

# Lecture 09

## IK cont ... &

# Manipulation

# New Frontiers

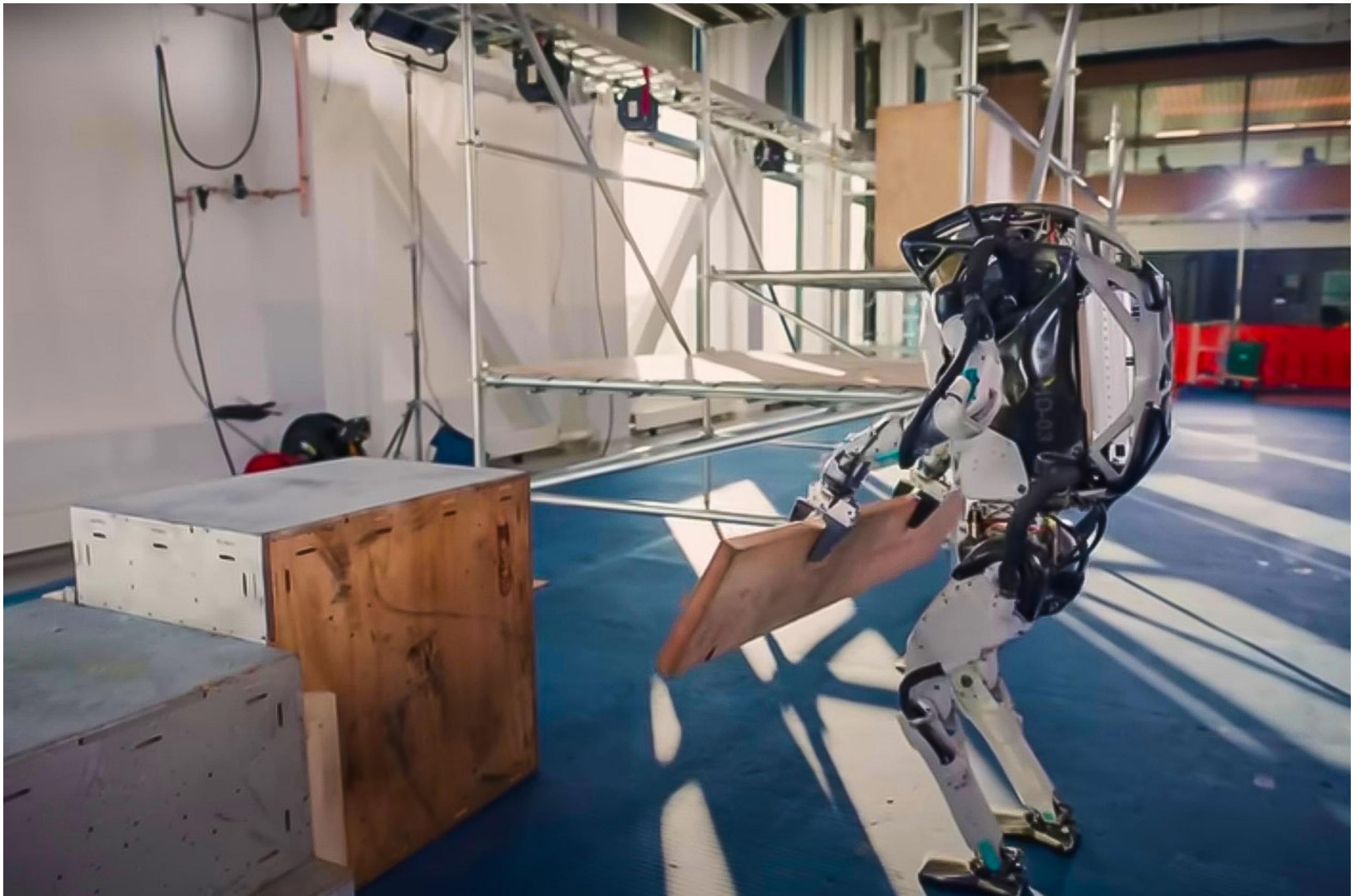


Image Credit - Boston Dynamics



# Course Logistics

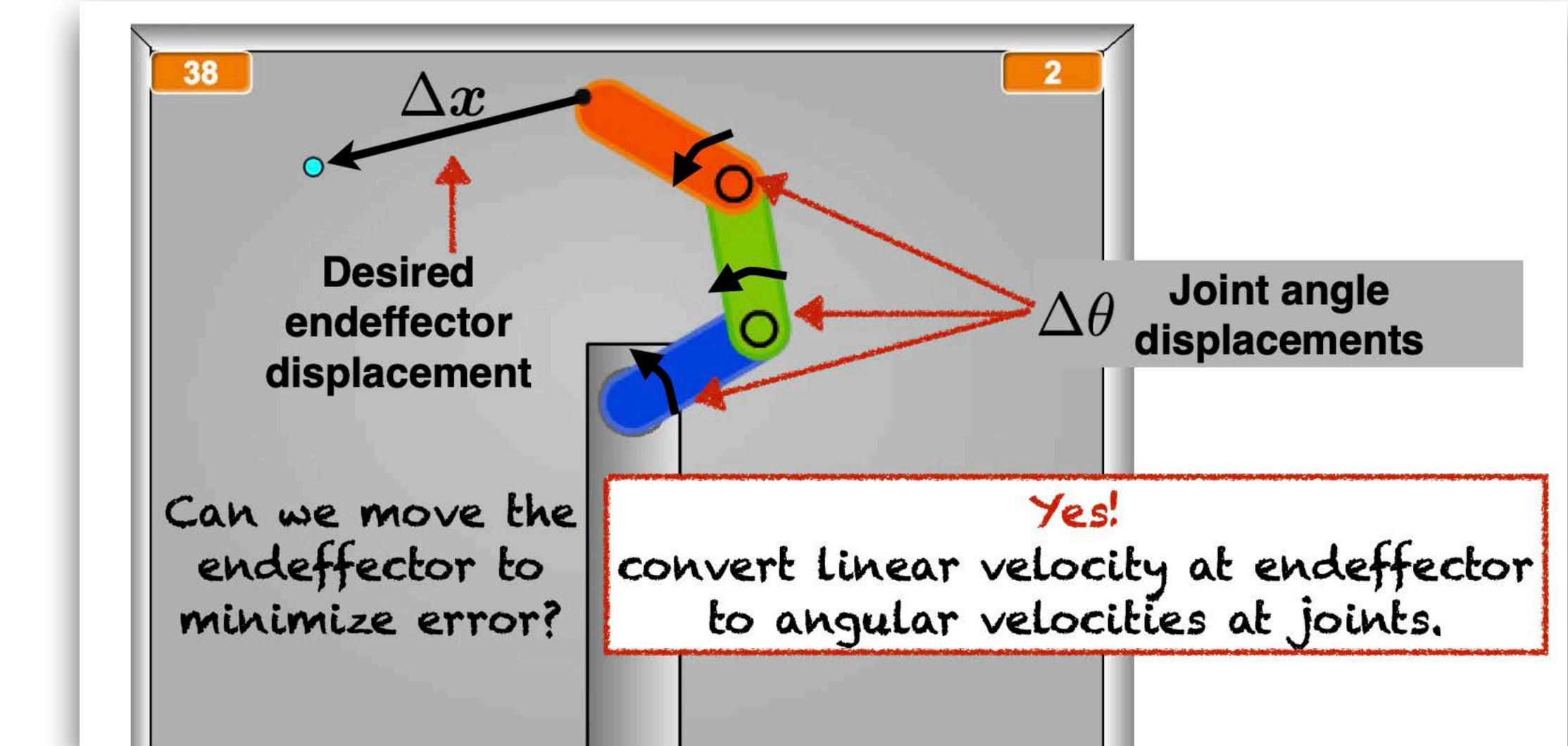
- Quiz 4 was posted yesterday and was due at noon today.
- Project 3 was posted on 02/12 and will be due 02/19 (today).
- Project 4 will be posted 02/19 (today) and will be due on 03/05.

# Previously

Inverse kinematics: how to solve for  $q = \{\theta_1, \dots, \theta_N\}$  from  $T^0_N$ ?

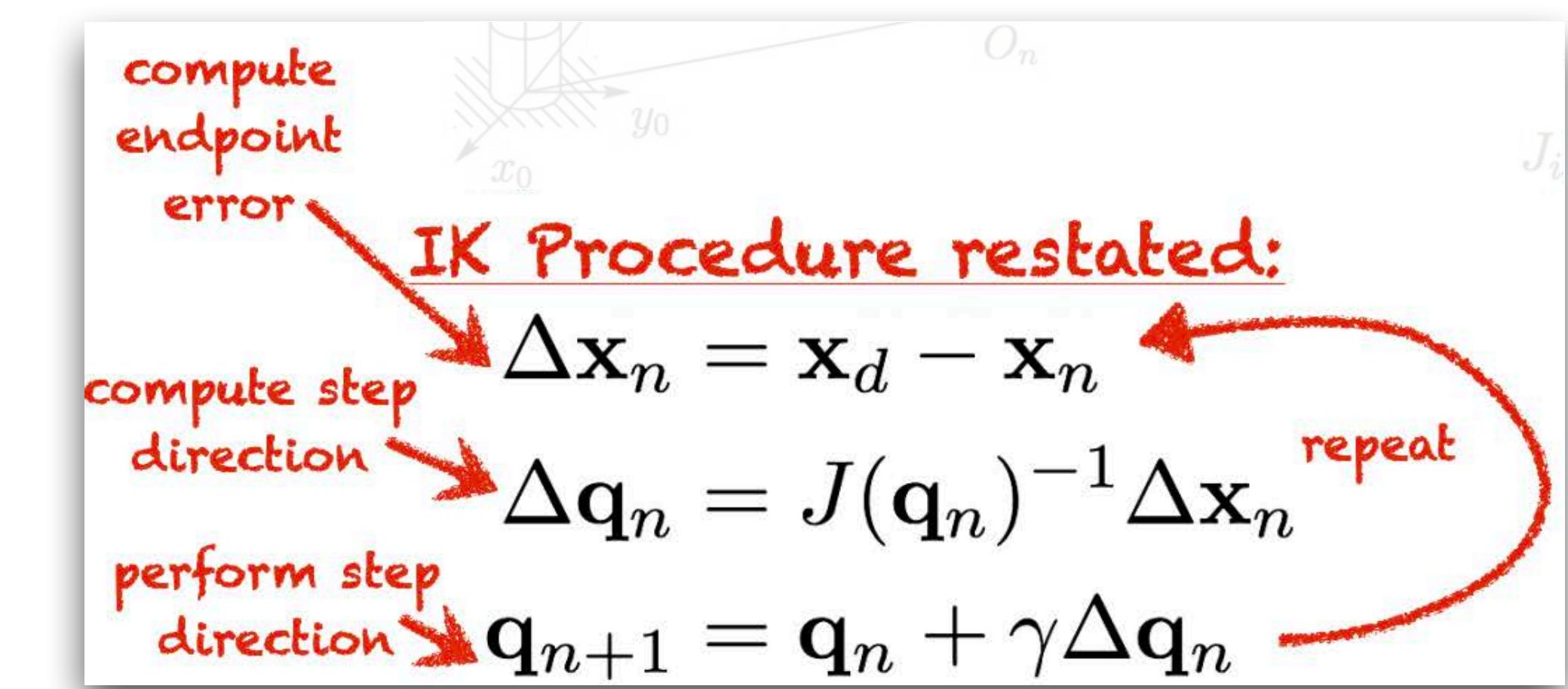
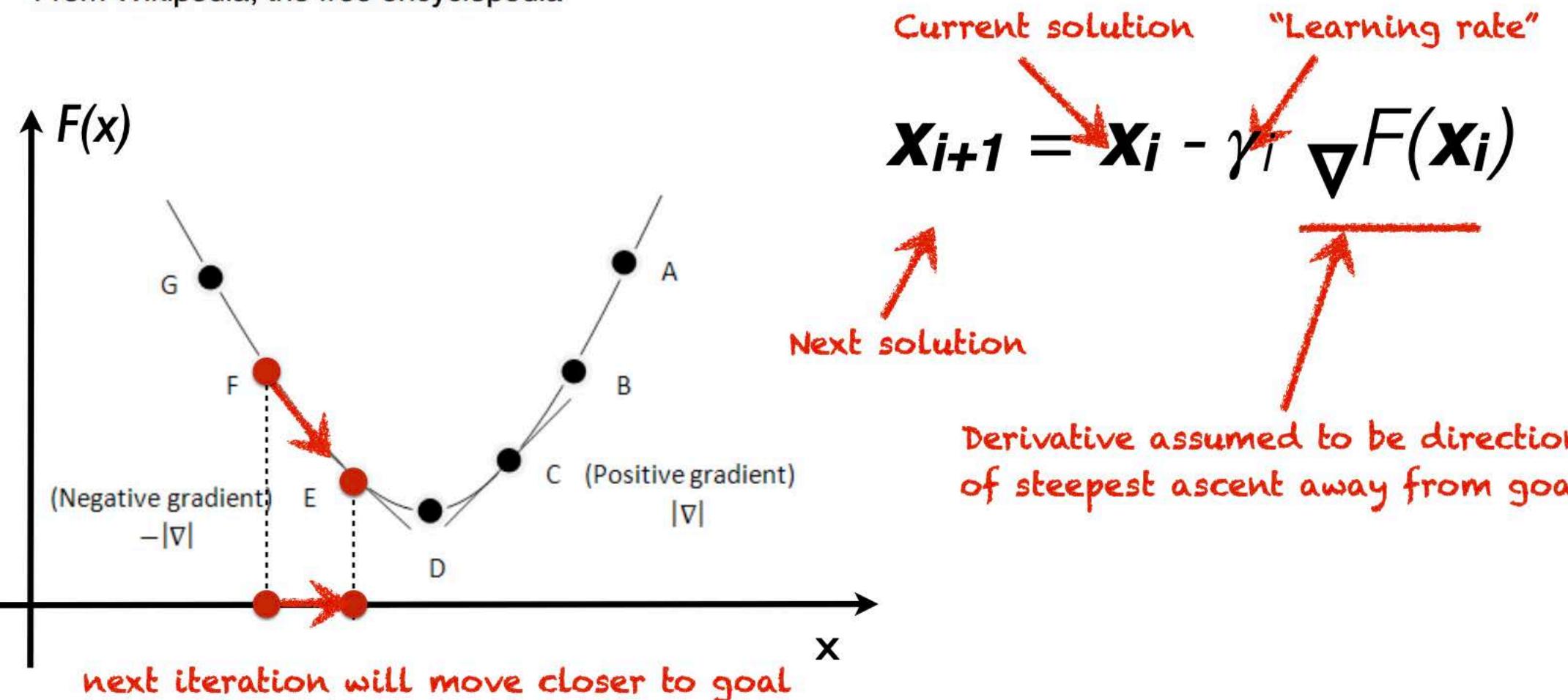
## Inverse Kinematics: 2 possibilites

- **Closed-form solution:** geometrically infer satisfying configuration
  - *Speed:* solution often computed in constant time
  - *Predictability:* solution is selected in a consistent manner
- **Solve by optimization:** minimize error of endeffector to desired pose
  - often some form of Gradient Descent (a la Jacobian Transpose)
  - *Generality:* same solver can be used for many different robots



## Gradient descent

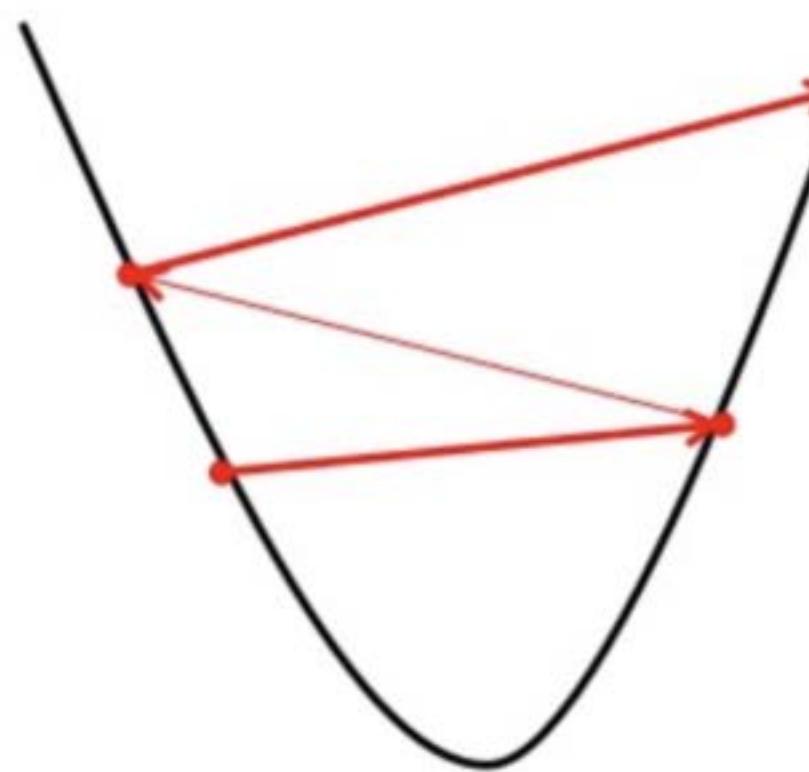
From Wikipedia, the free encyclopedia



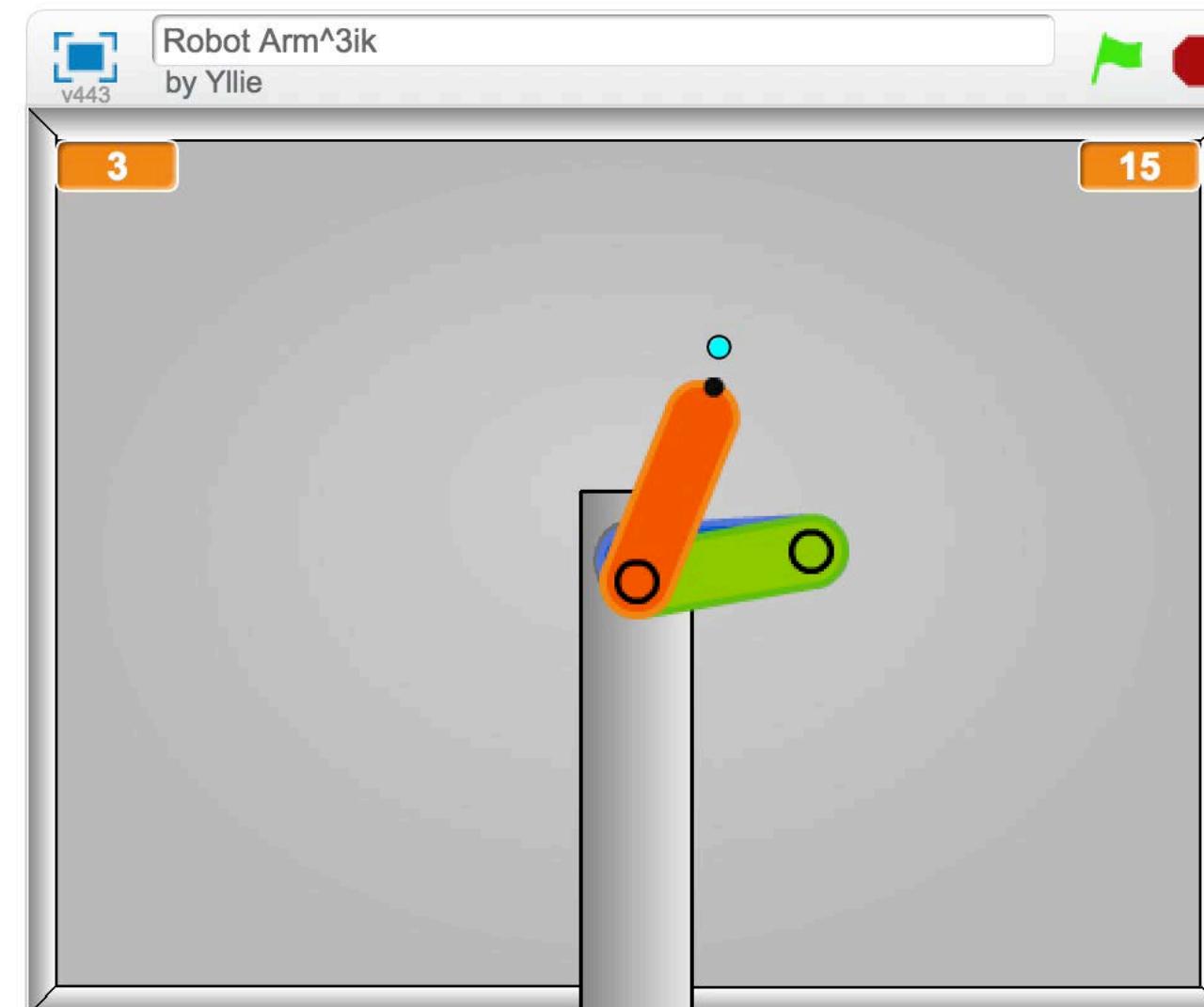
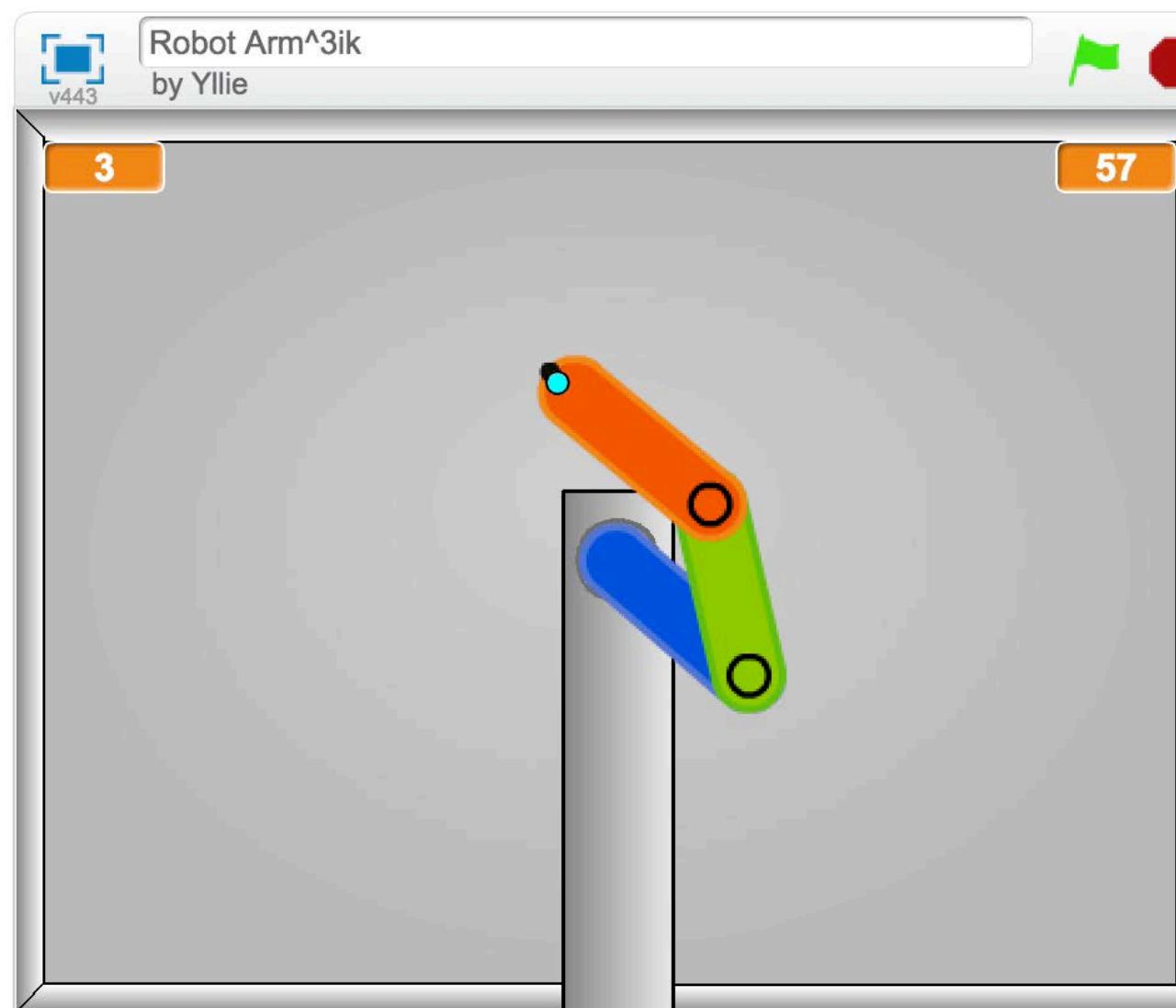
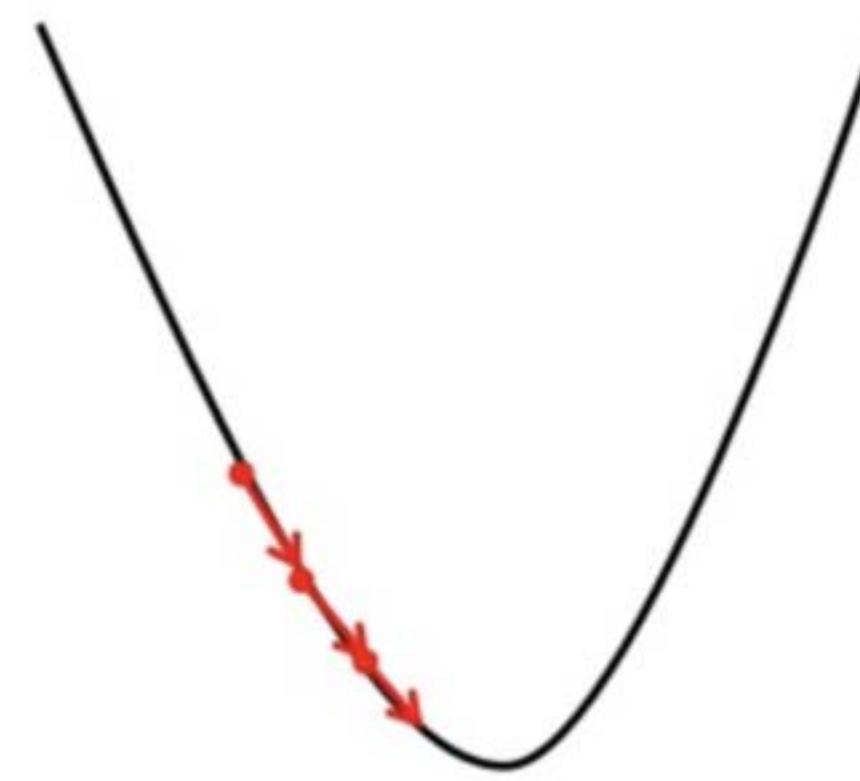
# IK by optimization

**Inverse kinematics:** how to solve for  $q = \{\theta_1, \dots, \theta_N\}$  from  $T^0_N$ ?

Big steps -> Aggressive



Small steps -> Conservative



Wait IK should give only the final robot configuration, isn't it?

In these videos, we see the entire path from the initial configuration. What's going on?

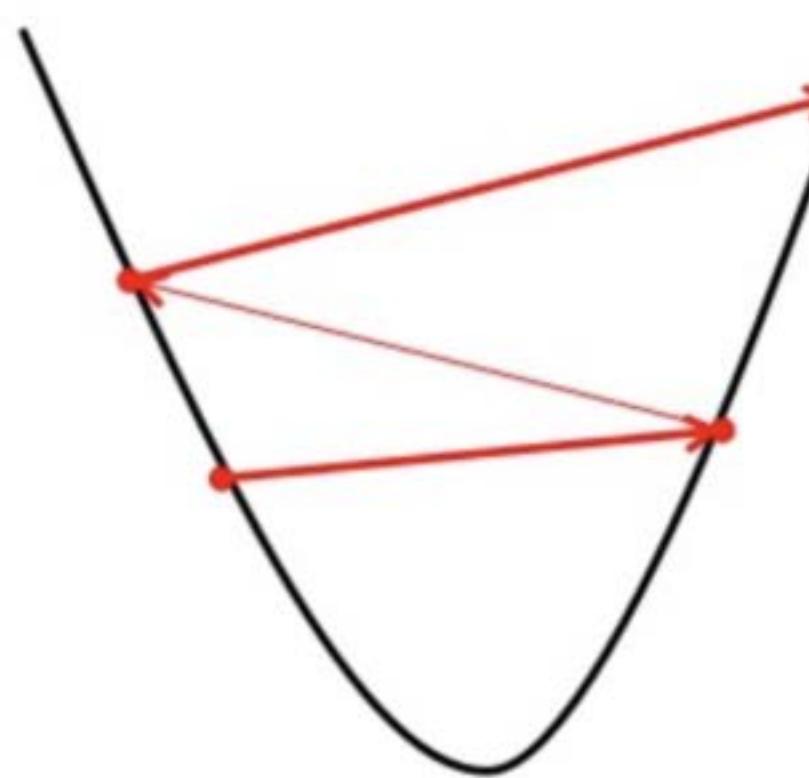
These videos are **illustrating** the optimization steps

In practice, you will use the solution ( $q_{desired}$ ) from the IK solver and invoke a motion planner that will plan a collision free trajectory/path to your solution

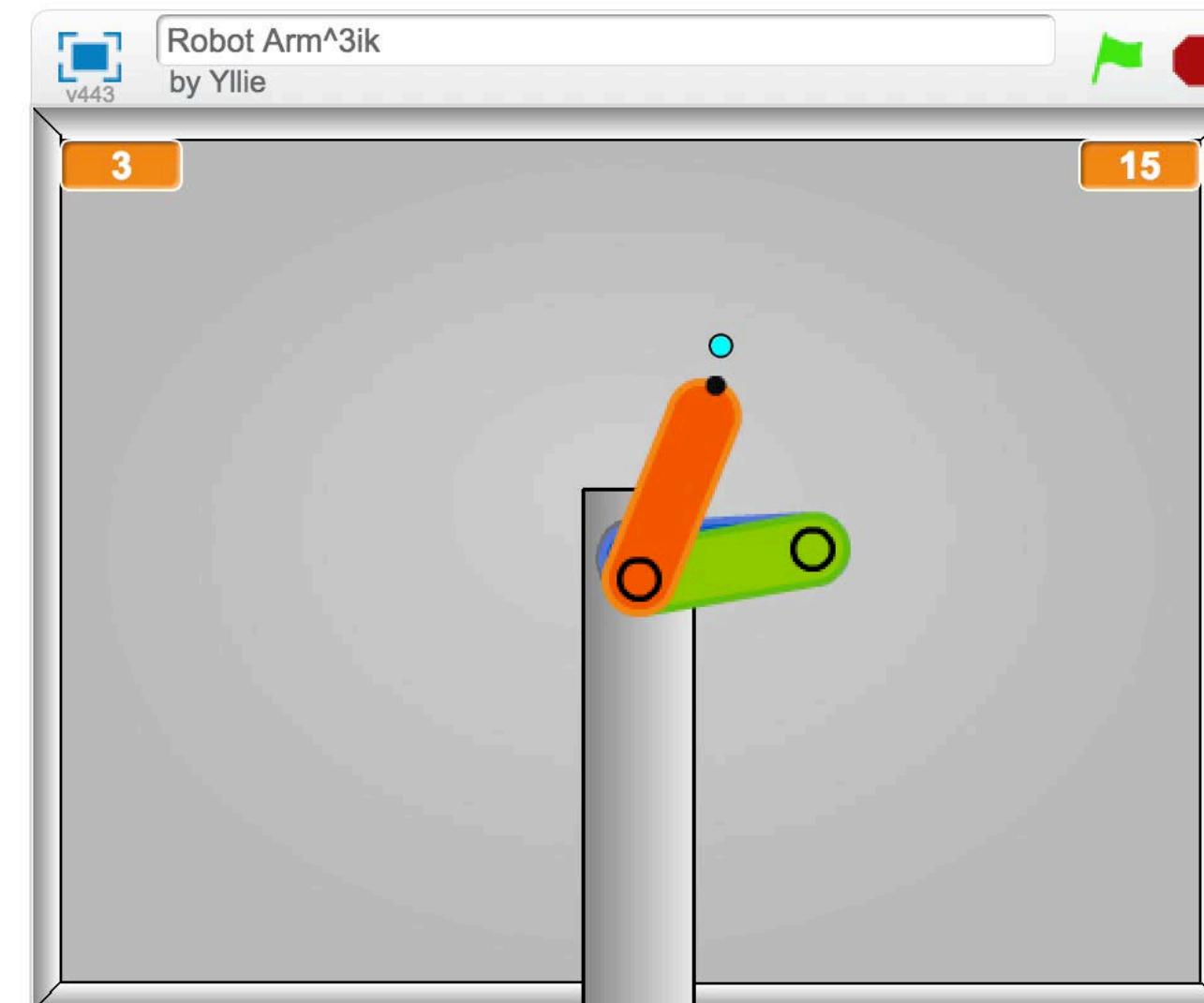
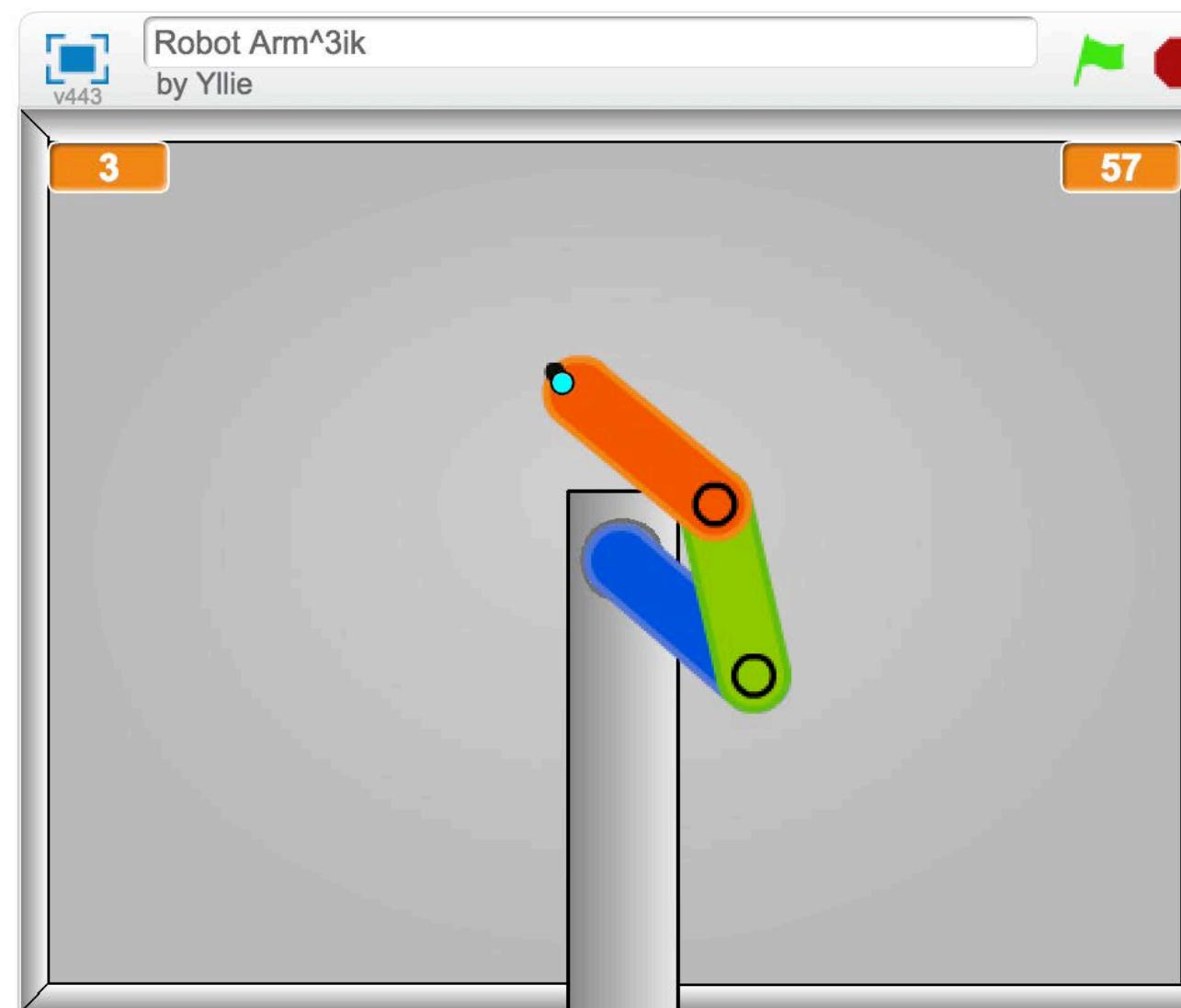
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These videos are **illustrating** the optimization steps

$$q_{\text{desired}} = \text{IKSolver}(x_{\text{desired}})$$

$$\text{Trajectory} = \text{MotionPlanner}(q_{\text{current}}, q_{\text{desired}})$$

We will talk about this in the future classes

# Robot arm and its Jacobian

3D N-joint arm

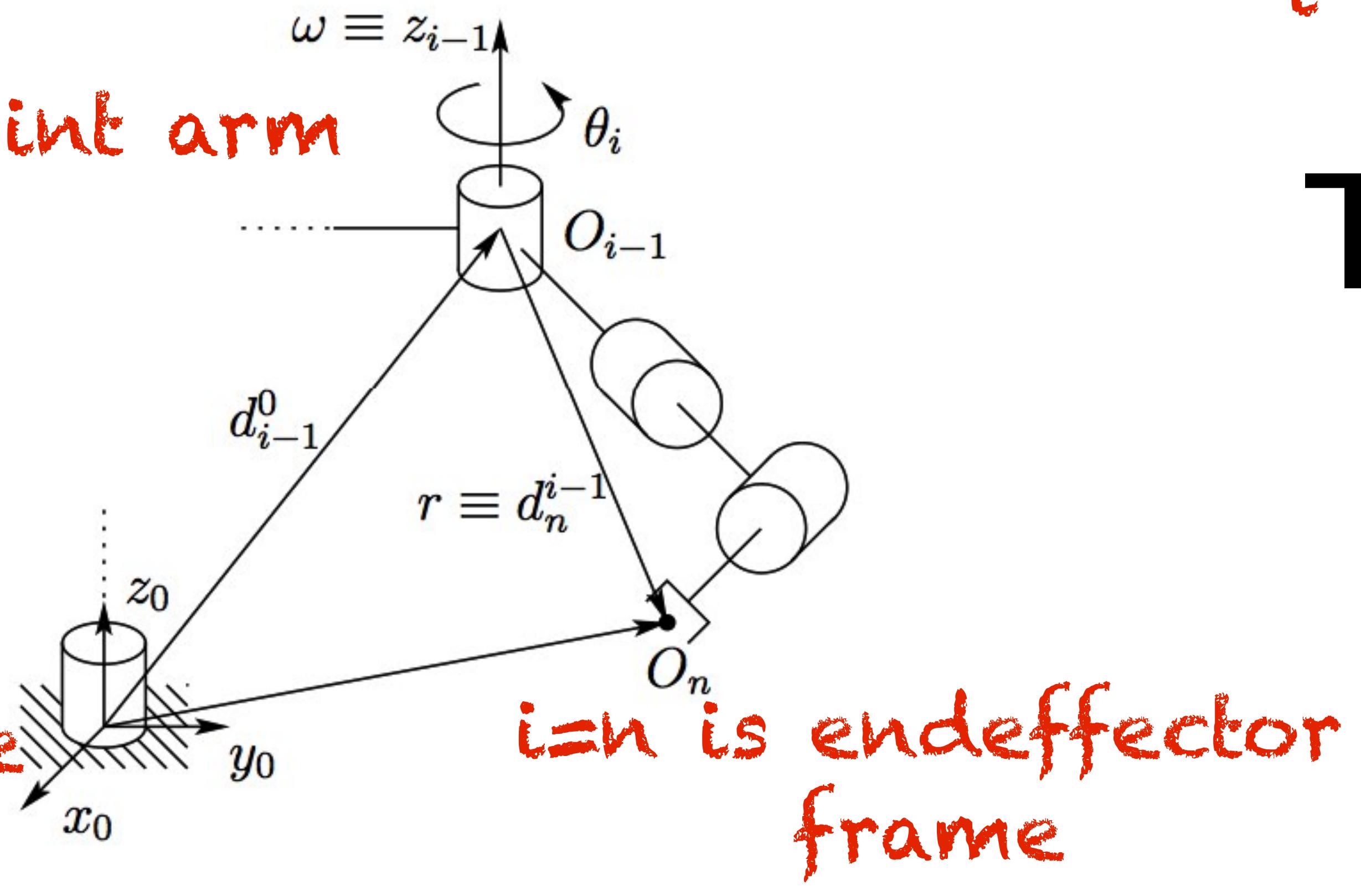


Figure 5.1: Motion of the end-effector due to link  $i$ .

$i-1^{\text{th}}$  frame maps to  $i^{\text{th}}$  column (Joint) in

## The Jacobian

A  $6 \times N$  matrix

$$J = [J_1 \ J_2 \ \cdots \ J_n]$$

# Robot arm and its Jacobian

Lets focus on  
*i-1<sup>th</sup> frame*

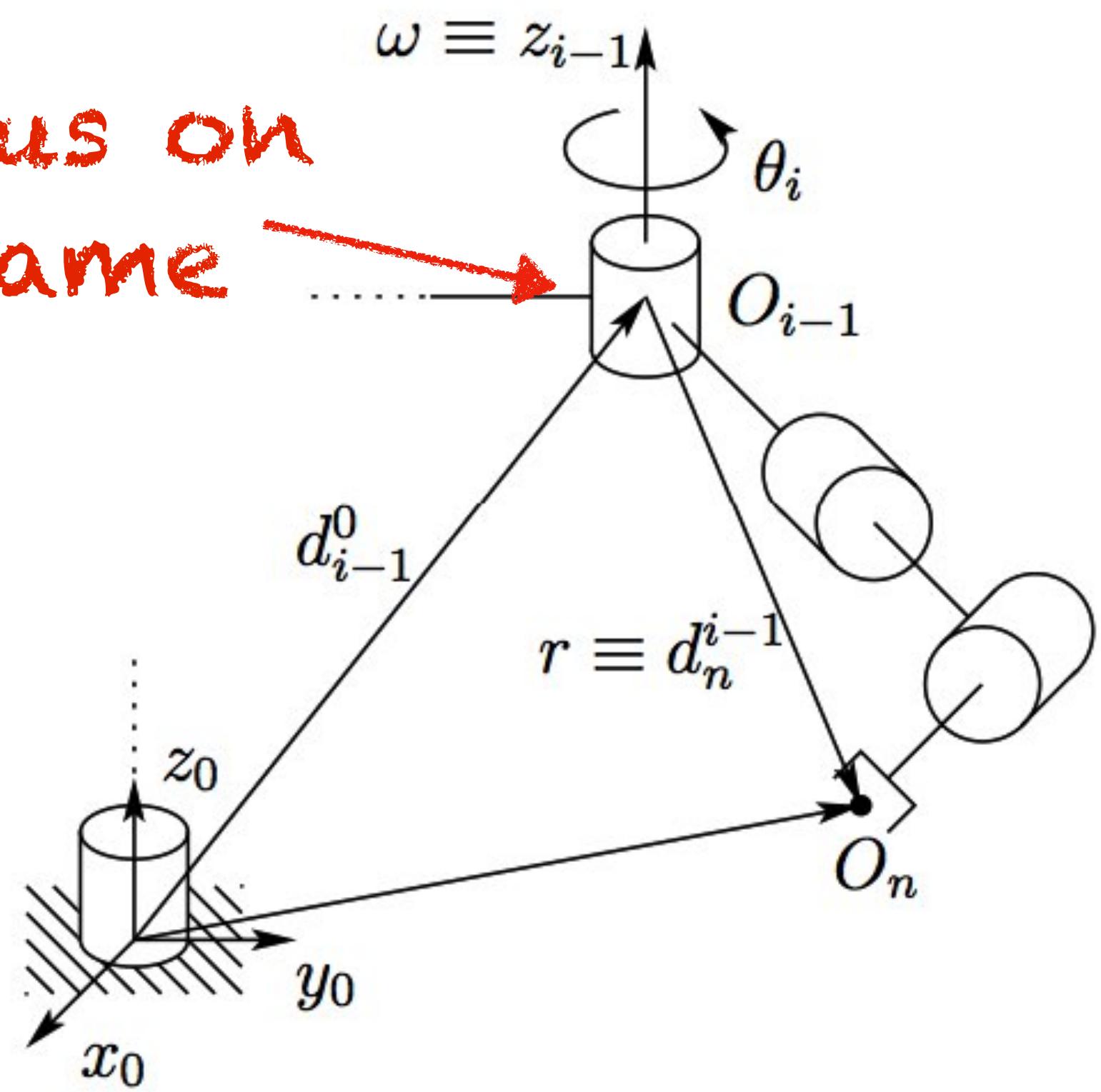


Figure 5.1: Motion of the end-effector due to link  $i$ .

*i-1<sup>th</sup> frame maps to *i<sup>th</sup> column (Joint) in The Jacobian**

A  $6 \times N$  matrix

$$J = [J_1 \ J_2 \ \cdots \ J_n]$$

*This will correspond to *i<sup>th</sup> column**

# Robot arm and its Jacobian

Lets focus on  
*i-1<sup>th</sup> frame*

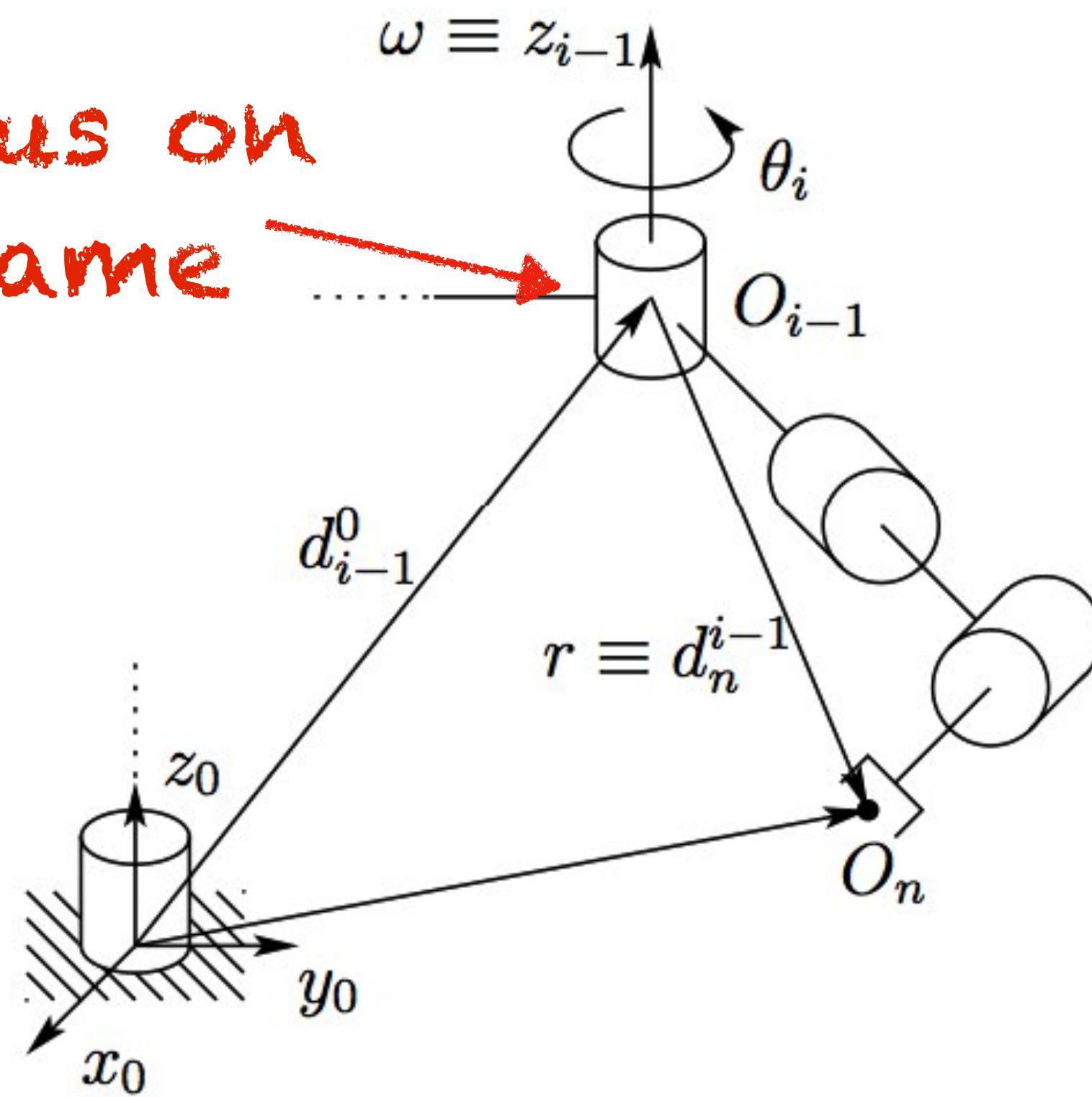


Figure 5.1: Motion of the end-effector due to link  $i$ .

$J_i$  for a prismatic joint

$$J_i = \begin{bmatrix} z_{i-1} \\ 0 \end{bmatrix}$$

$J_i$  for a rotational joint

$$J_i = \begin{bmatrix} z_{i-1} \times (o_n - o_{i-1}) \\ z_{i-1} \end{bmatrix}$$

*i-1<sup>th</sup> frame maps to i<sup>th</sup> column (Joint) in The Jacobian*

A  $6 \times N$  matrix

$$J = [J_1 \ J_2 \ \dots \ J_n]$$

consisting of two  $3 \times N$  matrices

$$J = \begin{bmatrix} J_v \\ J_\omega \end{bmatrix}$$

# Robot arm and its Jacobian

Lets focus on  
 $i-1$ th frame

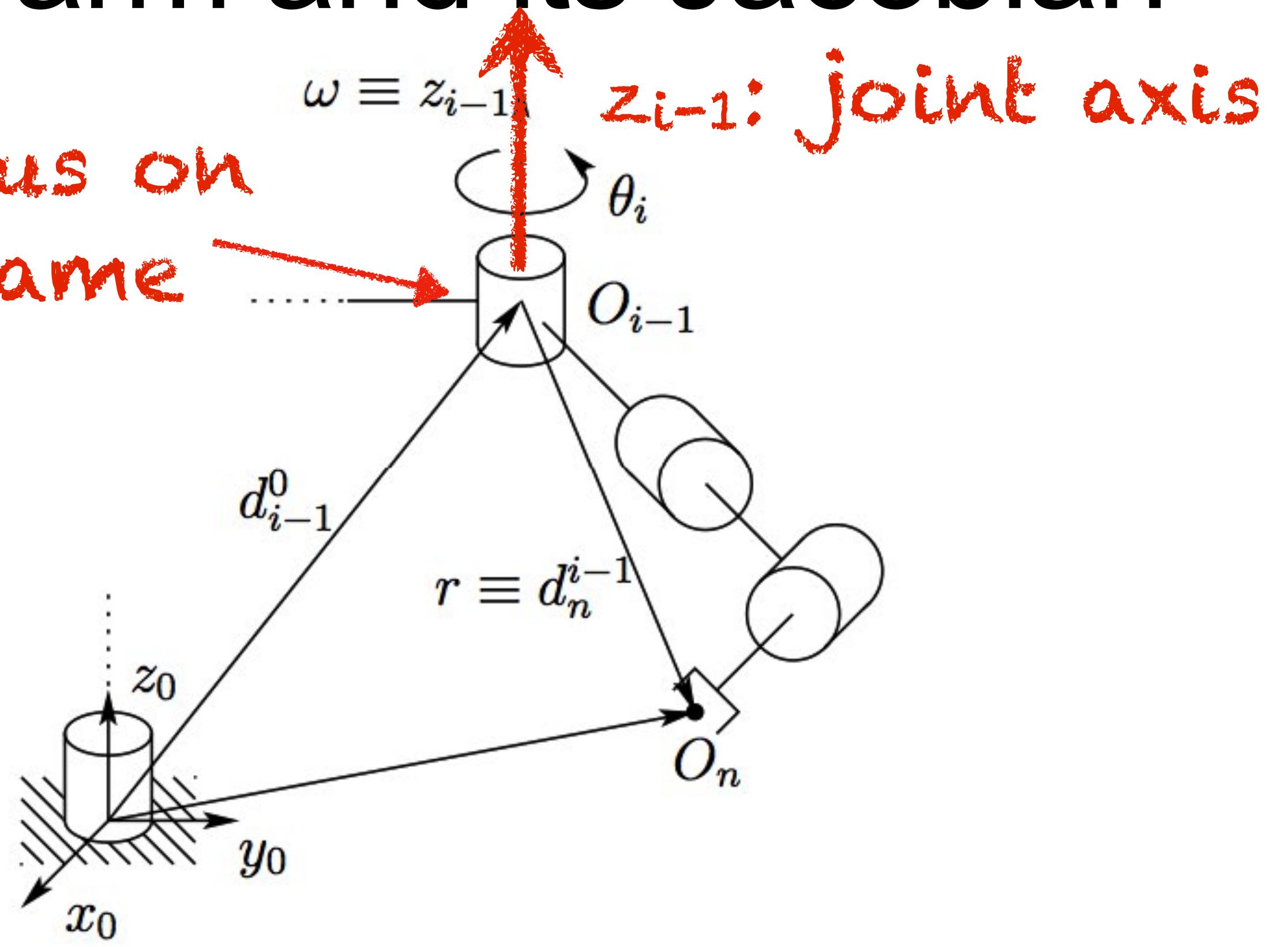


Figure 5.1: Motion of the end-effector due to link  $i$ .

If the  $i$ th joint is prismatic

$J_i$  for a prismatic joint

$$J_i = \begin{bmatrix} z_{i-1} \\ 0 \end{bmatrix}$$

What is  $z_{i-1}$  capturing?

$z_{i-1}$  is a  $3 \times 1$  vector capturing the influence of this joint on the end-effector pose.

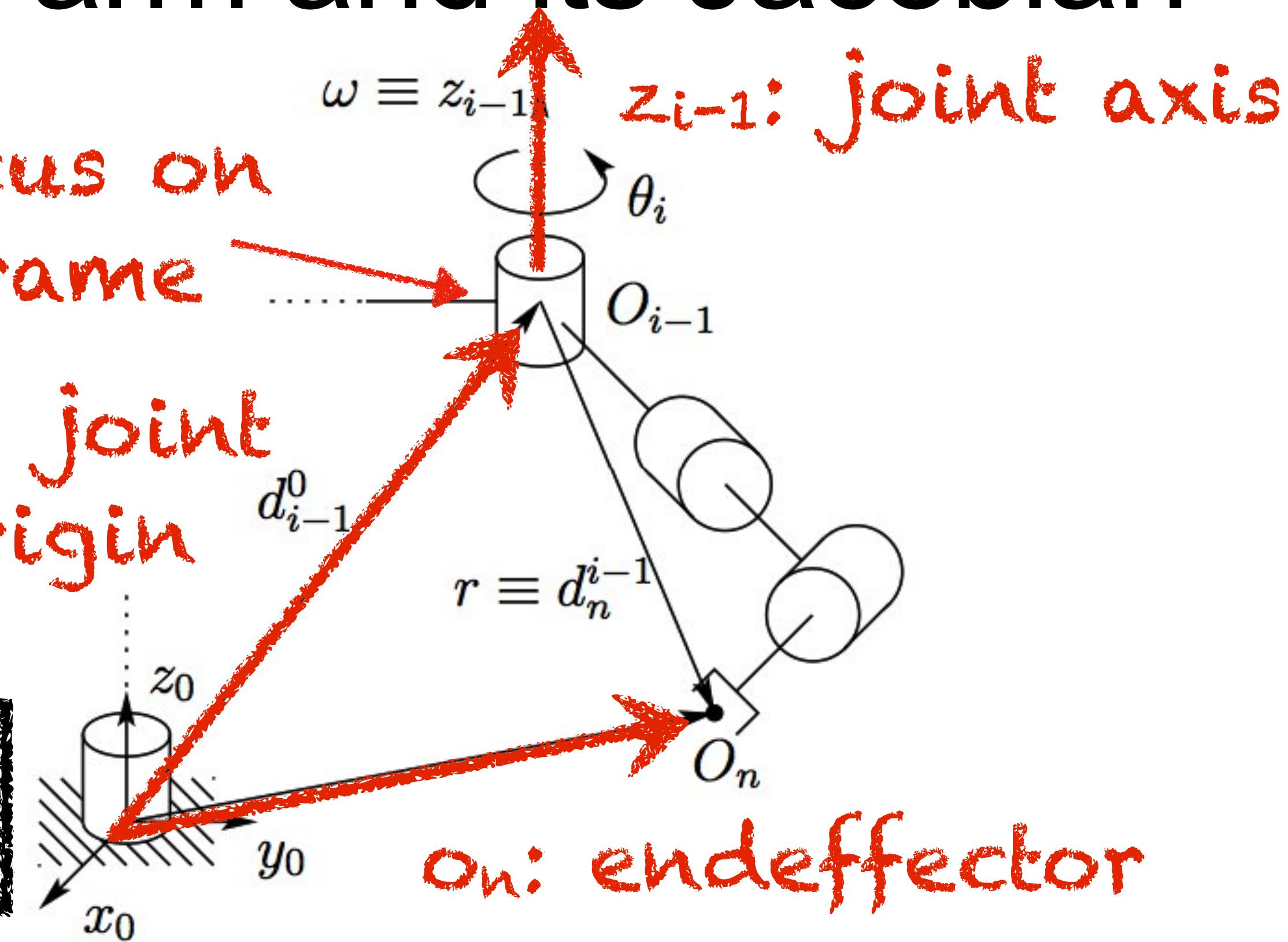
Only influences the translational (linear) component

# Robot arm and its Jacobian

Lets focus on  
 $i-1$ th frame

$O_{i-1}$ : joint  
origin

vectors in  
base frame



If the  $i$ th joint is  
prismatic

$J_i$  for a rotational joint

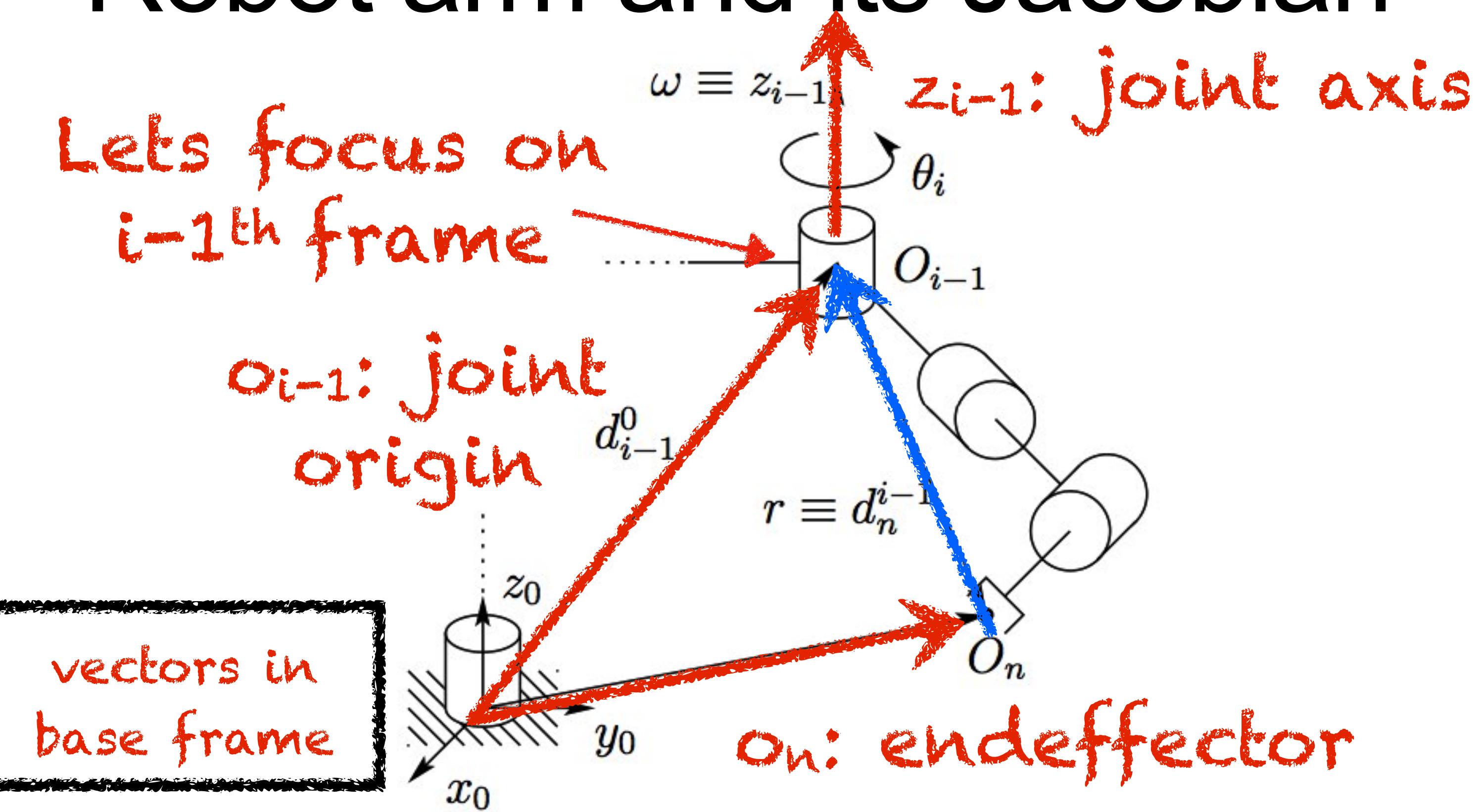
$$J_i = \begin{bmatrix} z_{i-1} \times (O_n - O_{i-1}) \\ z_{i-1} \end{bmatrix}$$

What is  $z_{i-1} \times (O_n - O_{i-1})$   
capturing?

Figure 5.1: Motion of the end-effector due to link  $i$ .

# Robot arm and its Jacobian

Lets focus on  
 $i-1$ th frame



If the  $i$ th joint is  
prismatic

$J_i$  for a rotational joint

$$J_i = \begin{bmatrix} z_{i-1} \times (O_n - O_{i-1}) \\ z_{i-1} \end{bmatrix}$$

What is  $z_{i-1} \times (O_n - O_{i-1})$   
capturing?

Figure 5.1: Motion of the end-effector due to link  $i$ .

# Robot arm and its Jacobian

vectors in base frame

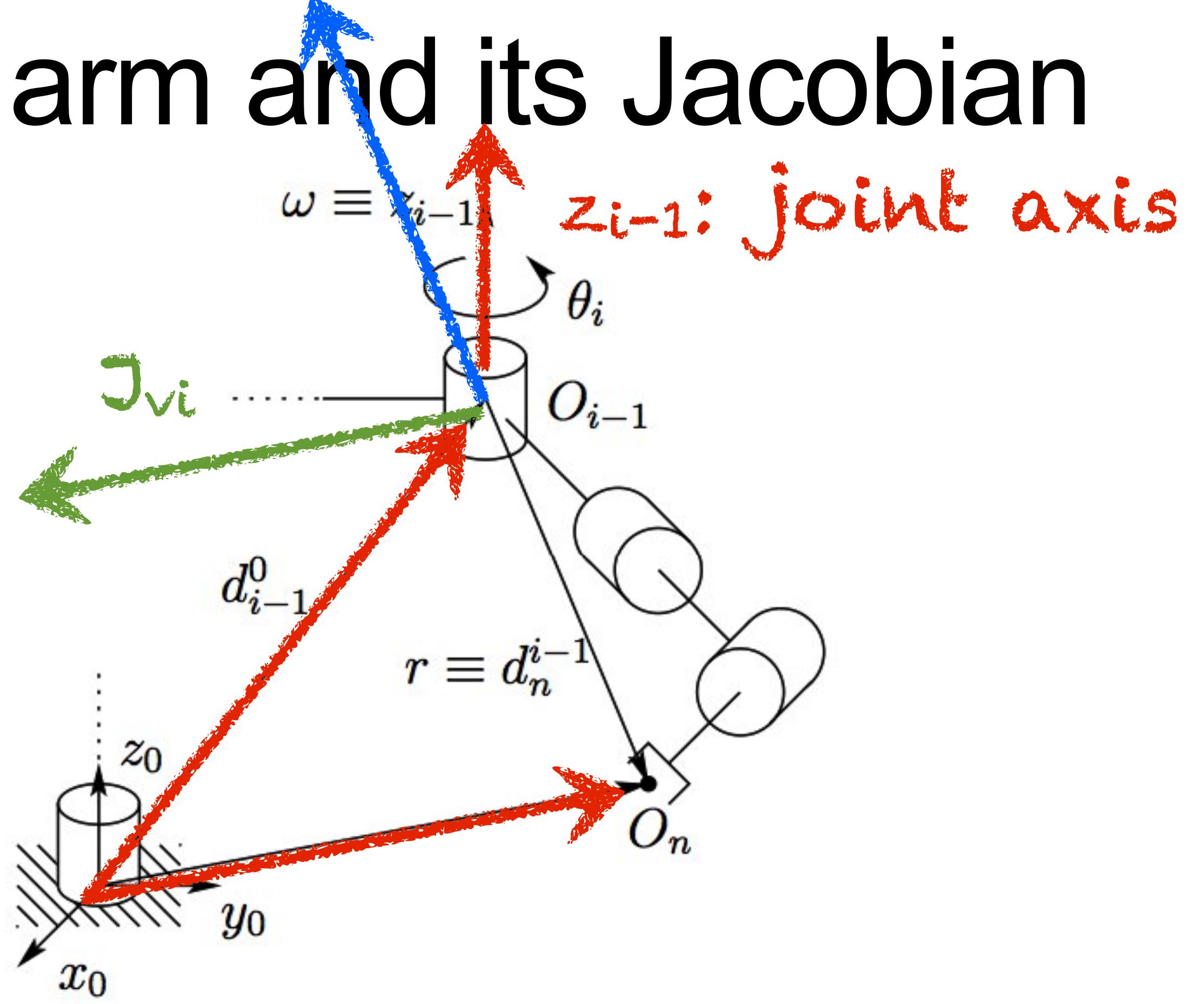


Figure 5.1: Motion of the end-effector due to link  $i$ .

If the  $i$ th joint is prismatic

$J_i$  for a rotational joint

$$J_i = \begin{bmatrix} z_{i-1} \times (O_n - O_{i-1}) \\ z_{i-1} \end{bmatrix}$$

What is  $z_{i-1} \times (O_n - O_{i-1})$  capturing?

The influence of this joint on the end-effector's translational component.

What is  $z_{i-1}$  capturing?

The influence of this joint on the end-effector's rotational component.

# How to use this Jacobian for IK as optimization?

compute  
endpoint  
error

IK Procedure restated:

compute step  
direction

$$\Delta \mathbf{x}_n = \mathbf{x}_d - \mathbf{x}_n$$

perform step  
direction

$$\Delta \mathbf{q}_n = \boxed{J(\mathbf{q}_n)}^{-1} \Delta \mathbf{x}_n$$

$$\mathbf{q}_{n+1} = \mathbf{q}_n + \gamma \Delta \mathbf{q}_n$$

Check point:

How will you get  $\mathbf{x}_{n+1}$  given  $\mathbf{q}_{n+1}$ ?

repeat

# How to use this Jacobian for IK as optimization?

compute  
endpoint  
error

## IK Procedure restated:

compute step  
direction

$$\Delta \mathbf{x}_n = \mathbf{x}_d - \mathbf{x}_n$$

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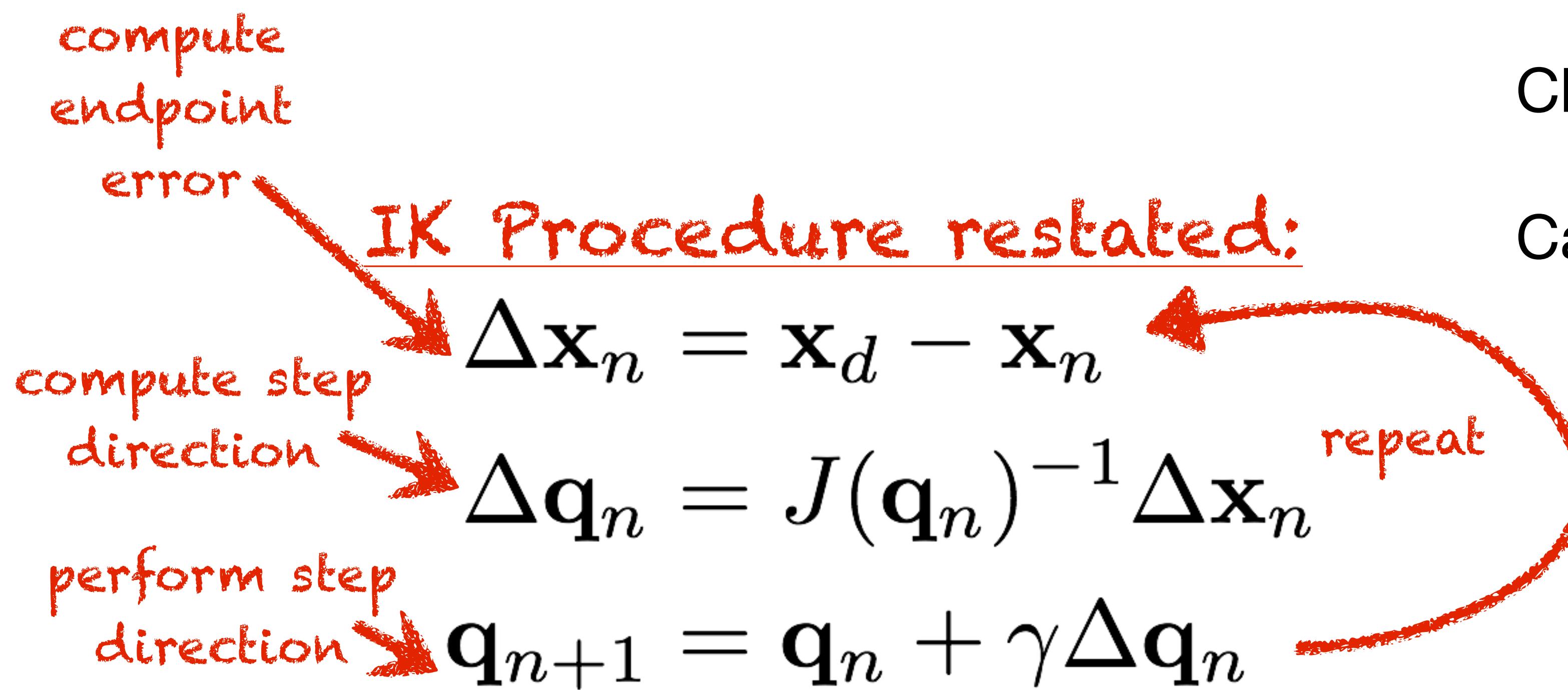
$$\mathbf{q}_{n+1} = \mathbf{q}_n + \gamma \Delta \mathbf{q}_n$$

Check point:

Can we compute the  $J^{-1}$  all the time?

repeat

# How to use this Jacobian for IK as optimization?



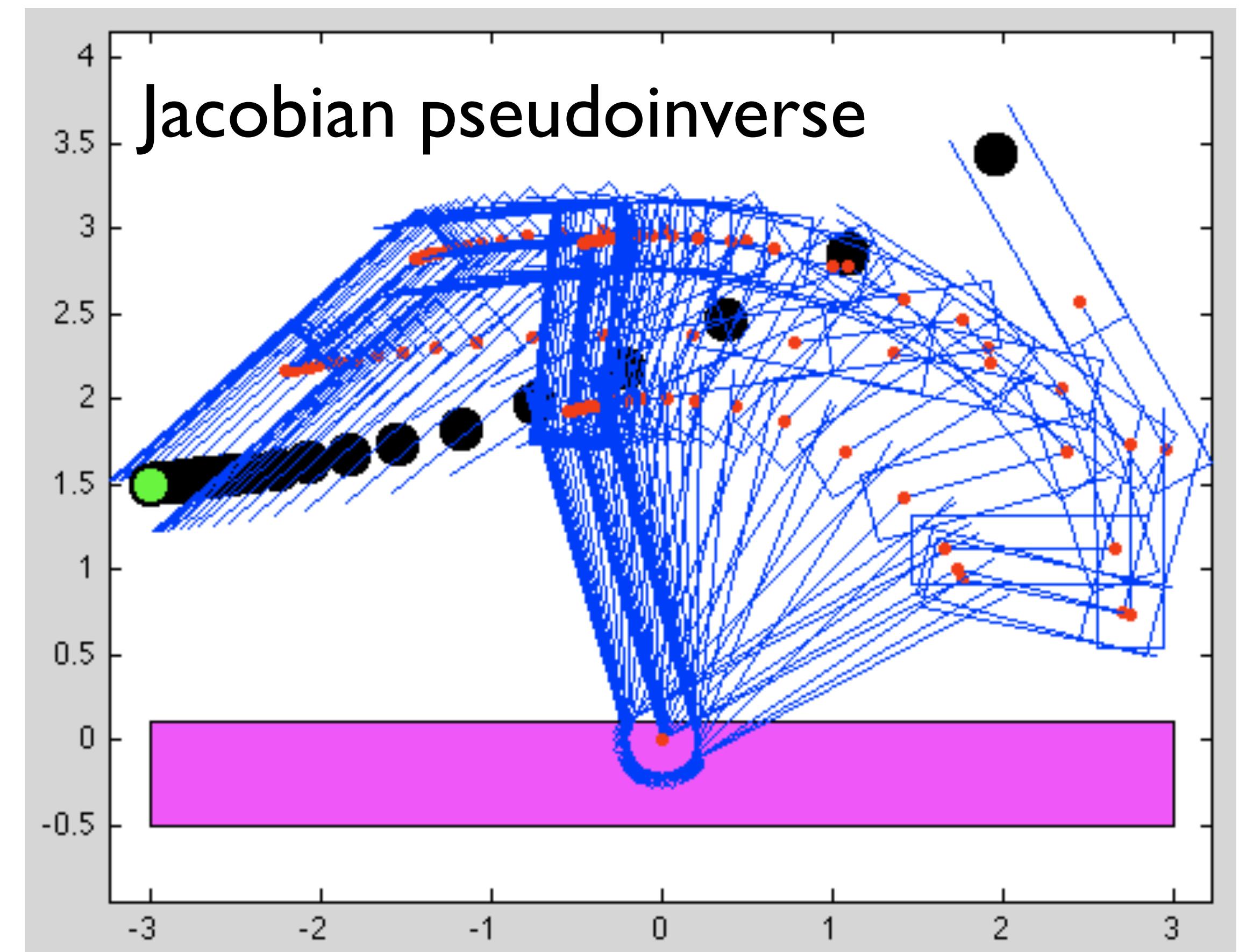
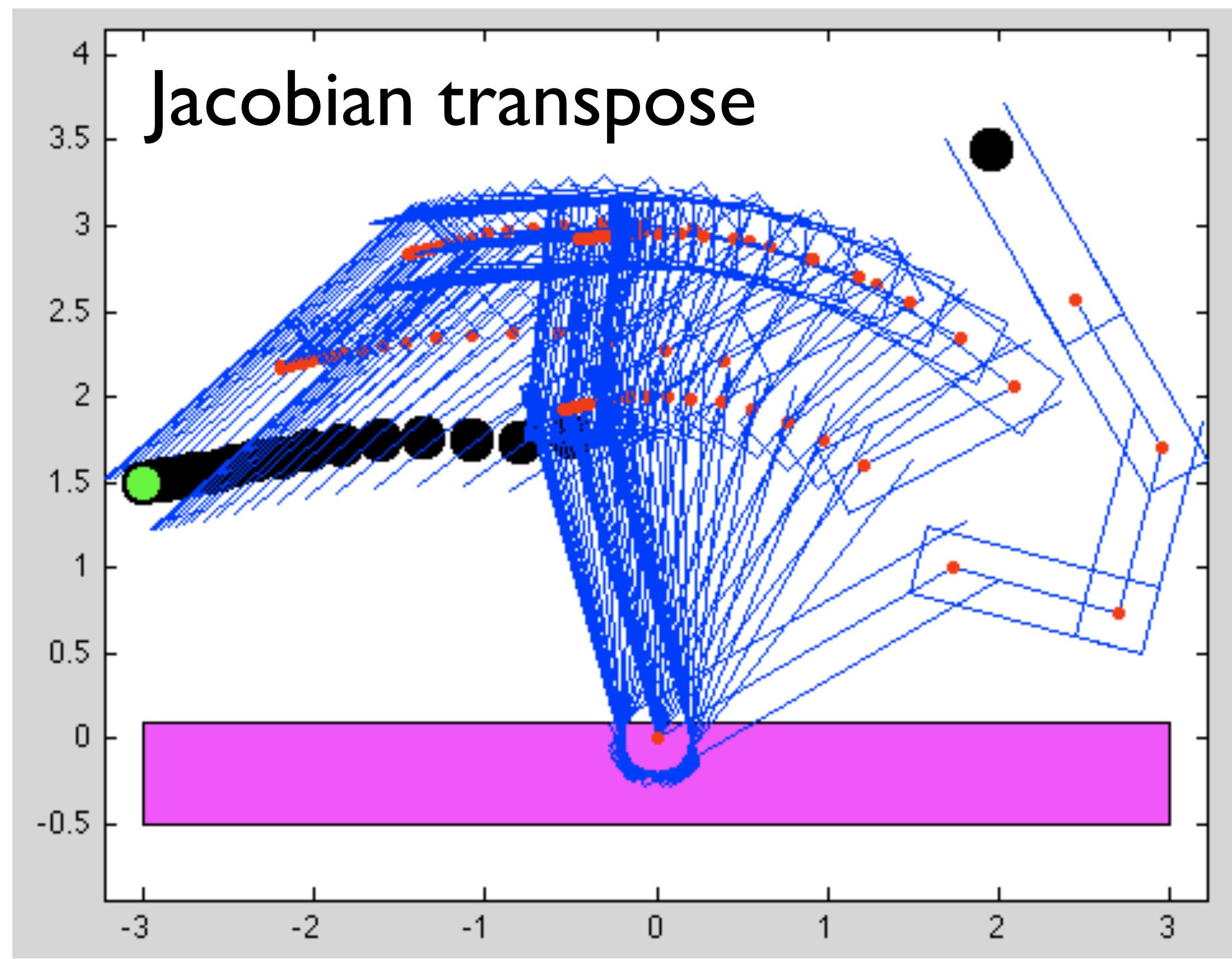
Check point:

Can we compute the  $J^{-1}$  all the time?

No

We can use  
Jacobian pseudoinverse  
or  
Jacobian Transpose

# Matlab 5-link arm example: Jacobian transpose



# Manipulation New Frontiers

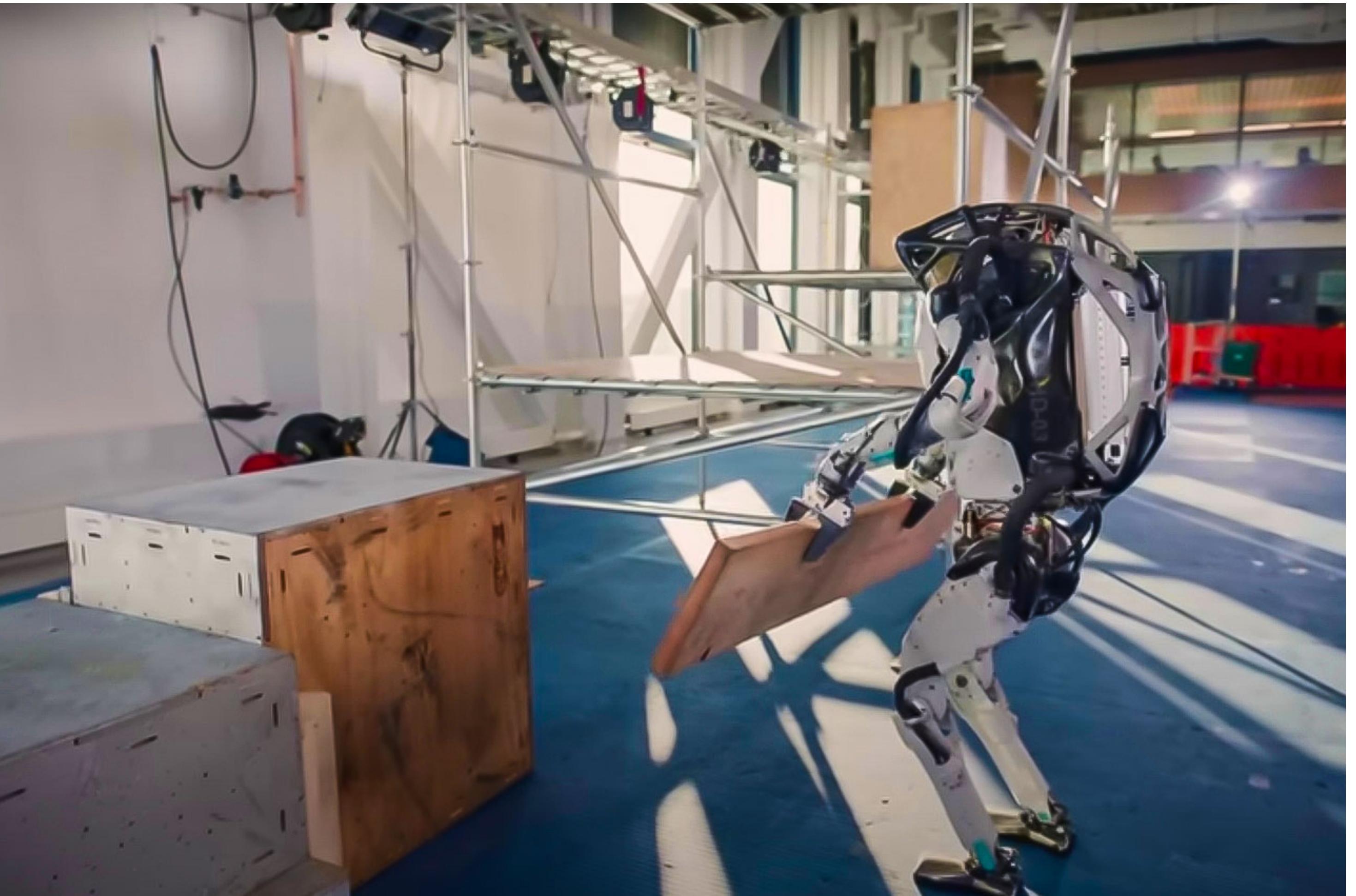


Image Credit - Boston Dynamics



# Definition of Manipulation

Mason, Matthew T. "Toward robotic manipulation."

*Annual Review of Control, Robotics, and Autonomous Systems* 1 (2018): 1-28.



*Annual Review of Control, Robotics, and Autonomous Systems*

## Toward Robotic Manipulation

Matthew T. Mason

Robotics Institute and Computer Science Department, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA; email: matt.mason@cs.cmu.edu

**Carnegie Mellon University**  
Robotics Institute

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**Professor Emeritus**  
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mm3x@andrew.cmu.edu  
**Mailing Address**

Statement	Research	Publications	Students/Affiliates
I am <b>formally retired</b> at CMU, although still supervising students as they finish and graduate. Most of my activity has shifted to my position as Chief Scientist at Berkshire Grey. I work in robotics. The primary venue for my work is the <a href="#">Manipulation Lab (MLab)</a> .			

Annu. Rev. Control Robot. Auton. Syst. 2018.  
1:19.1–19.28

The *Annual Review of Control, Robotics, and Autonomous Systems* is online at  
[control.annualreviews.org](http://control.annualreviews.org)

<https://doi.org/10.1146/annurev-control-060117-104848>

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### Keywords

robot, manipulation, evolution, engineering

### Abstract

This article surveys manipulation, including both biological and robotic manipulation. Biology inspires robotics and demonstrates aspects of manipulation that are far in the future of robotics. Robotics develops concepts and principles that become evident only in the creative process. Robotics also provides a test of our understanding. As Richard Feynman put it: "What I cannot create, I do not understand."

19.2

This lecture uses the structure and material from this review paper!



# Definition of Manipulation

Very few definitions of manipulation appear in the robotics literature. A European research road map defined manipulation as “the function of utilising the characteristics of a grasped object to achieve a task” (1, p. 38). A NASA road-mapping effort yields the following: “Manipulation pertains to making an intentional change in the environment or to objects that are being manipulated” (2, p. 13). My own earlier attempt at defining manipulation was “using one’s hands to rearrange one’s environment” (3, p. 1). Rather than sorting the pros and cons of those definitions, let us apply the shotgun method and identify every approach that we can.

Mason, Matthew T. "Toward robotic manipulation." Annual Review of Control, Robotics, and Autonomous Systems 1 (2018): 1-28.

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# Definition of Manipulation

**Definition 1 (etymological).** Manipulation refers to the activities performed by hands.

**Definition 2 (genus/differentia, ends only).** Manipulation is when an agent moves things other than itself.

**Definition 3 (genus/differentia, ends and means).** Manipulation is when an agent moves things other than itself through selective contact.

**Definition 4 (bottom up).** Manipulation is pick-and-place manipulation plus in-hand manipulation plus mechanical assembly plus . . .

**Definition 5.** Manipulation refers to an agent's control of its environment through selective contact.

Mason, Matthew T. "Toward robotic manipulation." Annual Review of Control, Robotics, and Autonomous Systems 1 (2018): 1-28.

# Animal Manipulation



# Animal Manipulation



Smaller-scale manipulation exhibited by flagella and cilia  
starting billion years ago

<https://makeagif.com/gif/flagella-cilia-VjpqAa>



# Animal Manipulation

“The brain of an ant is one of the most marvellous atoms of matter in the world, perhaps more marvellous than the brain of man.” - Darwin



Intermediate-scale Manipulation Weaver ants ~20 million years ago

[https://www.youtube.com/watch?v=1pkjpC4O\\_TM](https://www.youtube.com/watch?v=1pkjpC4O_TM)

# Animal Manipulation

Intermediate-scale Manipulation Dung Beetle

Mobile Manipulation???



Locomotion is a form of manipulation??  
Duality Principle

<https://youtu.be/xNjynt6oCcQ>

<https://cdn2.vectorstock.com/i/1000x1000/53/51/big-dung-beetle-that-pushes-dirty-ball-vector-19965351.jpg>

[https://t3.ftcdn.net/jpg/01/62/59/04/360\\_F\\_162590489\\_5lcesYmlOK0RC4T4r5lydft8aQmpCwI7.jpg](https://t3.ftcdn.net/jpg/01/62/59/04/360_F_162590489_5lcesYmlOK0RC4T4r5lydft8aQmpCwI7.jpg)

# Animal Manipulation

Large-scale Manipulation using Tool - Chimpanzee



<https://www.youtube.com/watch?v=inFkERO30oM>

# Animal Manipulation



<https://www.youtube.com/watch?v=YePKbjODrto>



# Animal Manipulation



<https://www.youtube.com/watch?v=BXi3xJriGZY>

# Animal Manipulation



<https://gifdb.com/images/high/insect-fly-rubbing-hands-tnpegh6d412vjafu.gif>

# Human Manipulation



[https://media.cnn.com/api/v1/images/stellar/prod/210807101343-restricted-01-neeraj-chopra-olympics-08-07-2021.jpg?q=w\\_2953,h\\_1984,x\\_0,y\\_0,c\\_fill](https://media.cnn.com/api/v1/images/stellar/prod/210807101343-restricted-01-neeraj-chopra-olympics-08-07-2021.jpg?q=w_2953,h_1984,x_0,y_0,c_fill)

<https://www.espncricinfo.com/photo/shoaib-akhtar-in-action-against-bangladesh-309353?objectId=306979>

[https://media.gq.com/photos/5e30a0329d87db000817865a/master/w\\_1600%2Cc\\_limit/03-how-kobe-bryant-changed-sneaker-history-gq-kanuary-2020.jpg](https://media.gq.com/photos/5e30a0329d87db000817865a/master/w_1600%2Cc_limit/03-how-kobe-bryant-changed-sneaker-history-gq-kanuary-2020.jpg)

# Human Manipulation

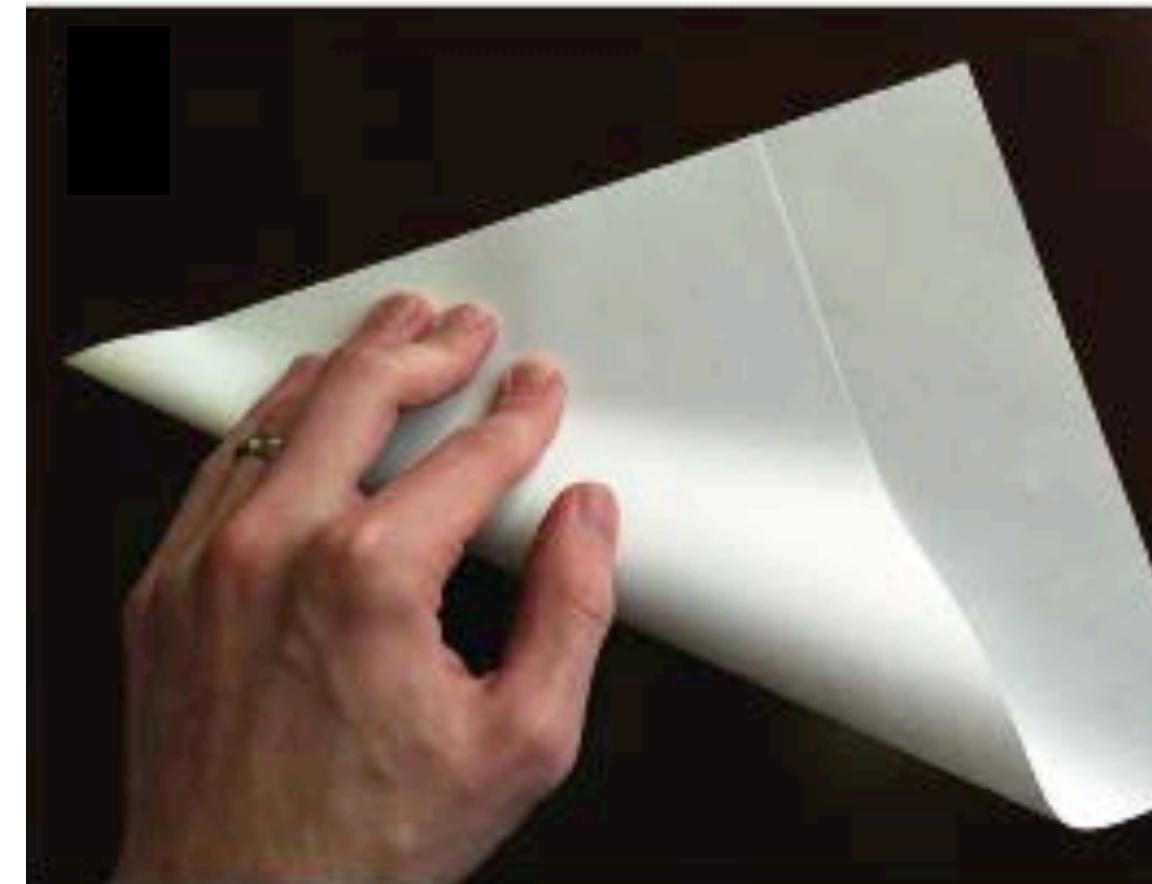


[https://live.staticflickr.com/6086/6098540957\\_6bfd63d5d1\\_b.jpg](https://live.staticflickr.com/6086/6098540957_6bfd63d5d1_b.jpg)



<https://qph.cf2.quoracdn.net/main-qimg-3252de8ffb3474dd57f5a534d343a7c3-lq>

# Human Manipulation



**Figure 2**

Examples of human manipulation. (a) Throwing a baseball. (b) Knapping a stone tool. (c) Folding origami. (d) Cutting a potato. (e) Bimanual manipulation of a potato while the knife is parked in an ulnar grasp. (f) Pushing potato slices with a knife and spread fingers. Panel *a* from video (<https://youtu.be/jZKvJY6gDfg>) by Power Drive Performance (<http://www.pitcherspowerdrive.com>), reproduced with permission. Panel *b* by Helen Beare (<https://australianmuseum.net.au/image/stone-tools-initial-reduction-flaking>), reproduced with permission from the Australian Museum. Panel *c* from video by YouTube user kiwiwhispers ASMR (<https://youtu.be/SNfLEnnP6Nc>), reproduced with permission. Panels *d-f* adapted from frames of *The French Chef* (28).

Figure from - Mason, Matthew T. "Toward robotic manipulation." Annual Review of Control, Robotics, and Autonomous Systems 1 (2018): 1-28.

# Elements of Robotic Manipulation

- Programmed Motion
- Compliant Motion
- Structured pick-and-place manipulation
- Unstructured pick-and-place manipulation
  - Path planning
  - General-purpose grippers
  - Grasp and placement pose planning
- Assembly and task mechanics
- In-hand Manipulation
- Nonprehensile Manipulation
- Whole-X Manipulation

# Programmed Motion

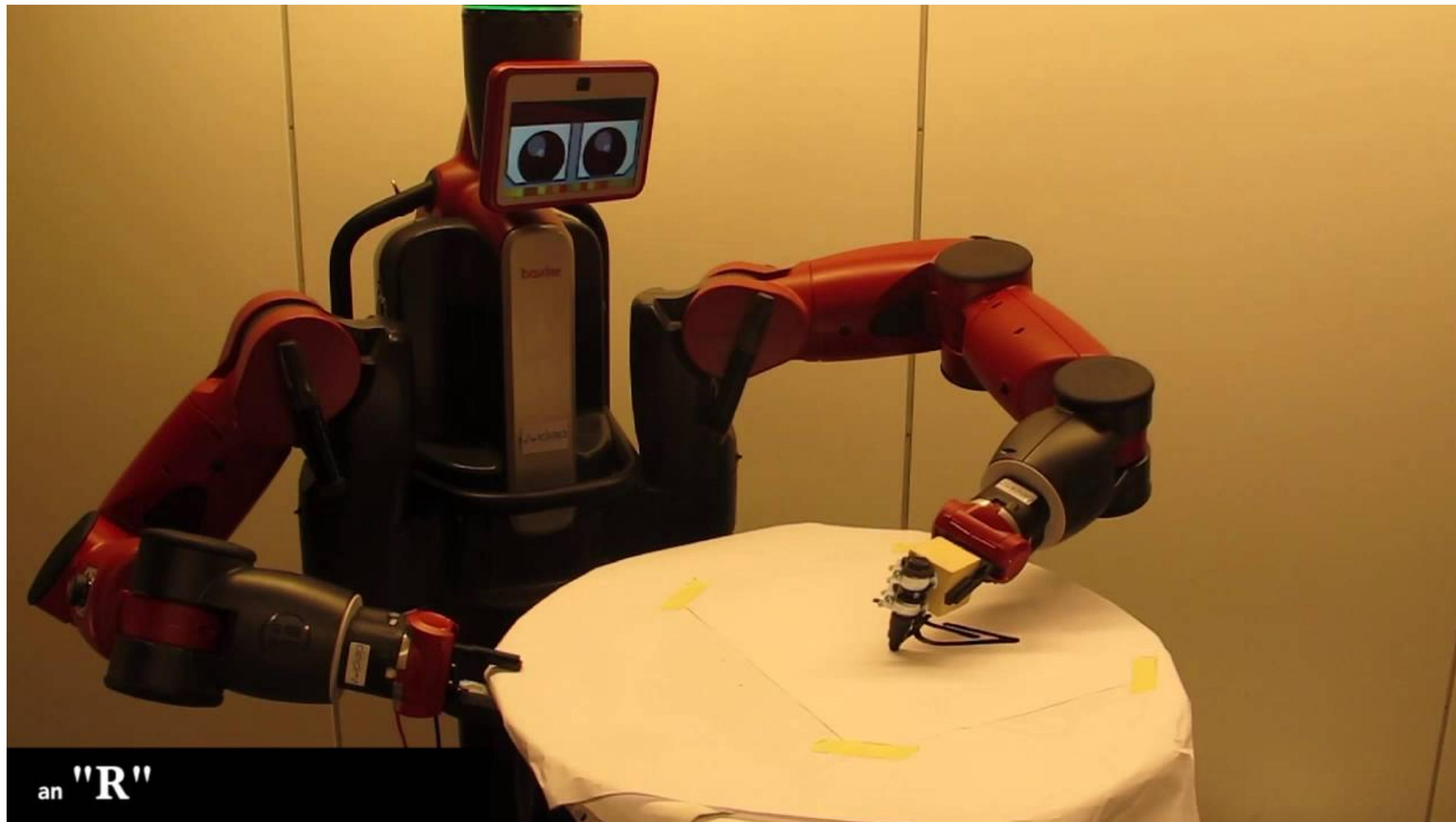
- Rests on the developments in motors, transmissions, encoders, kinematics, mechanism design, dynamic modeling and control



<https://www.therobotreport.com/wp-content/uploads/2023/03/kuka-robots-cars.jpg>

# Compliant Motion

- Context of teleoperation
- Hybrid-position/force control
- Impedance control



<https://www.youtube.com/watch?app=desktop&v=KU--TOMDDFU>

# Structured pick-and-place manipulation

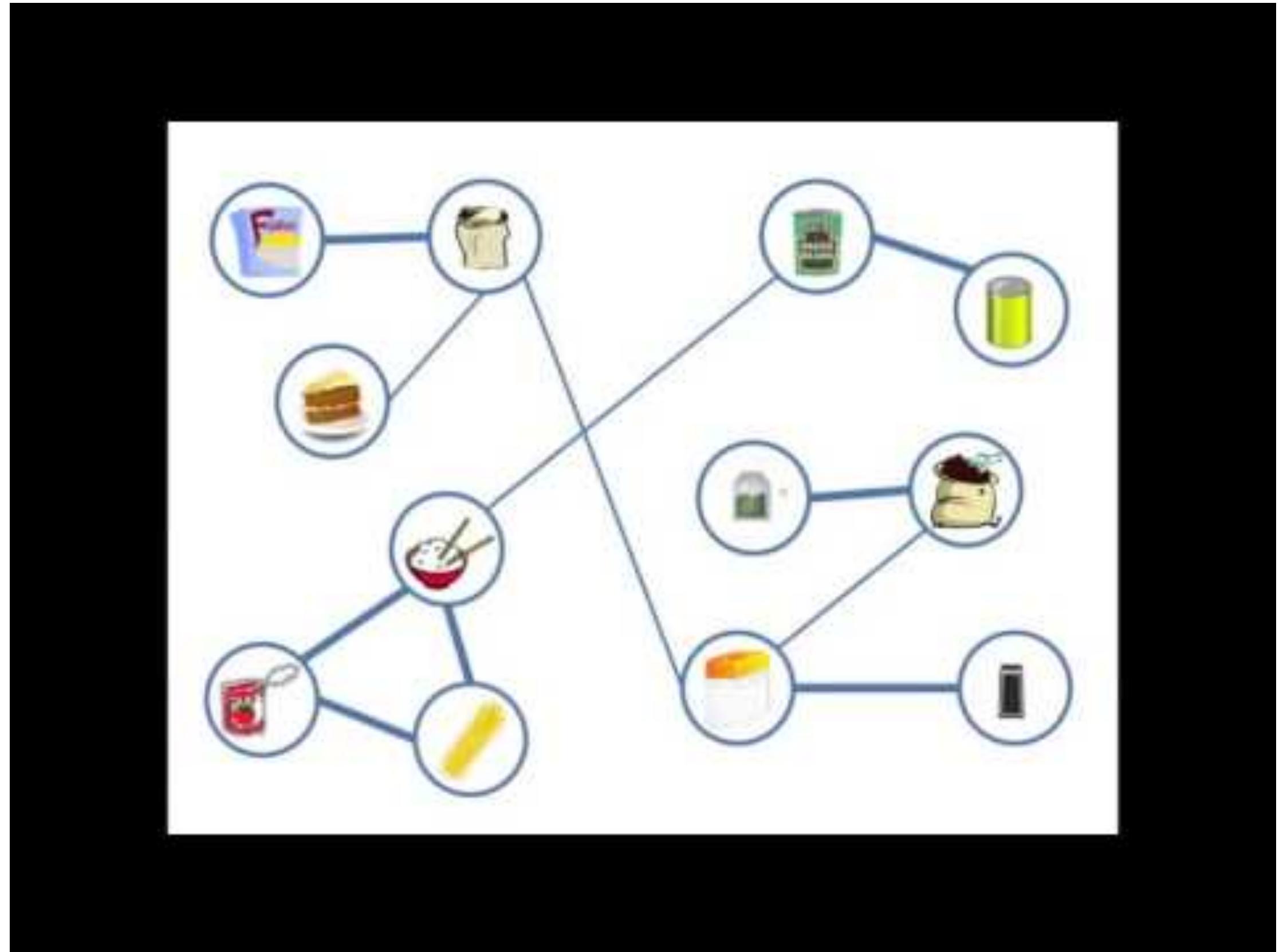
- Moving a sequence of objects one at a time from one place to another.
- Structured environment and scenario
  - Objects are identical
  - Motion is repetitive
  - Gripper design and motion programming is done offline.



<https://youtu.be/wg8YYuLLoM0?feature=shared&t=80>

# Unstructured pick-and-place manipulation

- Planning software to produce arm motions
- Grippers that can handle a broad range of objects
- Grasp pose planning
- Stable placement pose planning

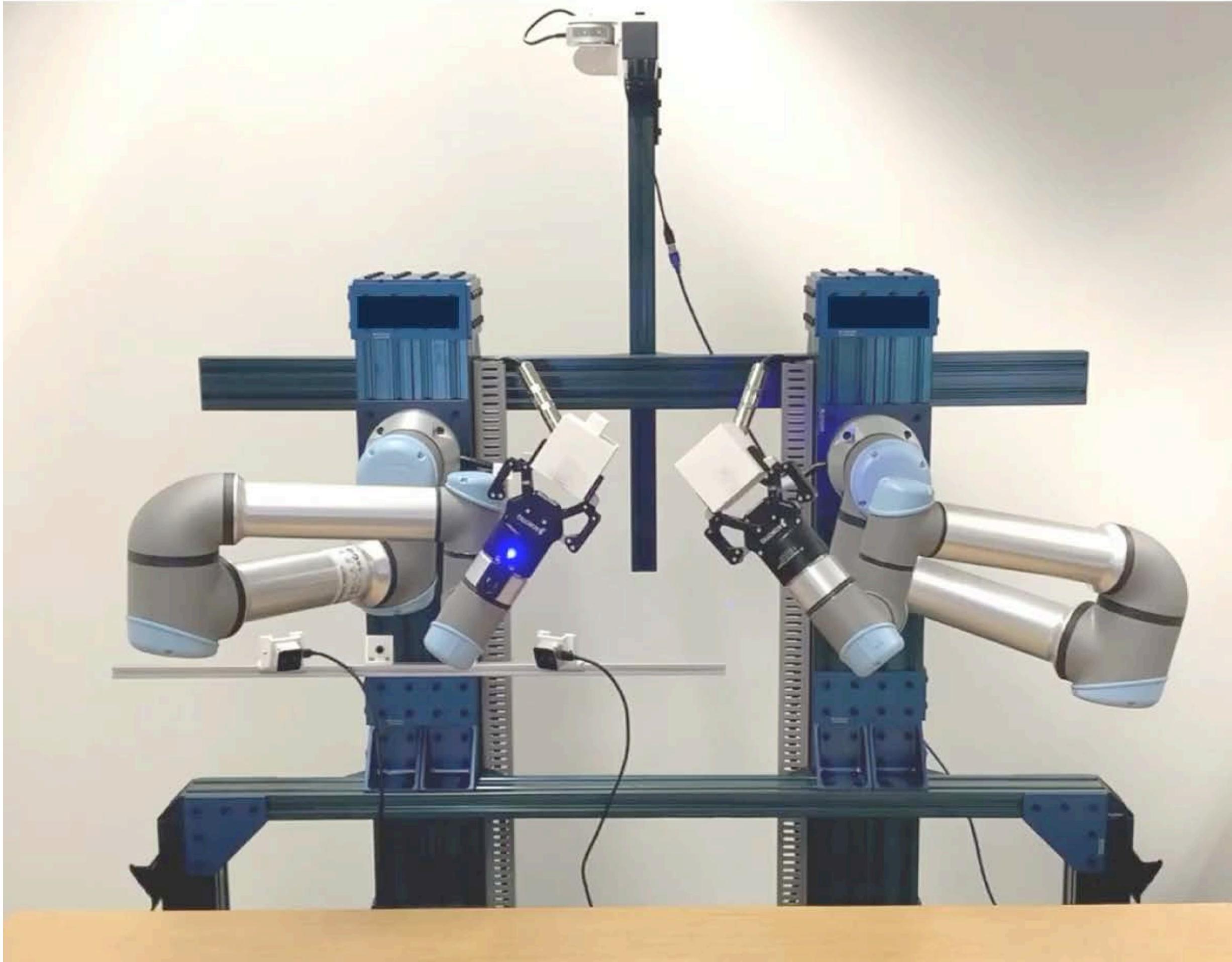


Abdo, Nichola, Cyrill Stachniss, Luciano Spinello, and Wolfram Burgard. "Organizing objects by predicting user preferences through collaborative filtering." *The International Journal of Robotics Research* 35, no. 13 (2016): 1587-1608.

[https://www.youtube.com/watch?app=desktop&v=\\_icB8QcycMM](https://www.youtube.com/watch?app=desktop&v=_icB8QcycMM)

# Robotic Assembly Task

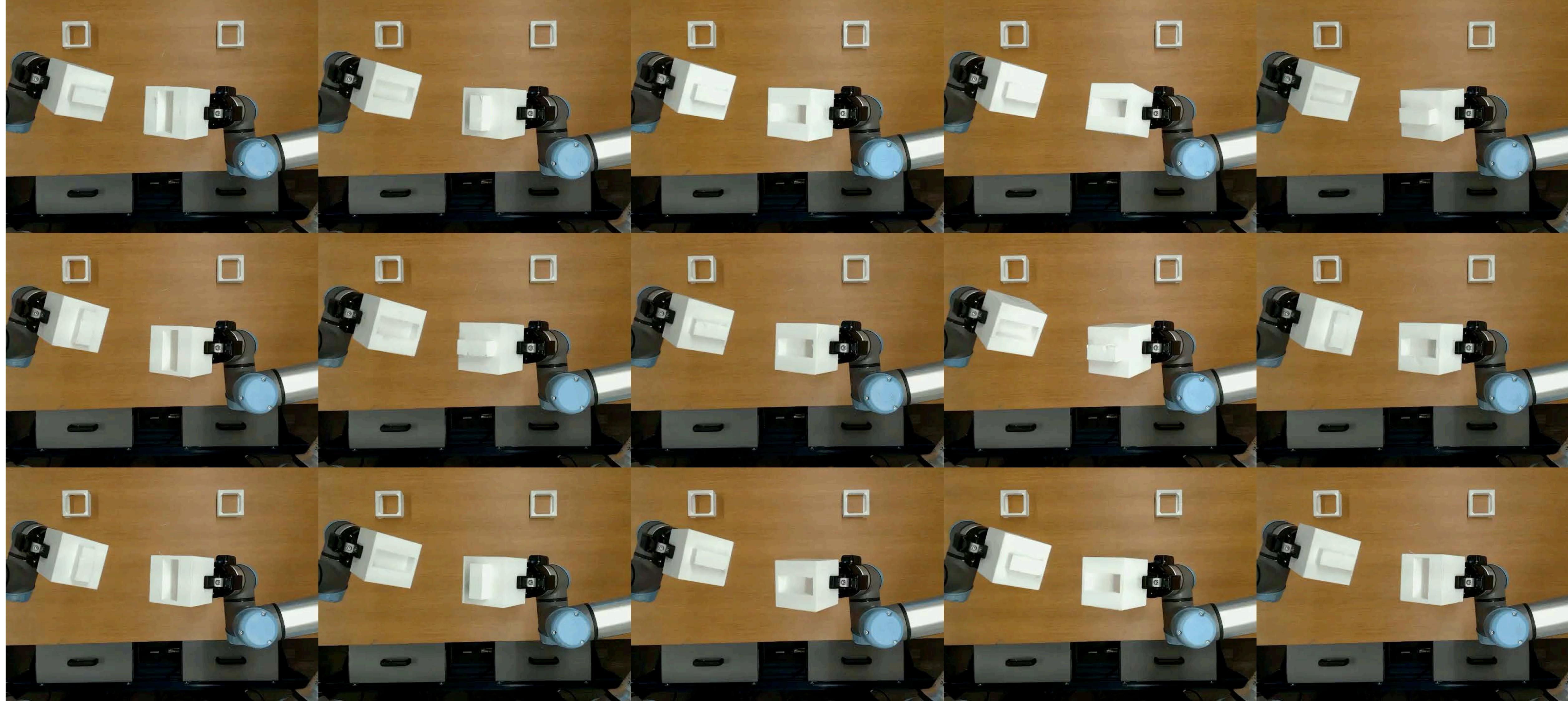
## Task: Geometry Informed Object Assembly



Chahyon Ku, Carl Winge, Ryan Diaz, Wentao Yuan, Karthik Desingh

“Evaluating Robustness of Visual Representations for Object Assembly Task Requiring Spatio-Geometrical Reasoning,” ICRA 2024.

# Robotic Assembly Task



Chahyon Ku, Carl Winge, Ryan Diaz, Wentao Yuan, Karthik Desingh

“Evaluating Robustness of Visual Representations for Object Assembly Task Requiring Spatio-Geometrical Reasoning,” ICRA 2024.



# In-hand Manipulation



Chen, Tao, Jie Xu, and Pulkit Agrawal. "A system for general in-hand object re-orientation." In *Conference on Robot Learning*, pp. 297-307. PMLR, 2022.

# Whole-body manipulation



Kindle, Julien, Fadri Furrer, Tonci Novkovic, Jen Jen Chung, Roland Siegwart, and Juan Nieto. "Whole-body control of a mobile manipulator using end-to-end reinforcement learning." *arXiv preprint arXiv:2003.02637* (2020).  
<https://www.youtube.com/watch?v=3qobNCMUMV4>

# Grasping for Mobile Manipulation



Xun Tu, Karthik Desingh, "SuperQ-GRASP: Superquadrics-based Grasp Pose Estimation on Larger Objects for Mobile-Manipulation," Accepted ICRA 2025  
**Video:** [https://youtu.be/CL\\_qik\\_k8c?feature=shared](https://youtu.be/CL_qik_k8c?feature=shared) and **Project page:** <https://rpm-lab-umn.github.io/superq-grasp-webpage/>

# Taxonomy of Grasps

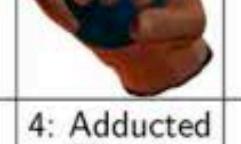
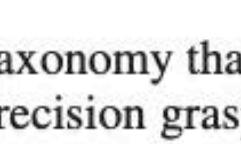
Opp: VF:	Power						Intermediate				Precision				
	Palm		Pad				Side			Pad		Side			
	3-5	2-5	2	2-3	2-4	2-5	2	3	3-4	2	2-3	2-4	2-5	3	
Thumb Abducted	1: Large Diameter 	2: Small Diameter 	3: Medium Wrap 	31: Ring 	28: Sphere 3 Finger 	18: Extension Type 	19: Distal Type 	23: Adduction Grip 	21: Tripod Variation 	9: Palmar Pinch 	8: Prismatic 2 Finger 	7: Prismatic 3 Finger 	6: Prismatic 4 Finger 	20: Writing Tripod 	
Thumb Adducted	10: Power Disk 	11: Power Sphere 	17: Index Finger Extension 	4: Adducted Thumb 	5: Light Tool 	15: Fixed Hook 	30: Palmar 	16: Lateral 	25: Lateral Tripod 	29: Stick 	32: Ventral 	22: Parallel Extension 			

Fig. 4. GRASP taxonomy that incorporates all previous grasp classifications. The grasps are classified in the columns according to their assignment into power, intermediate and precision grasp, the opposition type, and the VF assignment. The assignment of the rows is done by the position of the thumb that can be in an abducted or adducted position.

Feix, Thomas, Javier Romero, Heinz-Bodo Schmiedmayer, Aaron M. Dollar, and Danica Kragic. "The grasp taxonomy of human grasp types." *IEEE Transactions on human-machine systems* 46, no. 1 (2015): 66-77.



# Why is robot manipulation challenging?

- Mechanism
- Perception
- Modeling and Control
- Planning
- Uncertainty

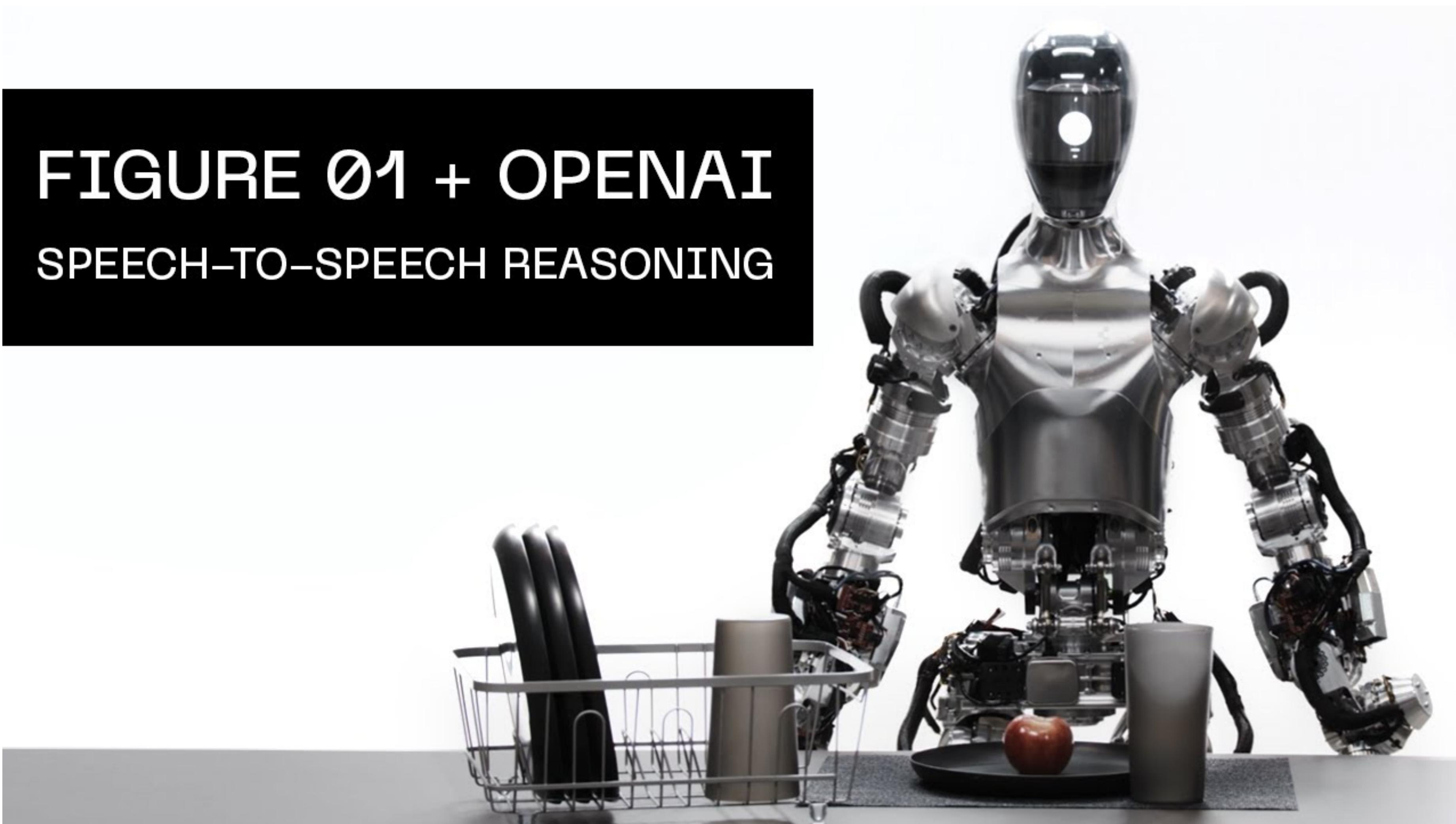
# Future research challenges

1. Is there a fundamental and precise metric for comparing manipulative behaviors, or for comparing tasks, that would provide a basis for measuring progress in the field?
2. How can we best take advantage of advances in machine learning to advance our understanding and improve our technology?
3. How do we develop the adaptability, robustness, and breadth of behaviors exhibited by animals and humans?

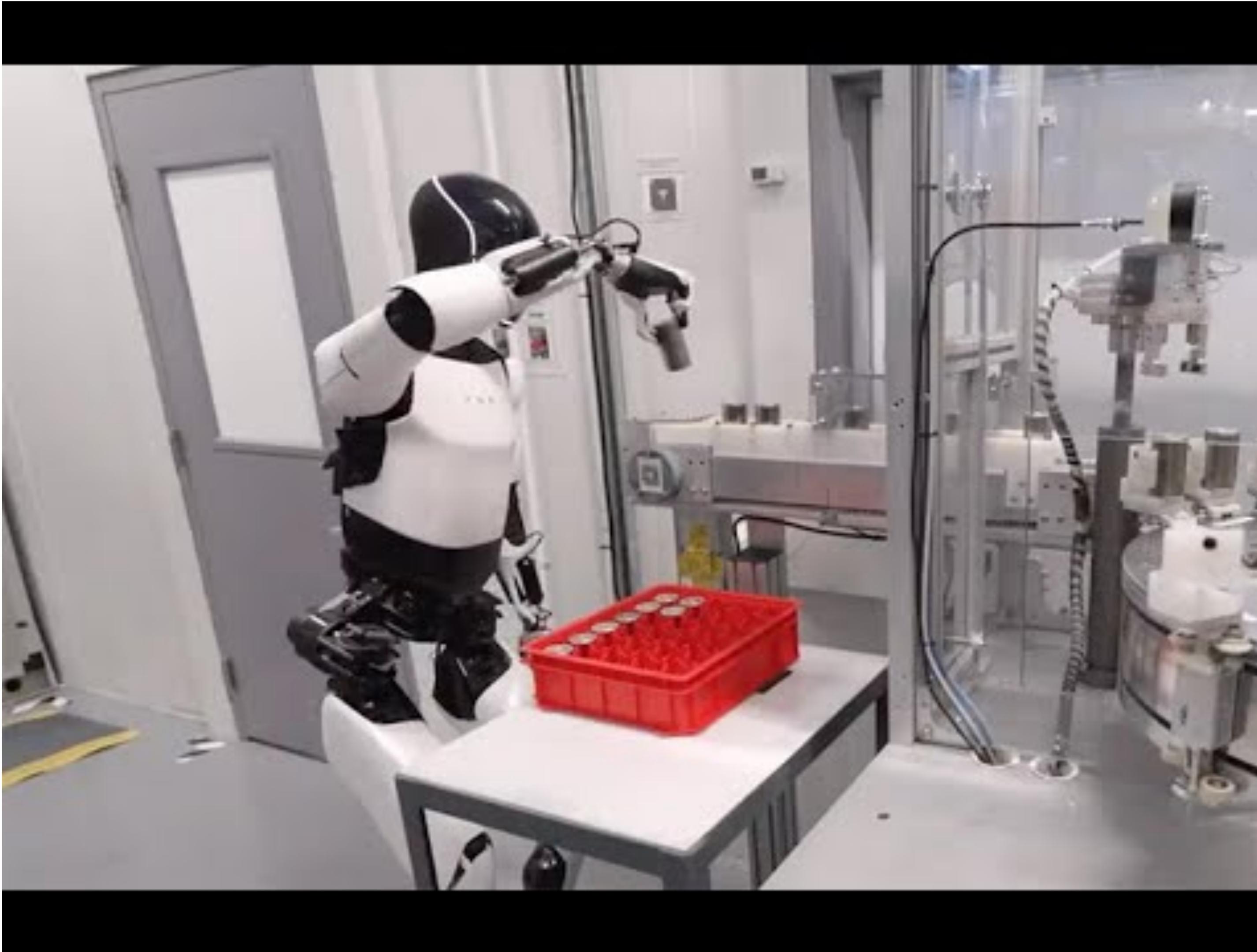
Mason, Matthew T. "Toward robotic manipulation." Annual Review of Control, Robotics, and Autonomous Systems 1 (2018): 1-28.

# Last couple of years!

**FIGURE 01 + OPENAI  
SPEECH-TO-SPEECH REASONING**



# Last couple of years!



Tesla Optimus

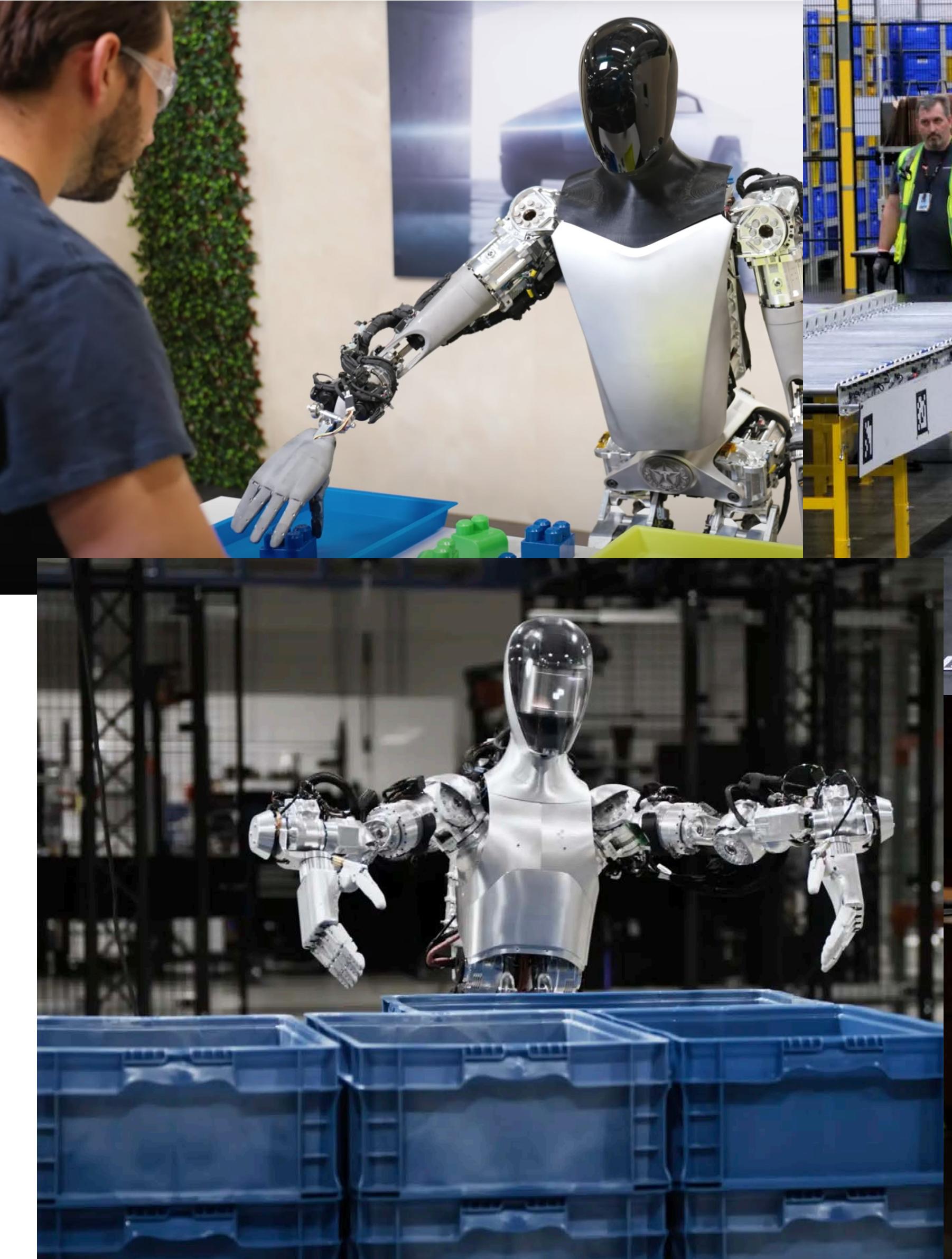
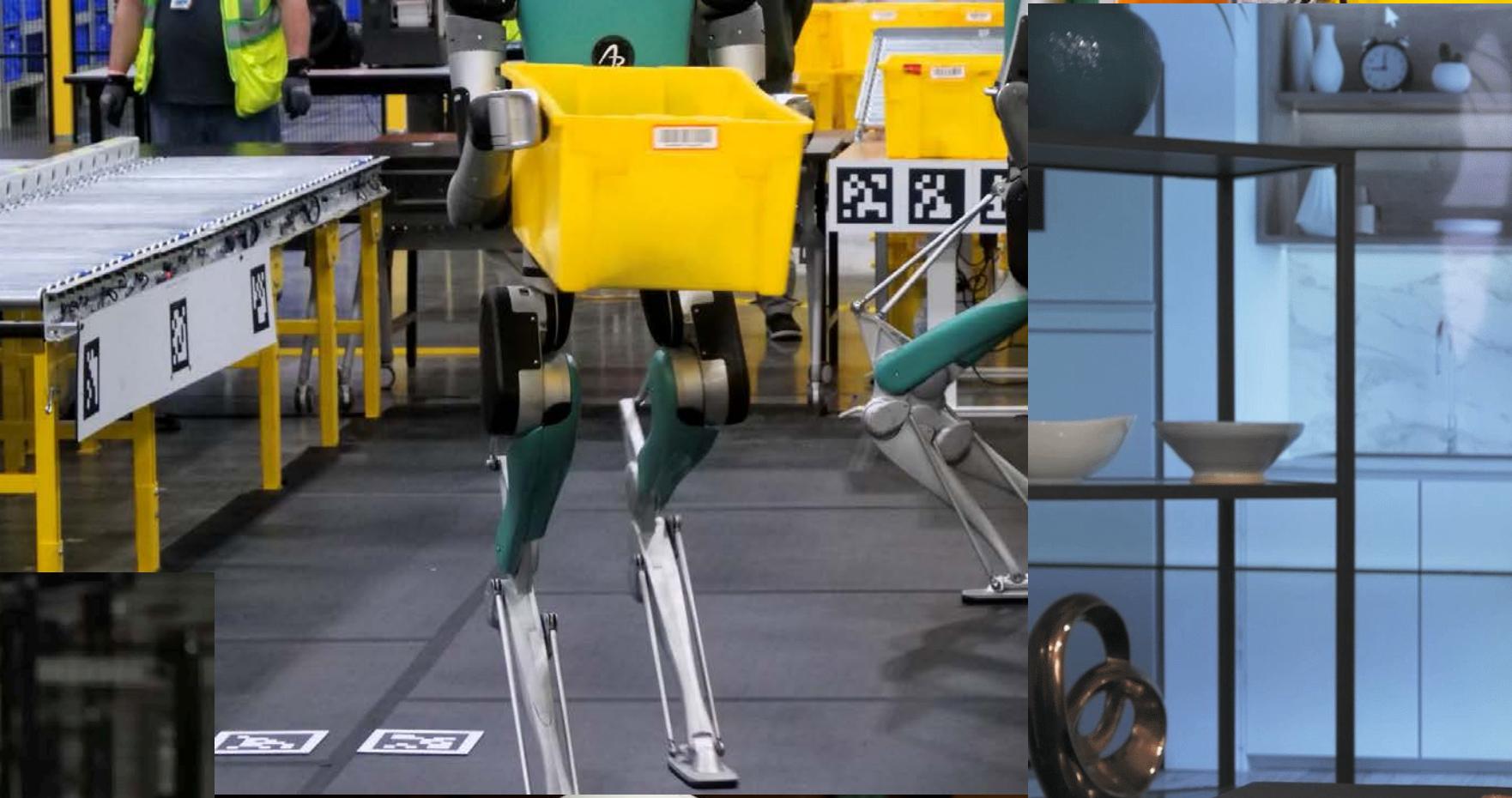


Figure 01

Agility Robotics



Aptronik



Sanctuary AI



# Next lecture: Planning