Lecture 09
IK cont … &
Manipulation New Frontiers

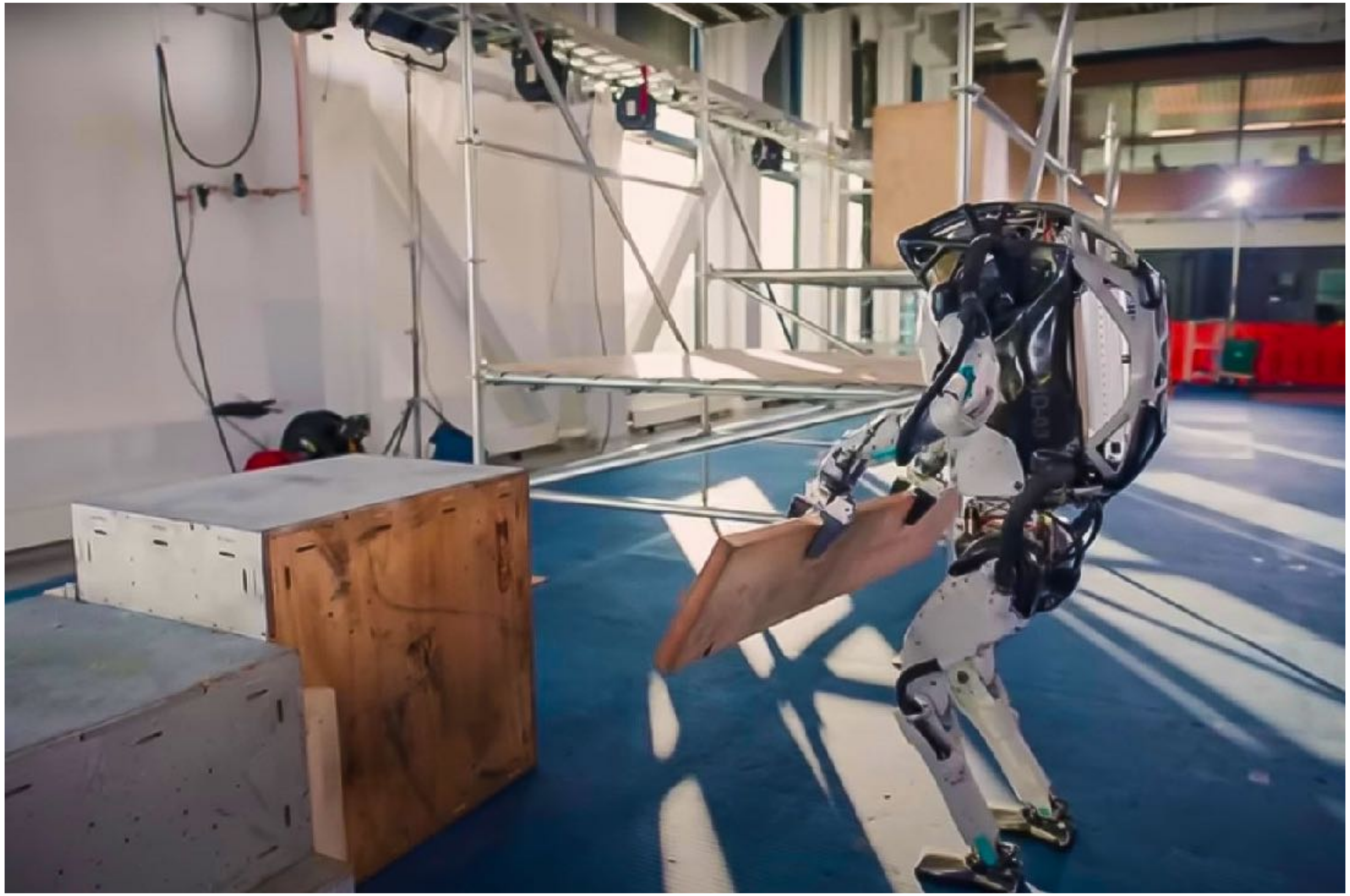


Image Credit - Boston Dynamics

Course Logistics

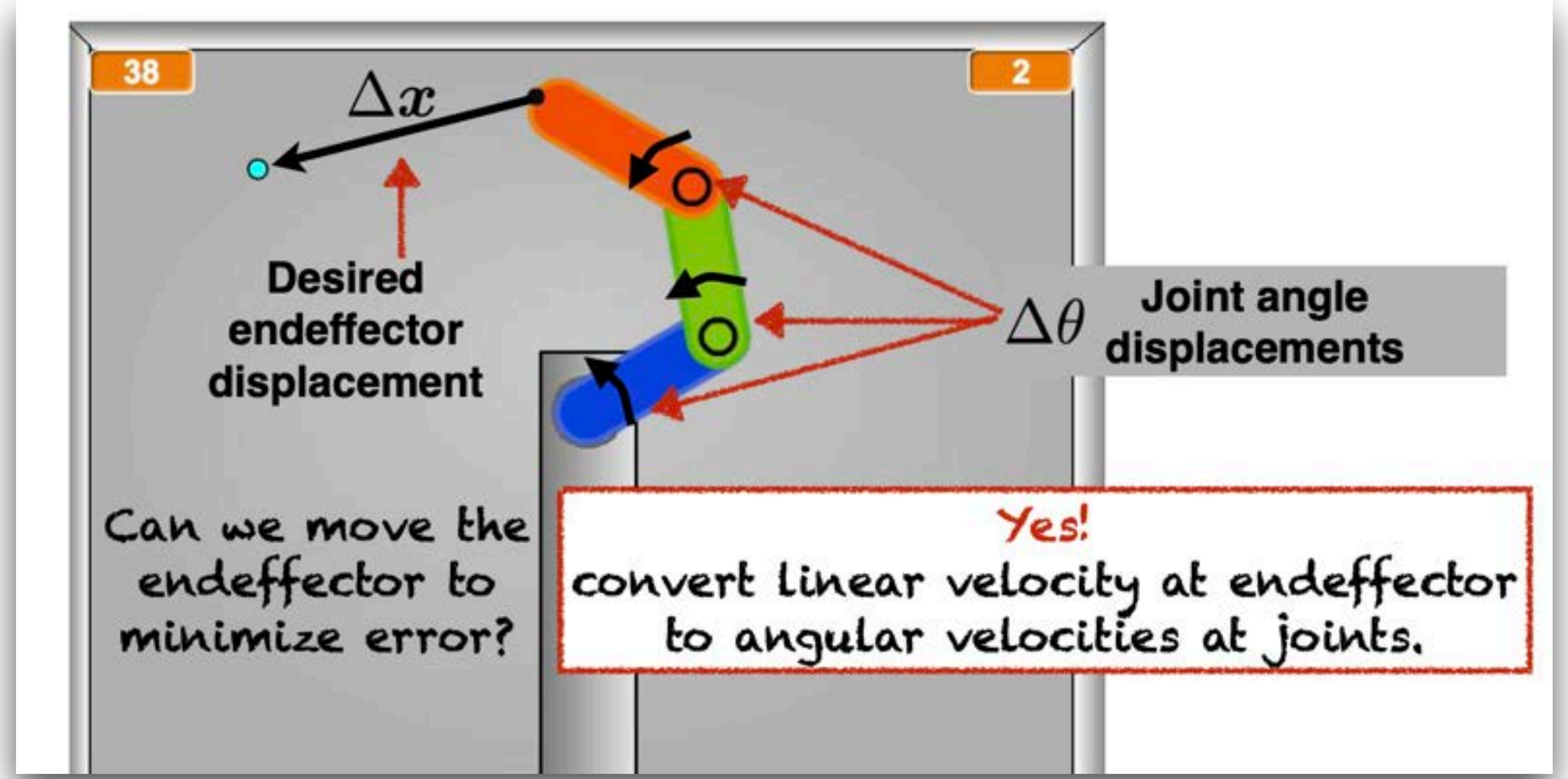
- **Quiz 4 was posted yesterday and was due at noon today.**
- Project 3 was posted on 02/07 and will be due 02/15 (tomorrow).
- Project 4 will be posted 02/14 (today) and will be due on 02/28.

Previously

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

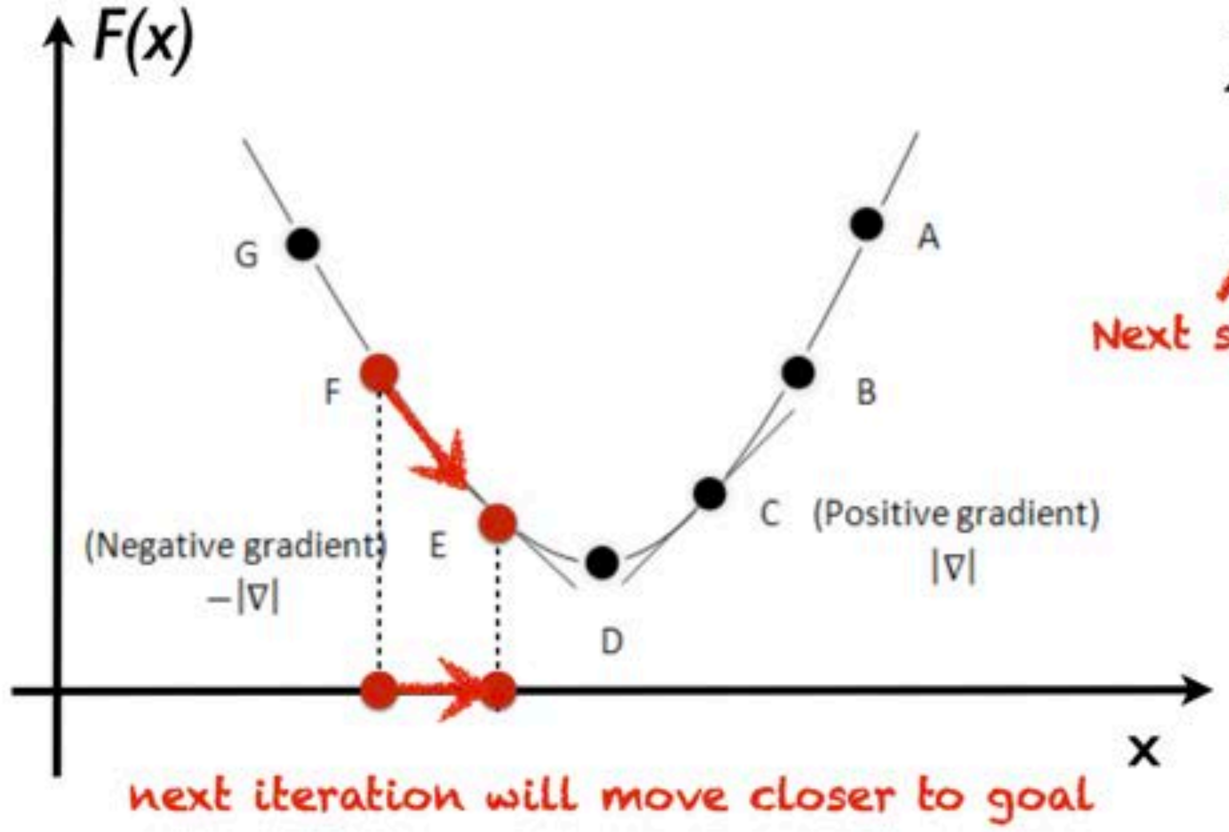
Inverse Kinematics: 2 possibilites

- **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



$$x_{i+1} = x_i - \gamma_i \nabla F(x_i)$$

Current solution

"Learning rate"

Next solution

Derivative assumed to be direction of steepest ascent away from goal

IK Procedure restated:

compute endpoint error
$$\Delta \mathbf{x}_n = \mathbf{x}_d - \mathbf{x}_n$$

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

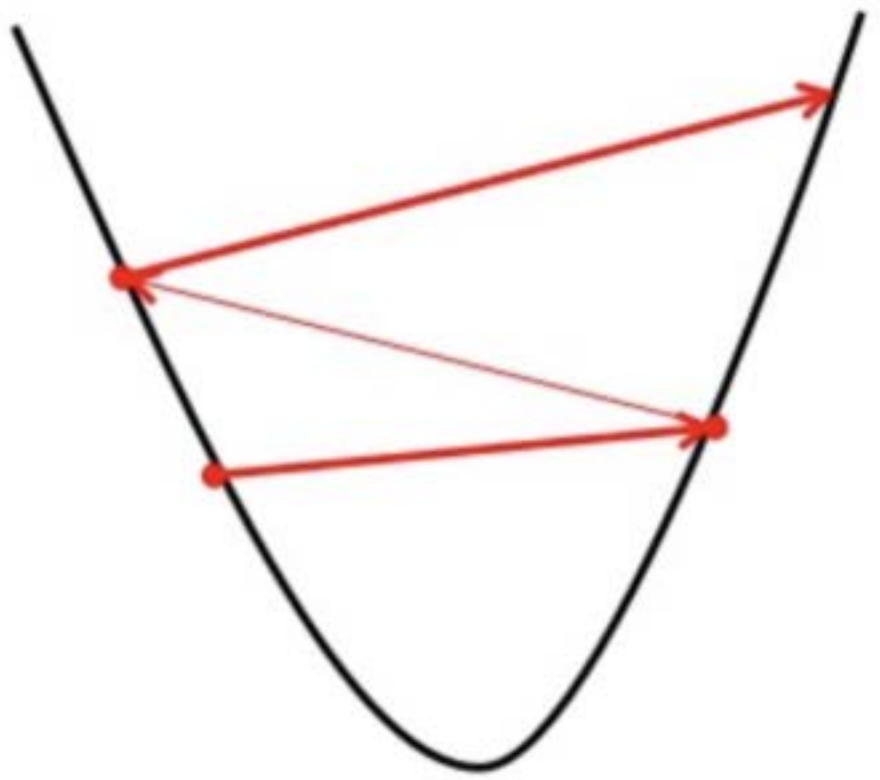
perform step direction
$$\mathbf{q}_{n+1} = \mathbf{q}_n + \gamma \Delta \mathbf{q}_n$$

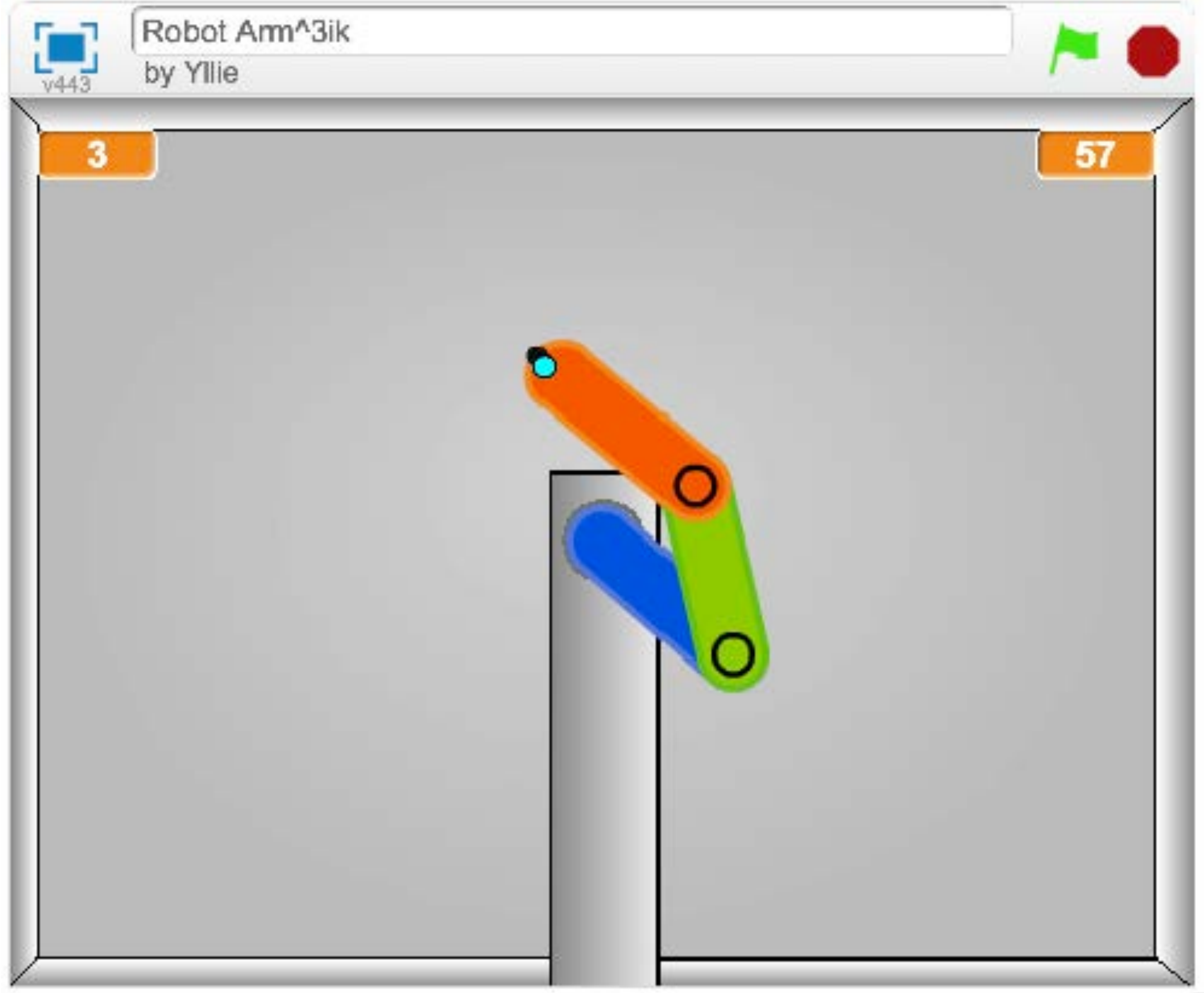
repeat

IK by optimization

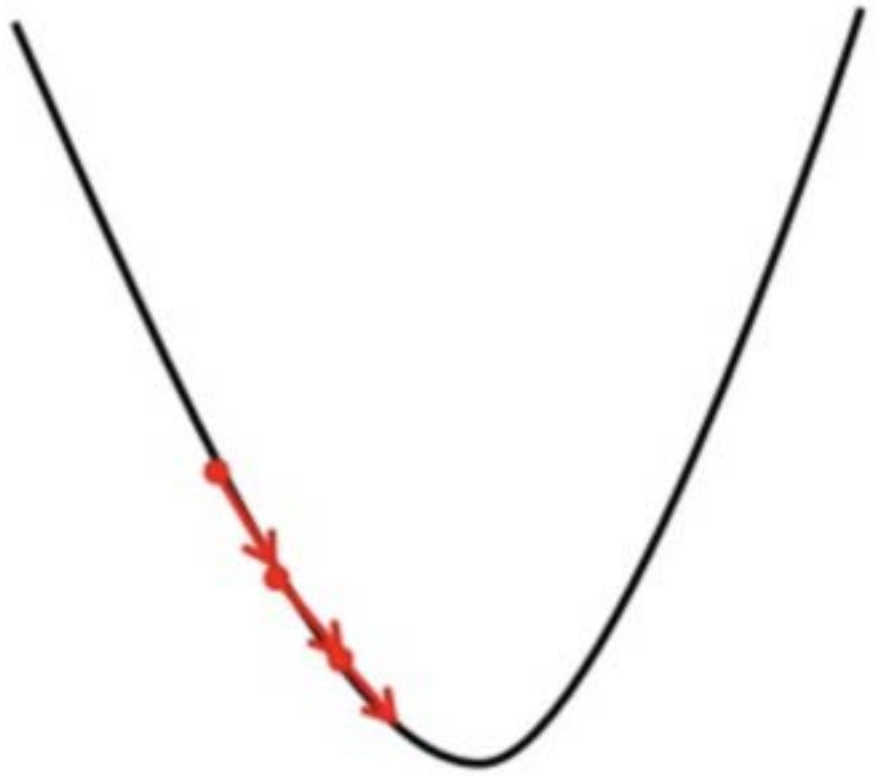
Inverse kinematics: how to solve for $q = \{\theta_1, \ldots, \theta_N\}$ from $T^0{}_N$?

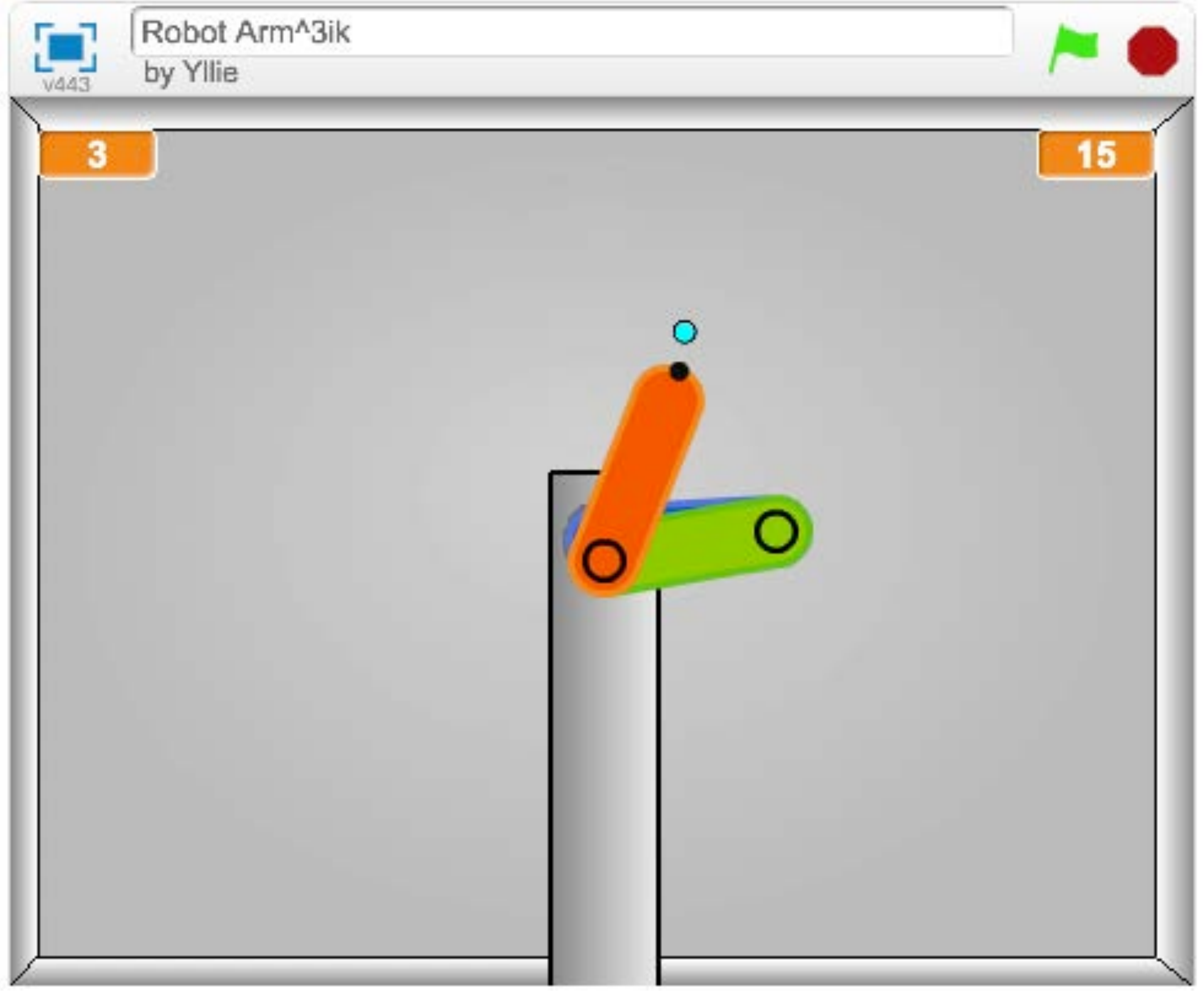
Big steps -> Aggressive





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?

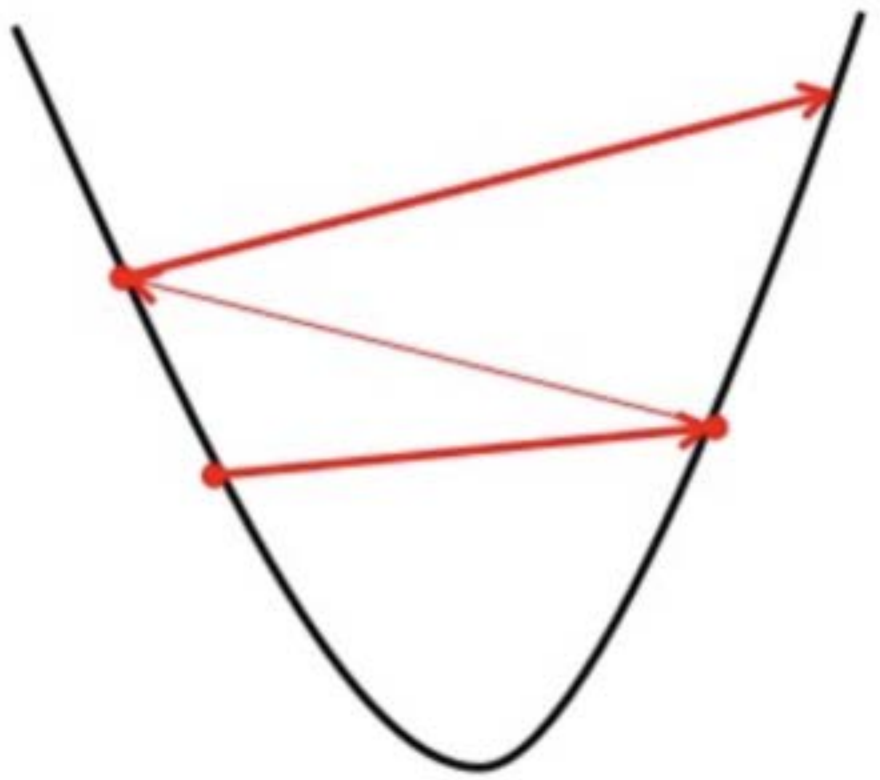
These videos are ***illustrating*** the optimization steps

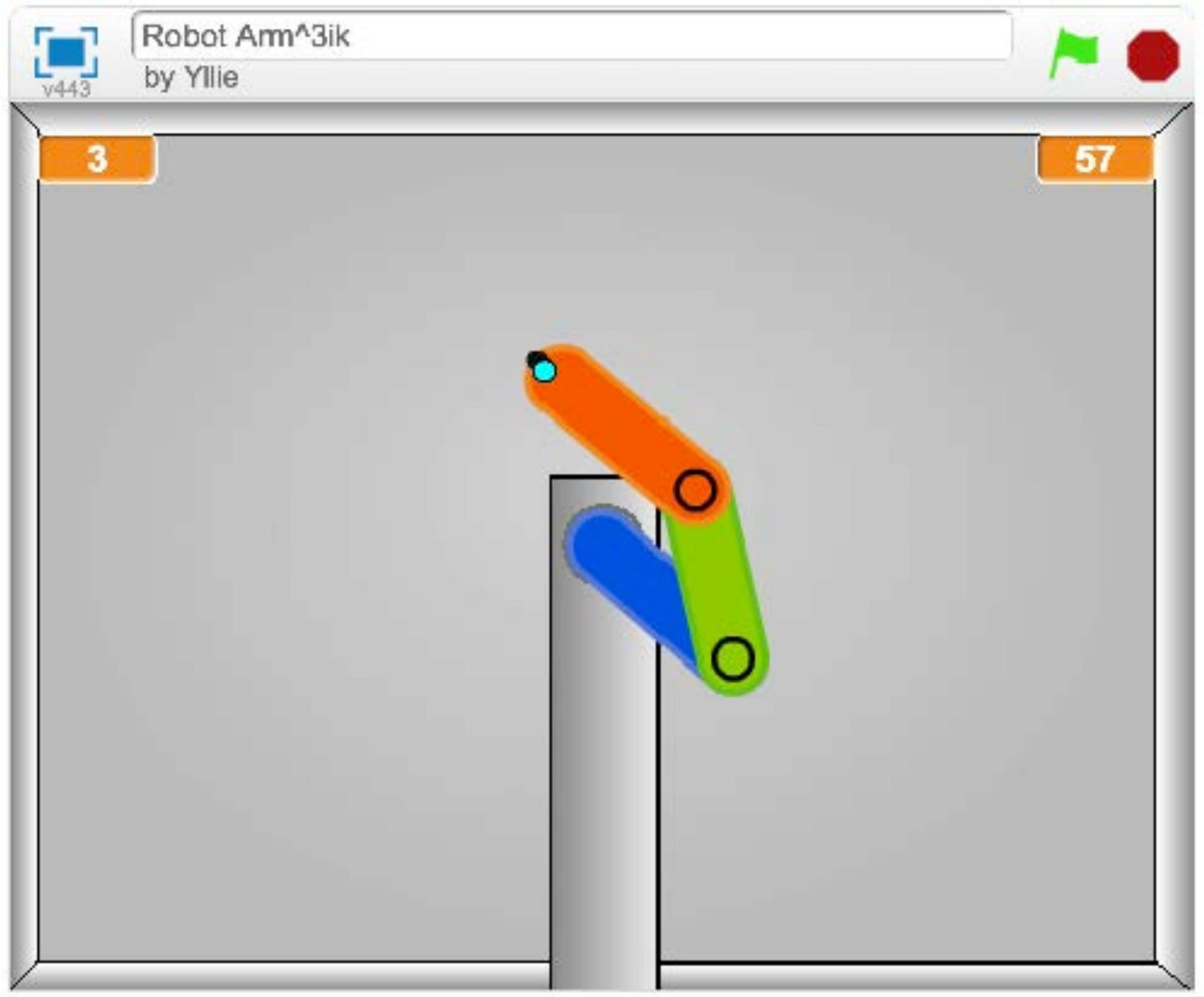
In practice, you will use the solution (q_desired) from the IK solver and invoke a motion planner that will plan a collision free trajectory/path to your solution

IK by optimization

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

Big steps -> Aggressive





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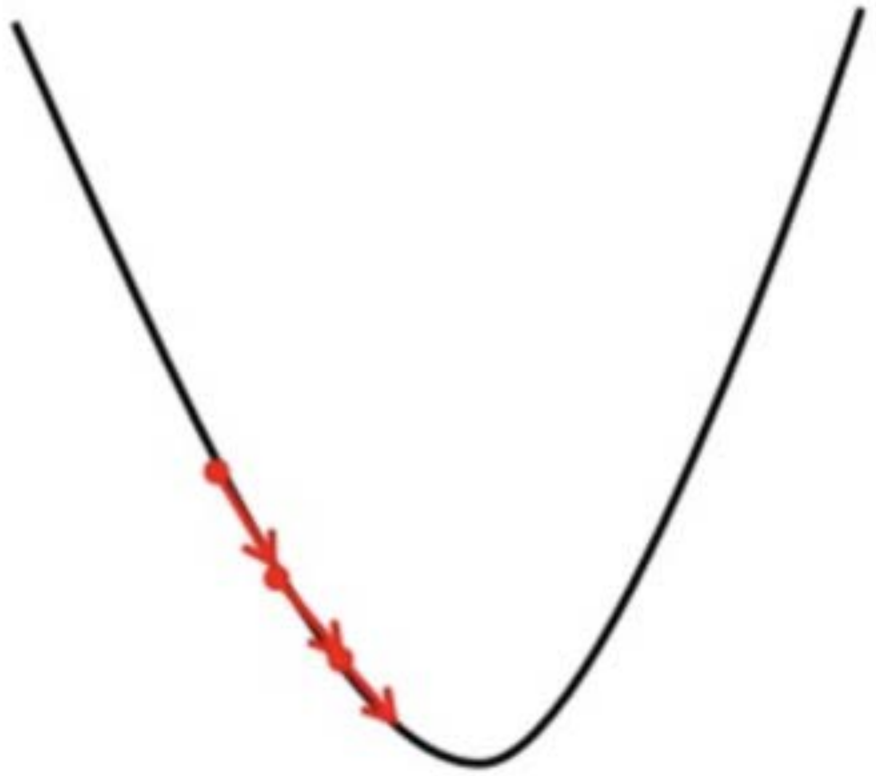

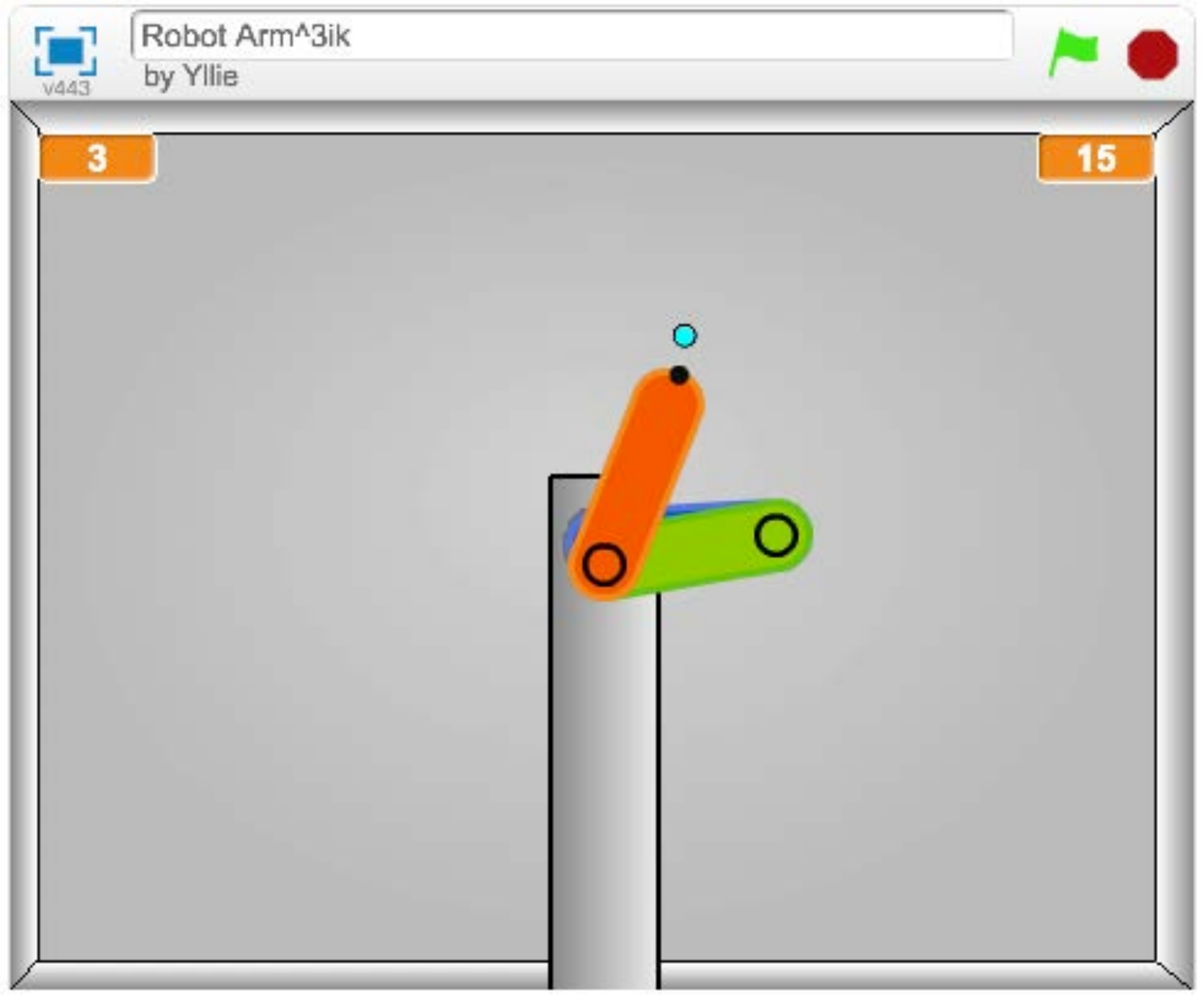

Wait IK should give only the final robot configuration, isn't it?

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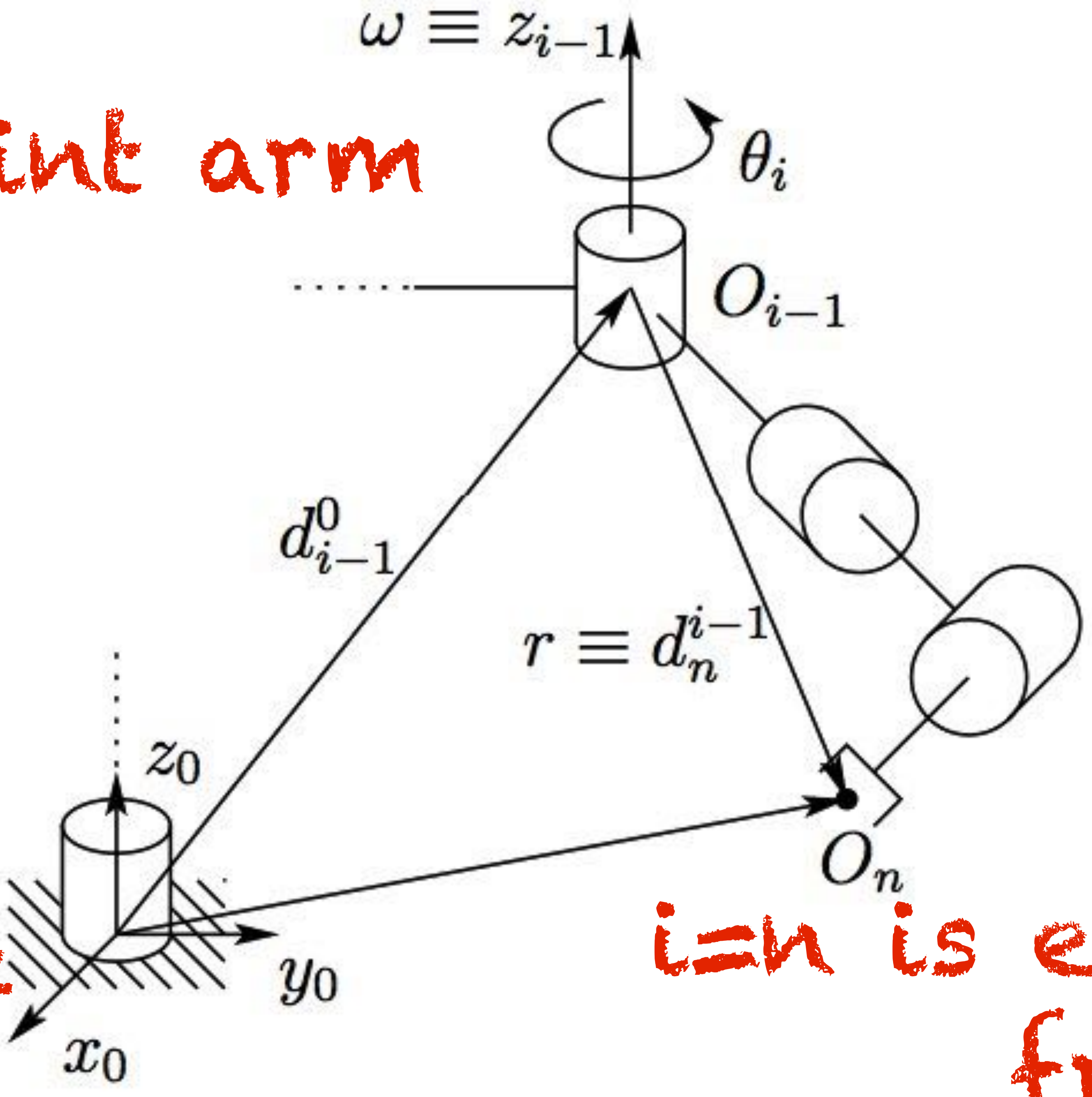
$$q_{\text{desired}} = \text{IKSolver}(x_{\text{desired}})$$

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

We will talk about this in the future classes

Robot arm and its Jacobian

3D N-joint arm



i=0 is base frame

i=n is endeffector frame

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

i-1th frame maps to ith column in

The Jacobian

A 6xN matrix

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

Robot arm and its Jacobian

Lets focus on i-1th frame

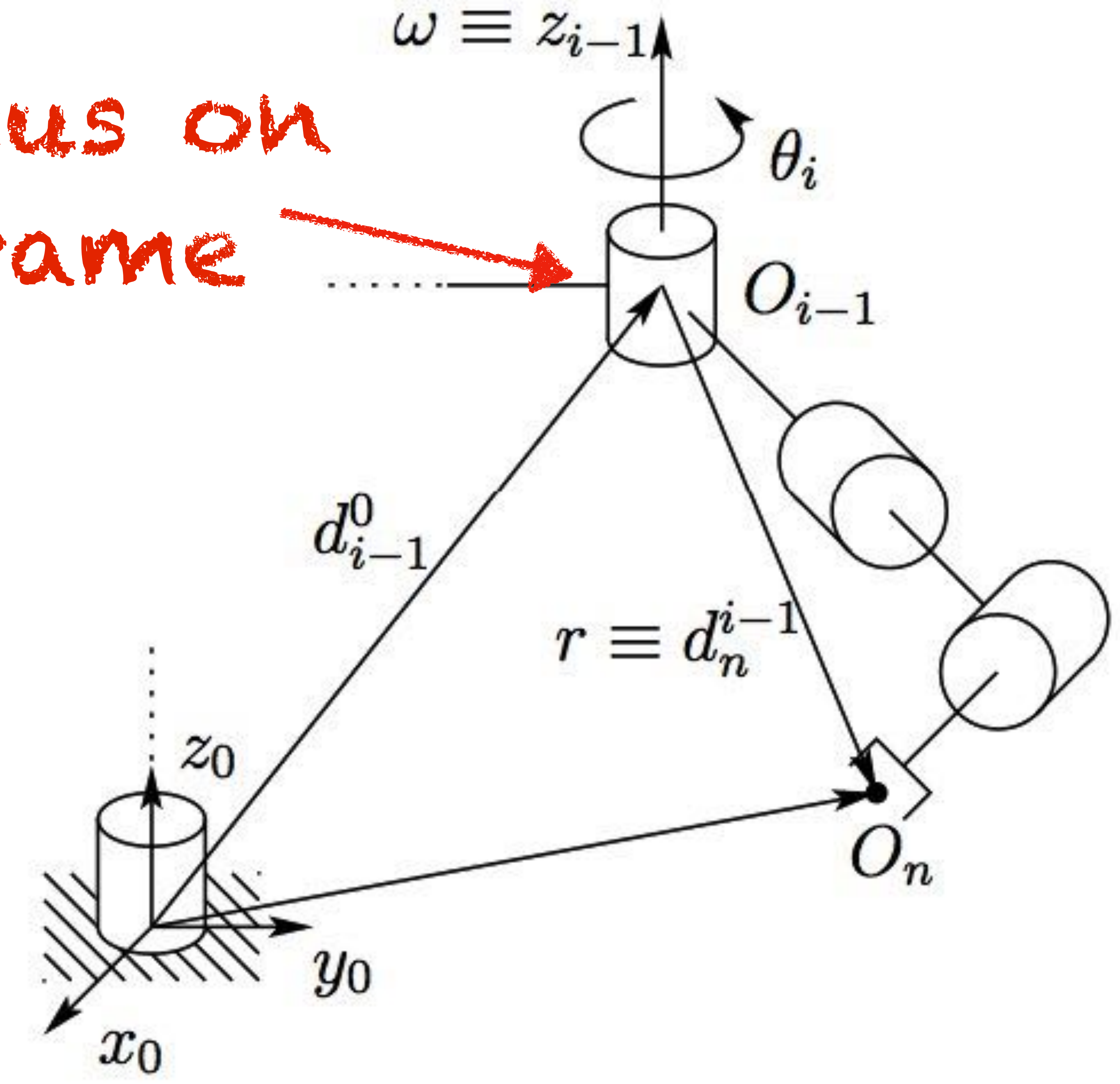


Figure 5.1: Motion of the end-effector due to link i.

i-1th frame maps to ith column in

The Jacobian

A 6xN matrix

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

This will correspond to ith column

Robot arm and its Jacobian

Lets focus on i-1th frame

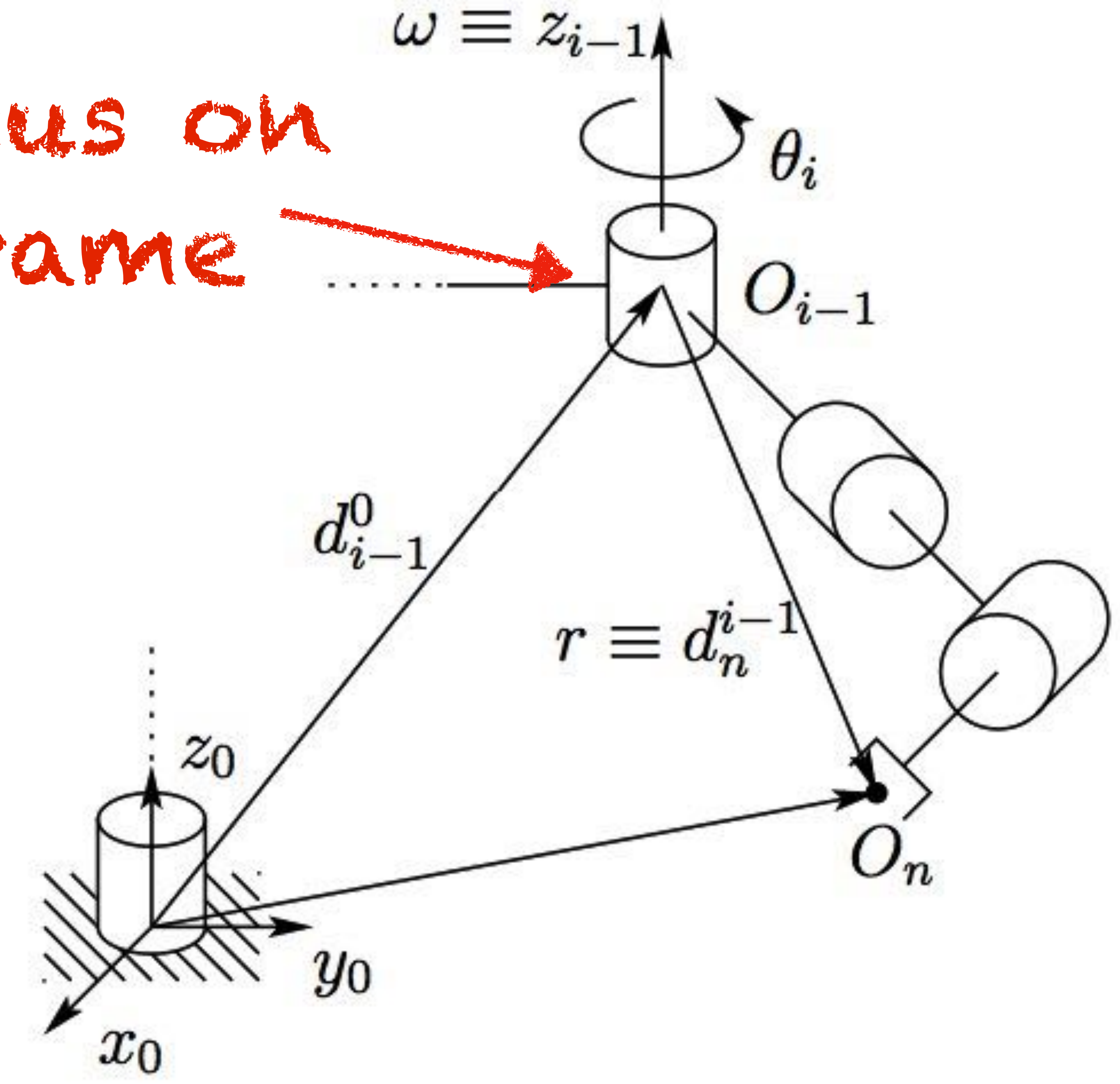


Figure 5.1: Motion of the end-effector due to link i.

i-1th frame maps to ith column in

The Jacobian

A 6xN matrix

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

consisting of two 3xN matrices

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

J_i for a prismatic joint

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

J_i for a rotational joint

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

Robot arm and its Jacobian

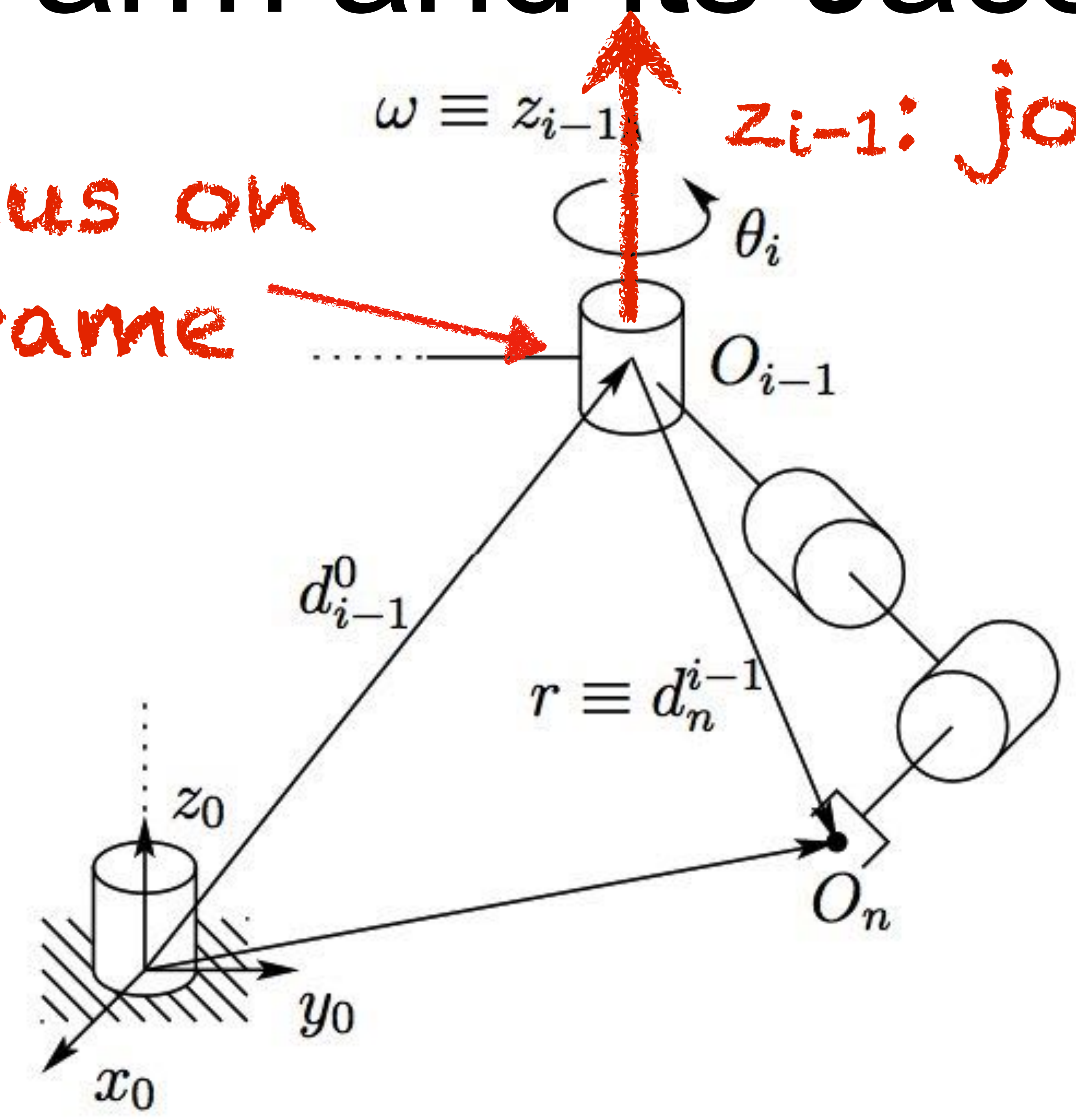


Figure 5.1: Motion of the end-effector due to link i.

If the i-1th 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 3x1 vector capturing the influence of this joint on the end-effector pose.

Only influences the translational (linear) component

Robot arm and its Jacobian

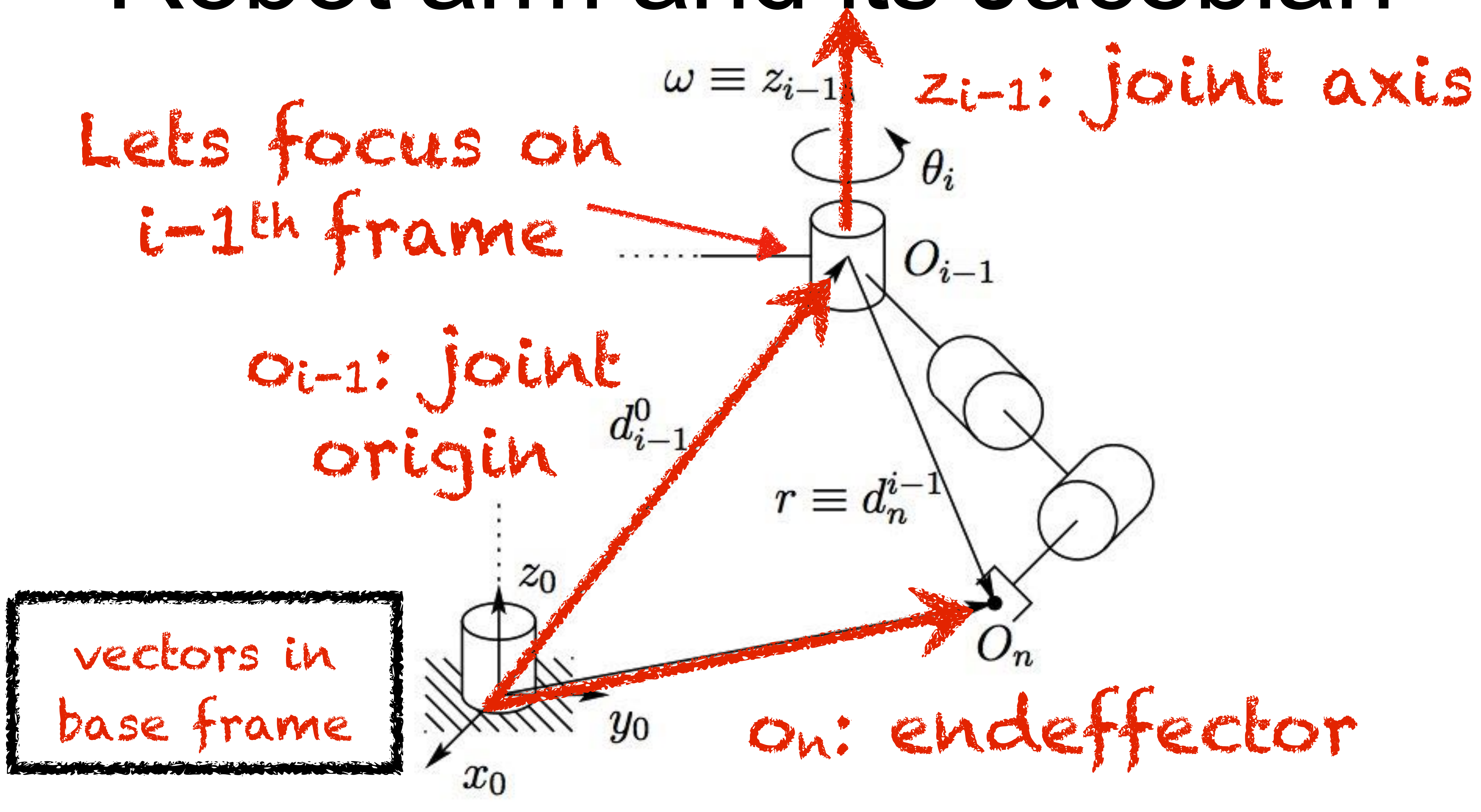


Figure 5.1: Motion of the end-effector due to link i.

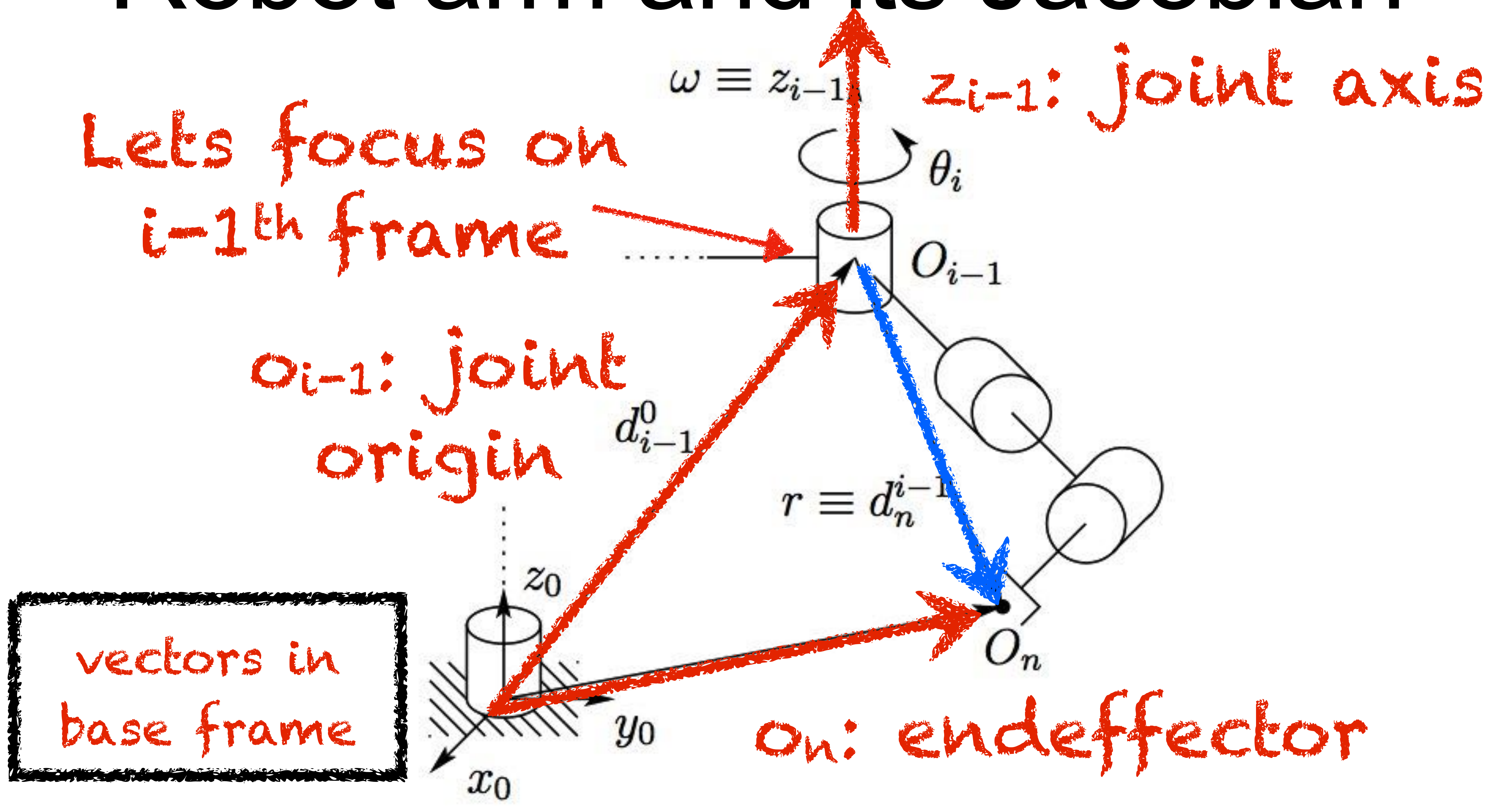
If the i-1th joint is revolute

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?

Robot arm and its Jacobian



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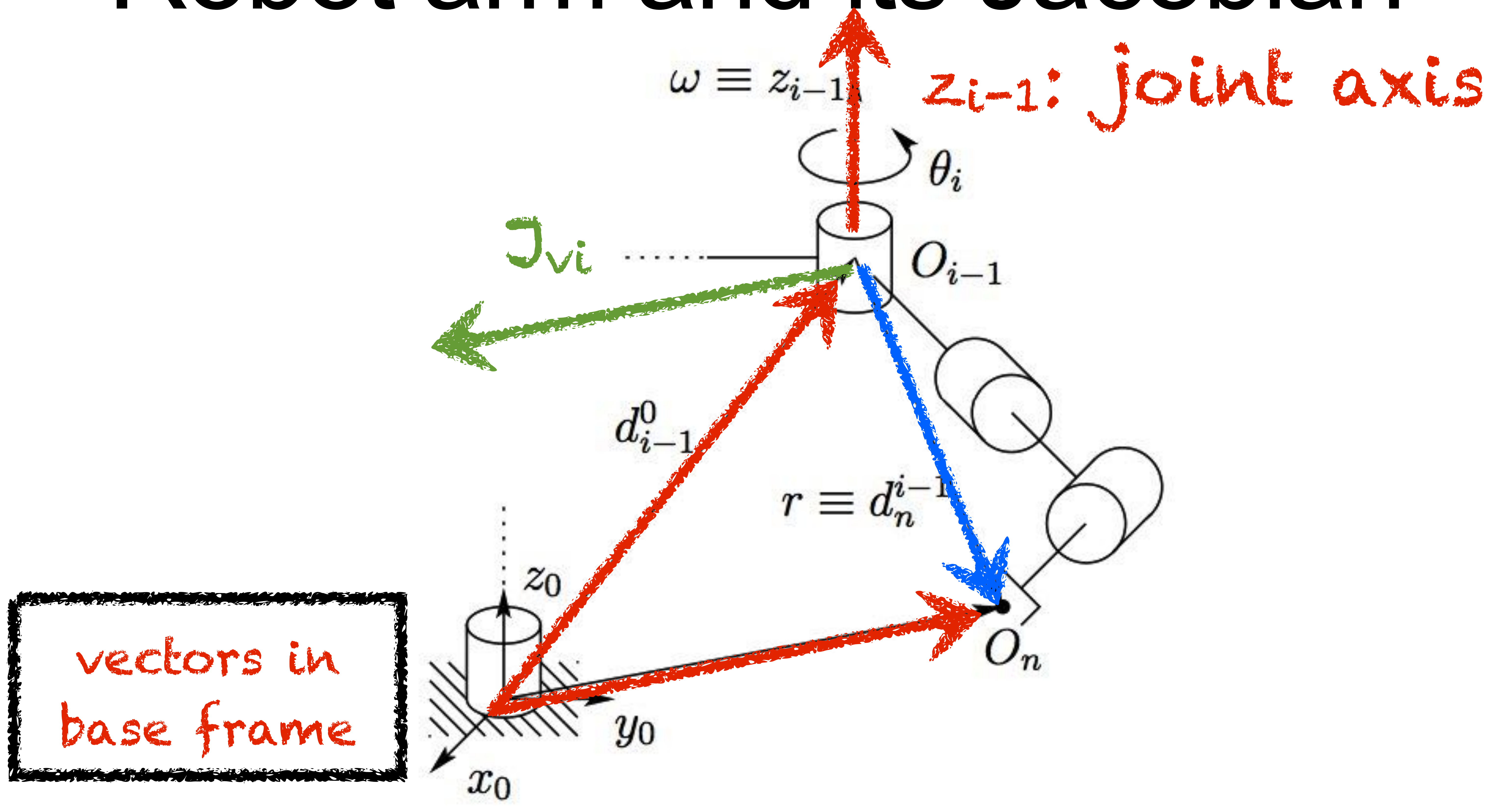

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If the i-1th joint is revolute

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

compute step direction

perform step direction

repeat

IK Procedure restated:

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

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

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

Check point:

How will you get x_{n+1} given q_{n+1}?

How to use this Jacobian for IK as optimization?

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Check point:

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

How to use this Jacobian for IK as optimization?

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perform step direction

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

repeat

Check point:

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

No

We can use pseudoinverse!

- For matrix A with dimensions N x M with full rank
- Left pseudoinverse, for when N > M, (i.e., "tall", less than than 6 DoFs)

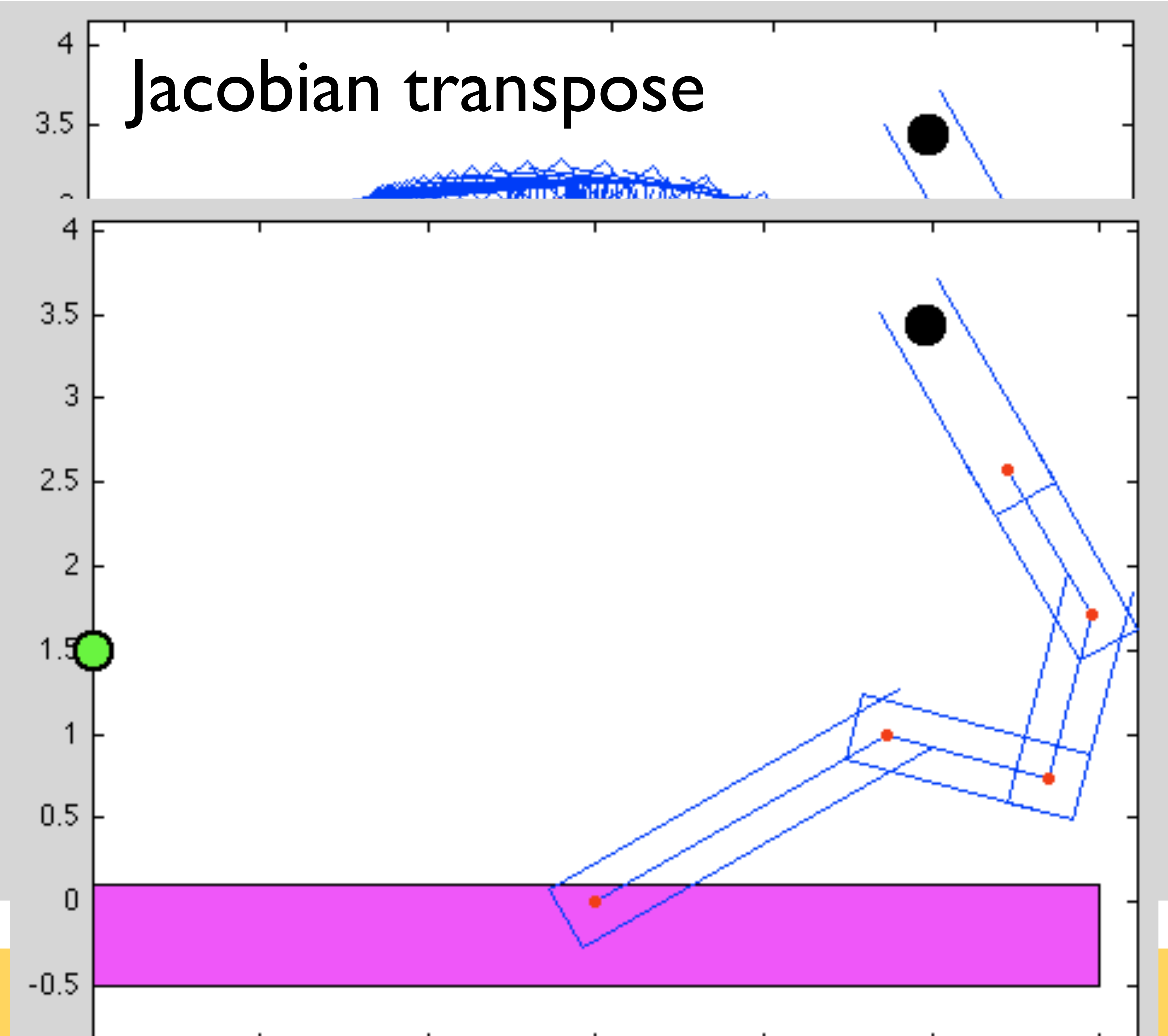
$$A^{-1}_{\text{left}} = \left(A^T A\right)^{-1} A^T \quad \text{s.t.} \quad A^{-1}_{\text{left}} A = I_n$$

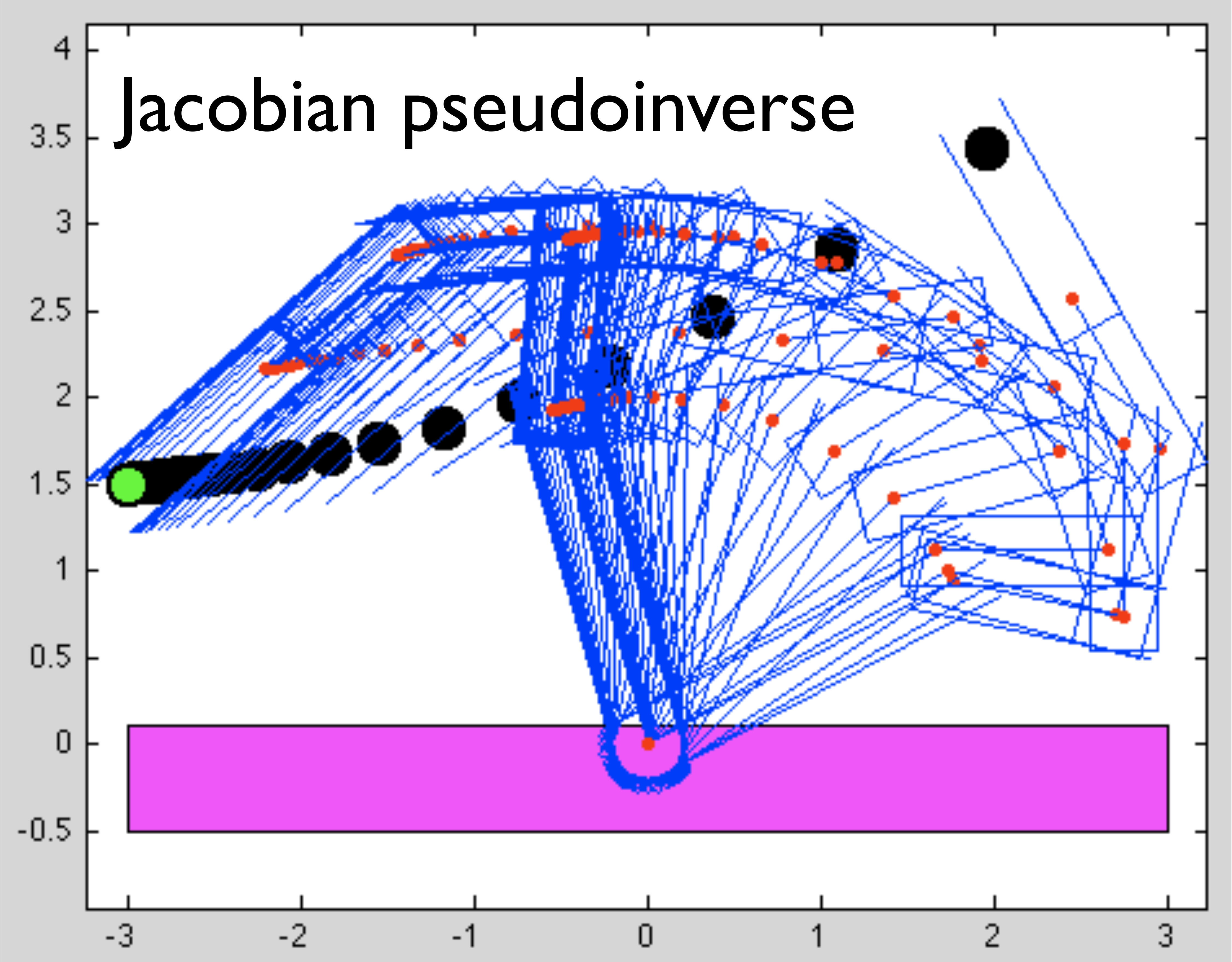
- Right pseudoinverse, for when N < M, (i.e., "wide", more than 6 DoFs)

$$A^{-1}_{\text{right}} = A^T \left(A A^T\right)^{-1} \quad \text{s.t.} \quad A A^{-1}_{\text{right}} = I_m$$

Jacobian Pseudoinverse

Matlab 5-link arm example: Jacobian Pseudoinverse





Error Minimization by Jacobian Pseudoinverse

$$J(\mathbf{q})\Delta\mathbf{q} = \Delta\mathbf{x}$$

Jacobian gives mapping from configuration displacement to endeffector displacement

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

Inverse of Jacobian maps endeffector displacement to configuration displacement

But, inverse of Jacobian is rarely an option. Why?

$$\arg\min_{\Delta\mathbf{q}} ||J(\mathbf{q})\Delta\mathbf{q} - \Delta\mathbf{x}||^2$$

Instead, find configuration displacement that minimizes endeffector error squared

Error Minimization by Jacobian Pseudoinverse

$$\arg\min_{\Delta\mathbf{q}} ||J(\mathbf{q})\Delta\mathbf{q} - \Delta\mathbf{x}||^2$$

Instead, find configuration displacement that minimizes endeffector error squared

$$\begin{aligned} C &= (J(\mathbf{q})\Delta\mathbf{q} - \Delta\mathbf{x})^2 \\ &= (J(\mathbf{q})\Delta\mathbf{q} - \Delta\mathbf{x})^T (J(\mathbf{q})\Delta\mathbf{q} - \Delta\mathbf{x}) \\ &= \Delta\mathbf{q}^T J(\mathbf{q})^T J(\mathbf{q})\Delta\mathbf{q} - \Delta\mathbf{q}^T J(\mathbf{q})^T \Delta\mathbf{x} - \Delta\mathbf{x}^T J(\mathbf{q})\Delta\mathbf{q} + \Delta\mathbf{x}^T\Delta\mathbf{x} \\ &= \Delta\mathbf{q}^T J(\mathbf{q})^T J(\mathbf{q})\Delta\mathbf{q} - 2\Delta\mathbf{q}^T J(\mathbf{q})^T \Delta\mathbf{x} + \Delta\mathbf{x}^T\Delta\mathbf{x} \end{aligned}$$

Define cost function expressing squared error

Error Minimization by Jacobian Pseudoinverse

Define cost function expressing squared error

$$C = \Delta\mathbf{q}^T J(\mathbf{q})^T J(\mathbf{q}) \Delta\mathbf{q} - 2\Delta\mathbf{q}^T J(\mathbf{q})^T \Delta\mathbf{x} + \Delta\mathbf{x}^T \Delta\mathbf{x}$$

Take cost derivative

$$\frac{dC}{d\Delta\mathbf{q}} = 2J(\mathbf{q})^T J(\mathbf{q}) \Delta\mathbf{q} - 2J(\mathbf{q})^T \Delta\mathbf{x} + 0$$

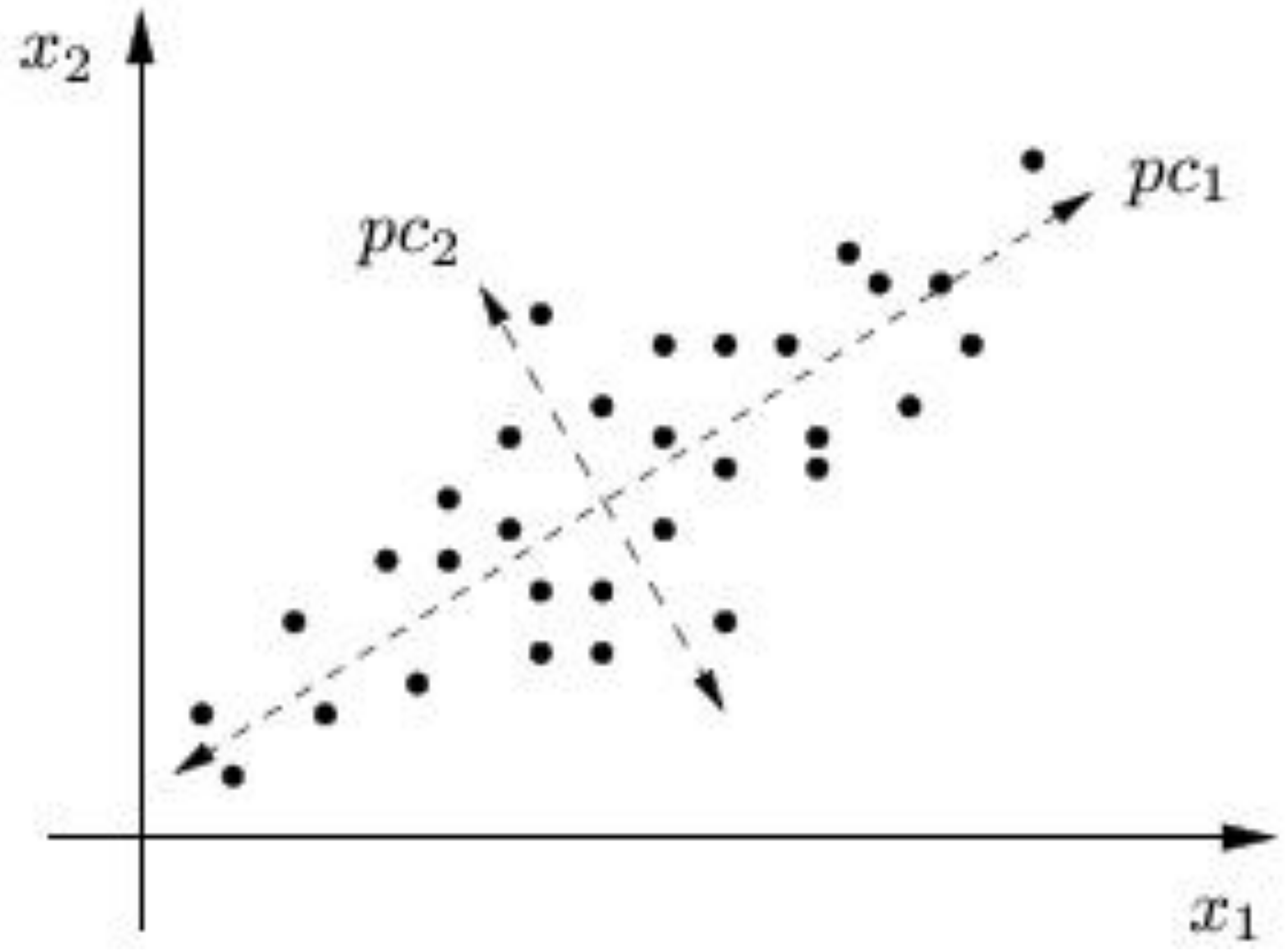
Set to zero and solve for configuration displacement

$$0 = 2J(\mathbf{q})^T J(\mathbf{q}) \Delta\mathbf{q} - 2J(\mathbf{q})^T \Delta\mathbf{x}$$

$$J(\mathbf{q})^T J(\mathbf{q}) \Delta\mathbf{q} = J(\mathbf{q})^T \Delta\mathbf{x}$$ ← Normal form

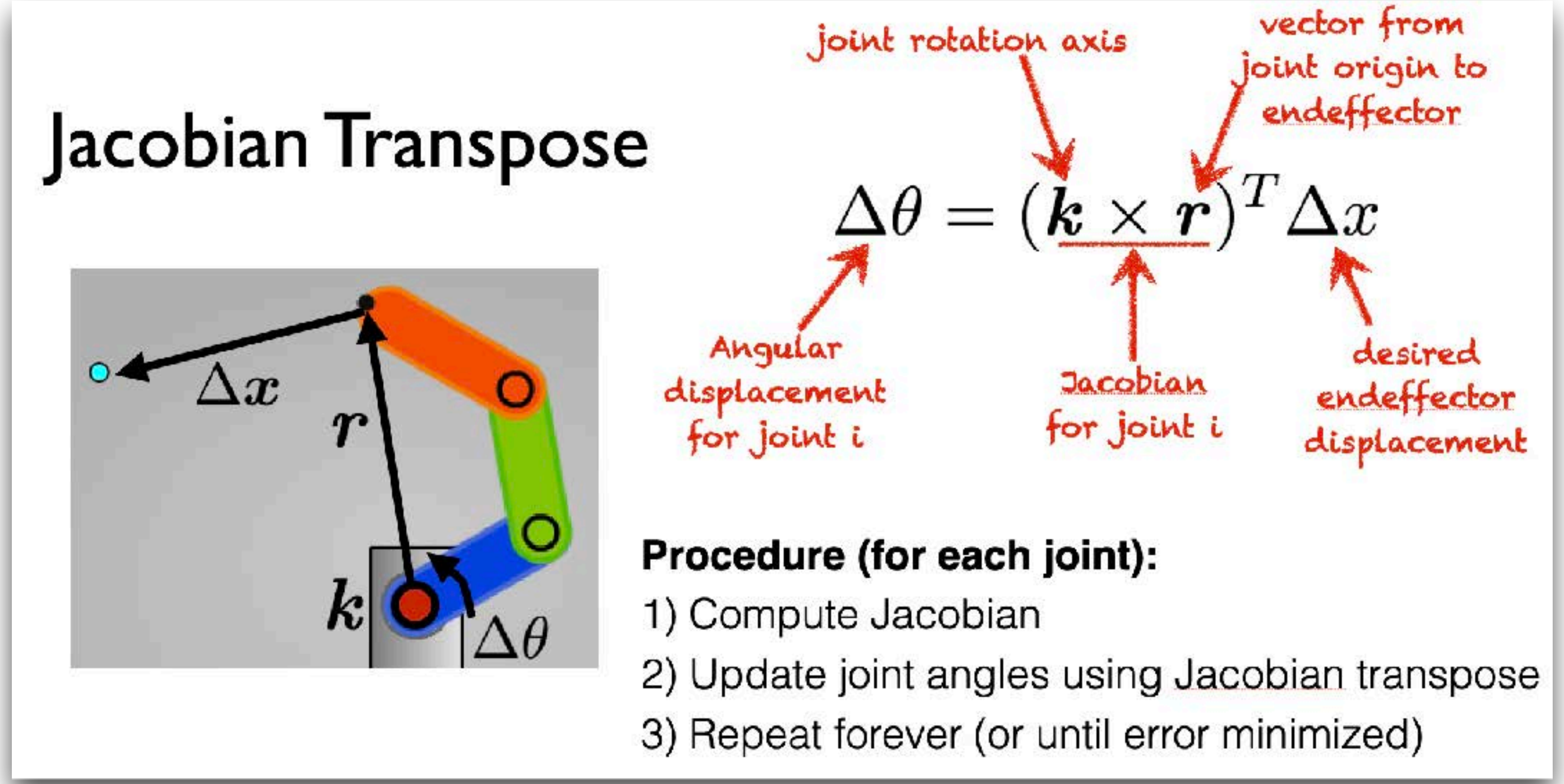
$$\Delta\mathbf{q} = (J(\mathbf{q})^T J(\mathbf{q}))^{-1} J(\mathbf{q})^T \Delta\mathbf{x}$$

Pseudoinverse, More Generally



- Pseudoinverse of matrix A: $A^+=(A^TA)^{-1}A^T$ approximates solution to linear system Ax=b
- The pseudoinverse A^+ is a least squares "best fit" approximate solution of an **overdetermined** system Ax=b, where there are more equations (m) than unknowns (n), or vice versa
- Often used for data fitting, as a singular value decomposition

Didn't we say **Jacobian Transpose** in the earlier lecture and not inverse?



We can also use **Jacobian Transponse**

Jacobian Transpose revisited

Error Minimization by Jacobian Transpose

Define cost function expressing squared error

$$C = \Delta\mathbf{q}^T J(\mathbf{q})^T J(\mathbf{q})\Delta\mathbf{q} - 2\Delta\mathbf{q}^T J(\mathbf{q})^T \Delta\mathbf{x} + \Delta\mathbf{x}^T \Delta\mathbf{x}$$

Take cost derivative wrt. change in configuration

$$\frac{dC}{d\Delta\mathbf{q}} = 2J(\mathbf{q})^T J(\mathbf{q})\Delta\mathbf{q} - 2J(\mathbf{q})^T \Delta\mathbf{x} + 0$$

Evaluate at convergence point, where change in configuration is zero

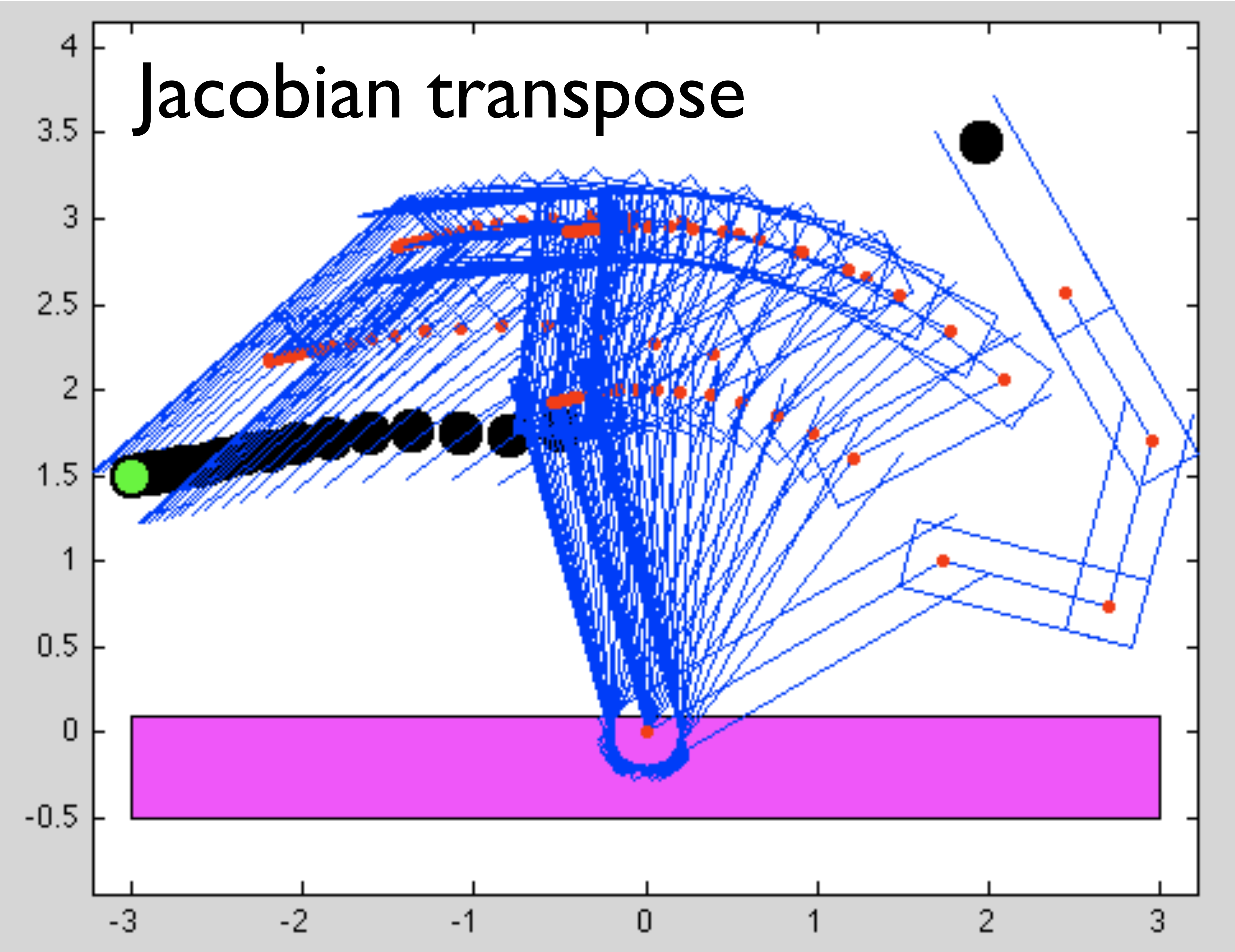
$$\left.\frac{dC}{d\Delta\mathbf{q}}\right|_{\Delta\mathbf{q}=0} = 2J(\mathbf{q})^T J(\mathbf{q})\Delta\mathbf{q} - 2J(\mathbf{q})^T \Delta\mathbf{x}\Big|_{\Delta\mathbf{q}=0}$$

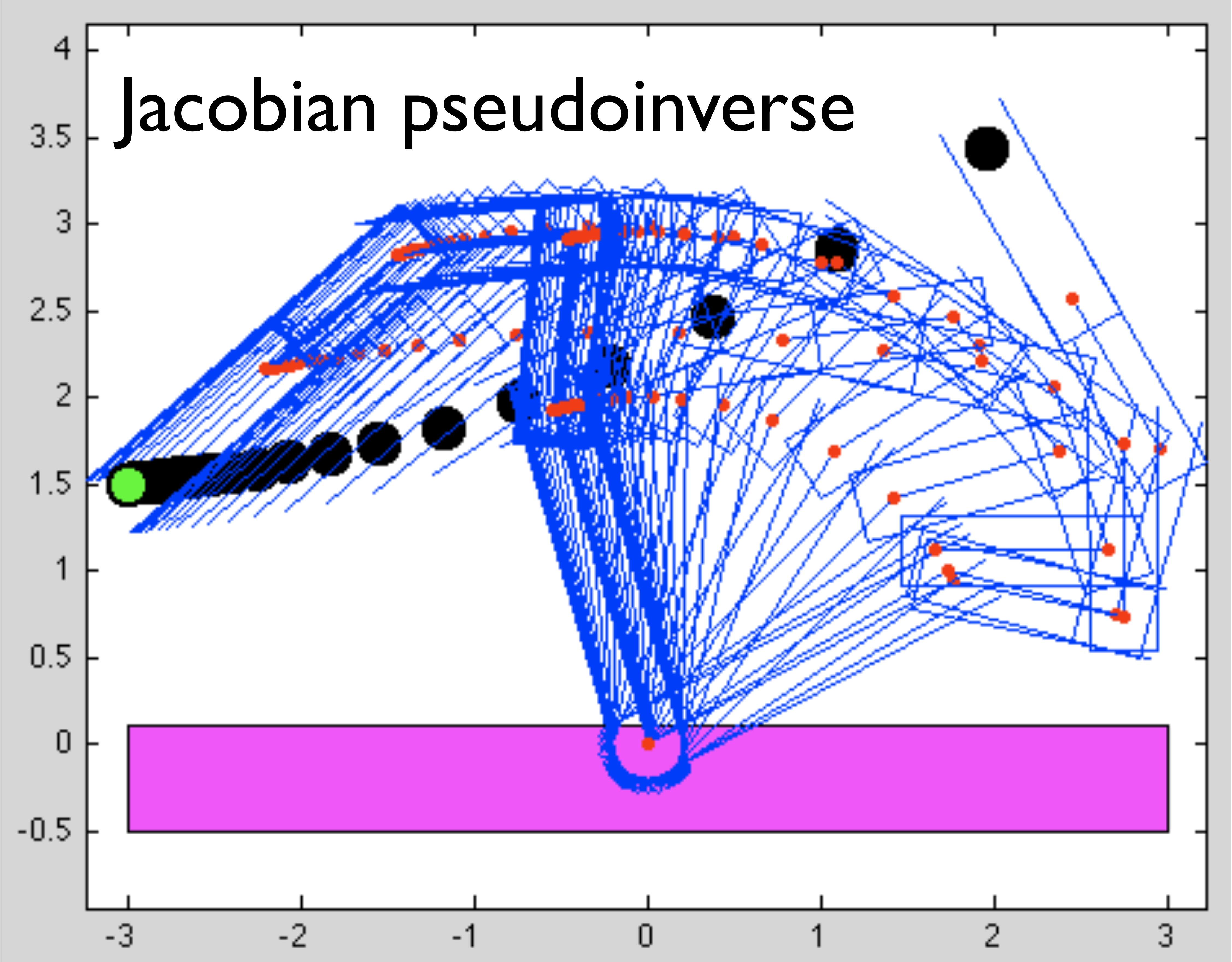
$$= 2J(\mathbf{q})^T \Delta\mathbf{x}$$

$$= \boxed{\gamma J(\mathbf{q})^T \Delta\mathbf{x}}$$

step length (gamma) chosen as update step scale

Matlab 5-link arm example: Jacobian transpose





Slide borrowed from Michigan Robotics autorob.org

Manipulation New Frontiers

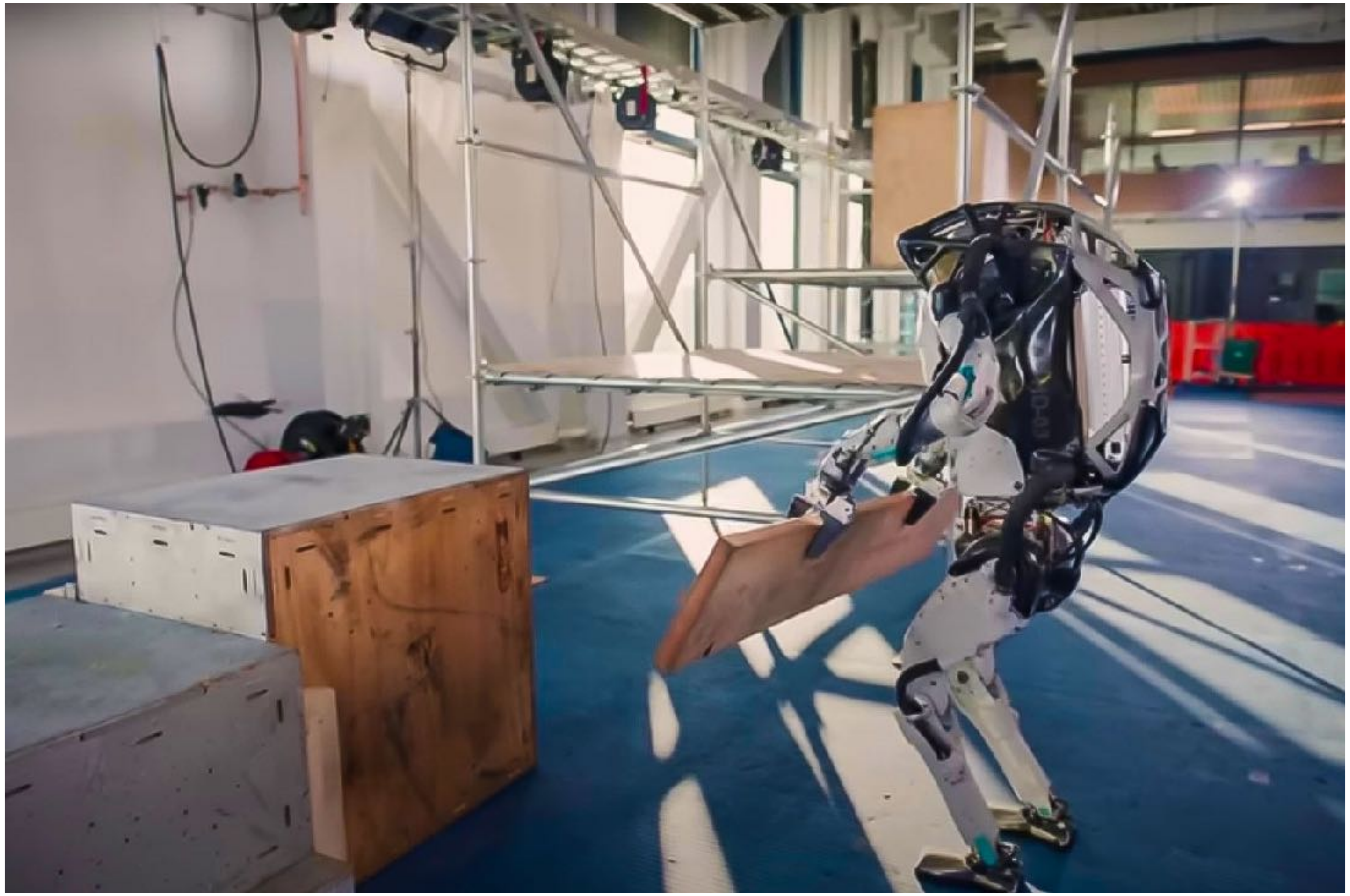


Image Credit - Boston Dynamics

Definition of **Manipulation**

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

Carnegie Mellon University
Robotics Institute

ABOUT PEOPLE RESEARCH EDUCATION NEWS EVENTS NREC

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Statement | Research | Publications | Students/Affiliates

I am **formally retired** 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 Manipulation Lab (MLab).

AS01CH19_Mason ARI 19 February 2018 14:24

ANNUAL REVIEWS

Annual Review of Control, Robotics, and Autonomous Systems

Toward Robotic Manipulation

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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

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

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."

19.1

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.

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Animal Manipulation

Animal Manipulation

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

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

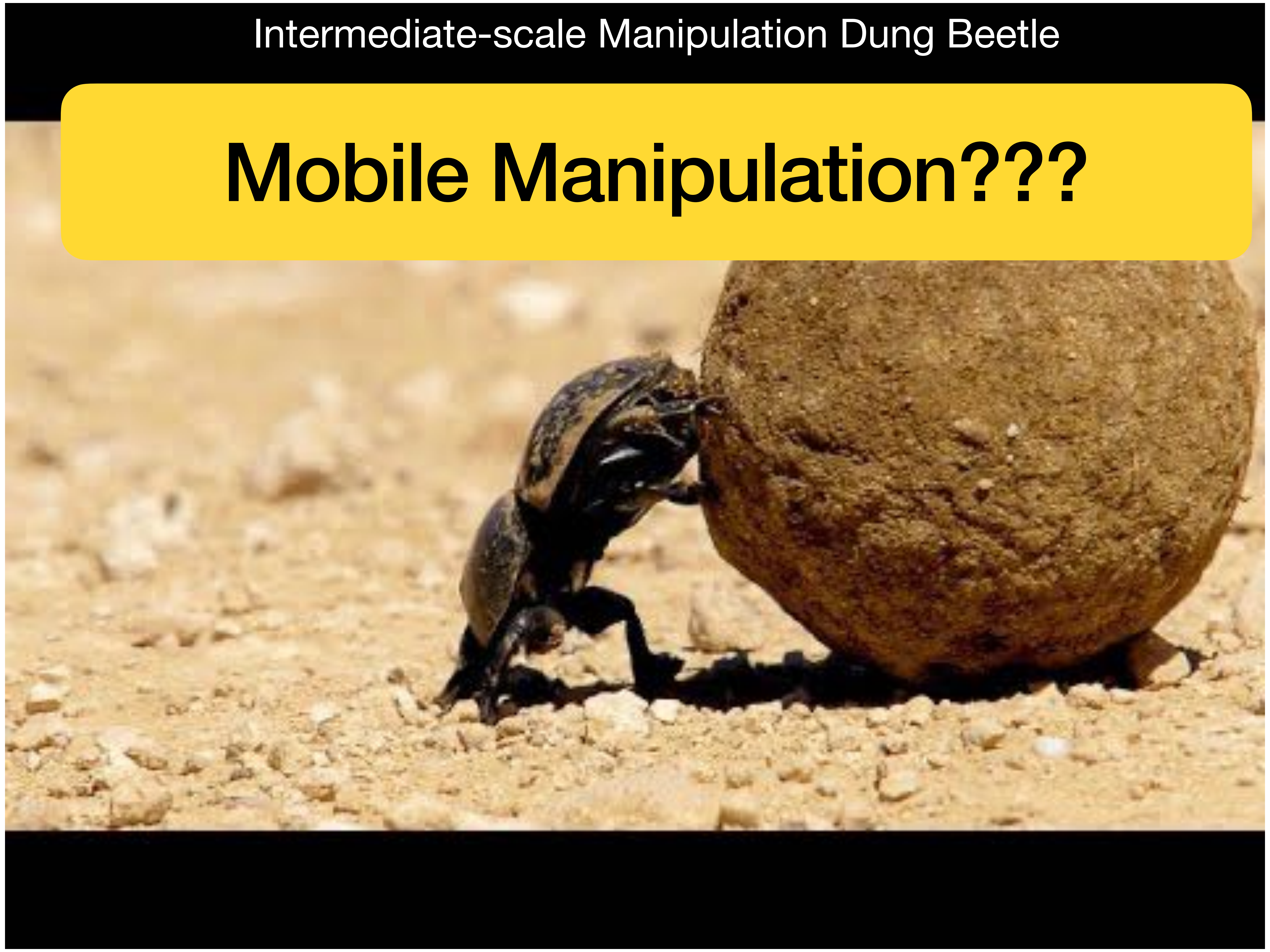
Animal Manipulation

"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." - Darvin

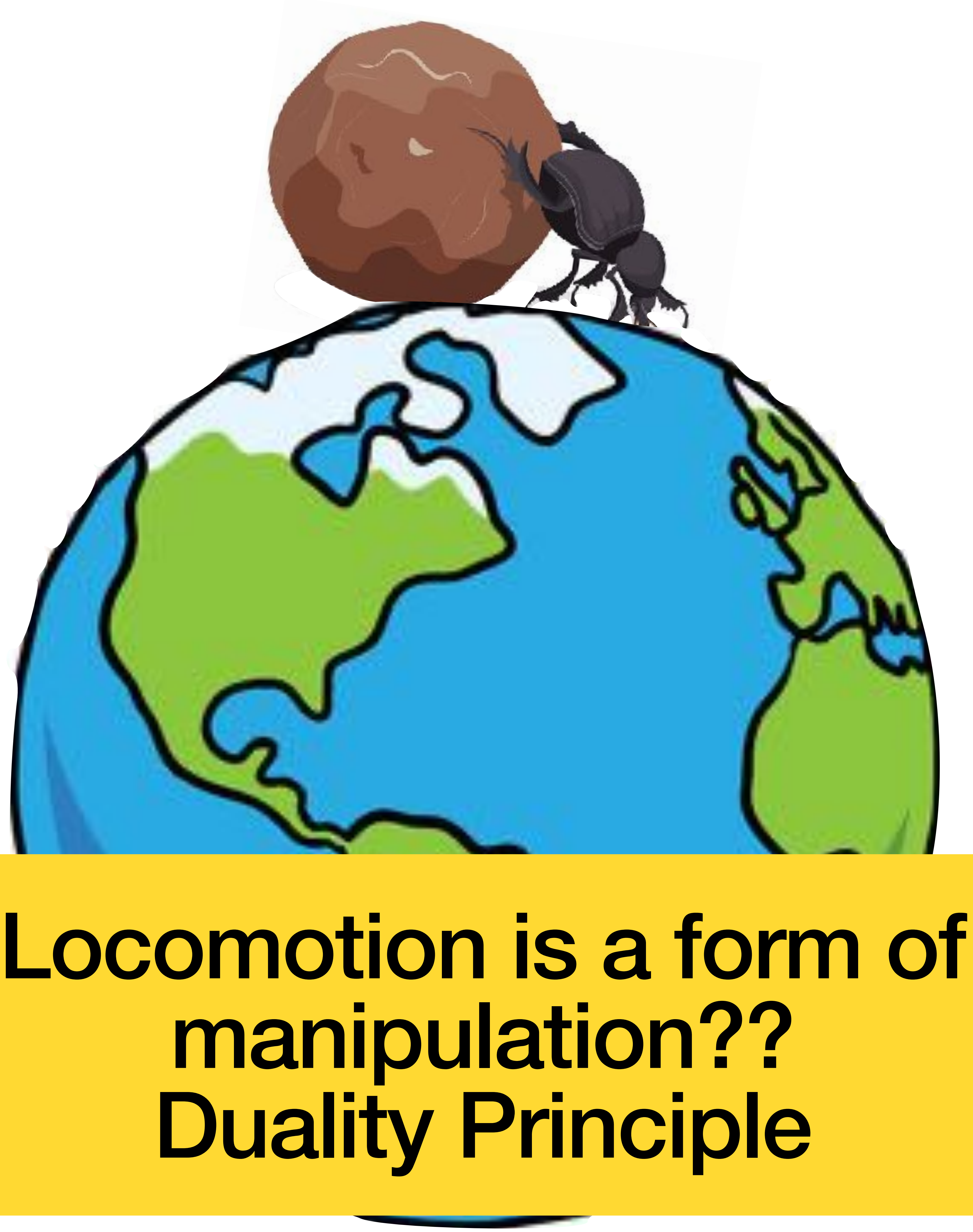
Intermediate-scale Manipulation Weaver ants ~20 million years ago

https://www.youtube.com/watch?v=1pkjpC4O_TM

Animal Manipulation



Mobile Manipulation???



Locomotion is a form of manipulation??
Duality Principle

https://youtu.be/xNjymt6oCcQ
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_5IcesYmlOK0RC4T4r5lydft8aQmpCwI7.jpg

Animal Manipulation

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

Animal Manipulation

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

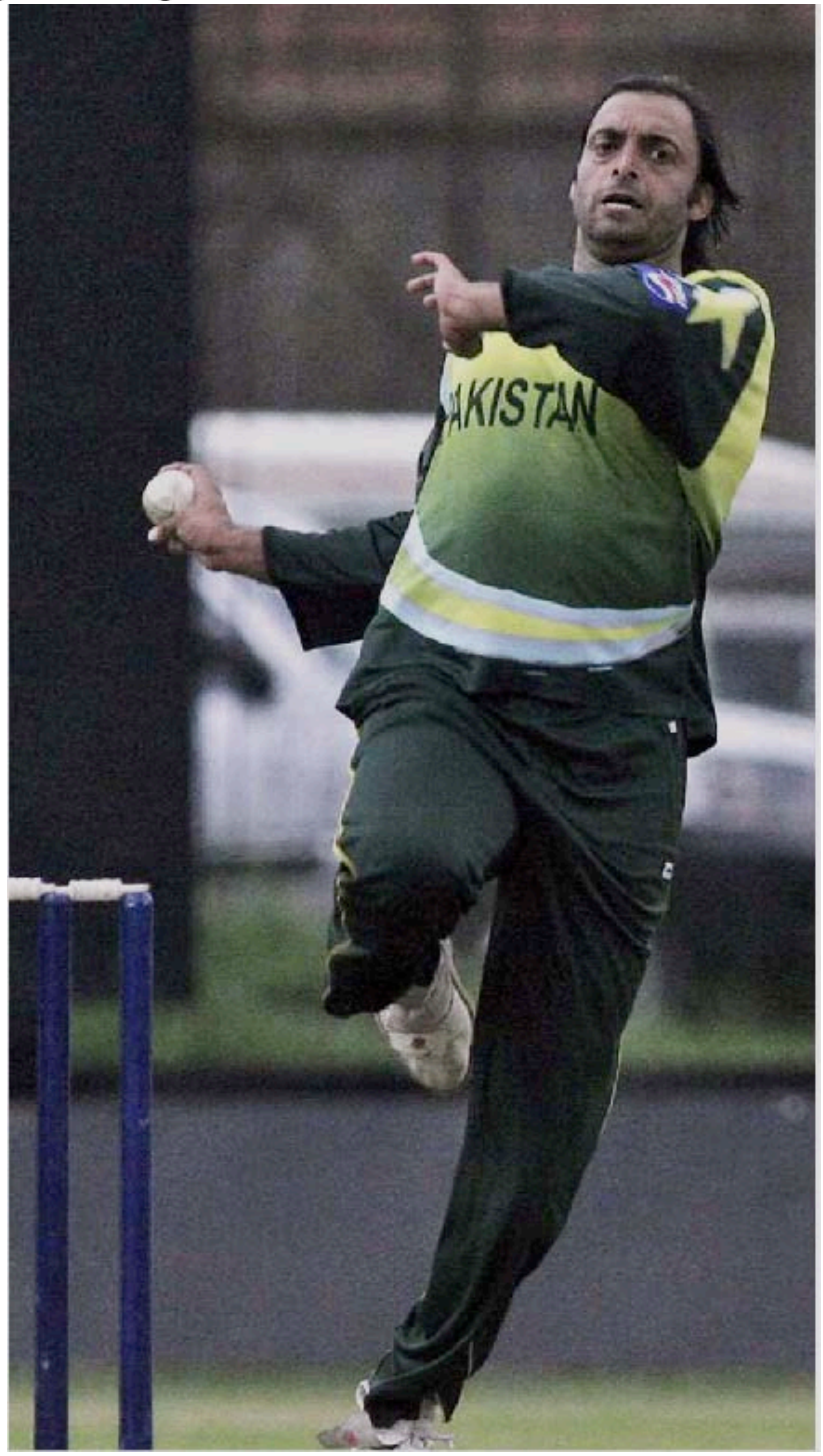
Animal Manipulation

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

Animal Manipulation

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

Human Manipulation



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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

Human Manipulation

https://live.staticflickr.com/6086/6098540957_6bfd63d5d1_b.jpg

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

Human Manipulation

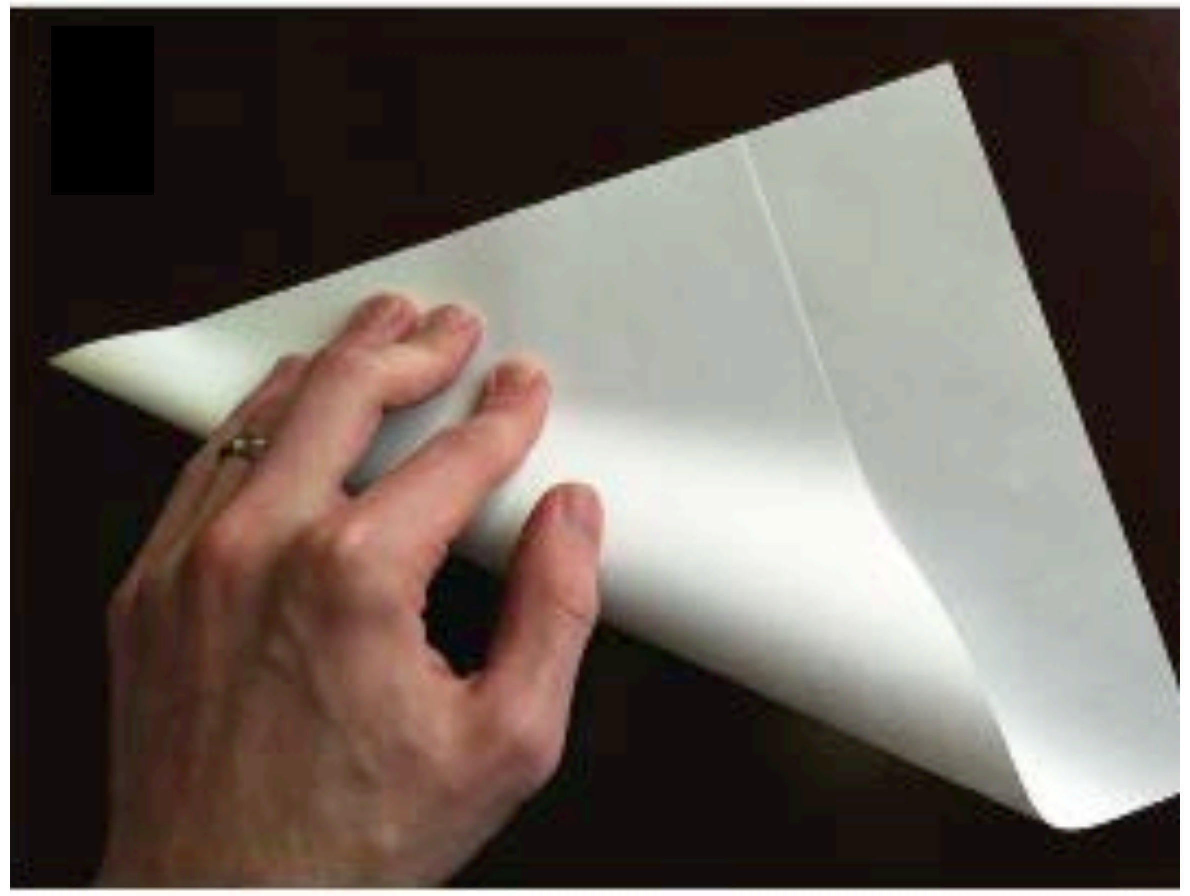


Figure 2

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

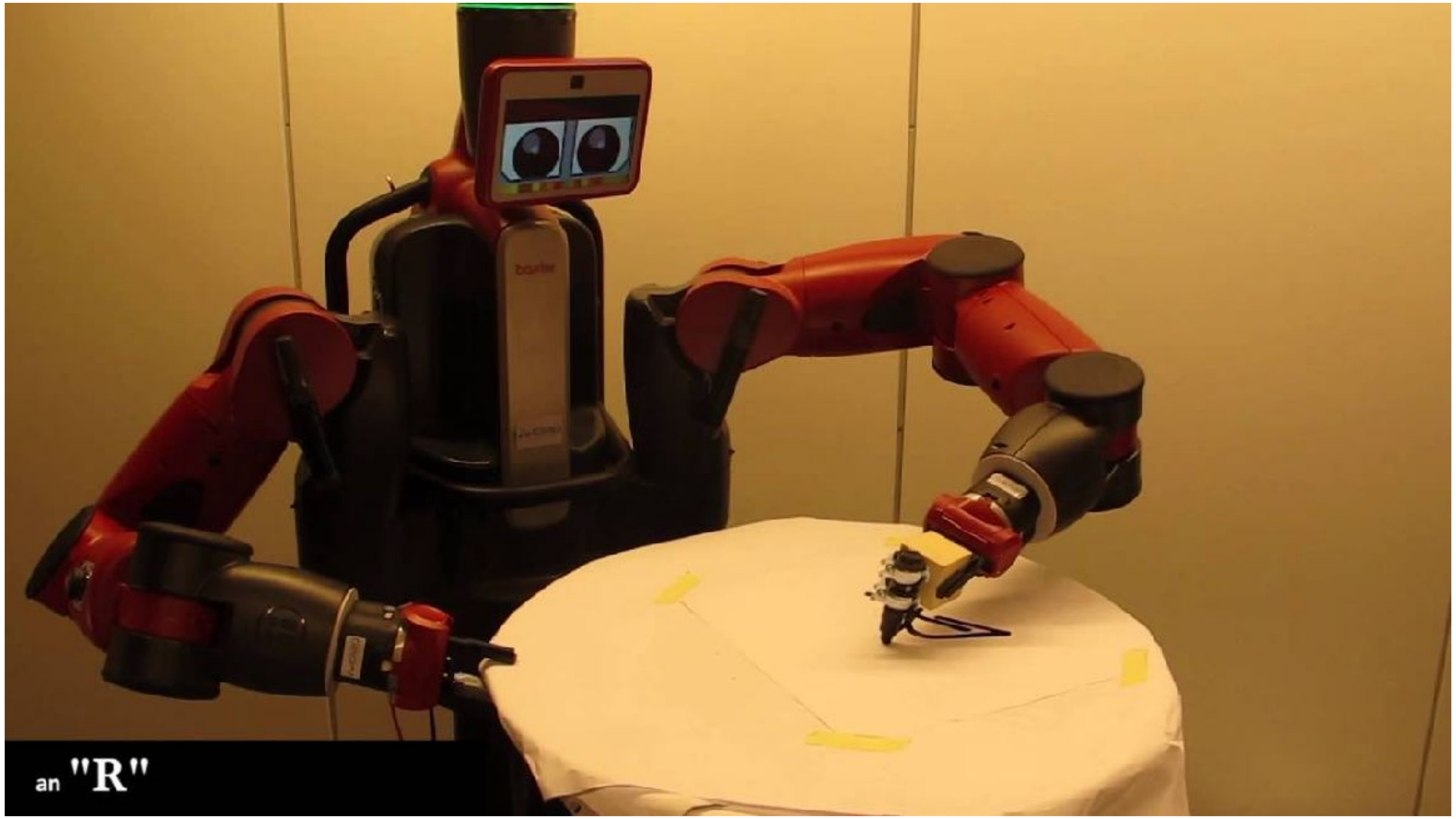
Programmed Motion

- 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
- Impedence control



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

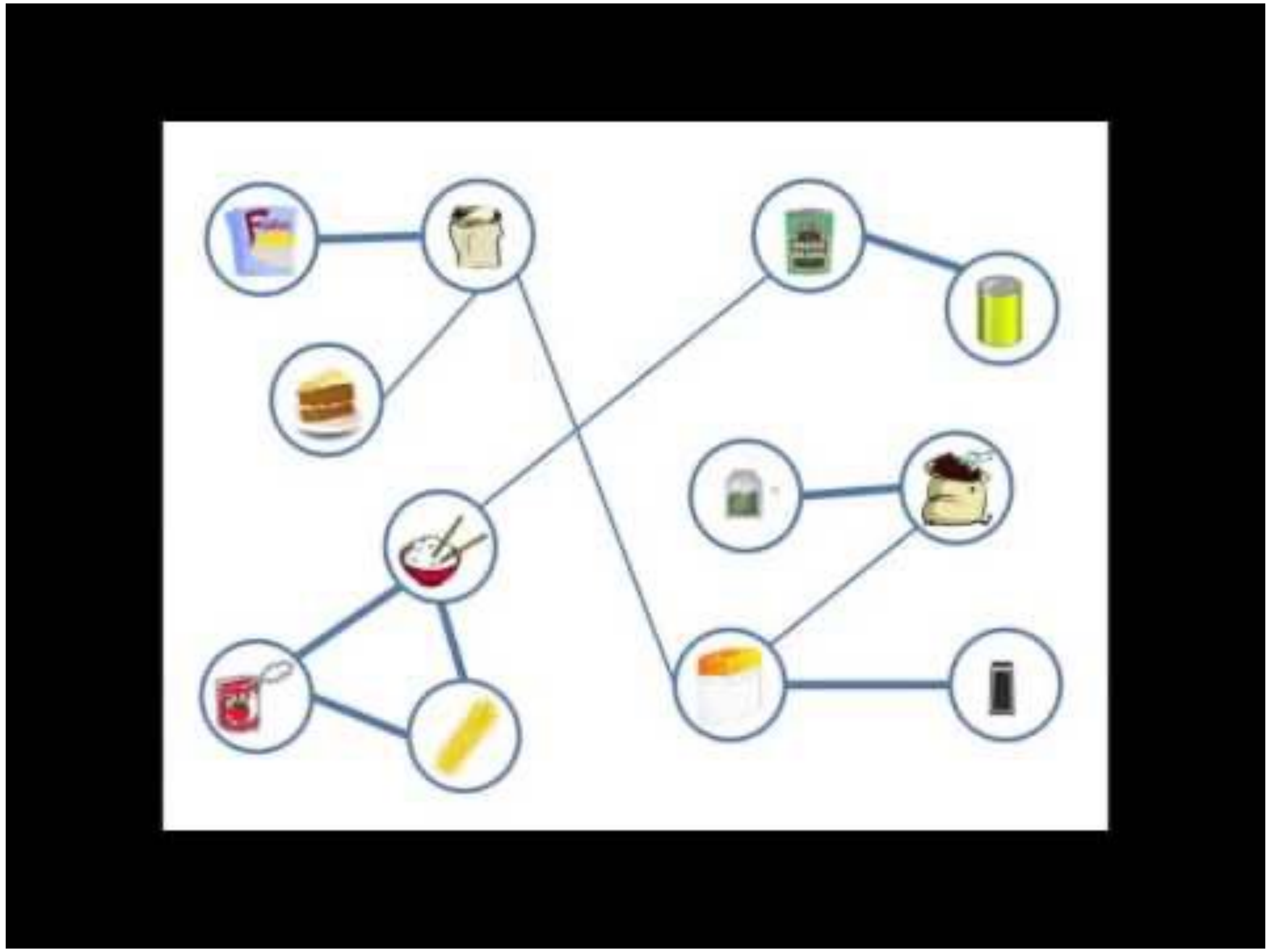
Structured pick-and-place manipulation

- 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

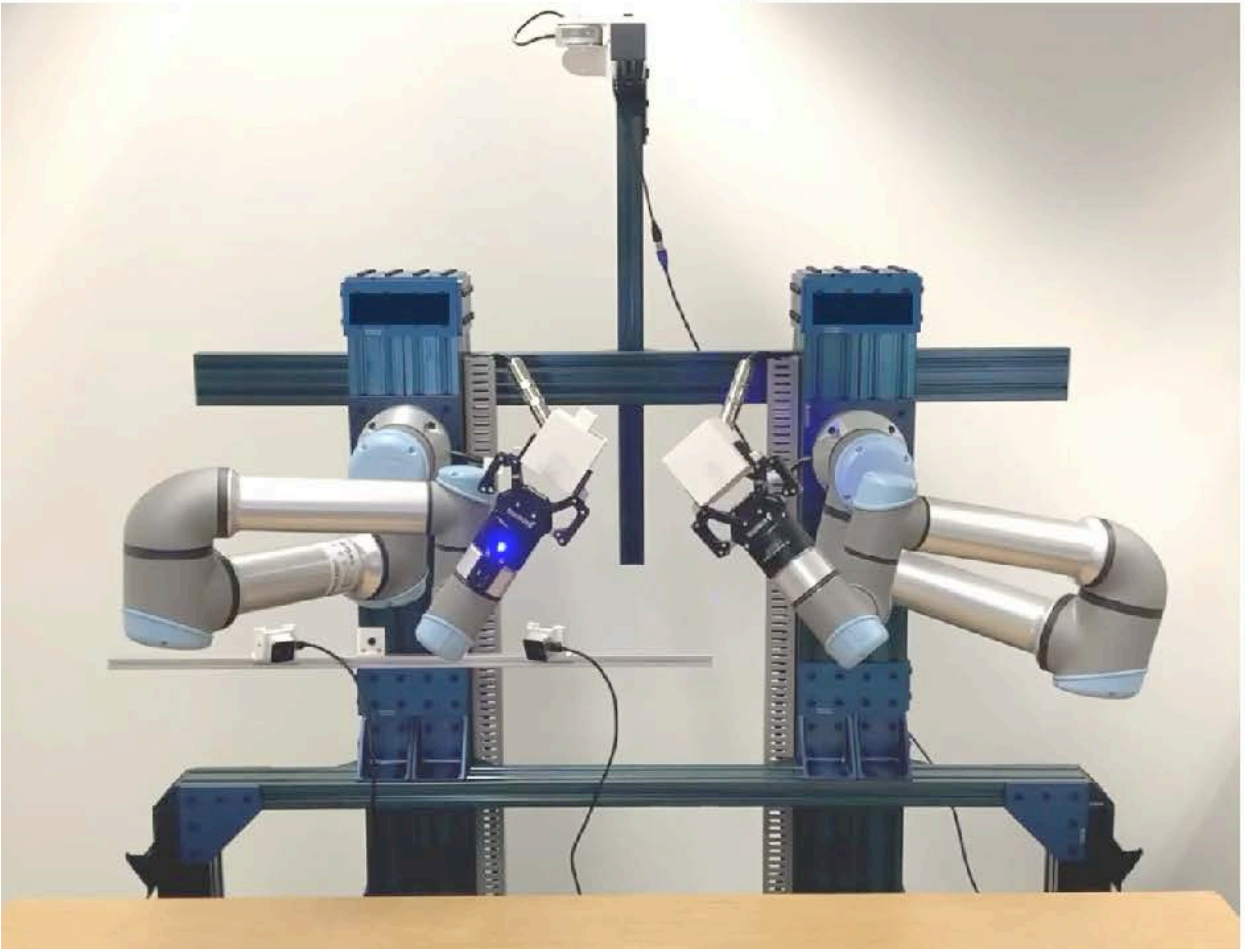


Abdo, Nichola, Cyrill Stachniss, Luciano Spinello, and Wolfram Burgard. "Organizing objects by predicting user preferences through collaborative filtering." *The International Journal of Robotics Research* 35, no. 13 (2016): 1587-1608.

https://www.youtube.com/watch?app=desktop&v=_icB8QcycMM

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,"Accepted 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

Taxonomy of Grasps

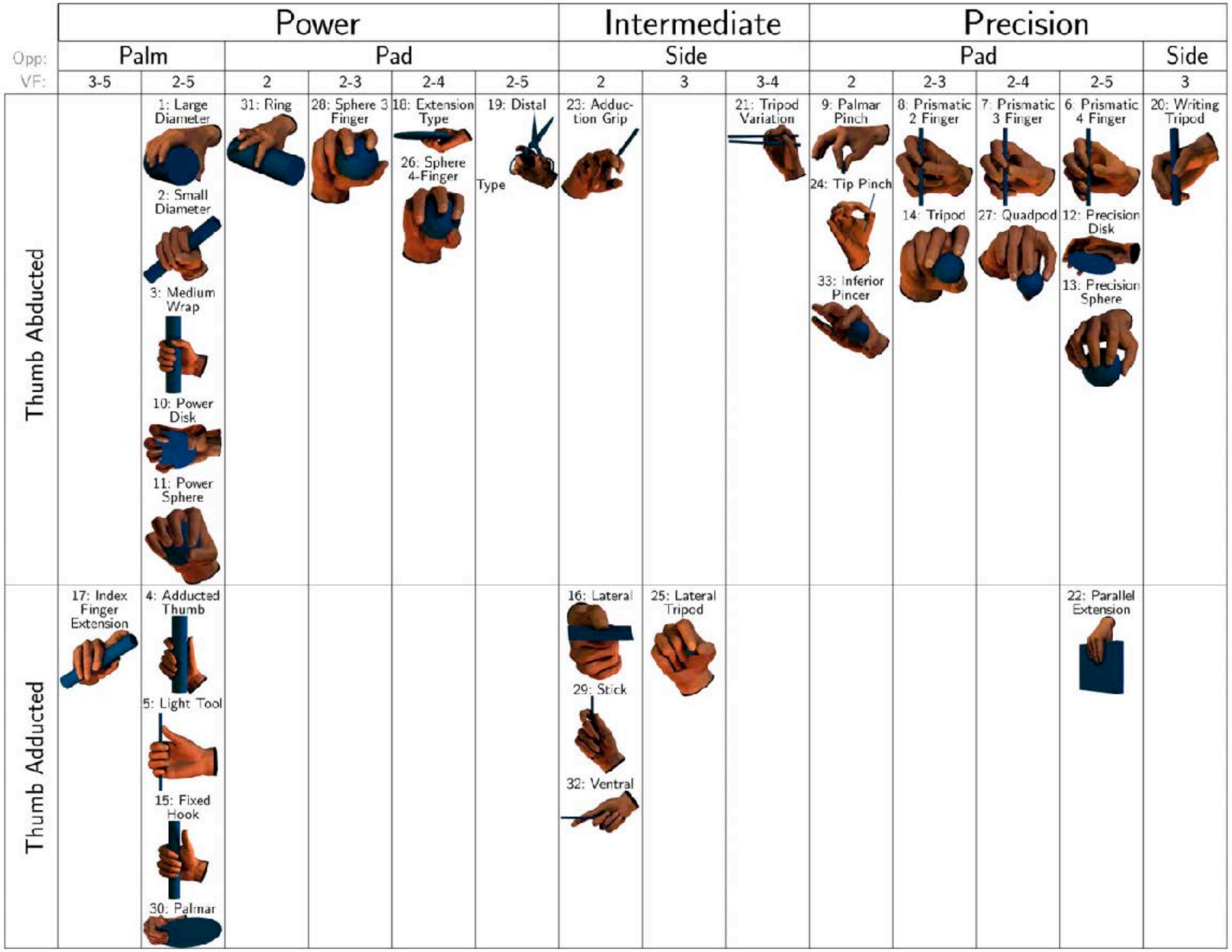


Fig. 4. GRASP taxonomy that incorporates all previous grasp classifications. The grasps are classified in the columns according to their assignment into power, intermediate and precision grasp, the opposition type, and the VF assignment. The assignment of the rows is done be the position of the thumb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

Next lecture:
Planning