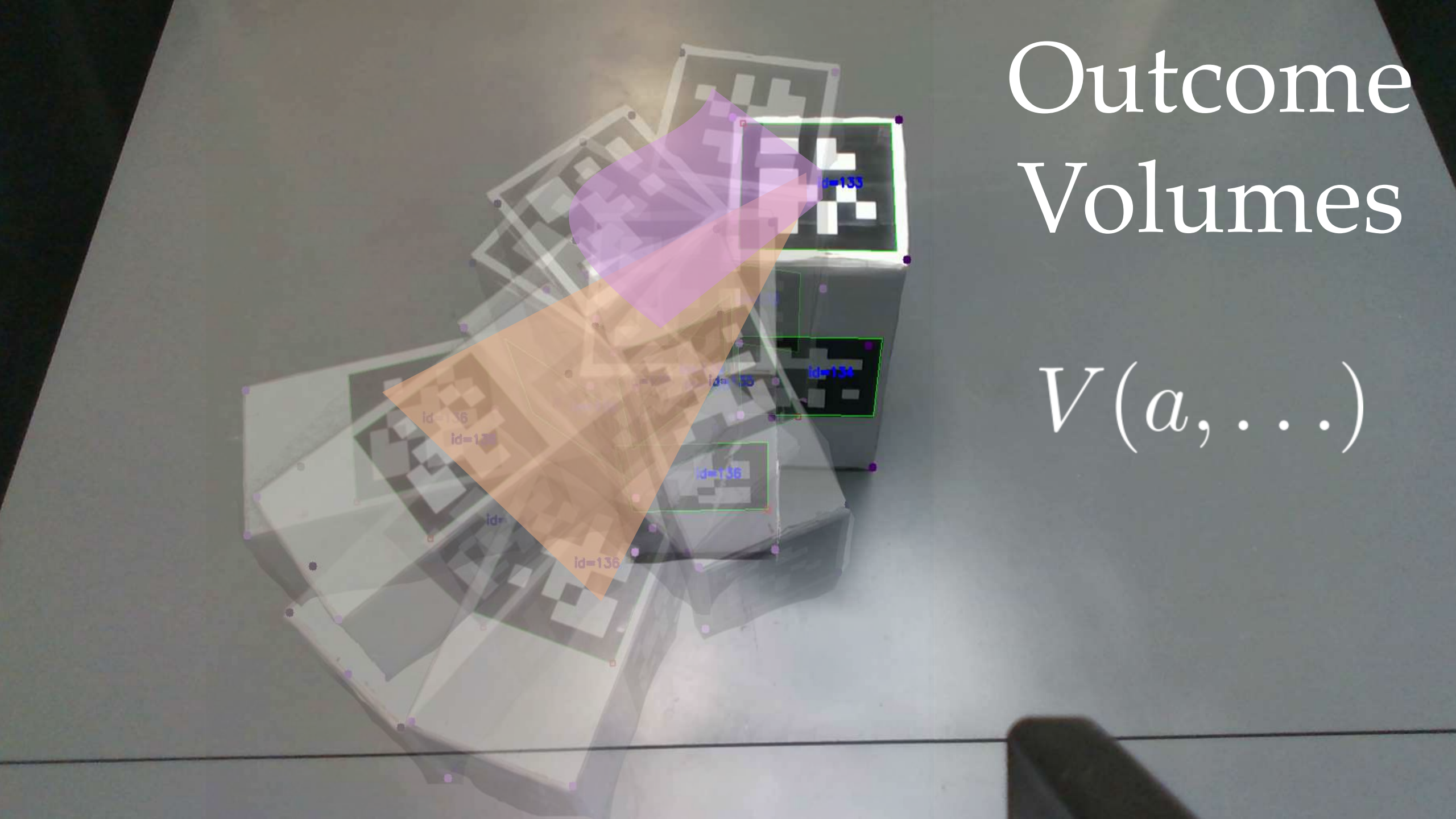
Outcome
Volumes
$V(a, \ldots)$
id=133
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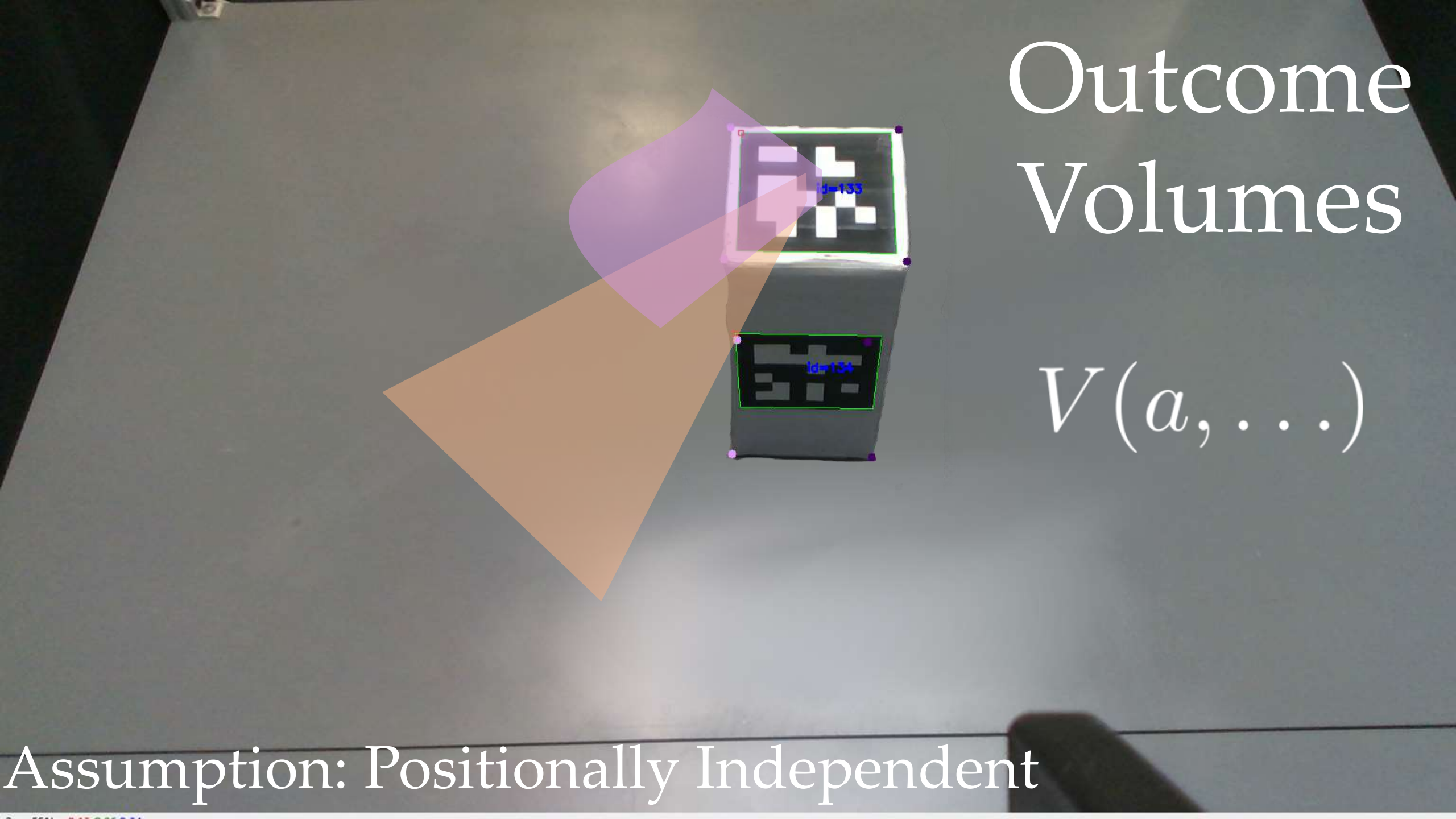


Outcome Volumes

$$V(a, \ldots)$$

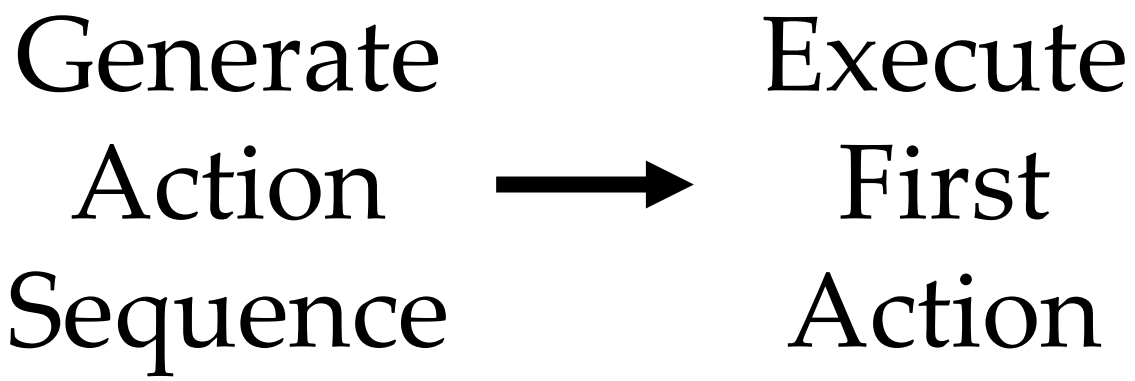
Assumption: Positionally Independent

dnp_move(obj, p_s, P_g, …):

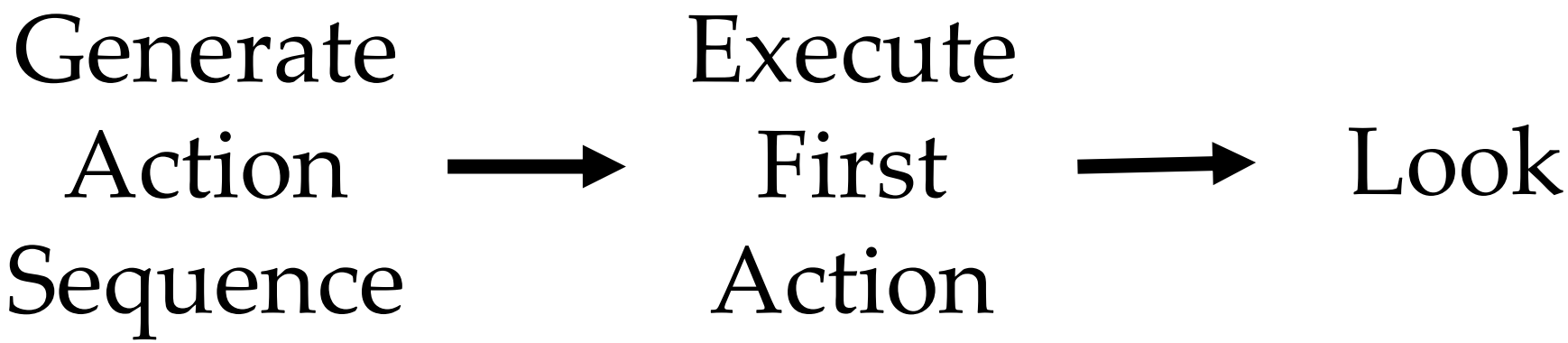
dnp_move(obj, p_s, P_g, …):

Generate
Action
Sequence

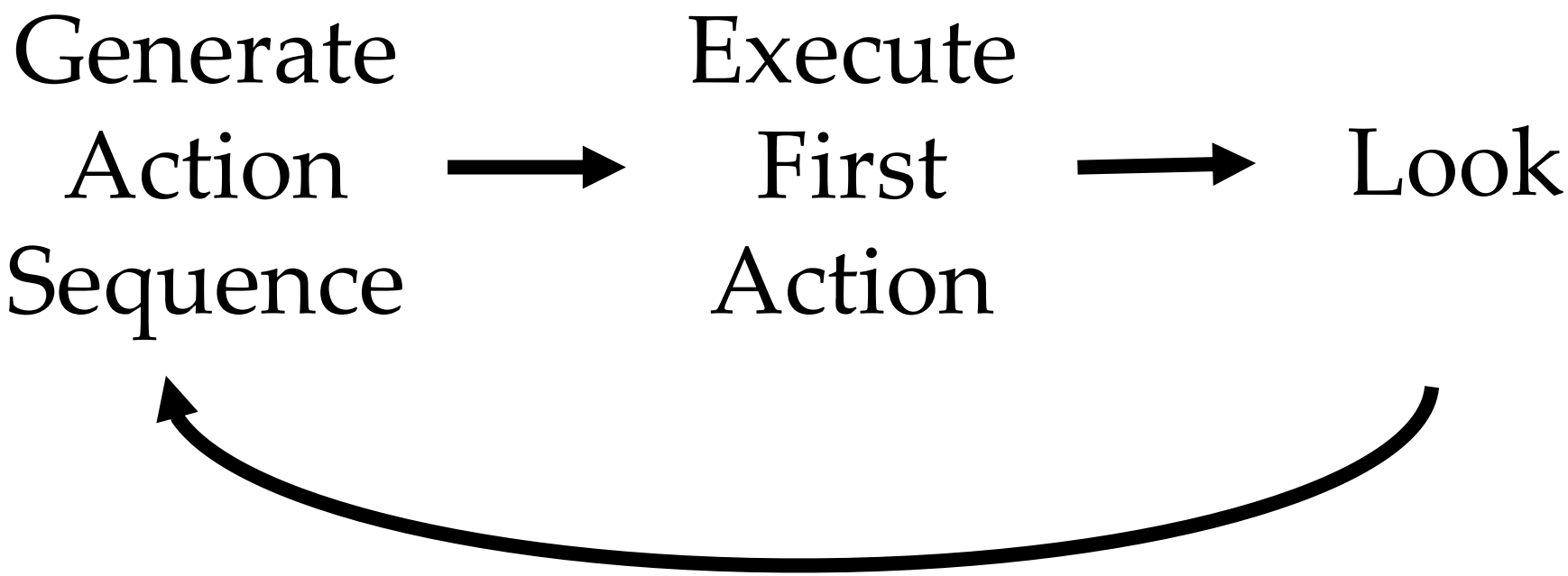
dnp_move(obj, p_s, p_g, …):



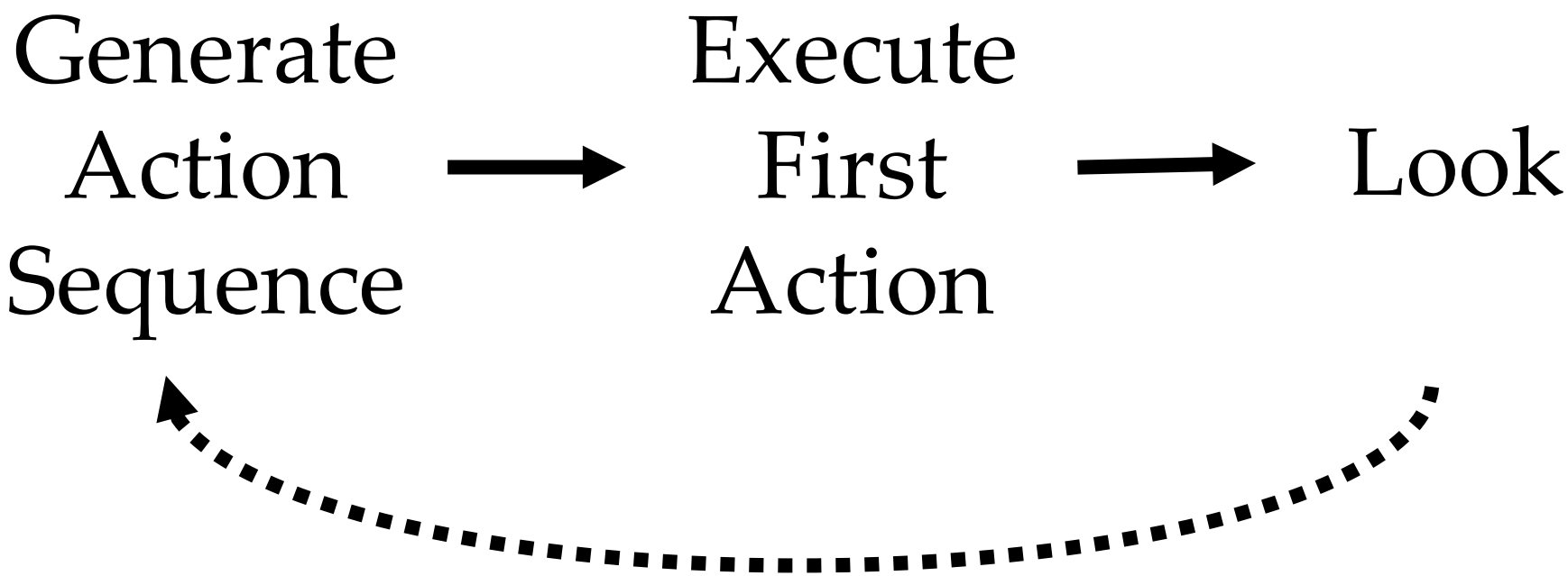
dnp_move(obj, p_s, P_g, …):

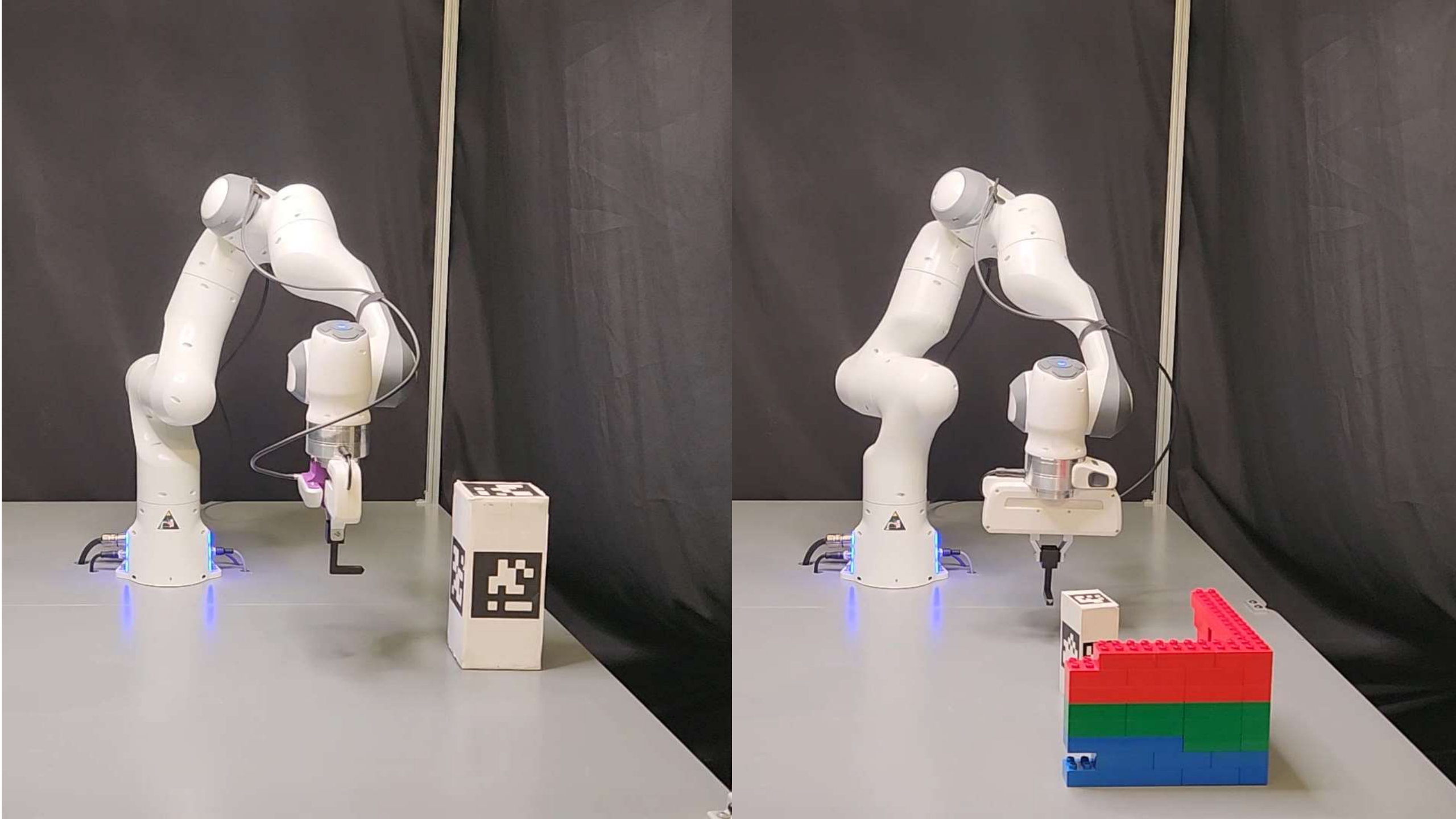


dnp_move(obj, p_s, P_g, …):

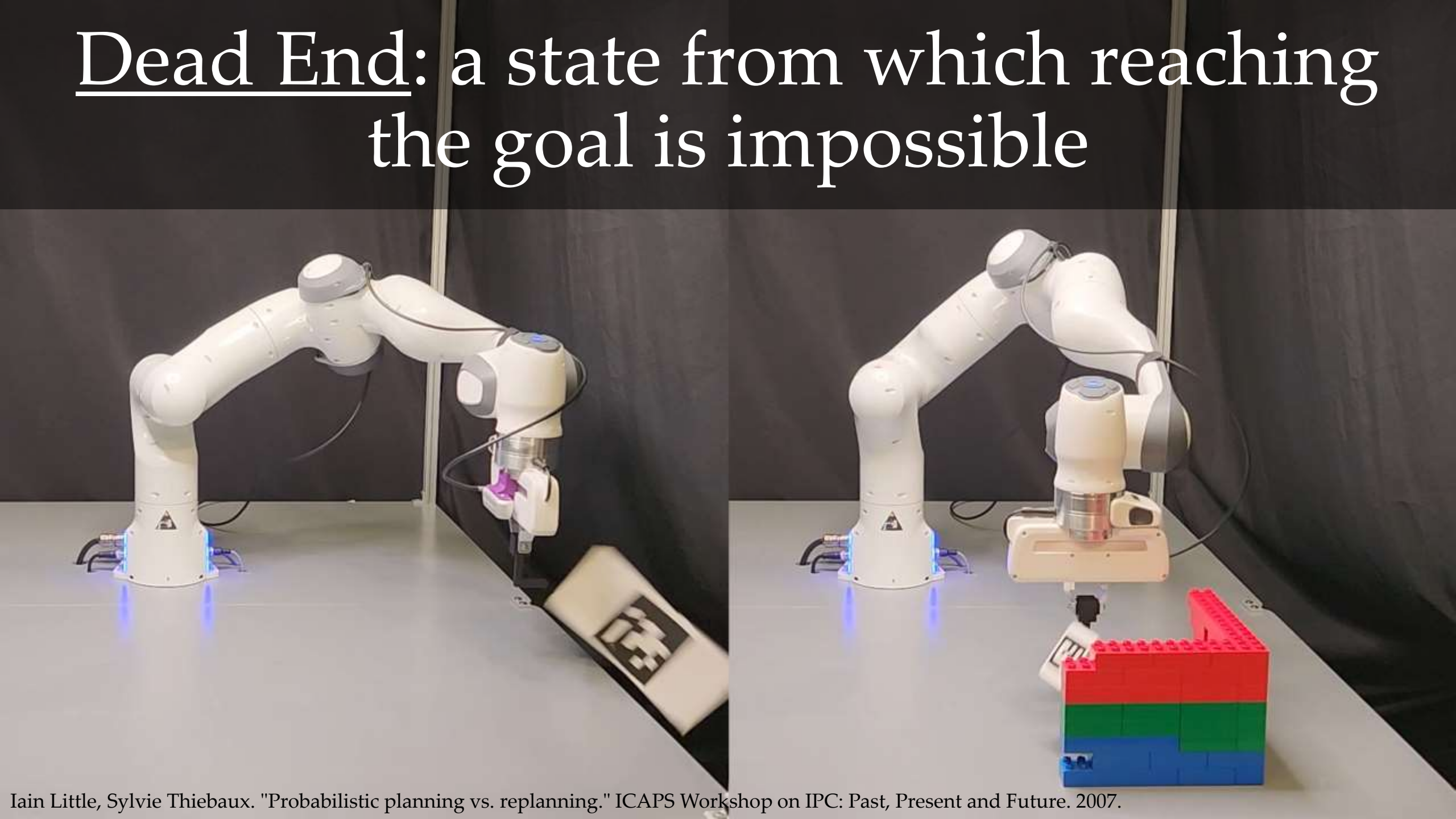


dnp_move(obj, p_s, P_g, …):



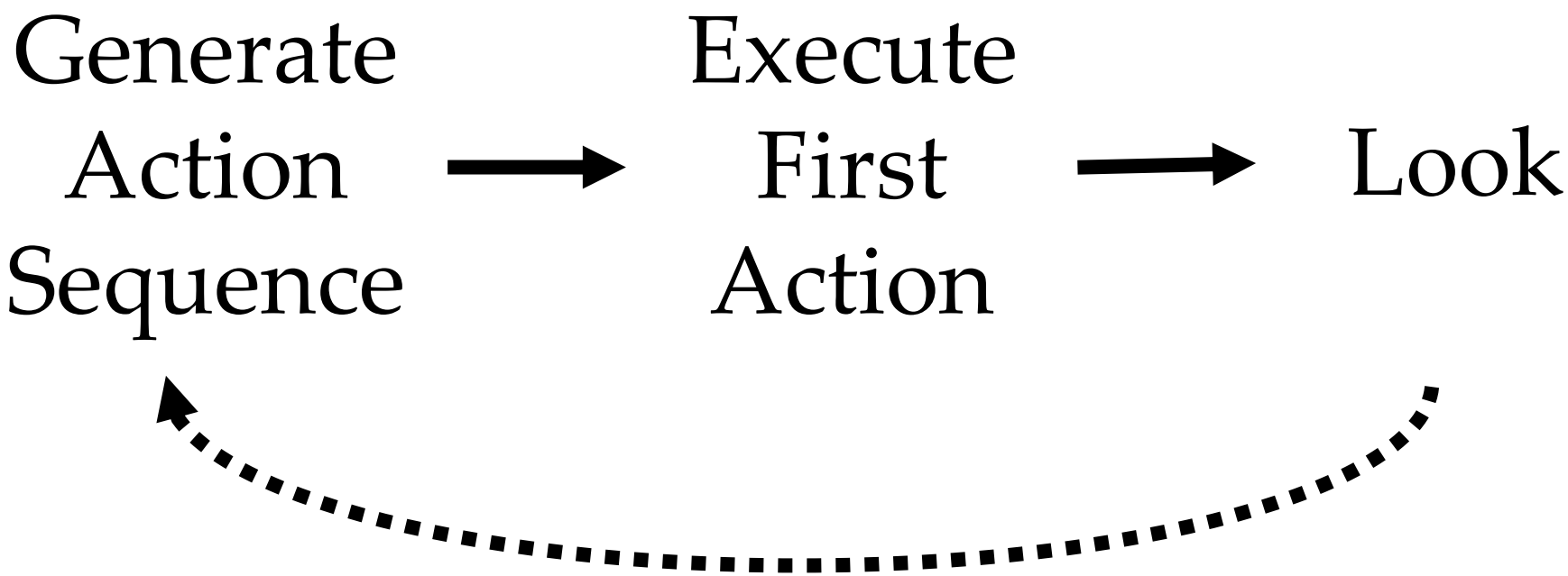


Dead End: a state from which reaching the goal is impossible



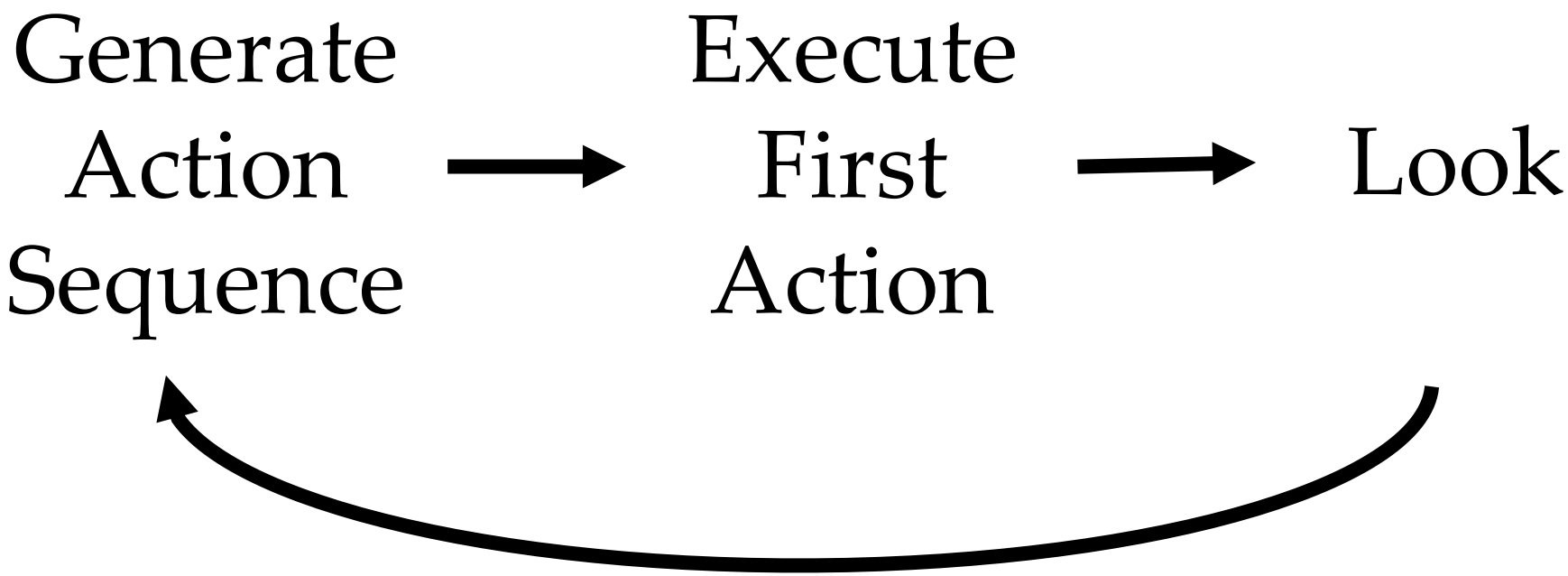
Iain Little, Sylvie Thiebaux. "Probabilistic planning vs. replanning." ICAPS Workshop on IPC: Past, Present and Future. 2007.

dnp_move(obj, p_s, P_g, …):

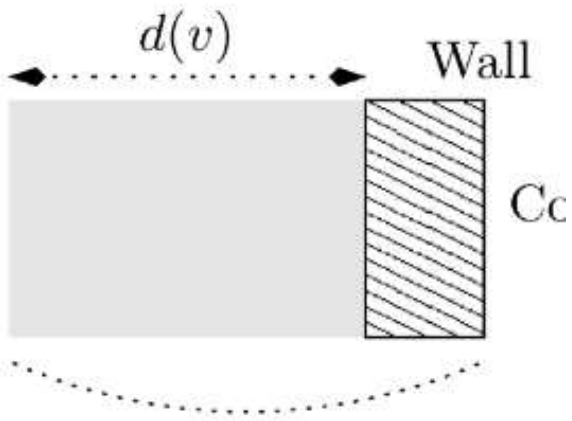


`dnp_move(obj, p_s, p_g, …):`

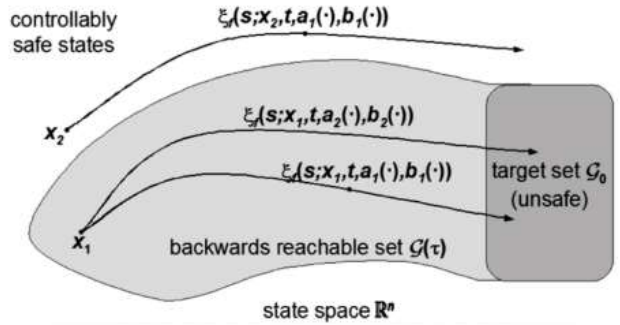
s.t. no action leads to a dead end



Inevitable Collision States



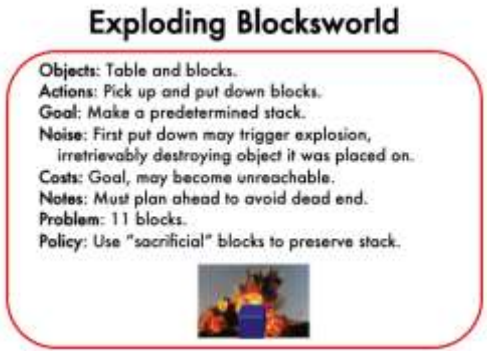
[Fraichard, Asama 2004, Bautin, Martinez-Gomez, Fraichard, 2010]



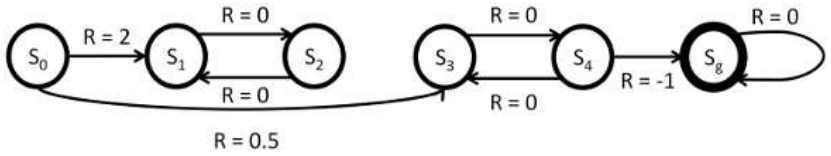
[Bansal et al 2017, Borquez et al 2024]

Hamilton Jacobi Reachability

Dead-Ends in Classical Planning



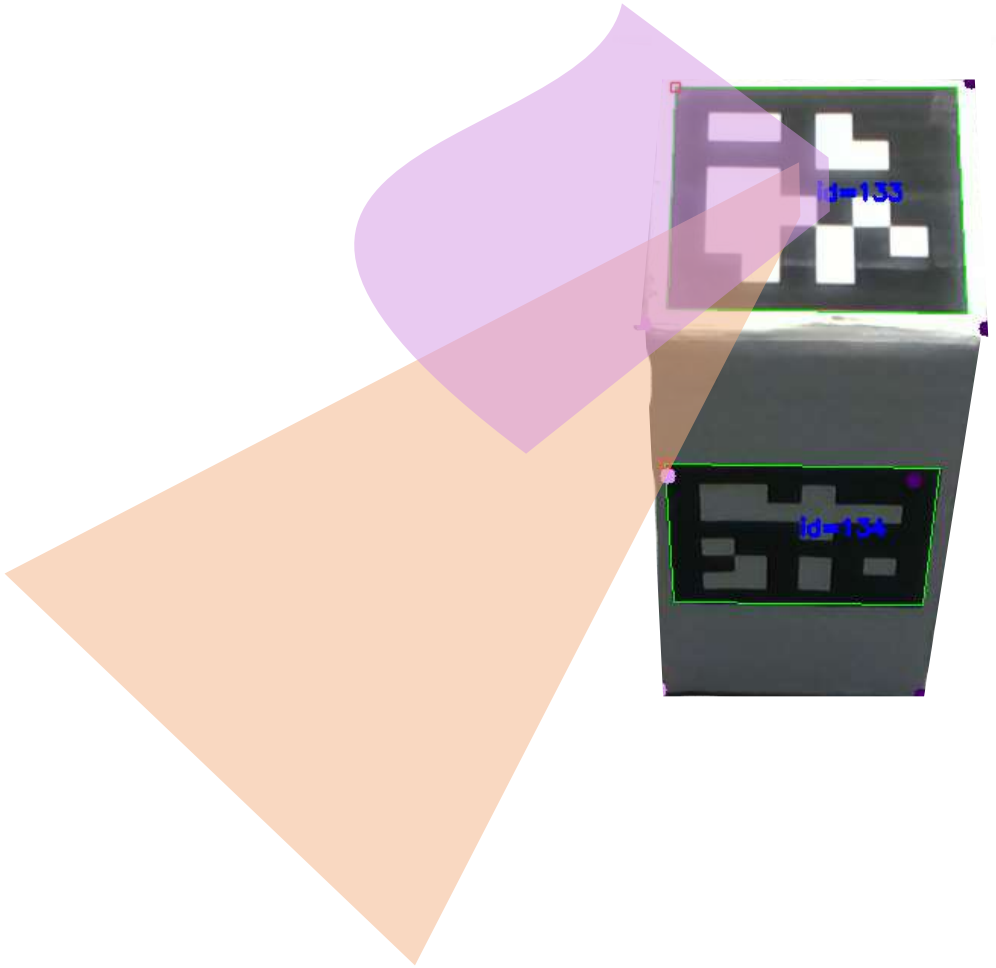
[Lipovetzky et al., 2016, Kolobov et al., 2010]

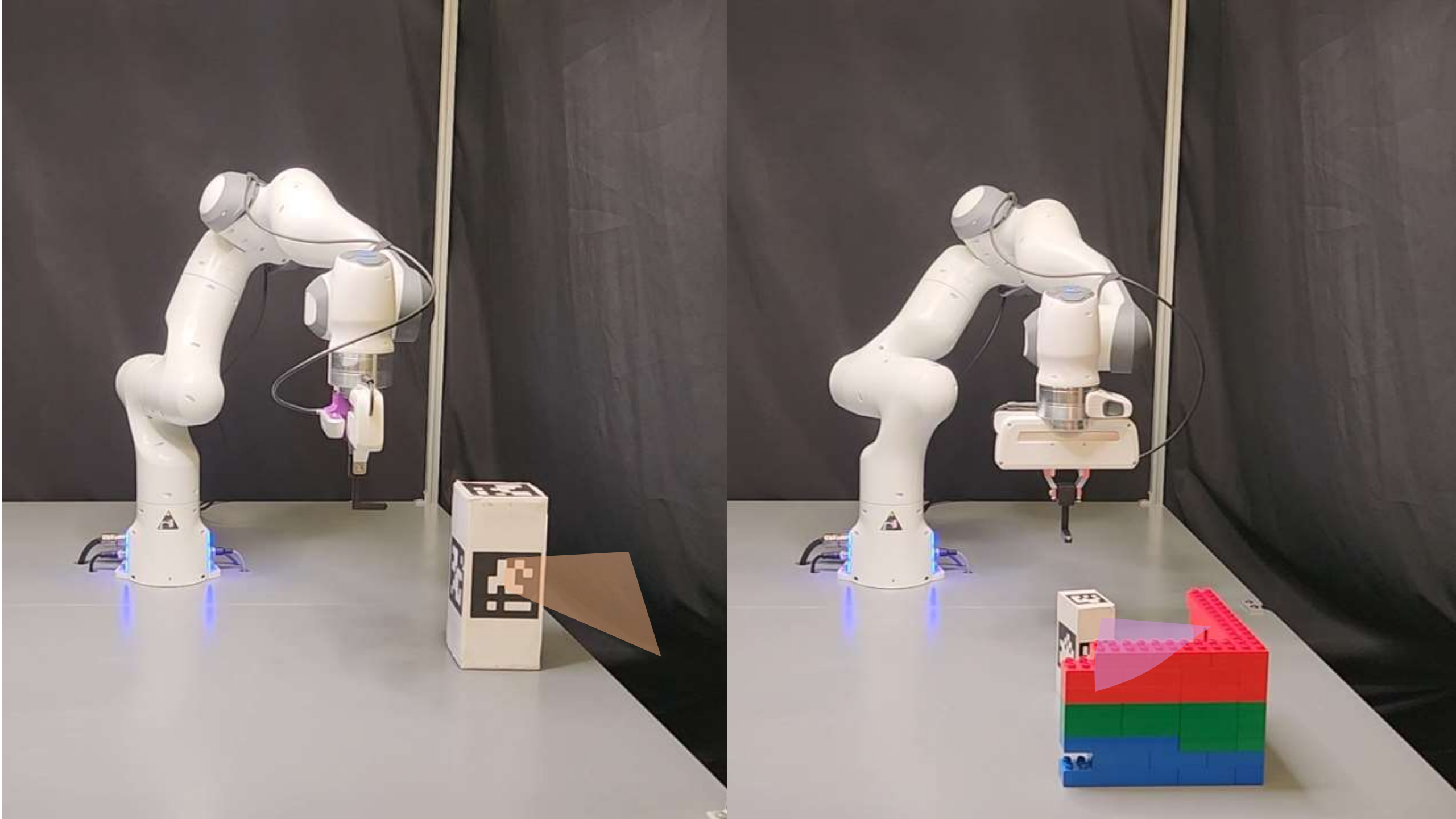


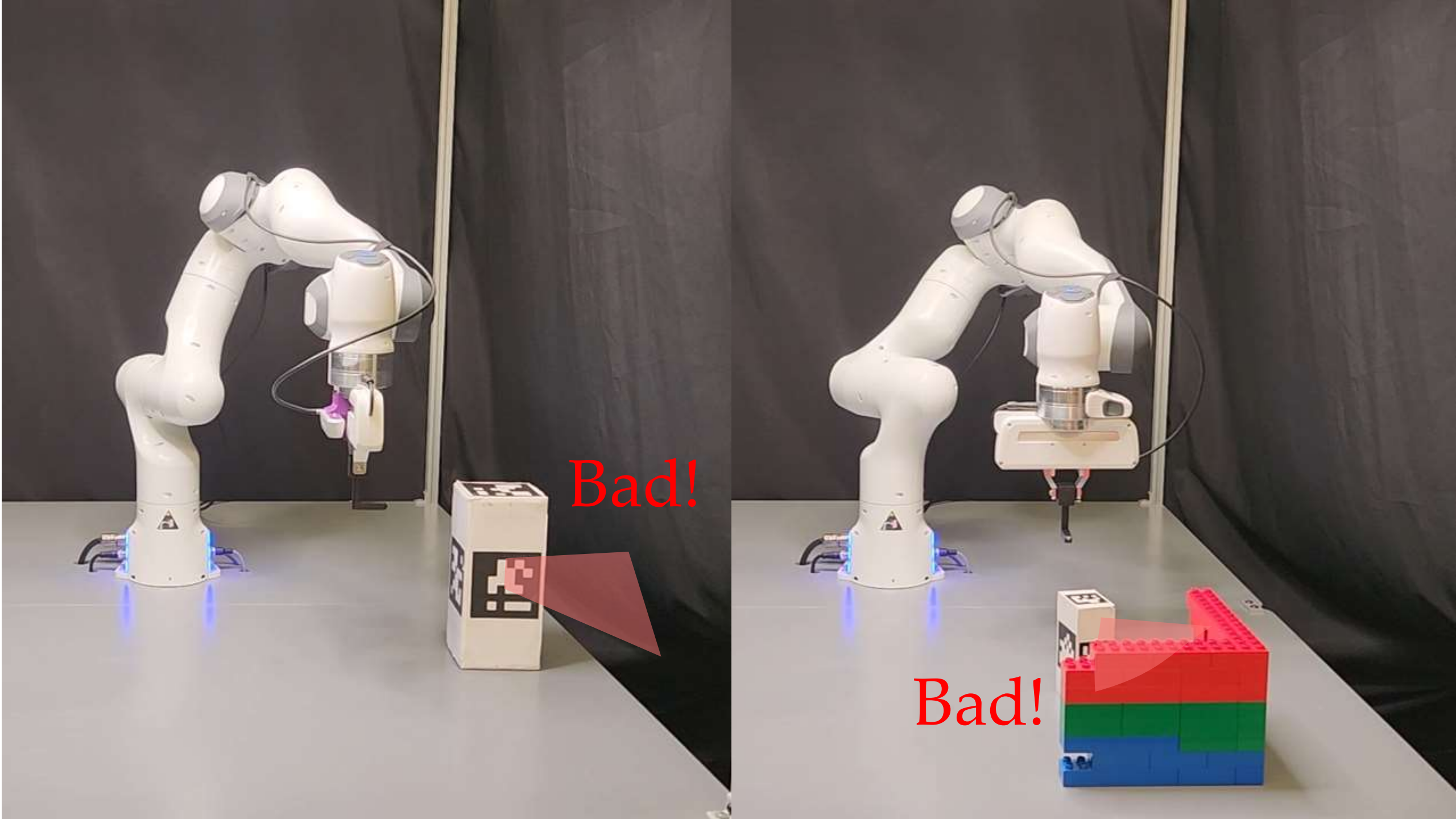
[Kolobov et al., 2011 Kolobov et al., 2012, Teichteil-Königsbuch 2012]

Dead-Ends in Markov Decision Processes (MDPs)

Leverage outcome volumes to (continuously) characterize dead-end areas






Bad!
Bad!

Be GUARD(ed)

Be GUARD(ed)

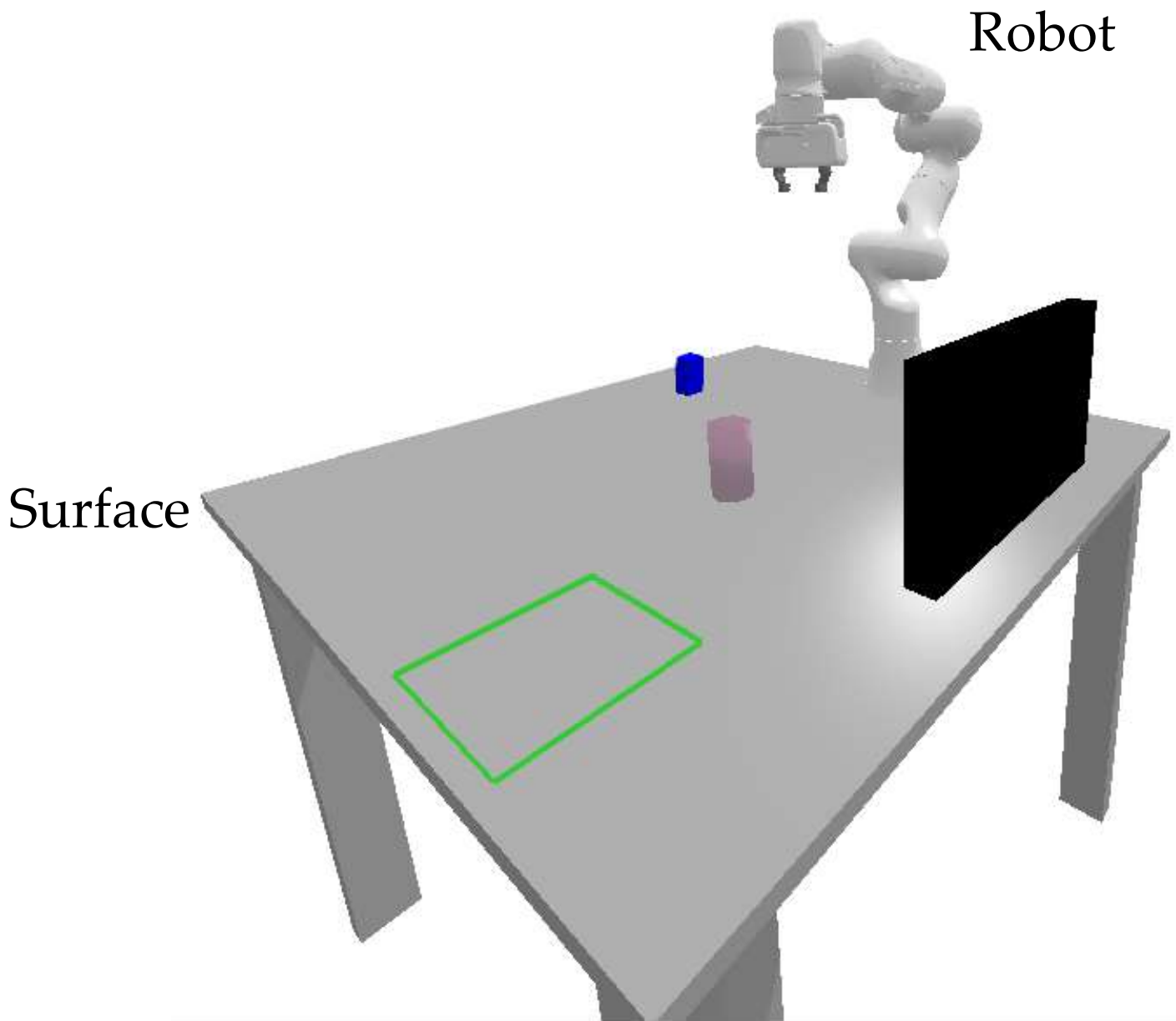
Guiding Uncertainty Accounting for Risk and Dynamics

Be GUARD(ed)

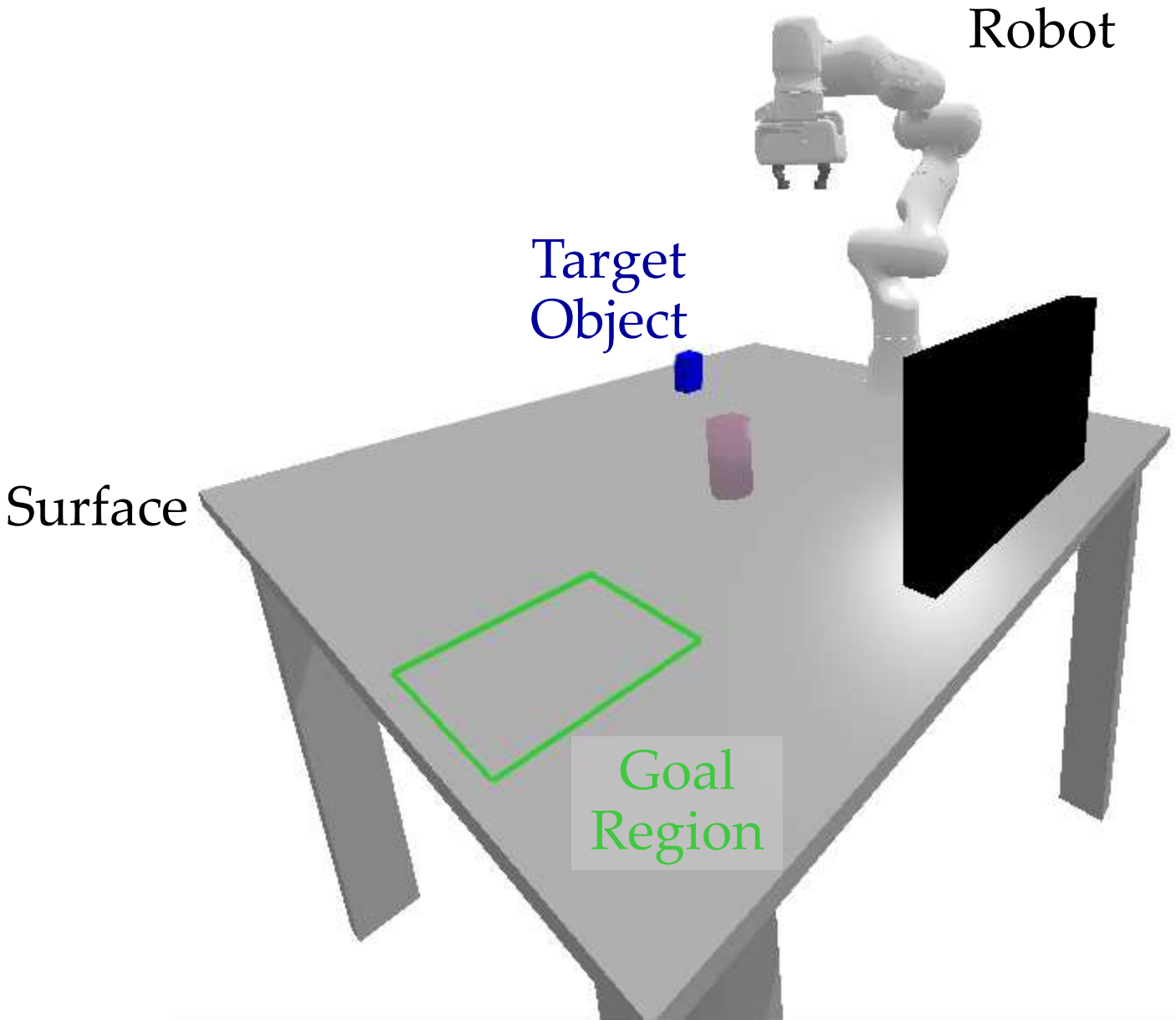
Guiding Uncertainty Accounting for Risk and Dynamics

Environment Algorithm Results

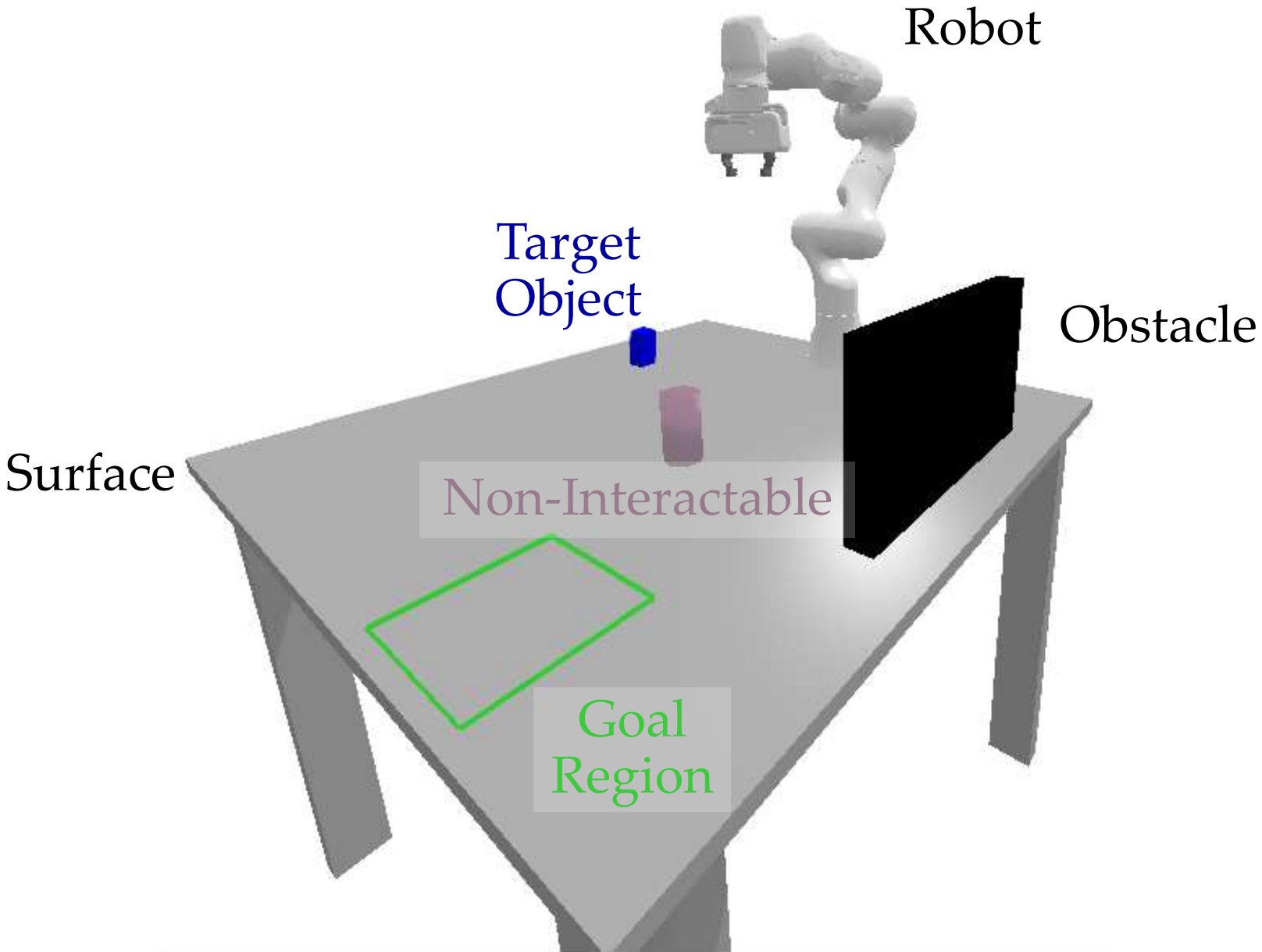
Environment



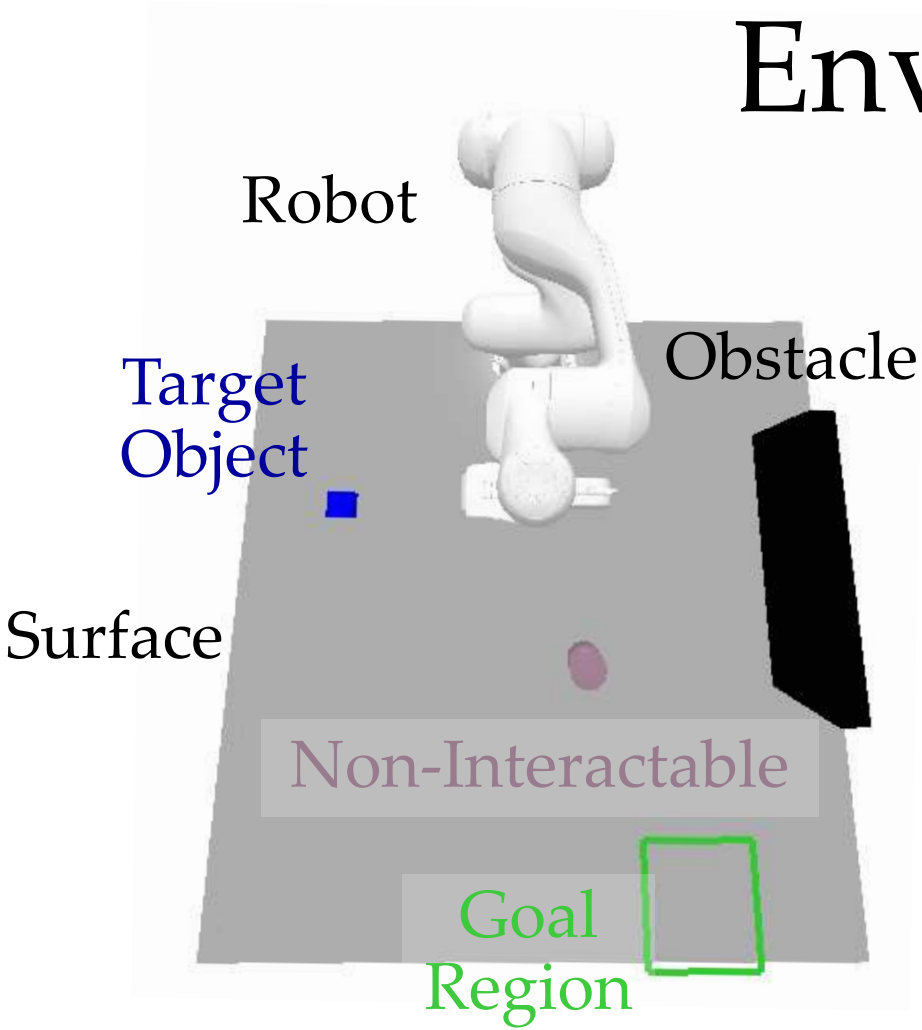
Environment



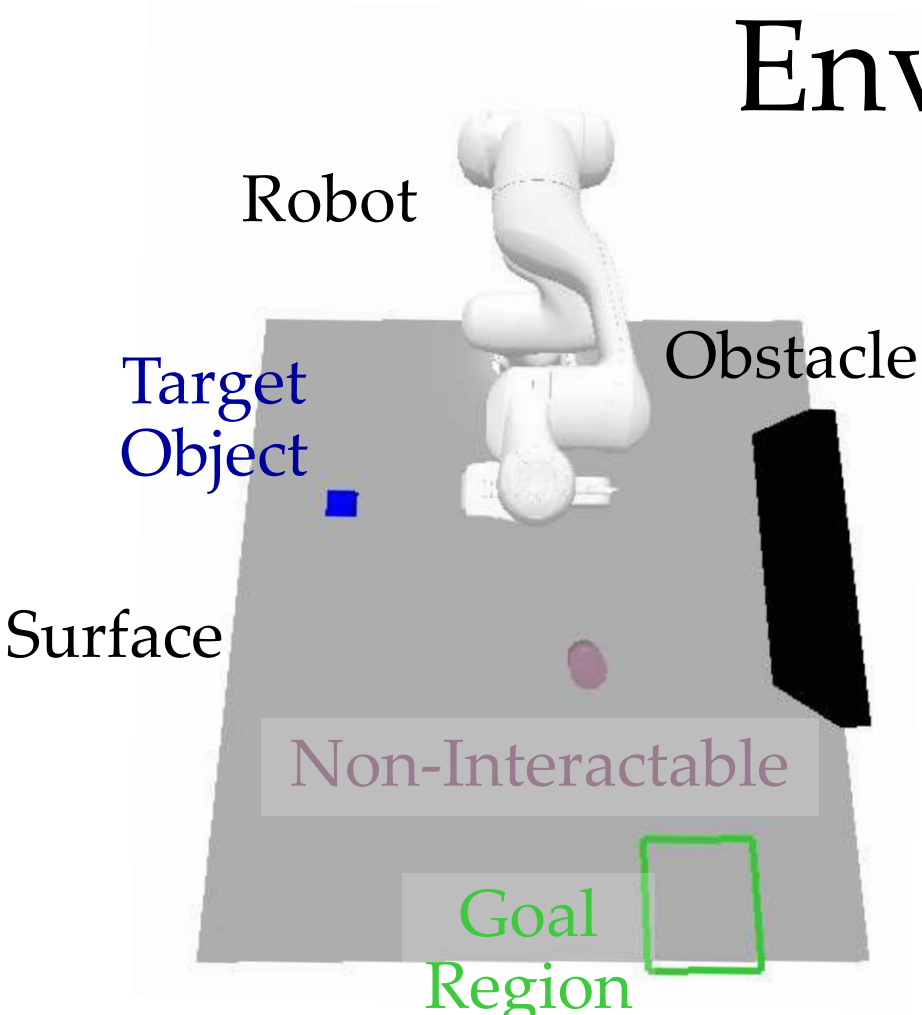
Environment



Environment

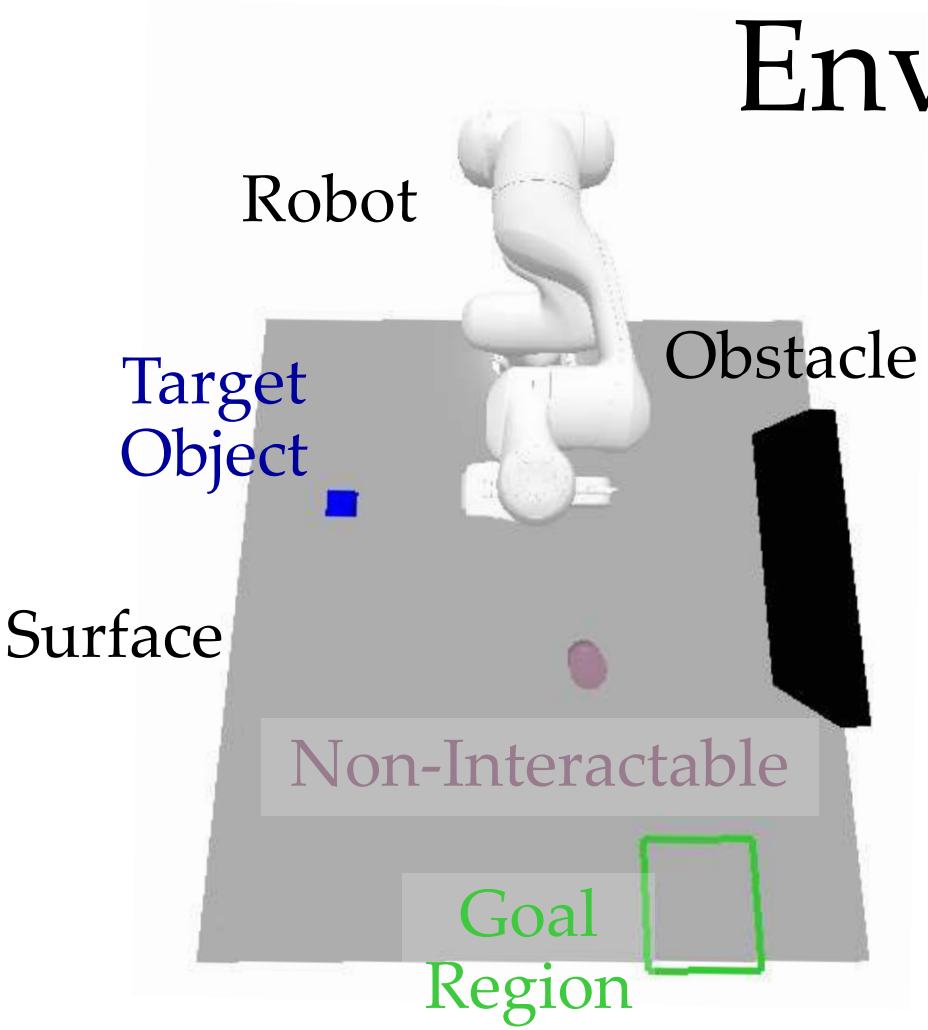


Environment



$$q_o \in \mathrm{SE}(3)$$

Environment



$$q_o \in \mathrm{SE}(3)$$

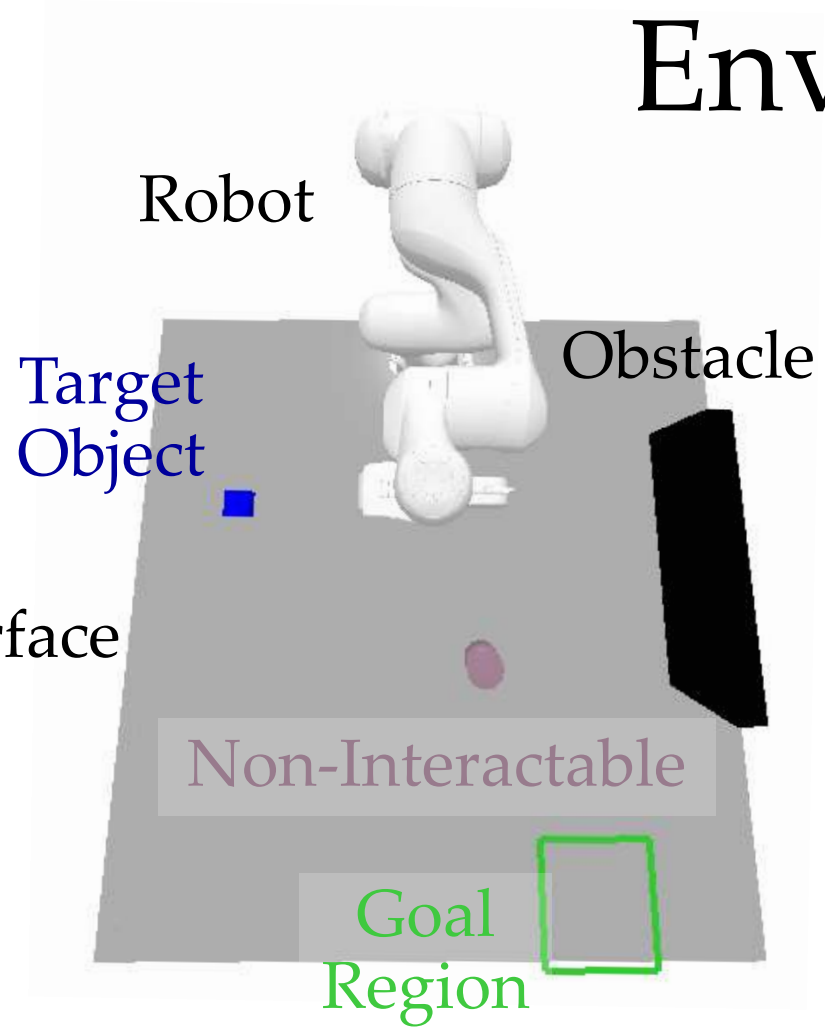
$$q_o = (f_j, \theta_k, (x, y))$$

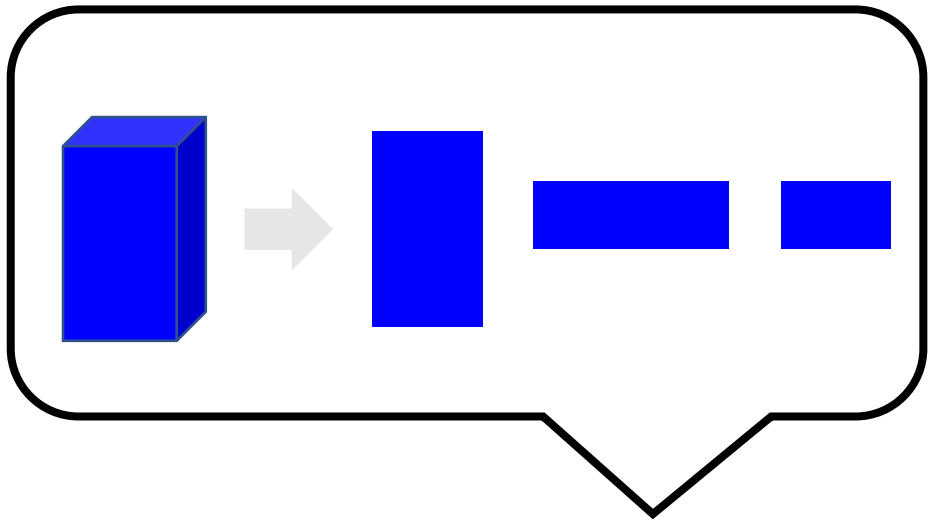
face in contact

Discretized planar orientation

planar position

Environment





$$q_o \in \mathrm{SE}(3)$$

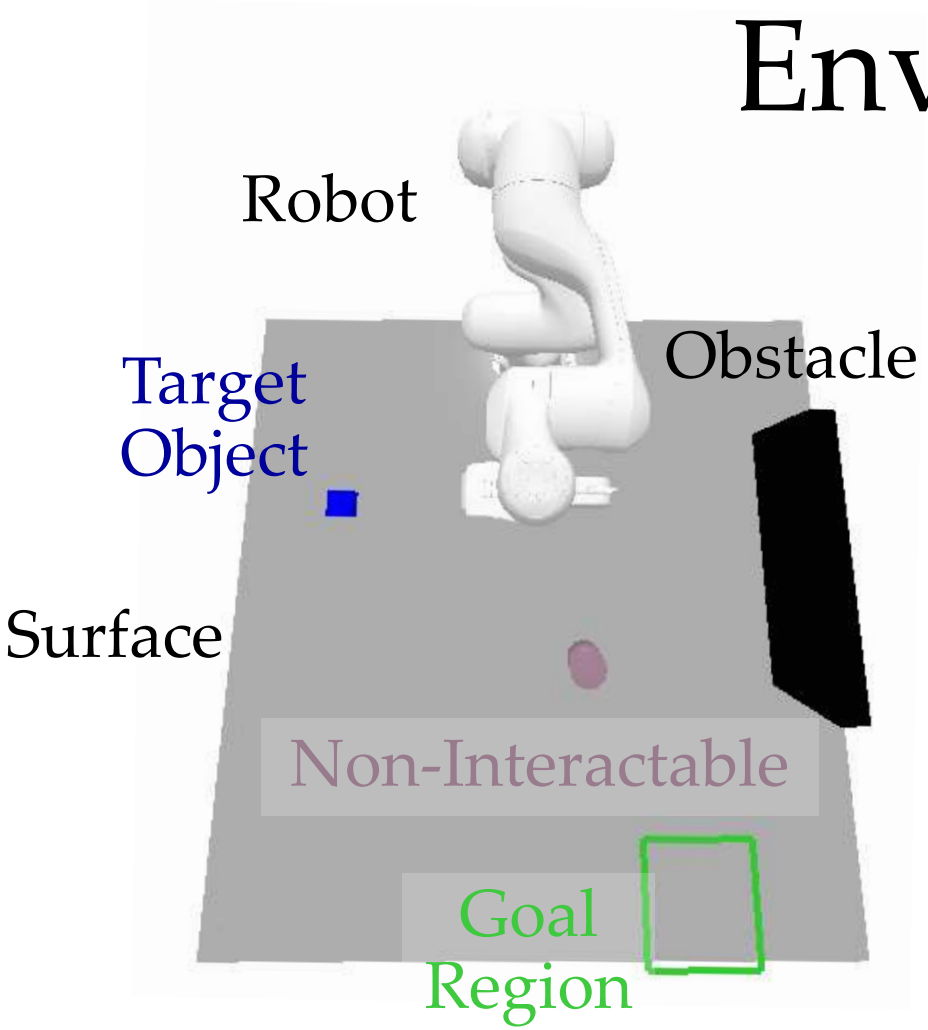
$$q_o = (f_j, \theta_k, (x, y))$$

face in contact

Discretized planar orientation

planar position

Environment



$$q_o \in \mathrm{SE}(3)$$

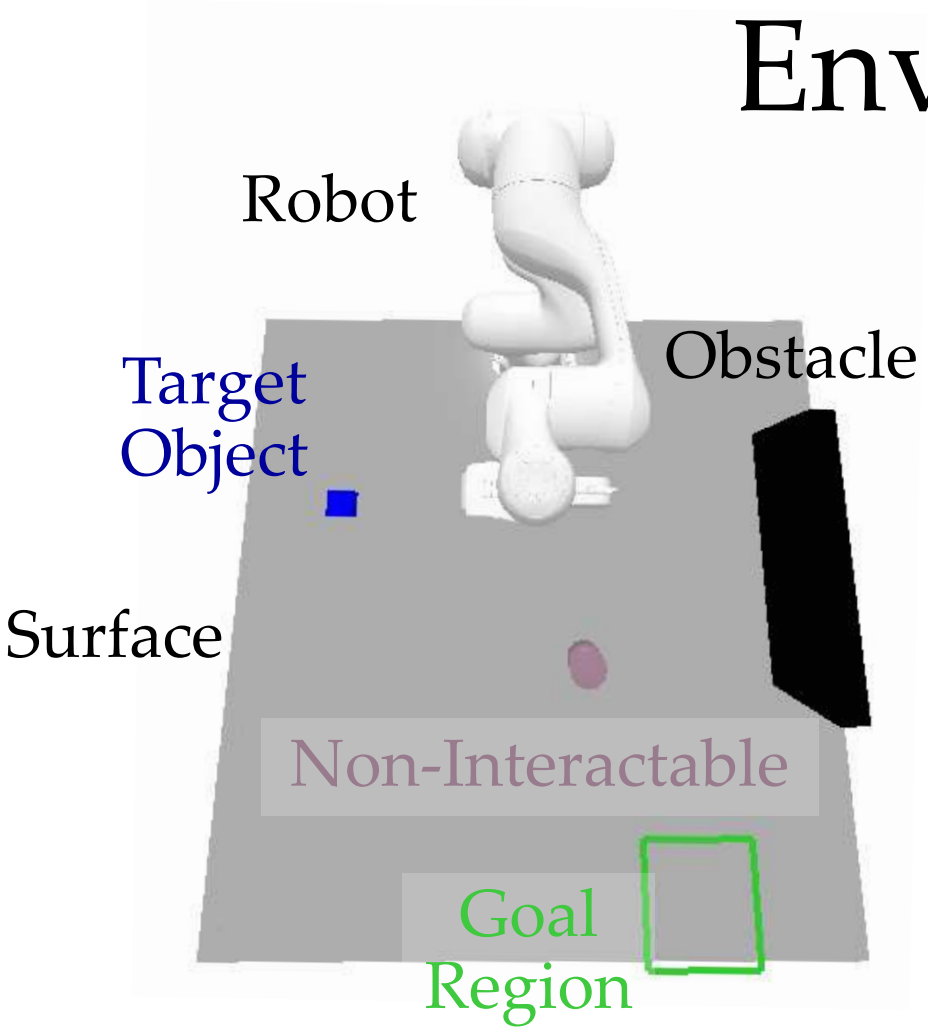
$$q_o = (f_j, \theta_k, (x, y))$$

face in contact

Discretized planar orientation

planar position

Environment



$$q_o \in \mathrm{SE}(3)$$

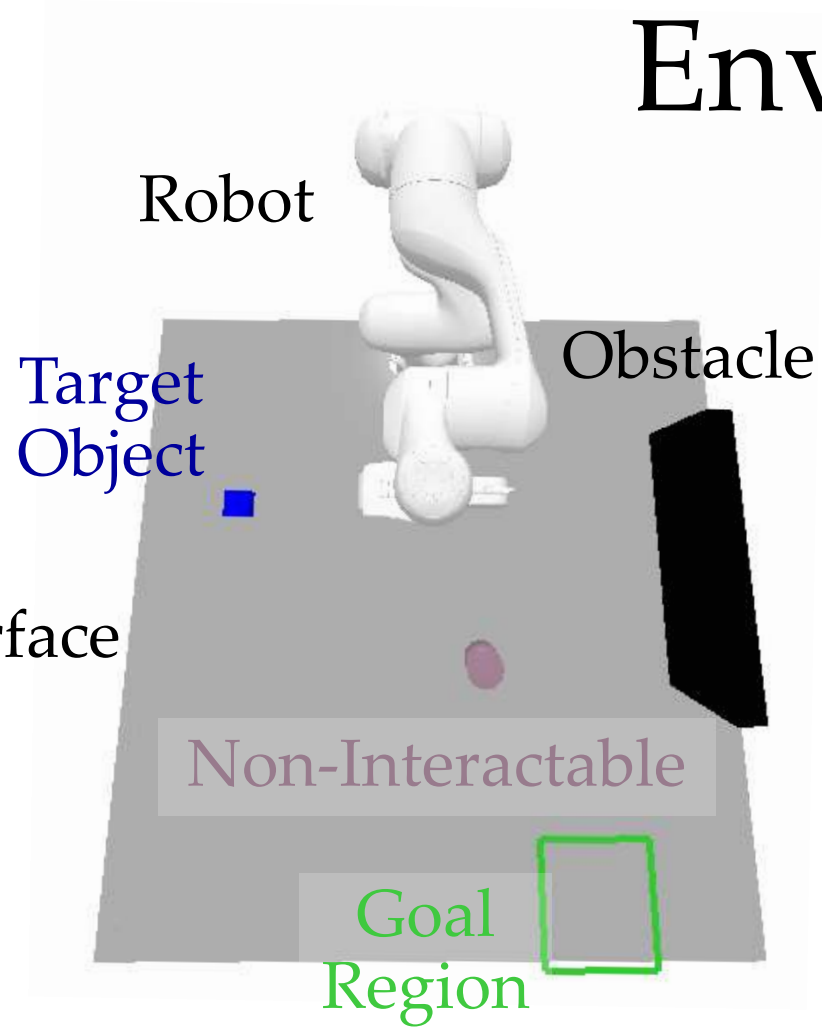
$$q_o = (\overbrace{f_j, \theta_k}^{\text{mode}}, (x, y))$$

face in contact

Discretized planar orientation

planar position

Environment



$$q_o \in \mathrm{SE}(3)$$

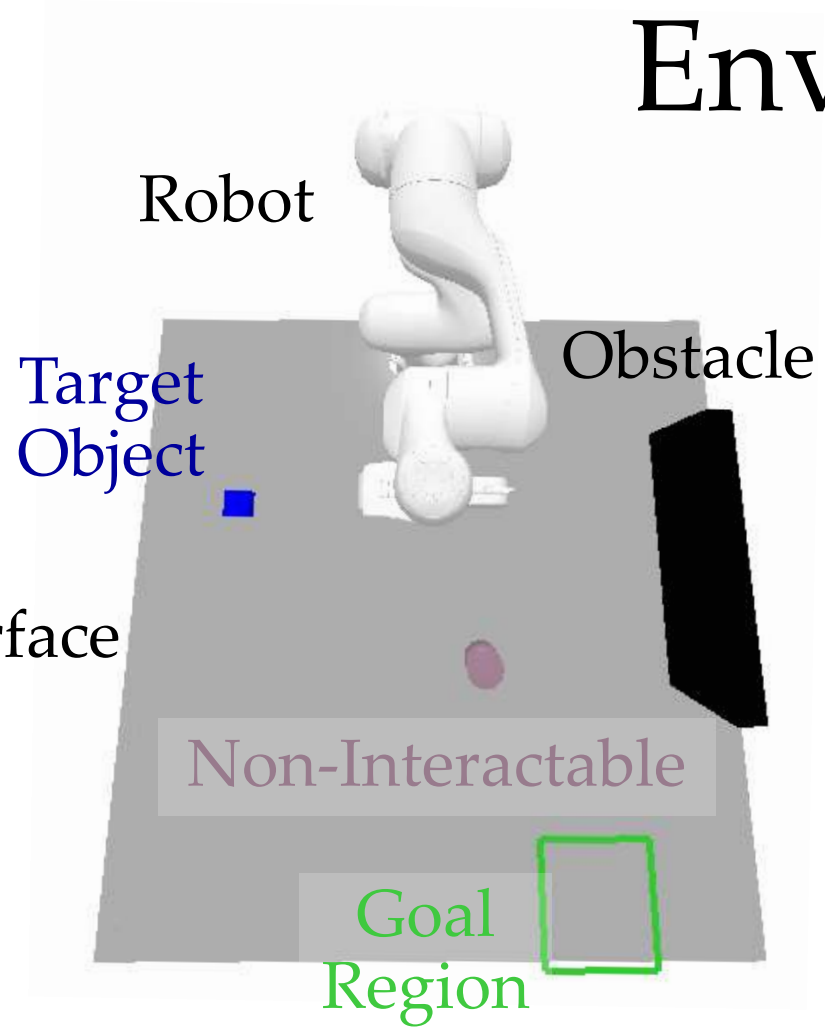
$$q_o = (\overbrace{f_j, \theta_k}^{\text{mode}}, (x, y))$$

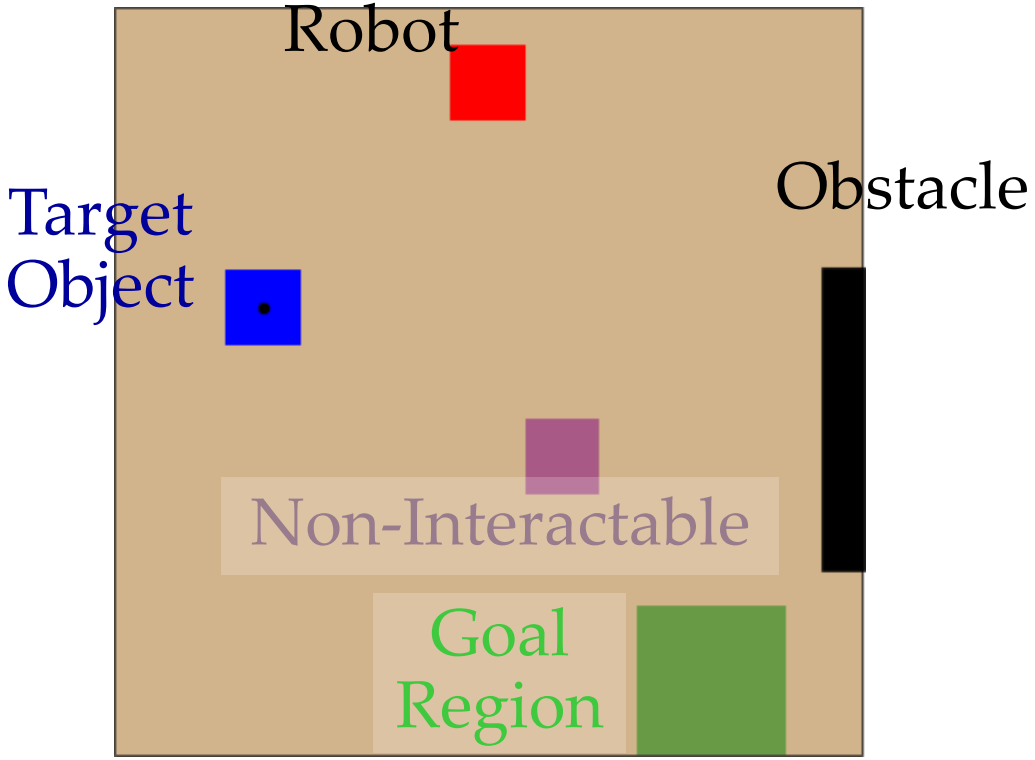
face in contact

Discretized planar orientation

planar position

Environment





$$q_o \in \mathrm{SE}(3)$$

$$q_o = (f_j, \theta_k, (x, y))$$

face in contact

Discretized planar orientation

planar position

Be GUARD(ed)

Guiding Uncertainty Accounting for Risk and Dynamics

Environment Algorithm Results

Action Regions

Danger Zones

Search

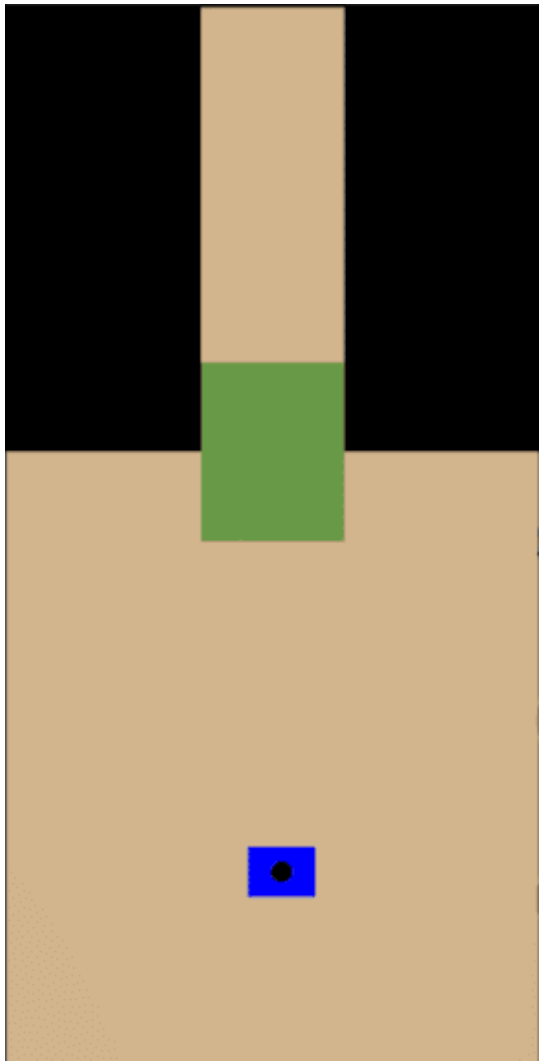
GUARD

Guiding Uncertainty Accounting for Risk and Dynamics

Action Regions

Danger Zones

Search

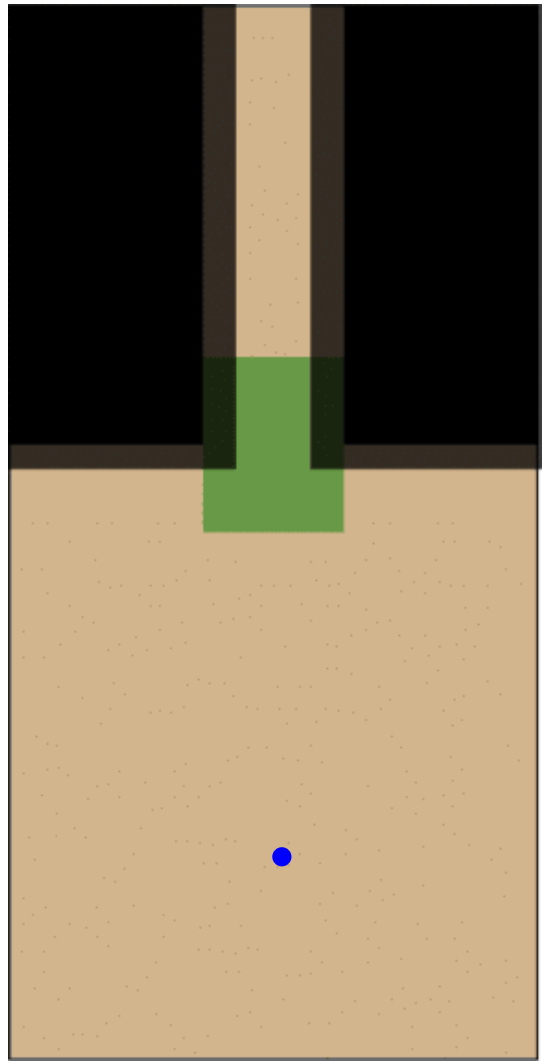


Action Regions

Danger Zones

Search

- Object is Collision-Free and Stably Supported
- Action in Robot's Collision-Free Reachable Workspace

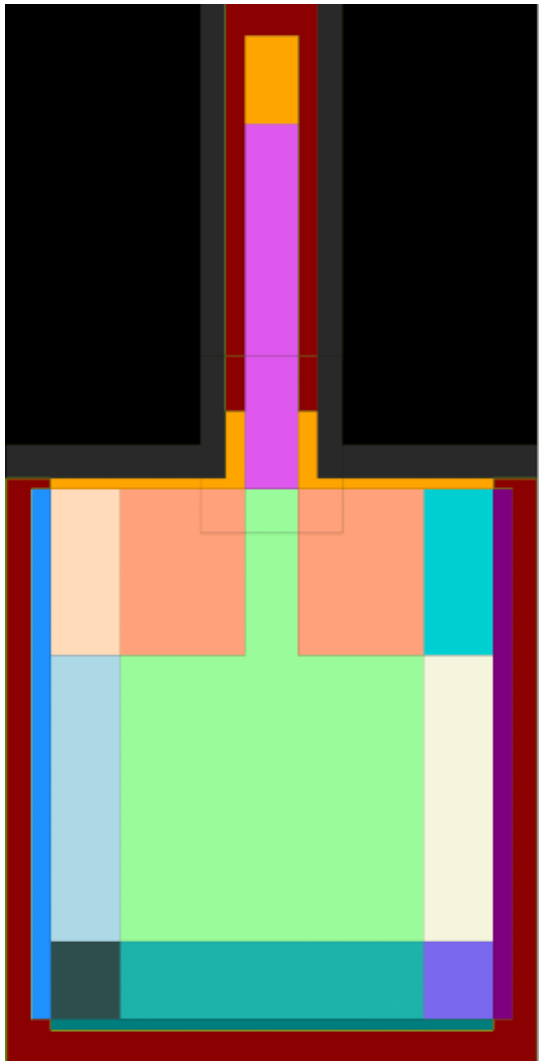


Action Regions

Danger Zones

Search

- Object is Collision-Free and Stably Supported
- Action in Robot's Collision-Free Reachable Workspace

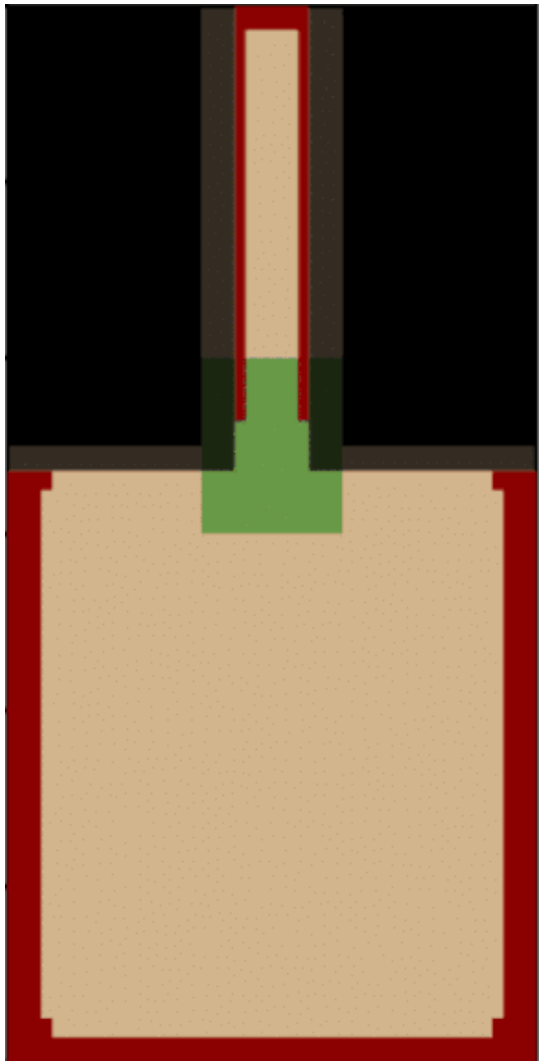


Action Regions

Danger Zones

Search

z_0 : Dead Ends!

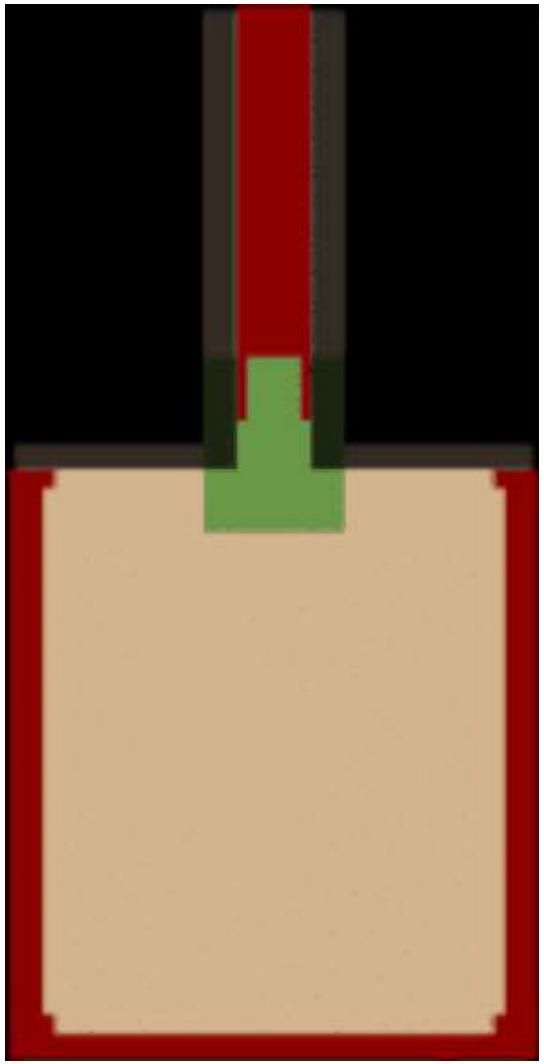


Action Regions

Danger Zones

Search

z_0 : Dead Ends!



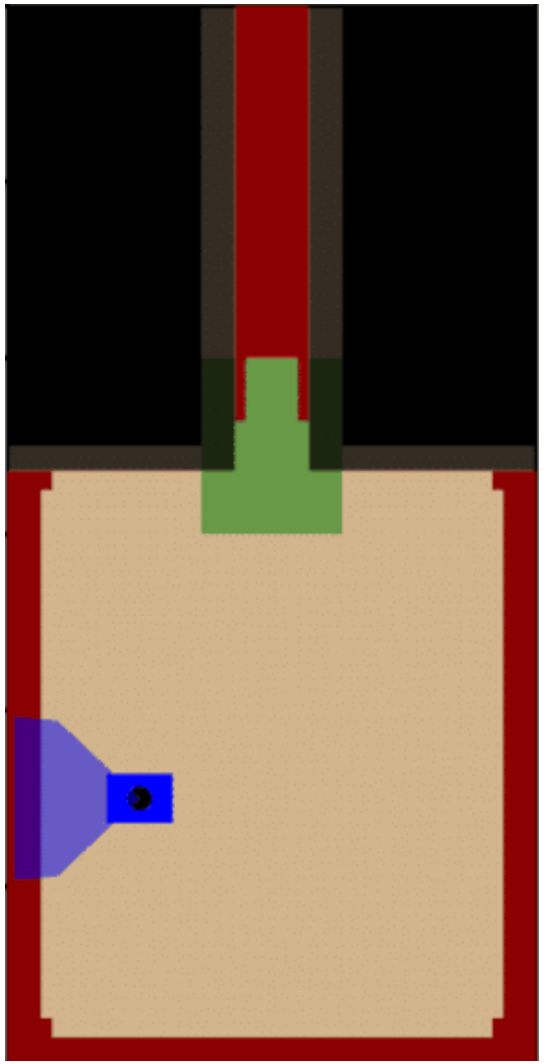
Action Regions

Danger Zones

Search

z_0 : Dead Ends!

<u>Compute:</u>
Preimage of z_0 under action a



Action Regions

Danger Zones

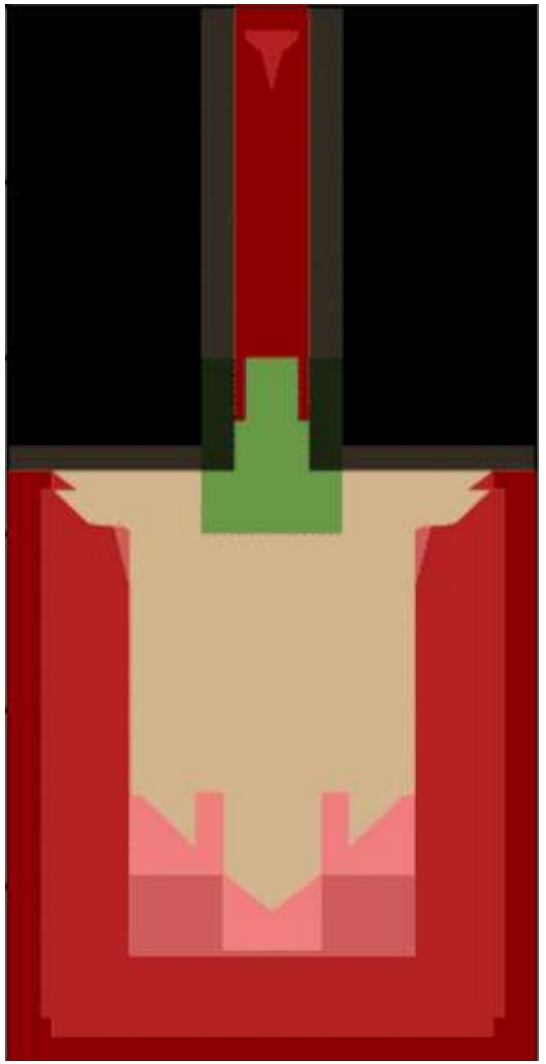
Search

z_0 : Dead Ends!

z_1 : Lead to z_0

z_2 : Lead to z_1

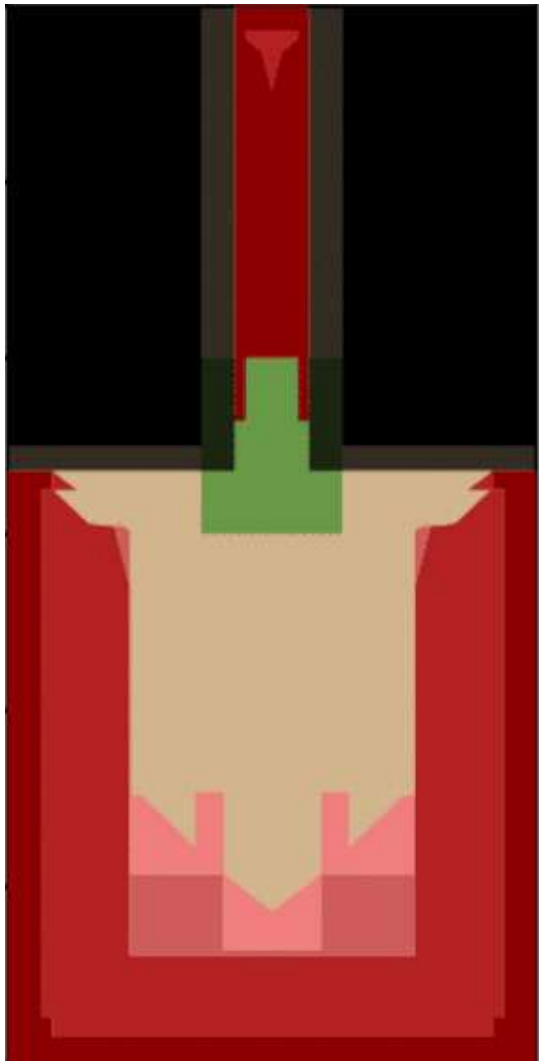
z_i : Lead to $z_{j<i}$



Action Regions

Danger Zones

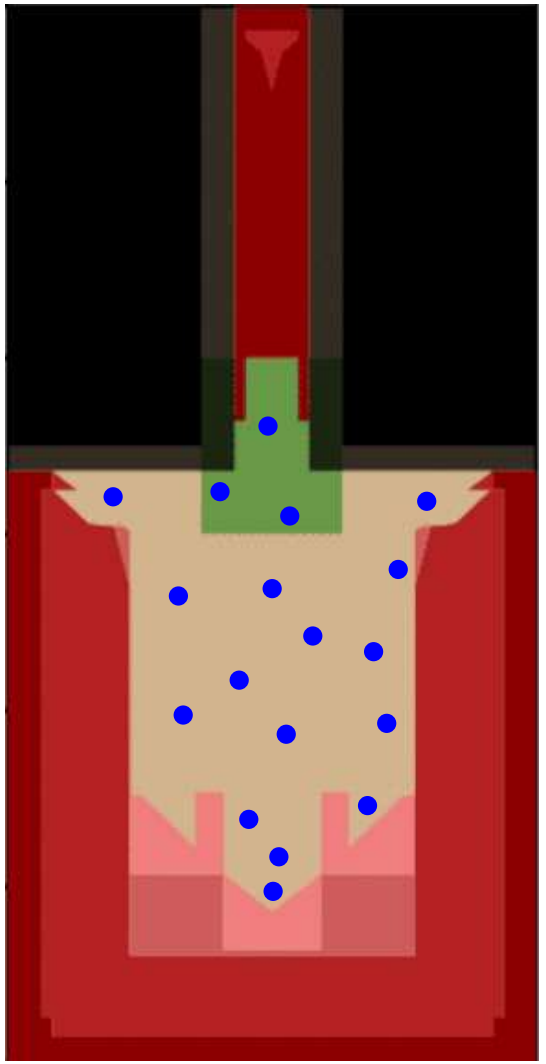
Search



Action Regions

Danger Zones

Search



Action Regions

Danger Zones

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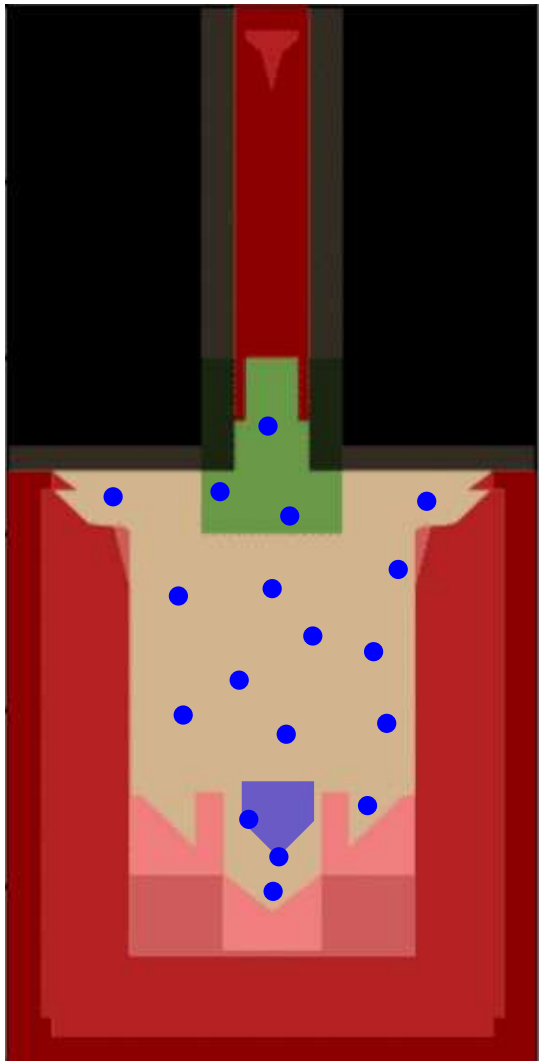

Action Regions

Danger Zones

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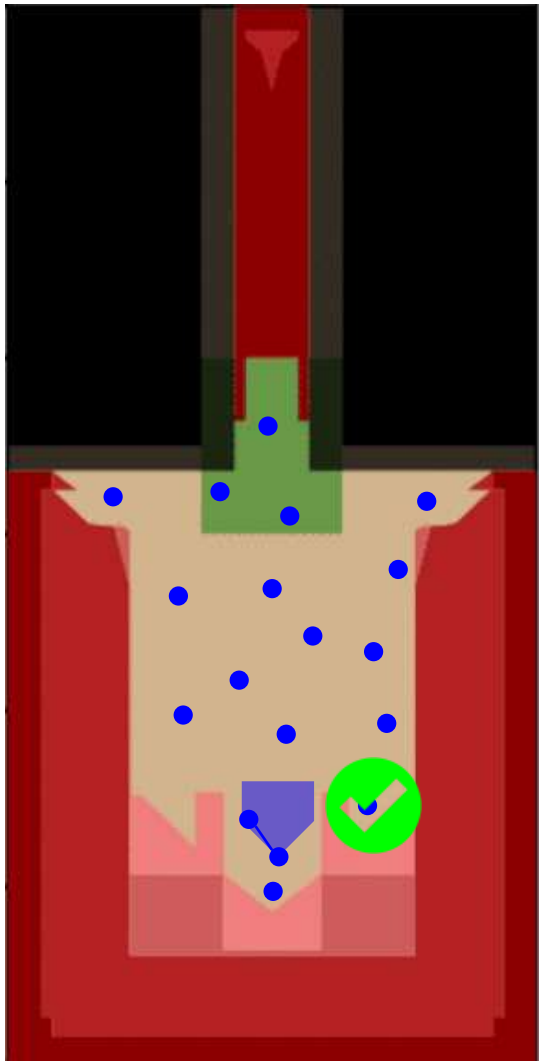

Action Regions

Danger Zones

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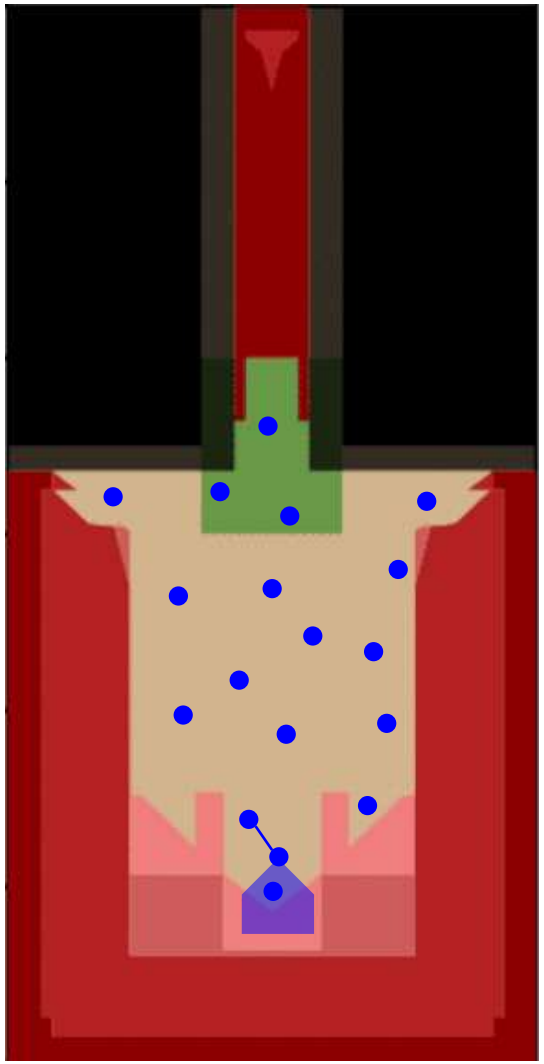

Action Regions

Danger Zones

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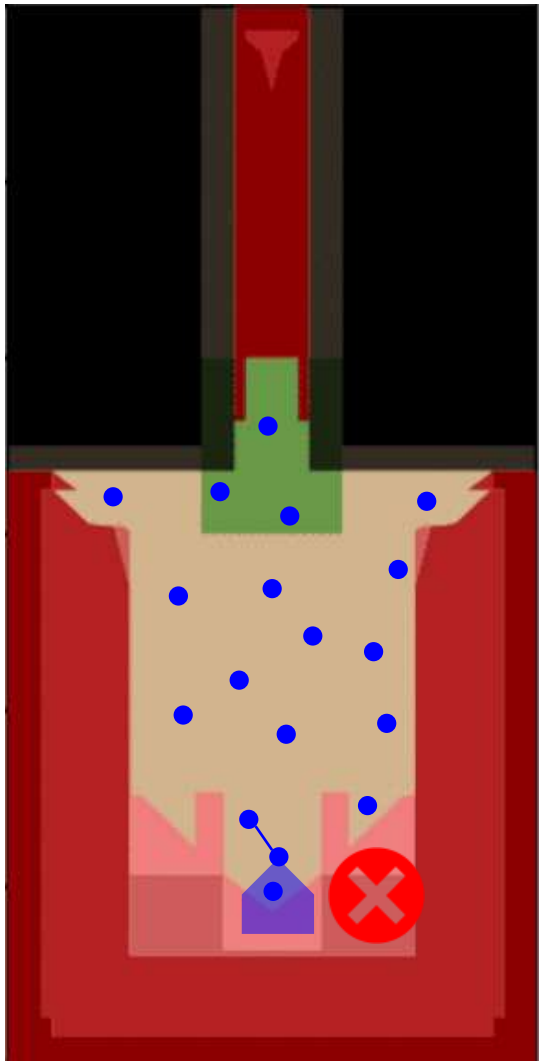

Action Regions

Danger Zones

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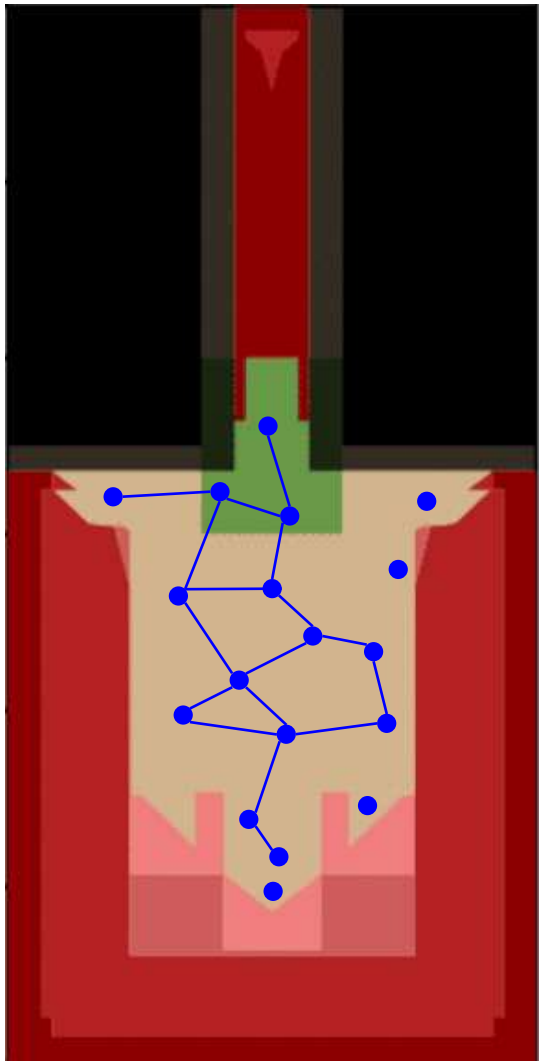

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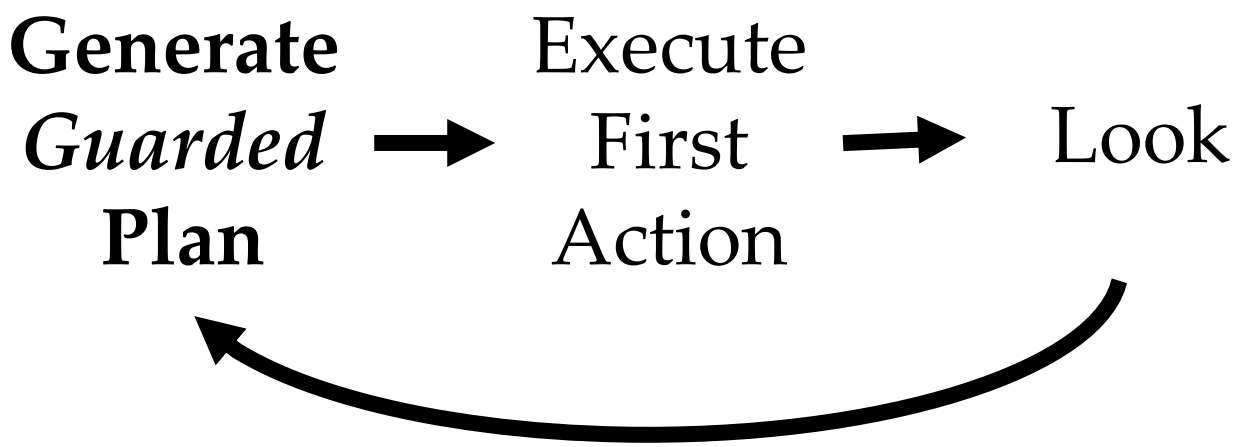

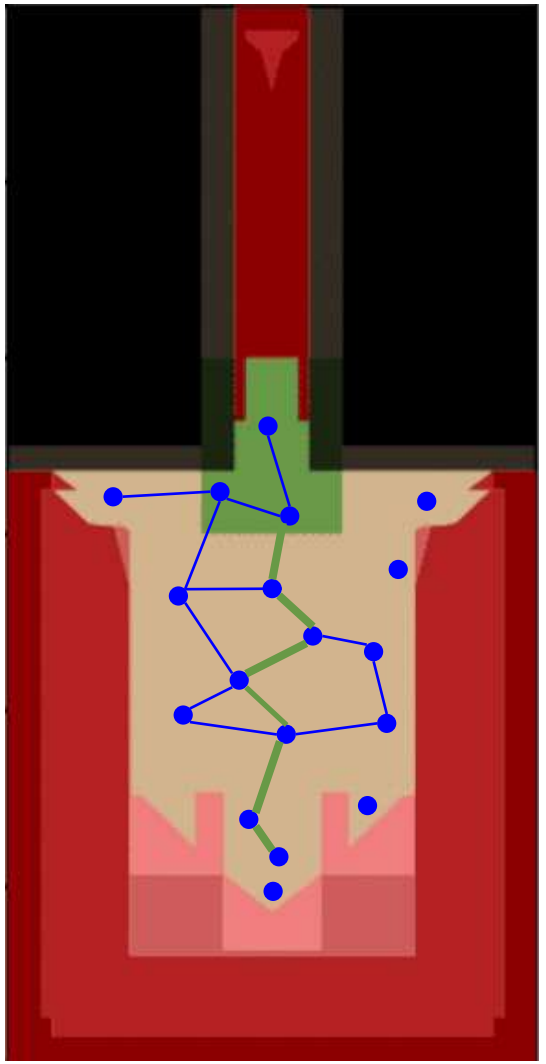

Action Regions

Danger Zones

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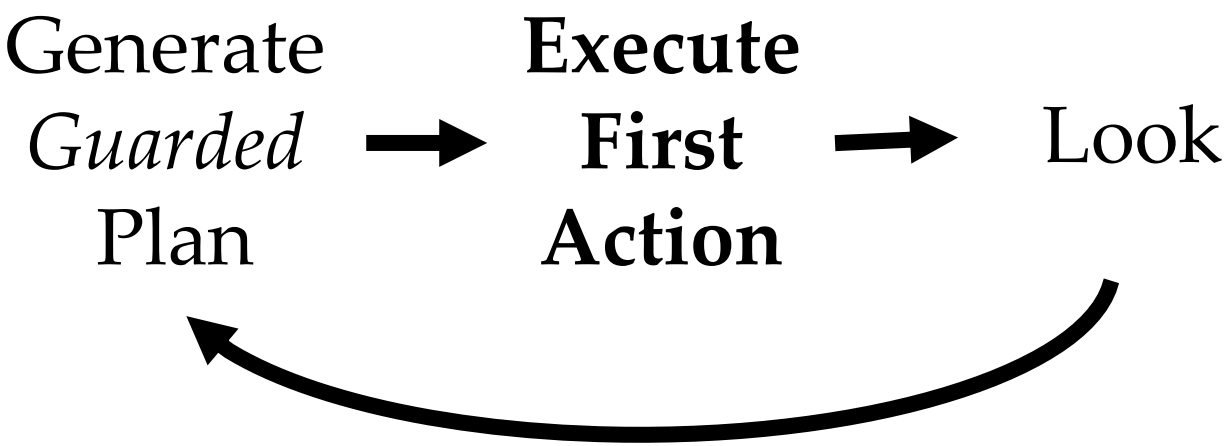

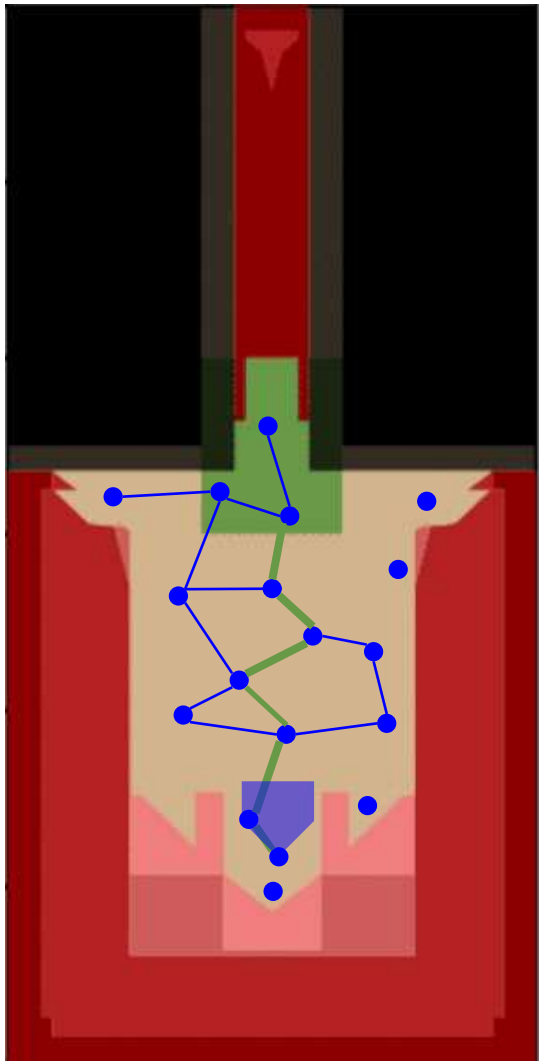

Action Regions

Danger Zones

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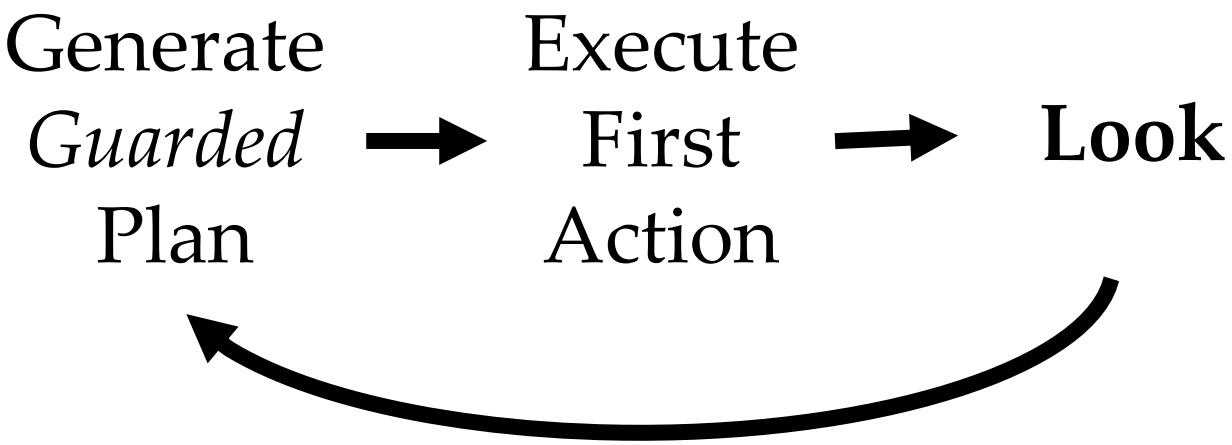

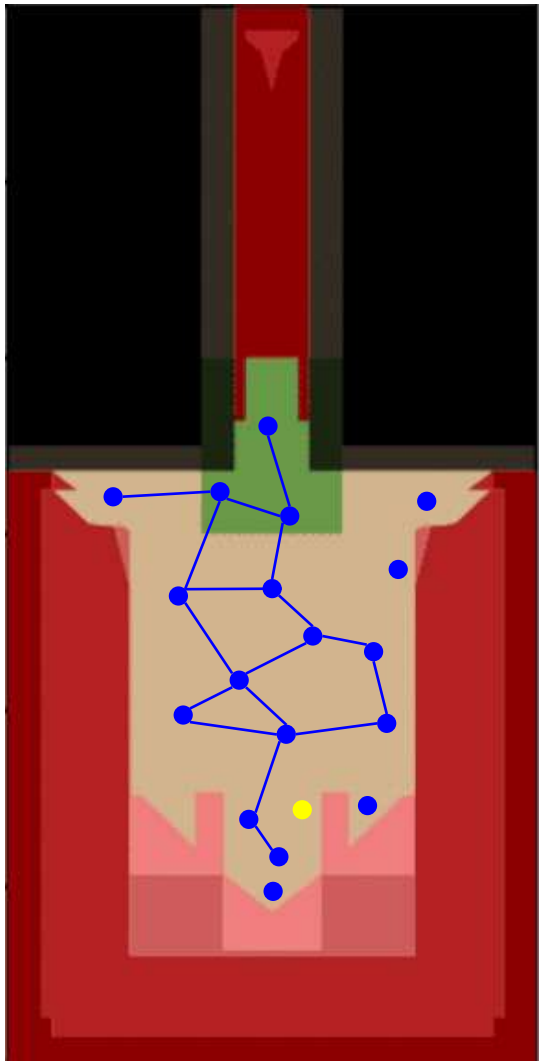

Action Regions

Danger Zones

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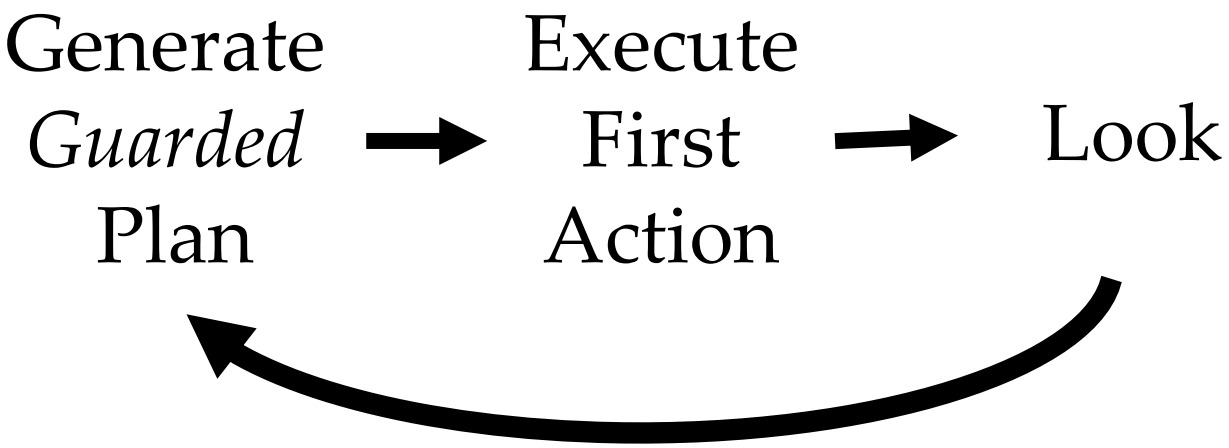
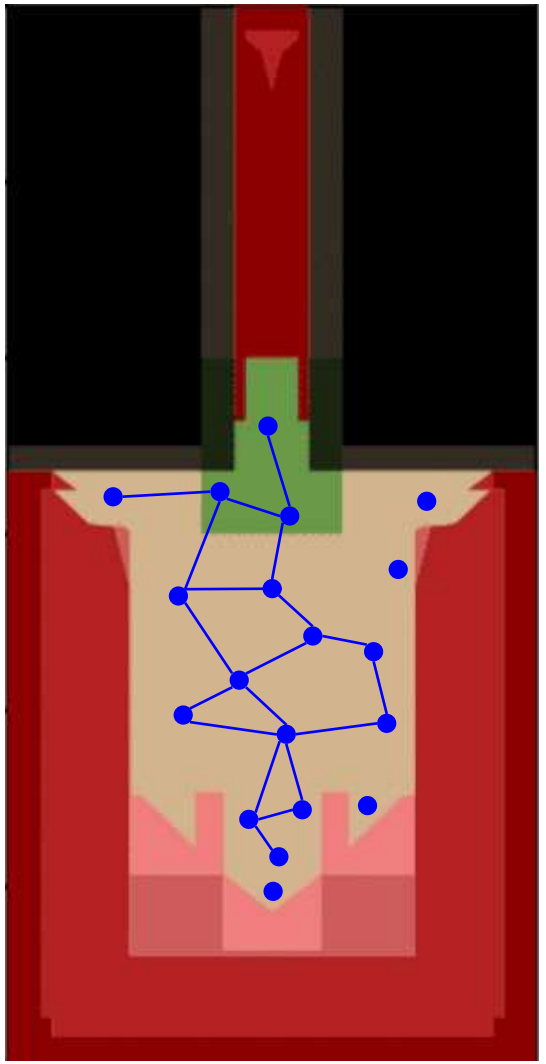




Be GUARD(ed)

Guiding Uncertainty Accounting for Risk and Dynamics

Environment Algorithm Results

Environment
Corner
SlipperySlope
GlassWall

Environment	Algorithm
Corner	GUARD
	Baseline
SlipperySlope	GUARD
	Baseline
GlassWall	GUARD
	Baseline

Environment	Algorithm	Results		
		S	TO	DE
Corner	GUARD			
	Baseline			
SlipperySlope	GUARD			
	Baseline			
GlassWall	GUARD			
	Baseline			

Environment	Algorithm	Results		
		S	TO	DE
Corner	GUARD	10	0	0
	Baseline	7	1	2
SlipperySlope	GUARD	7	3	0
	Baseline	8	2	0
GlassWall	GUARD	9	1	0
	Baseline	1	7	2

Environment	Algorithm	Results			Time	
		S	TO	DE	Offline (SE)	Online (SE)
Corner	GUARD	10	0	0	22.5 (0.32)	19.3 (4.9)
	Baseline	7	1	2	3.01 (0.03)	6.77 (3.1)
SlipperySlope	GUARD	7	3	0	48.3 (0.36)	21.3 (7.8)
	Baseline	8	2	0	6.9 (0.03)	11.9 (7.6)
GlassWall	GUARD	9	1	0	133 (1.70)	69.9 (16)
	Baseline	1	7	2	14.9 (0.12)	39.9 (4.8)

Characterize briefly-dynamic manipulation as planning under uncertainty with dead-ends

Characterize briefly-dynamic manipulation as planning under uncertainty with dead-ends

Propose GUARD

Accomplish Long-Horizon Manipulation Tasks

https://people.csail.mit.edu/rholladay/

Enable Reasoning over Geometry *and* Physics to Accomplish Long-Horizon Manipulation Tasks

https://people.csail.mit.edu/rholladay/

Models and Algorithms that Enable Reasoning over Geometry *and* Physics to Accomplish Long-Horizon Manipulation Tasks

https://people.csail.mit.edu/rholladay/

Acknowledgements


4
6


BOSTON

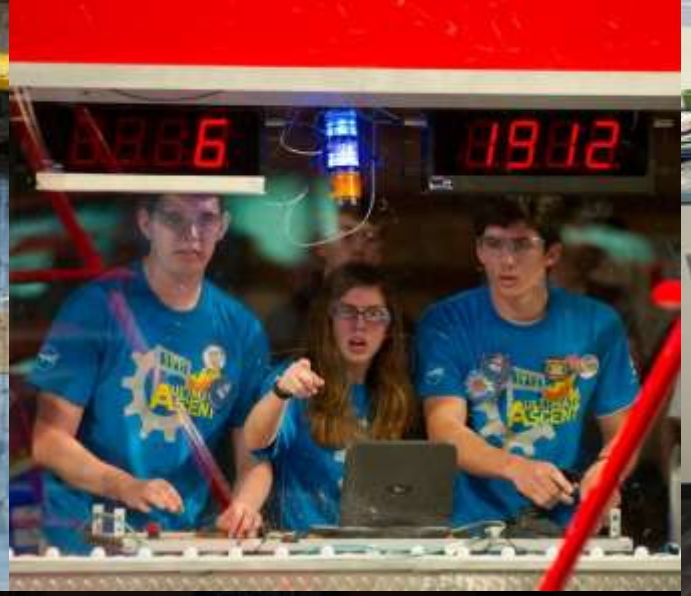

Thank you
• Thanks to all my group members, especially Jing-Jin Song
• Thanks to my friends and family
Thank you Sunny


BERKELEY


PWP
985.649.3234


Twin
Sam


1912


1912


Carnegie Mellon University
HERB
Carnegie Mellon University


FRC
CHAIRMA
AWAR


BYHAM











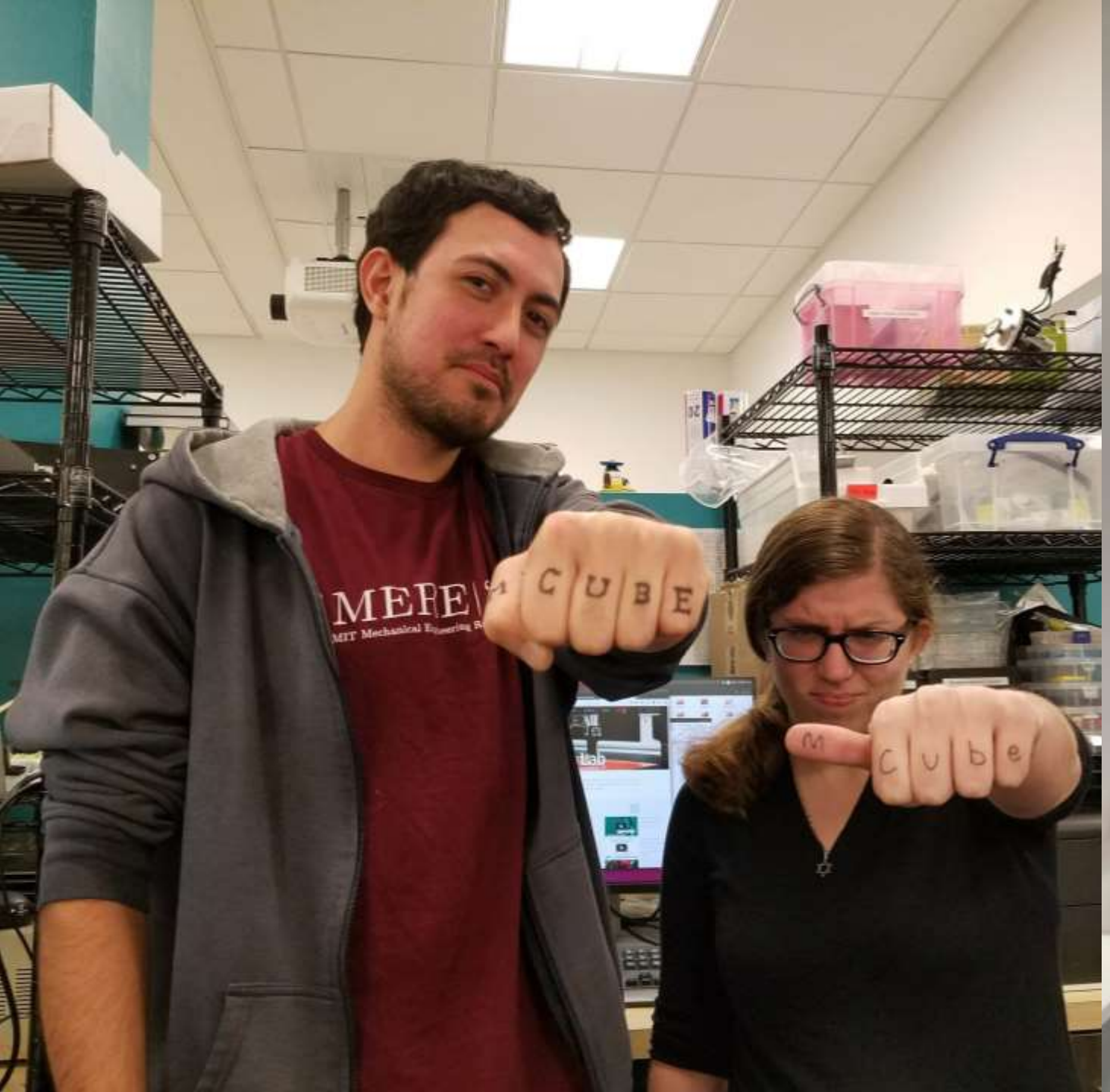


Berkelium
97
Bk
247.07
Periodic Table of Elements

The LIS Group

The MCube Lab

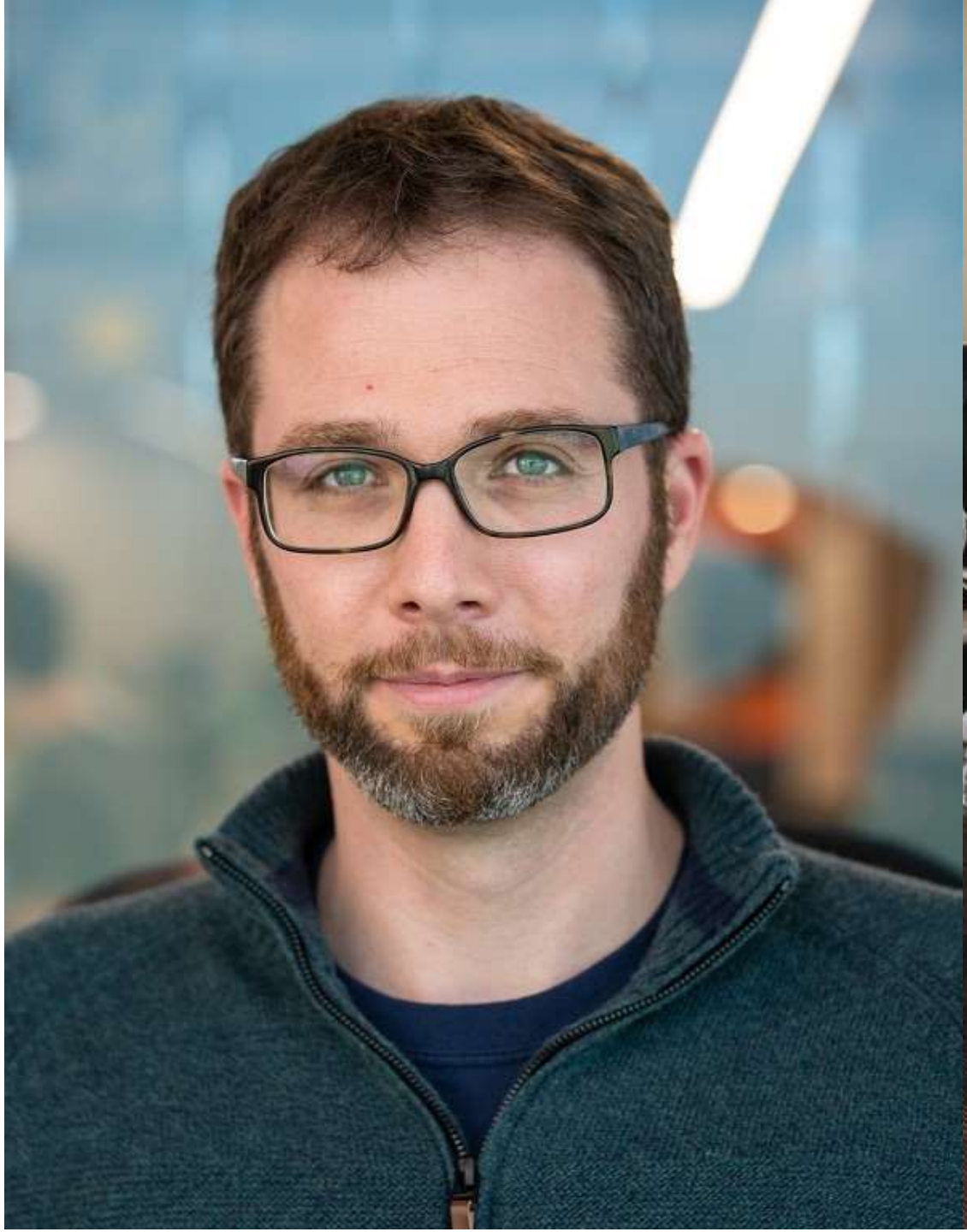

CUSTOMER

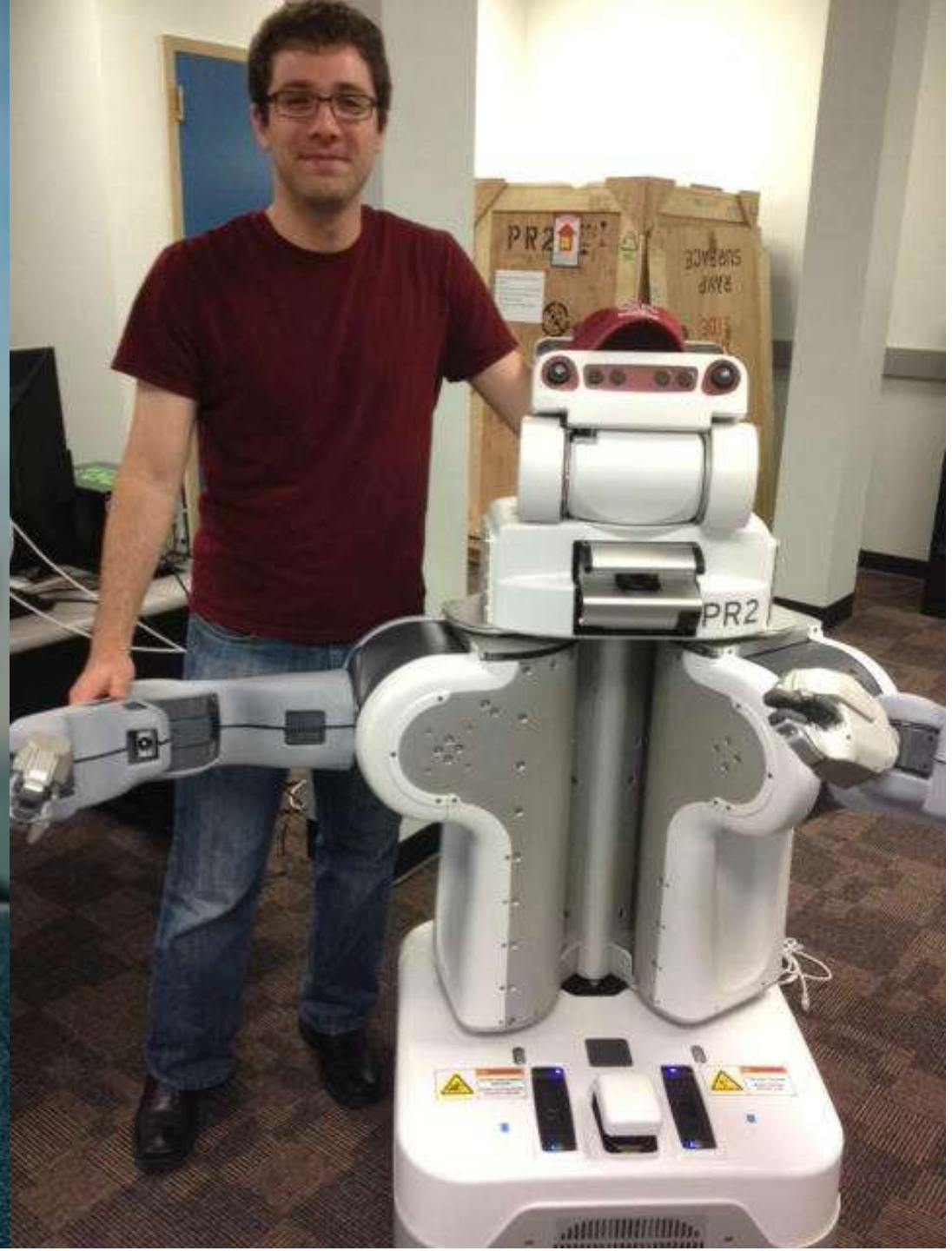

MEFE
MIT Mechanical Engineering
CUBE
M
CUBE

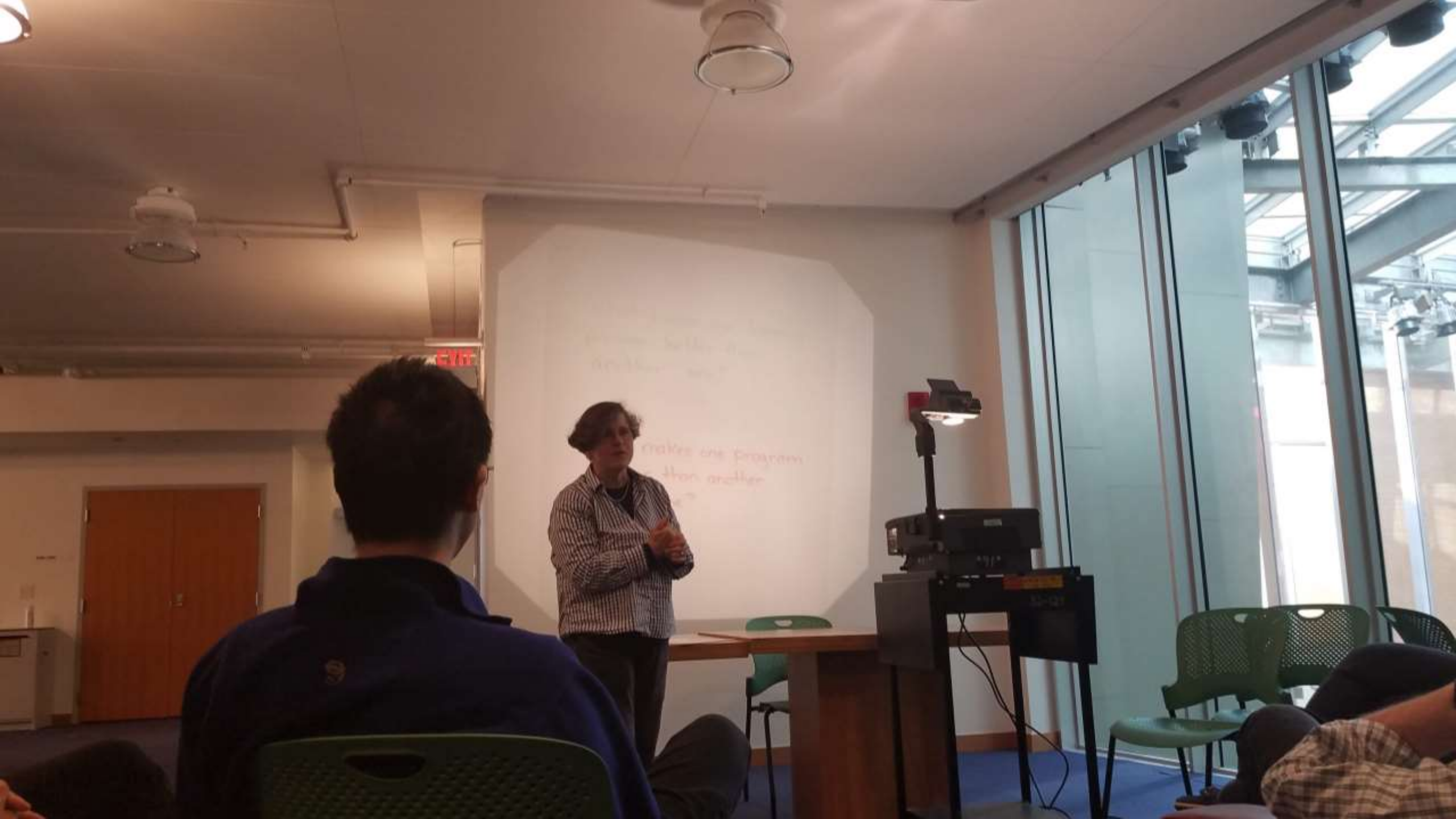

A Tactile-Enabled Hybrid Rigid-Soft Continuum Manipulator for Forceful Enveloping Grasps Via Scale Invariant Design
Compliant Mechanism Analysis
Design of Continuum Manipulator
Demonstrations
Results
MCube Manipulations and Mechatronics Lab
BOSCH
BOSCH


ROBOTICS
SCIENCE AND SYSTEMS

Teaching + Learning Lab




PR2
PR2


Exit

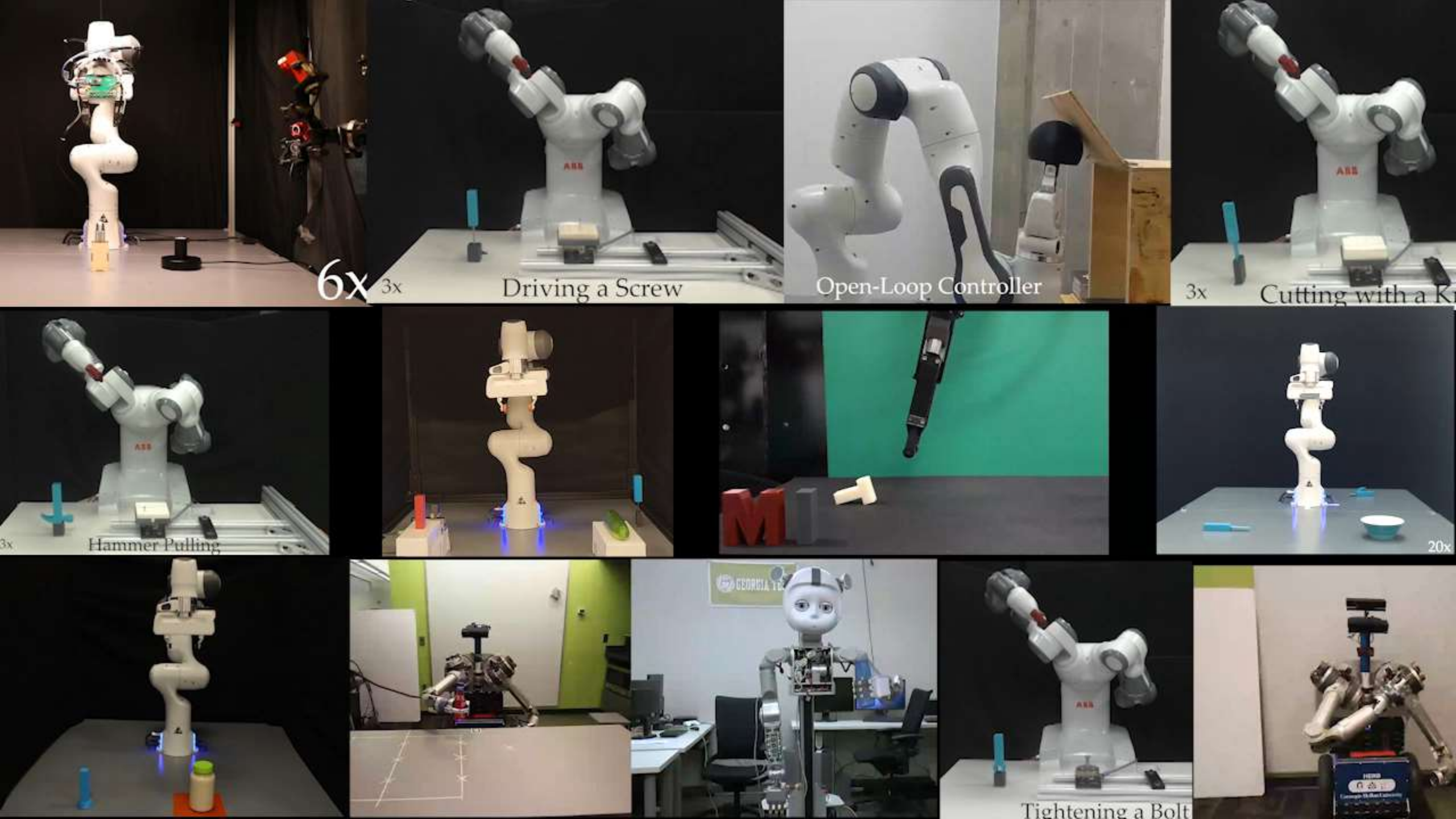

16 March
31 August

“Damn the torpedoes, full speed ahead!”

- Admiral David Farragut,

Battle of Mobile Bay (1864)

[apocryphal]


6x
3x
Driving a Screw
Open-Loop Controller
3x
Cutting with a K
3x
Hammer Pulling
20x
Tightening a Bolt