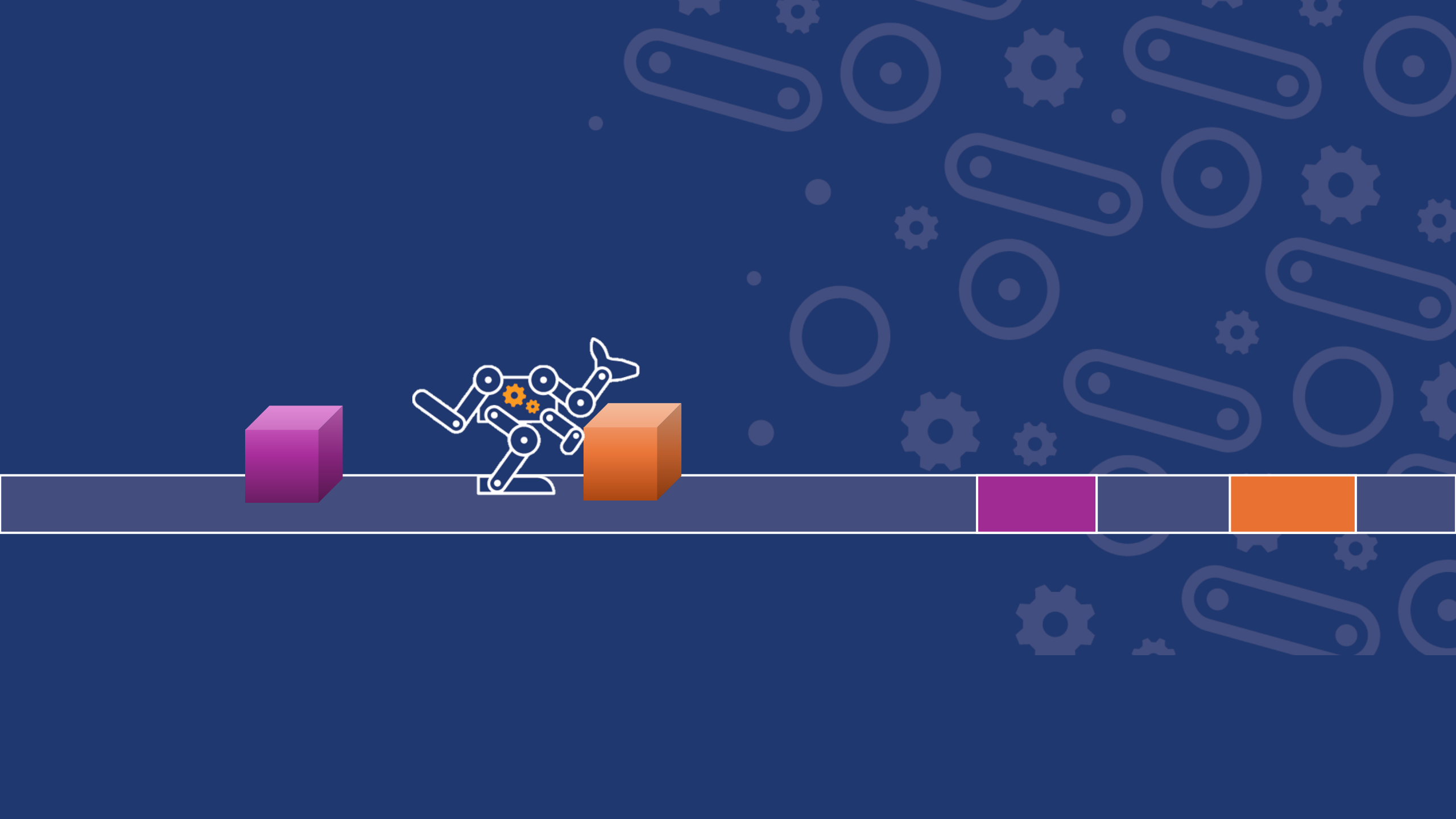
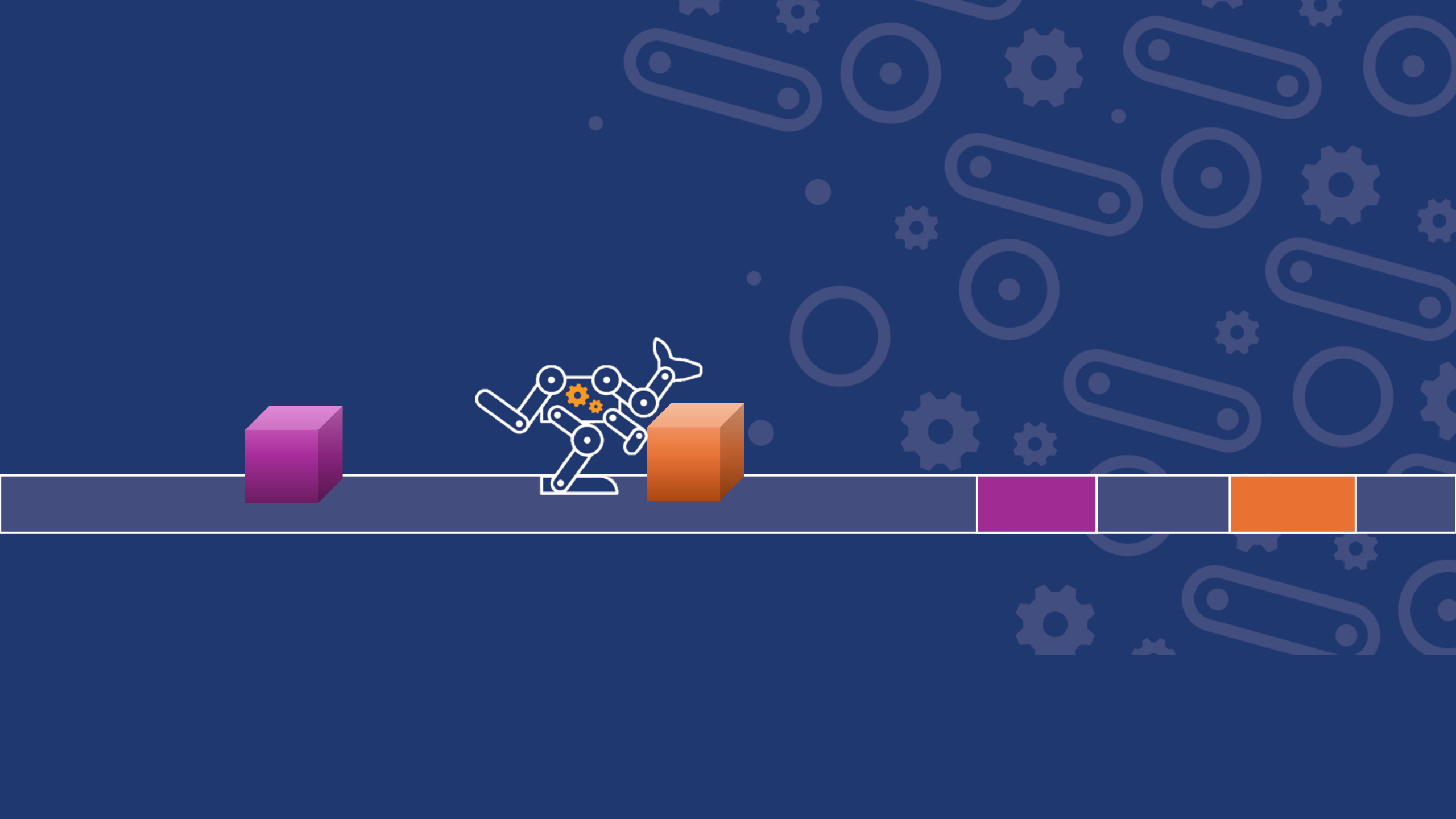
AuSRoS

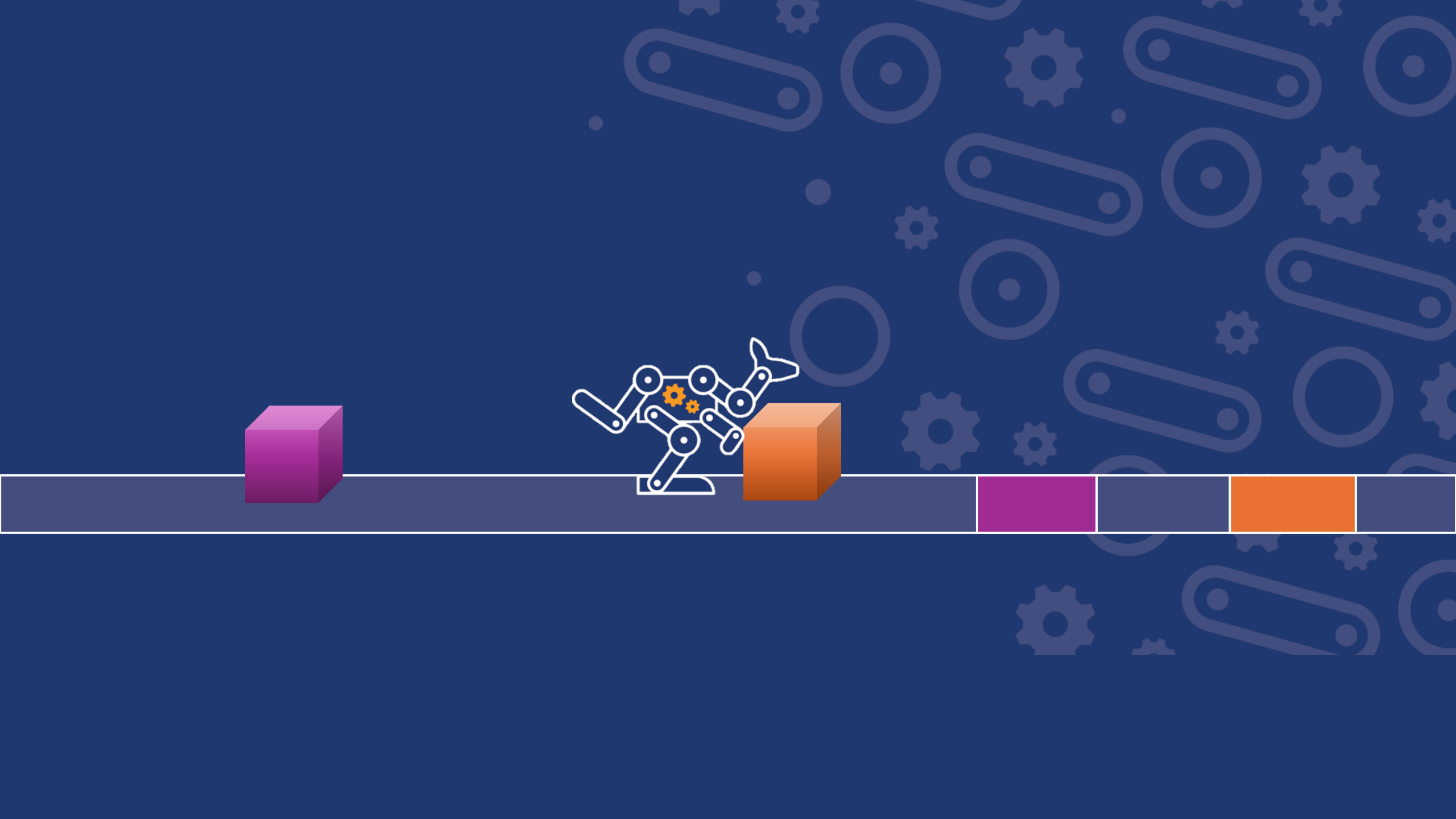
Australian School of Robotic Systems

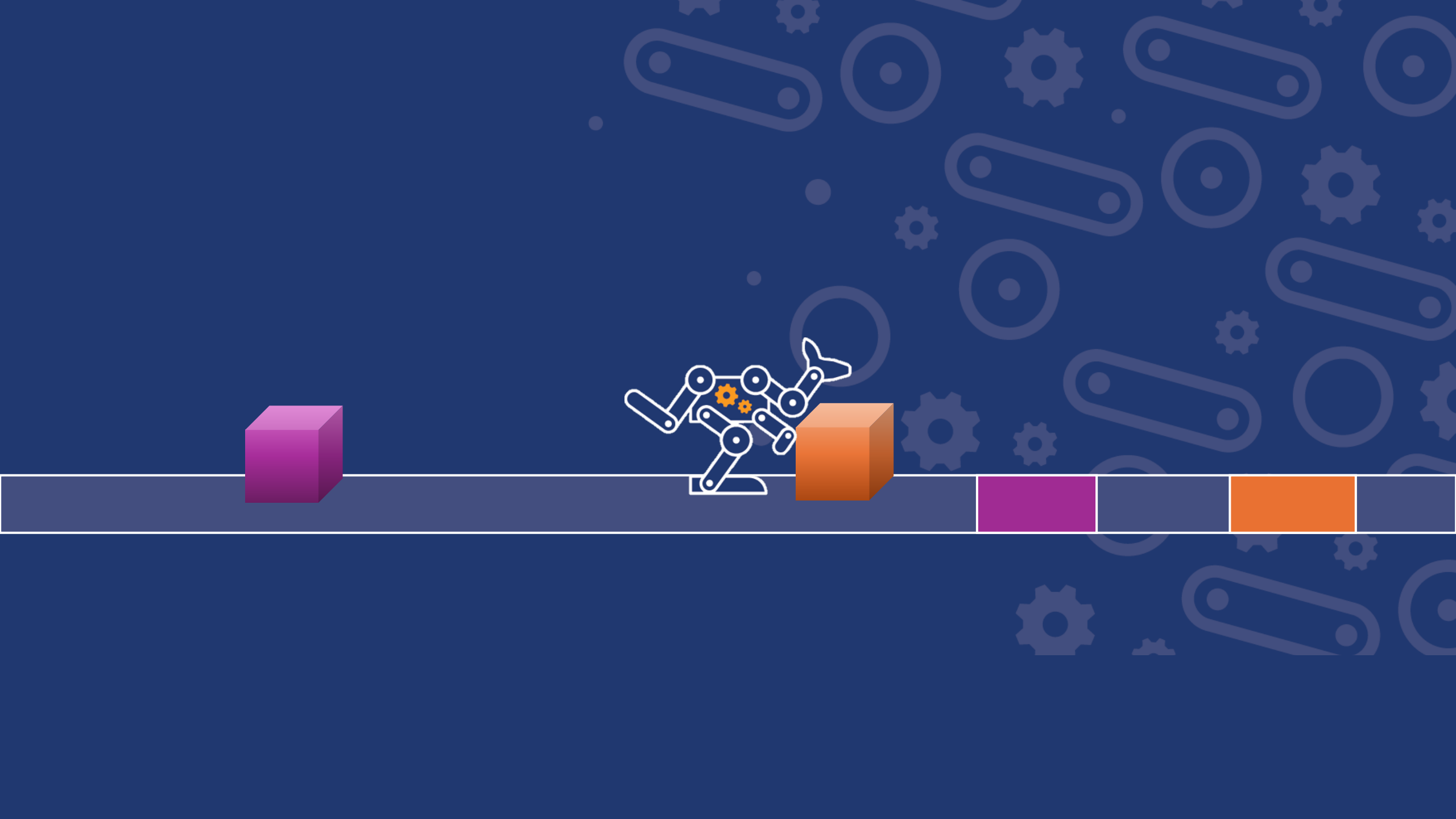
B1 – From Manipulation Planning to Task and Motion Planning

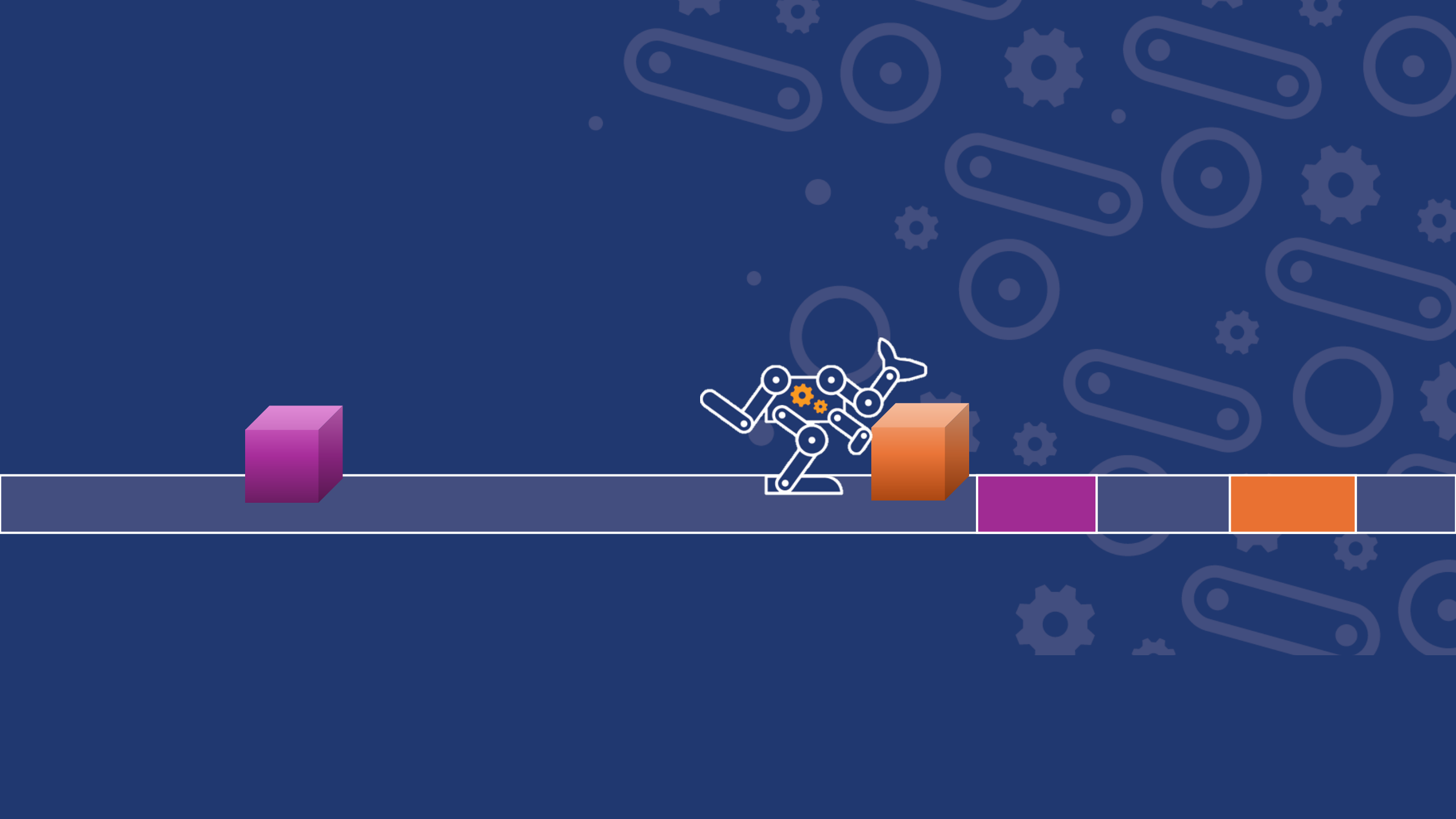
Rahul Shome
Lecturer, School of Computing
Australian National University

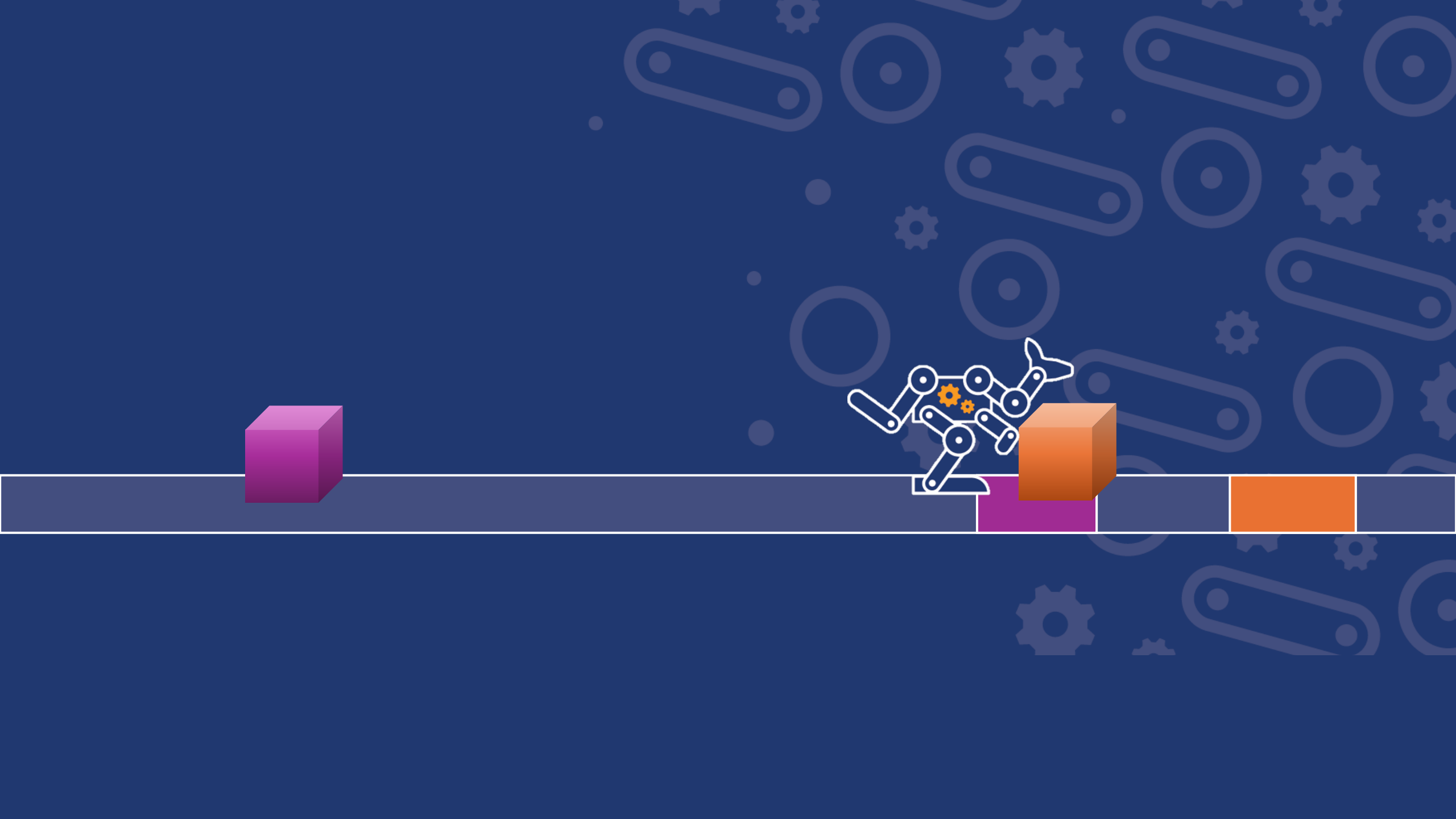


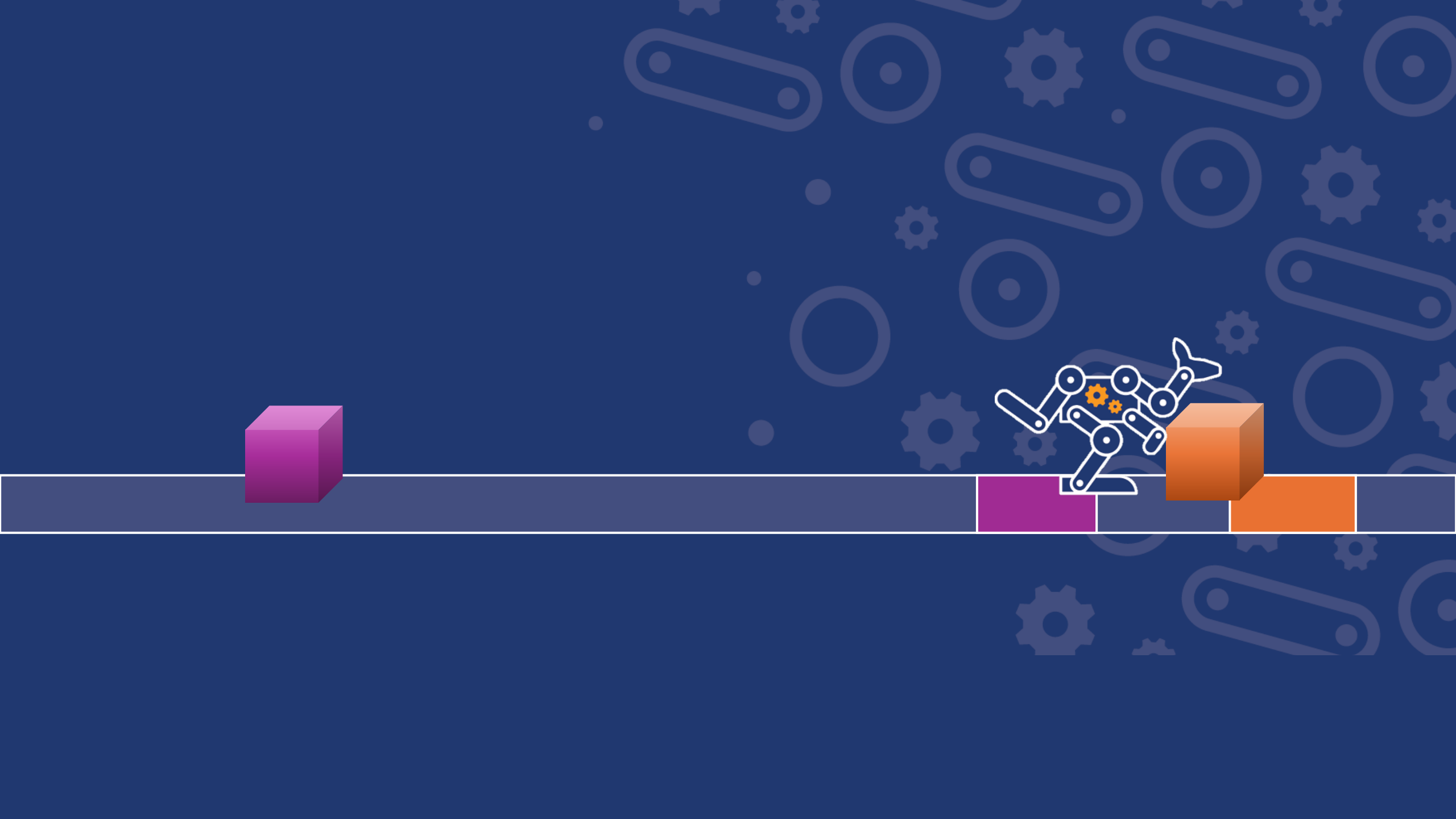


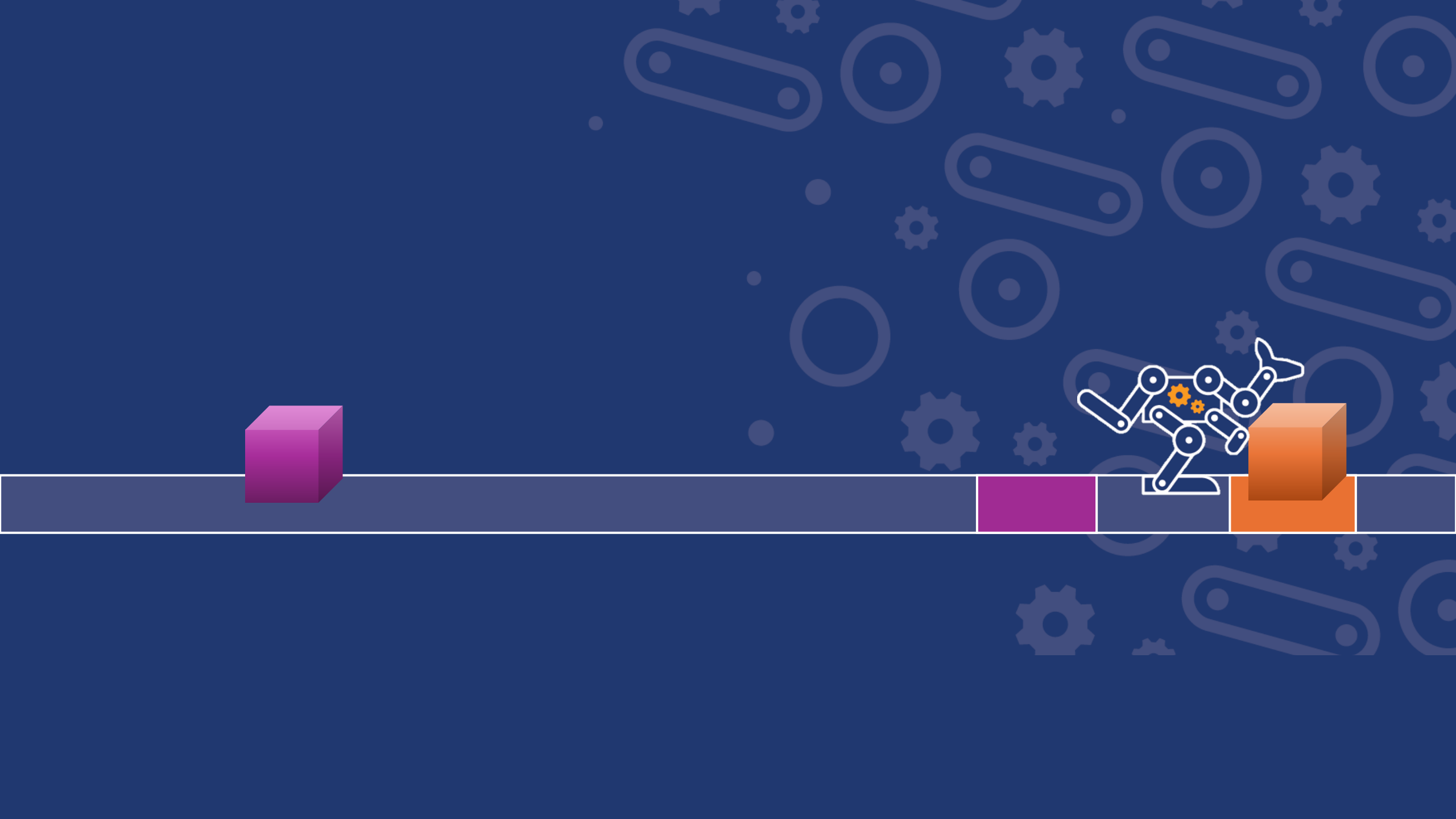


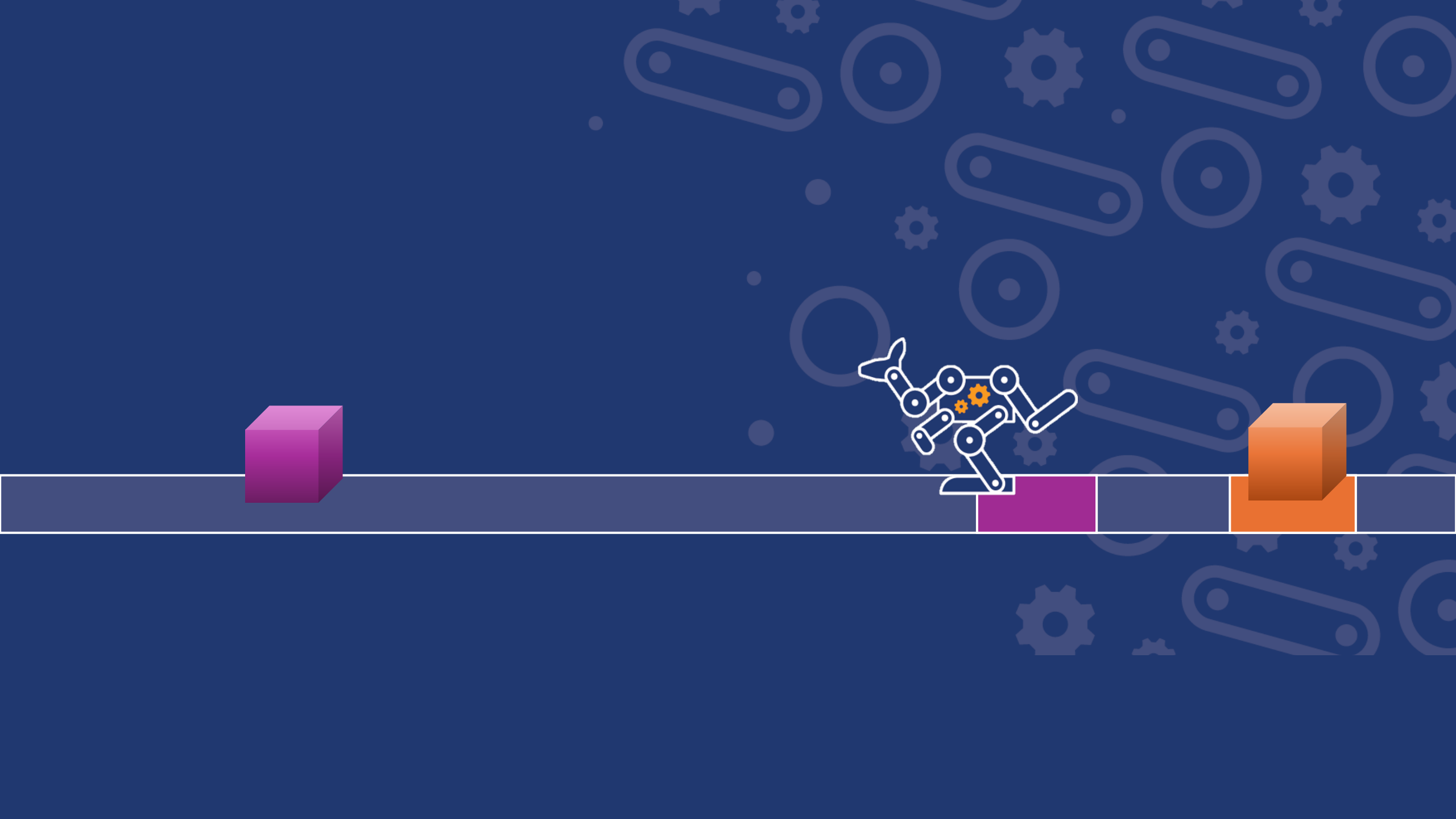


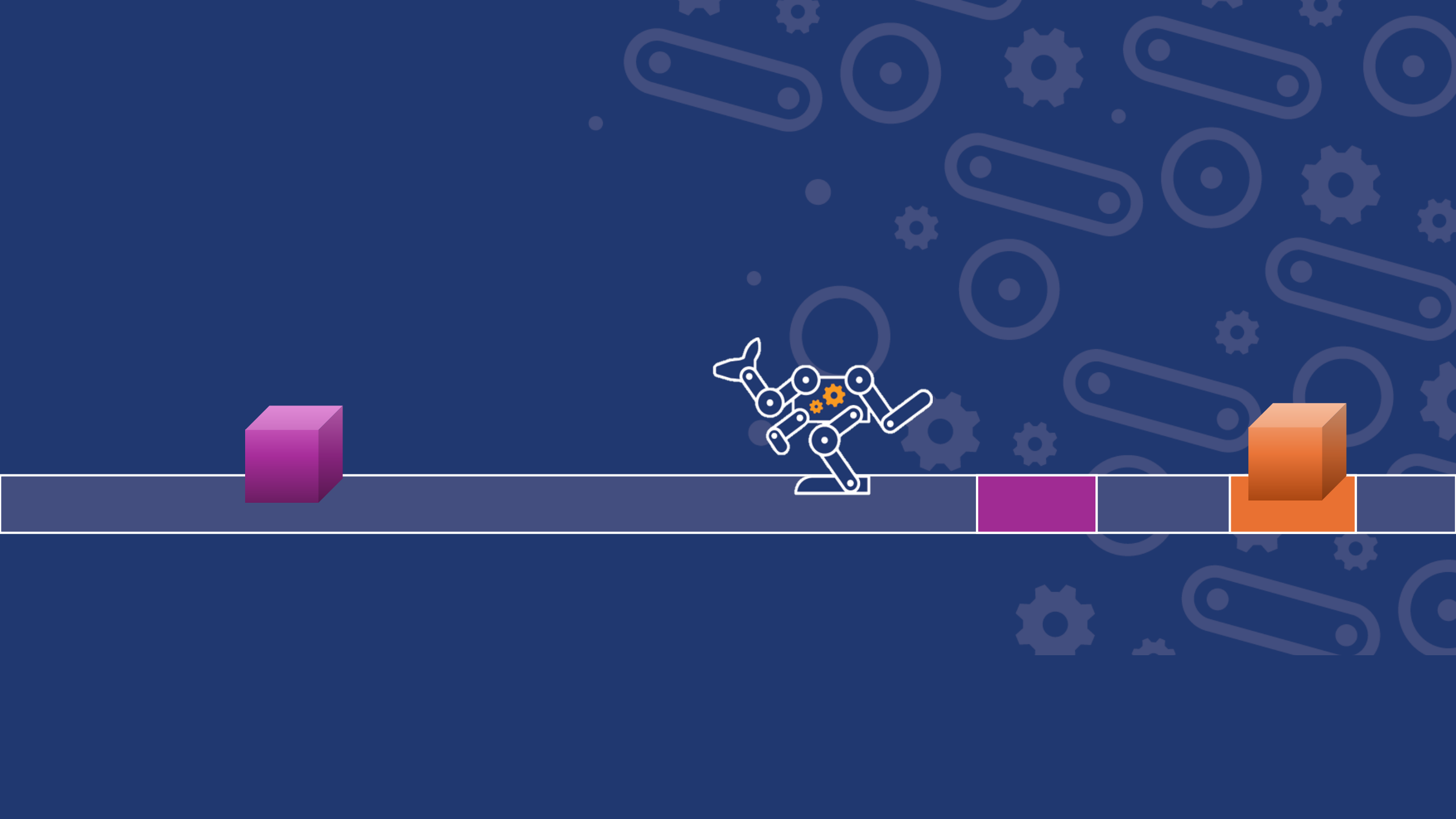


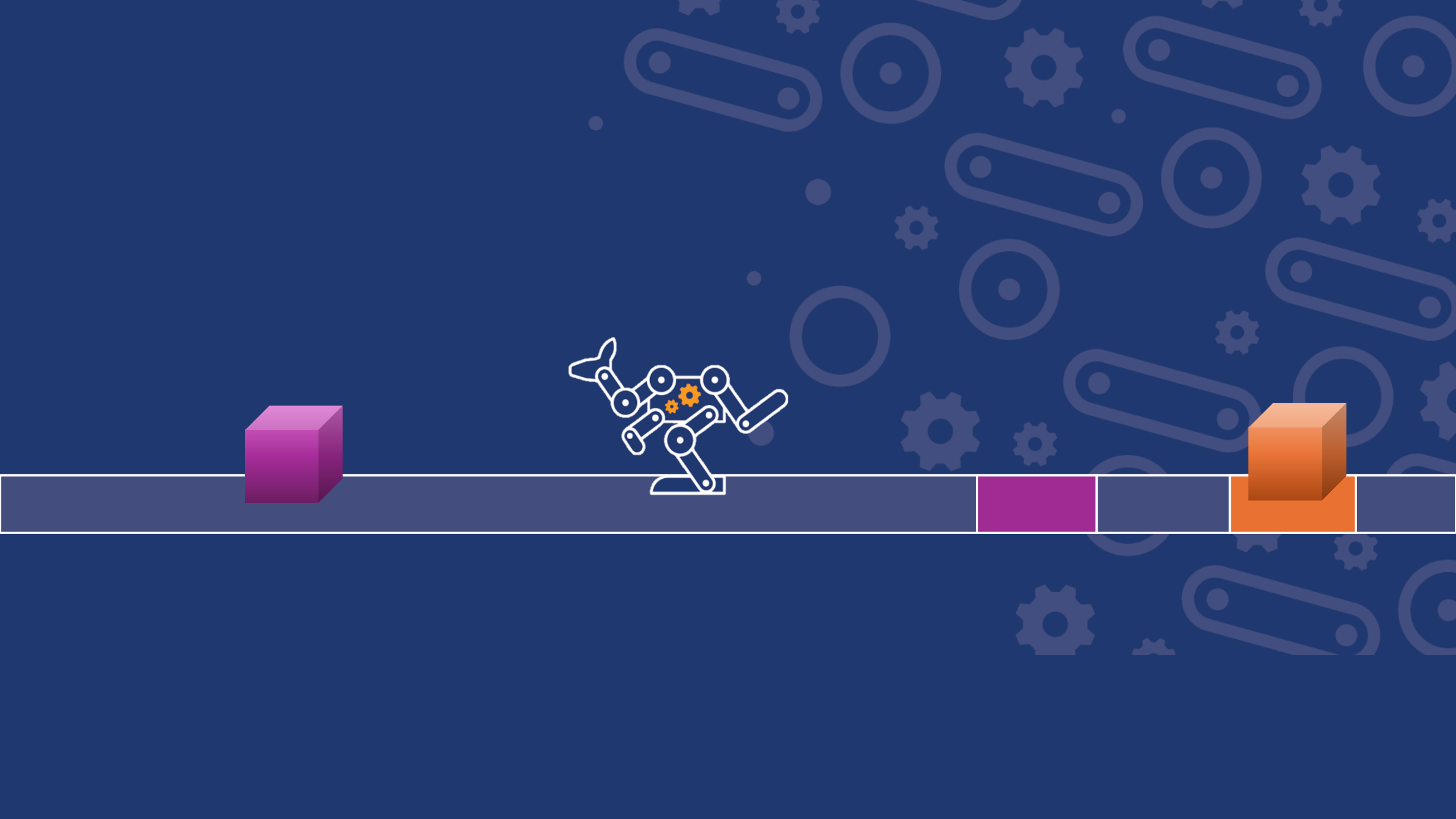


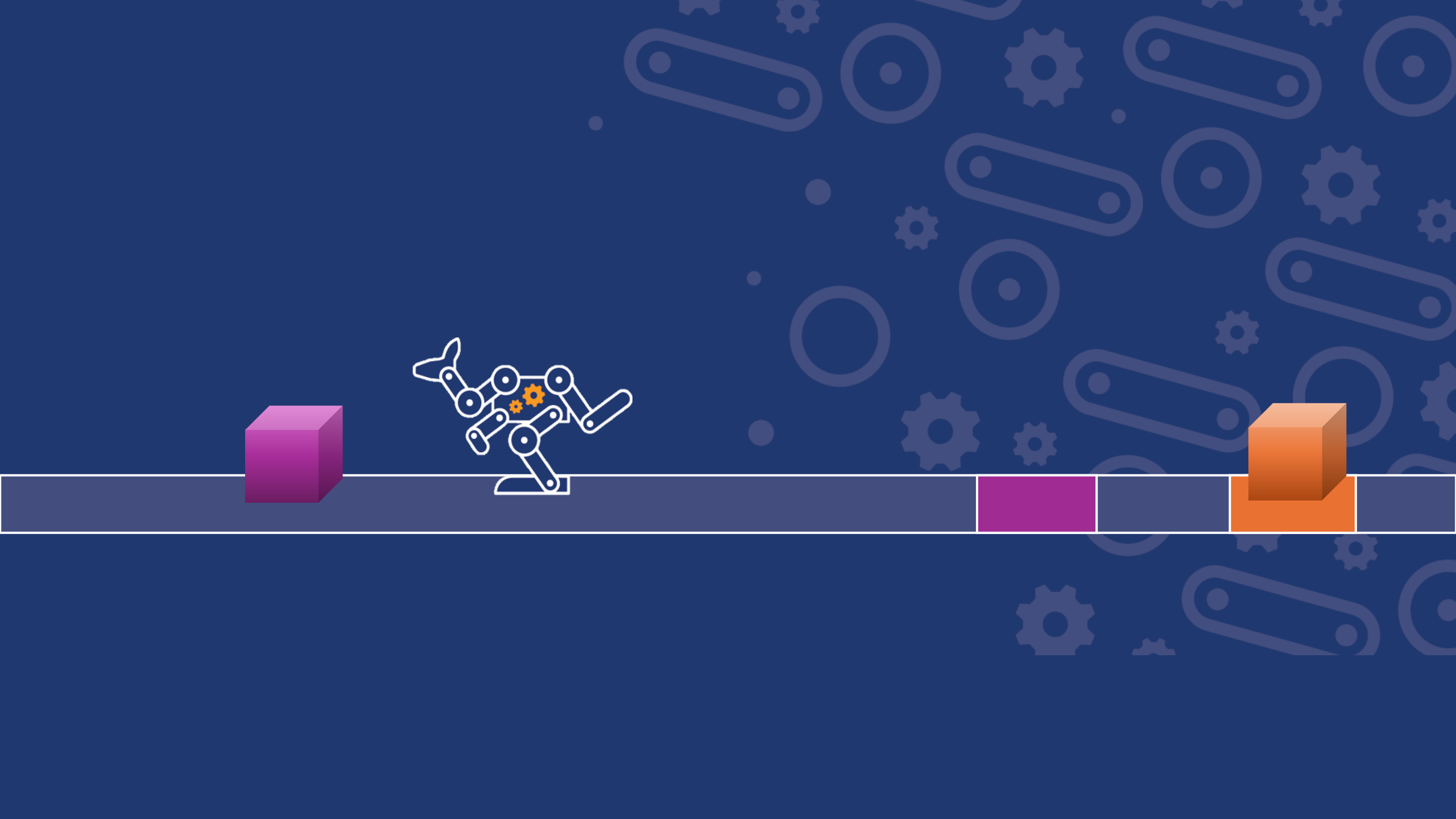


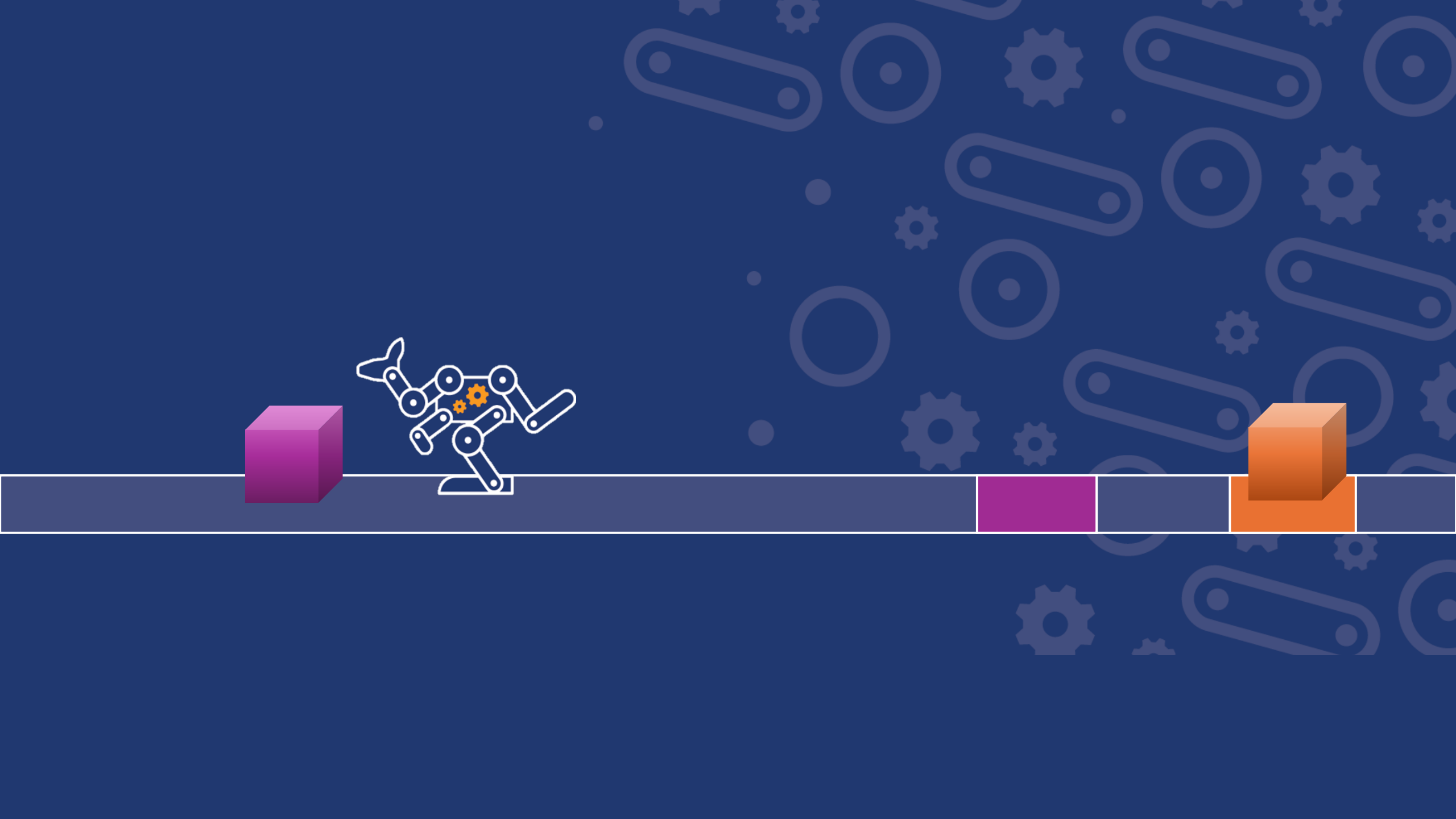


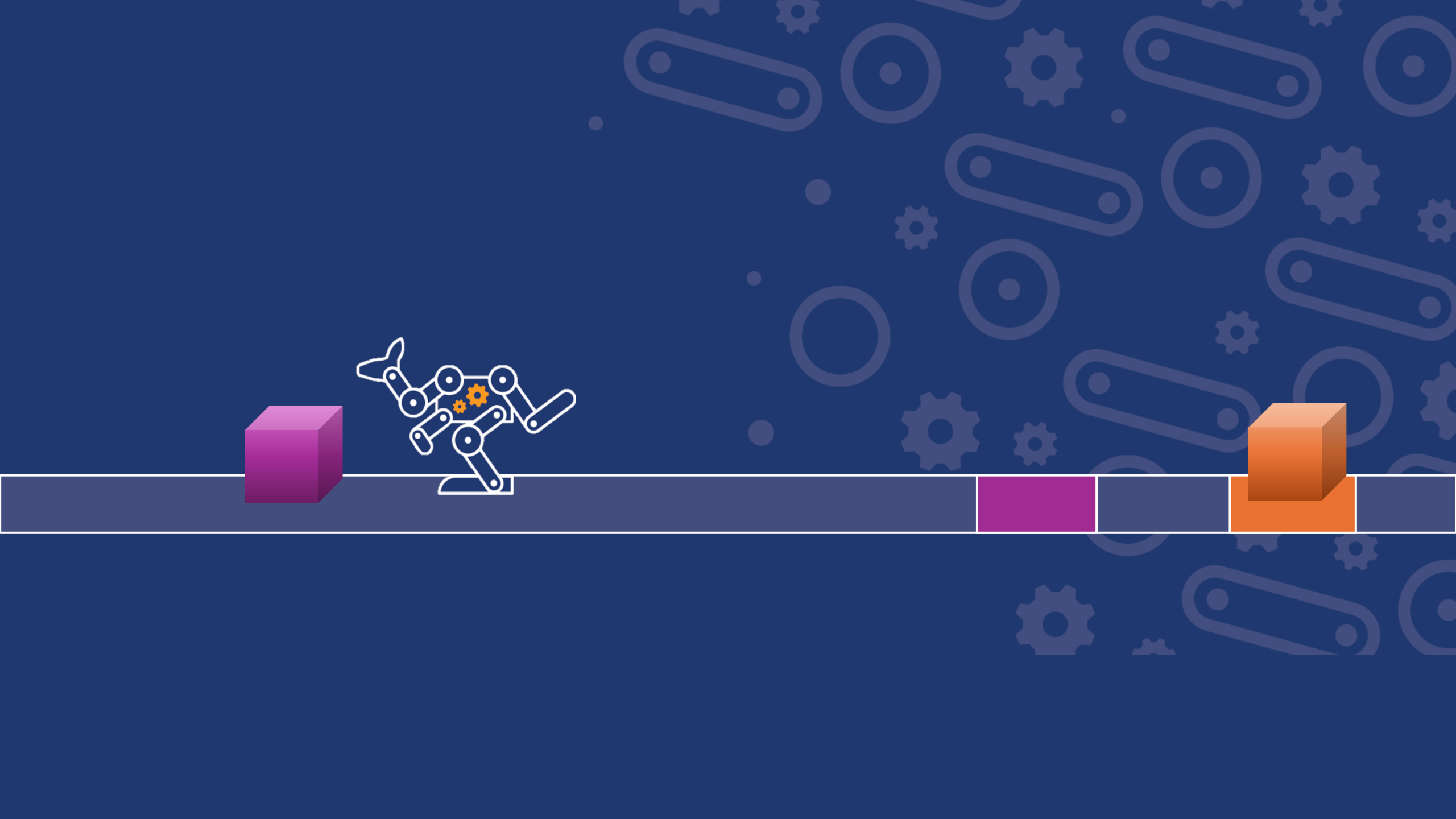


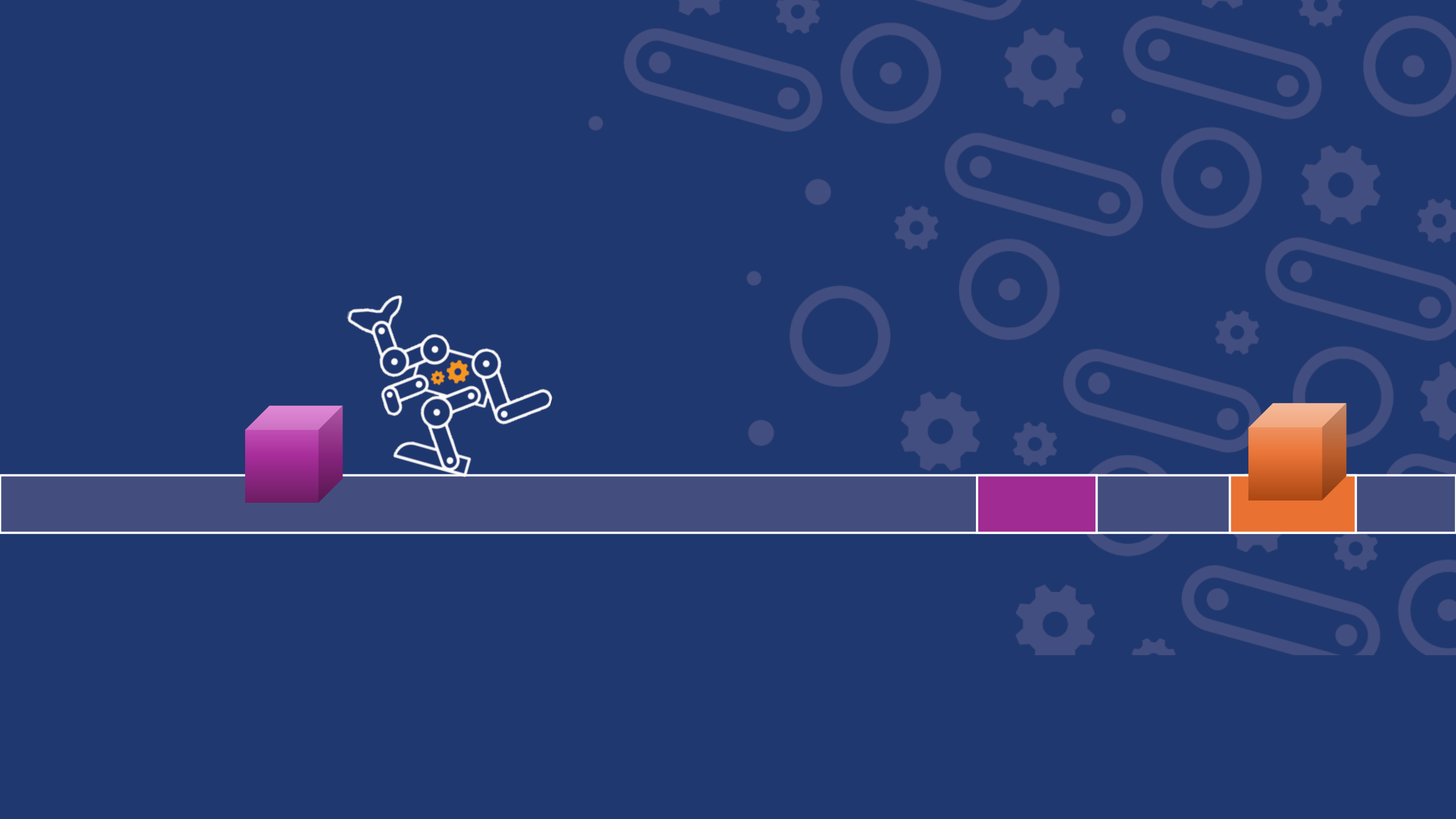


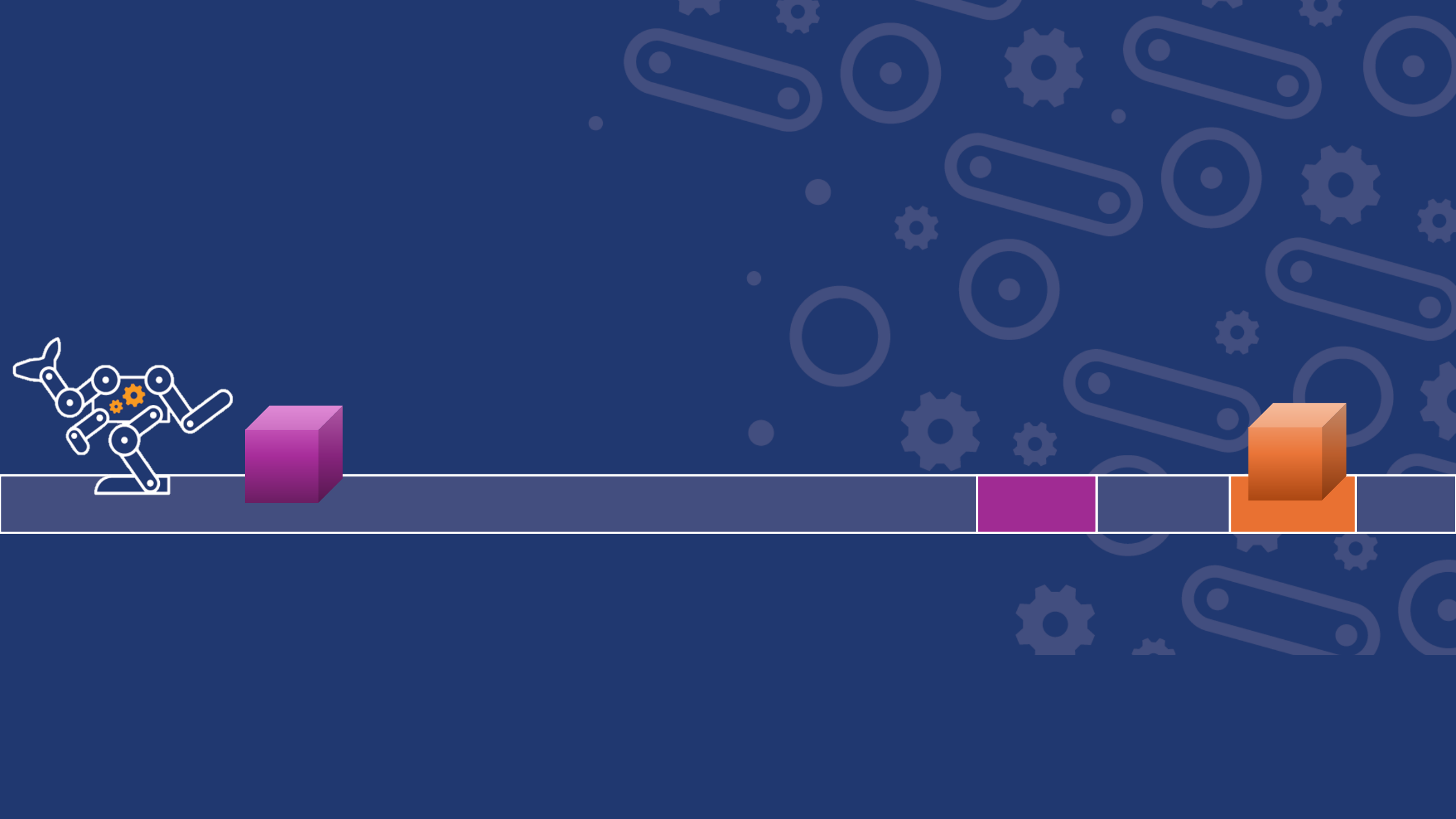


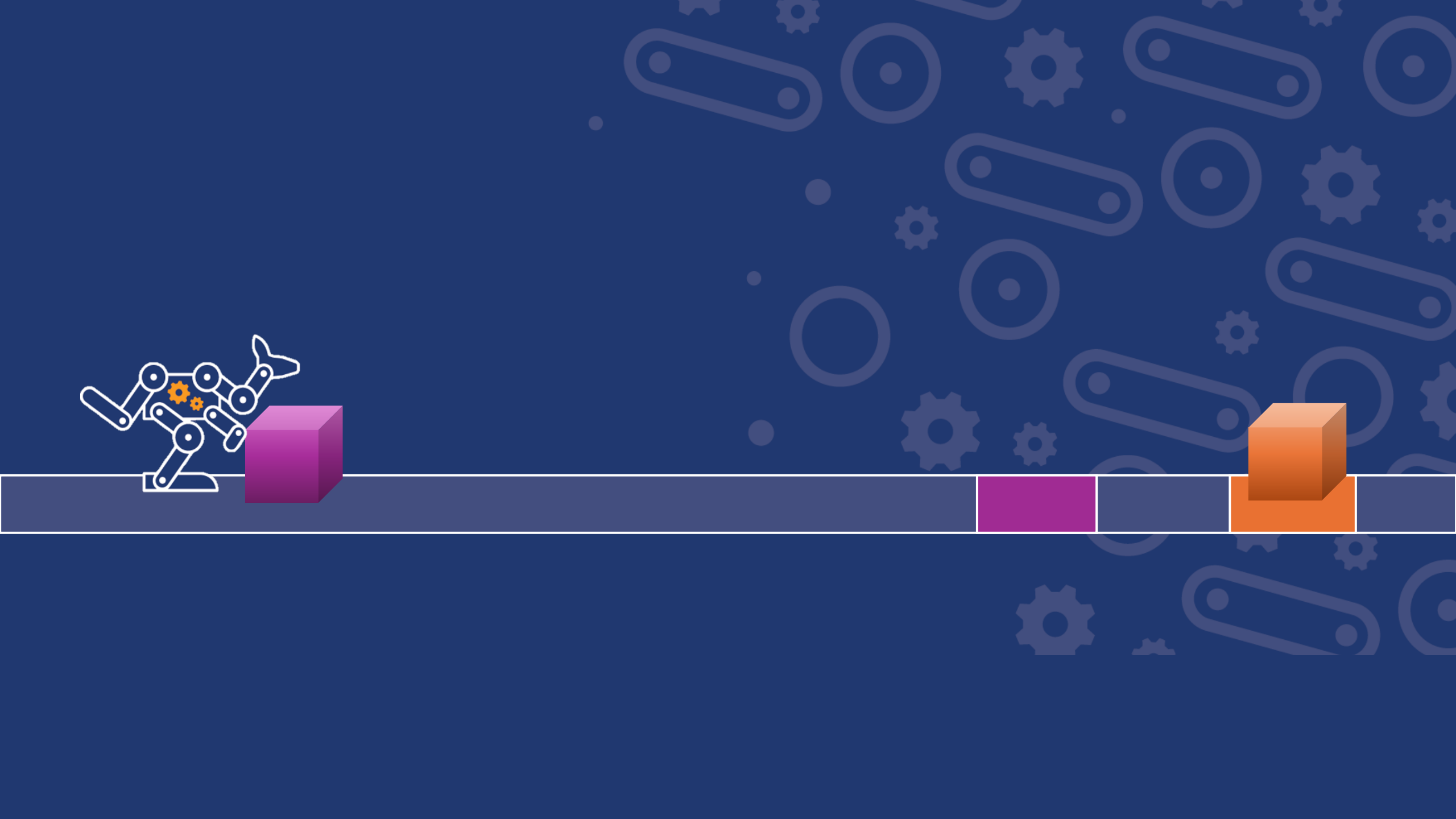


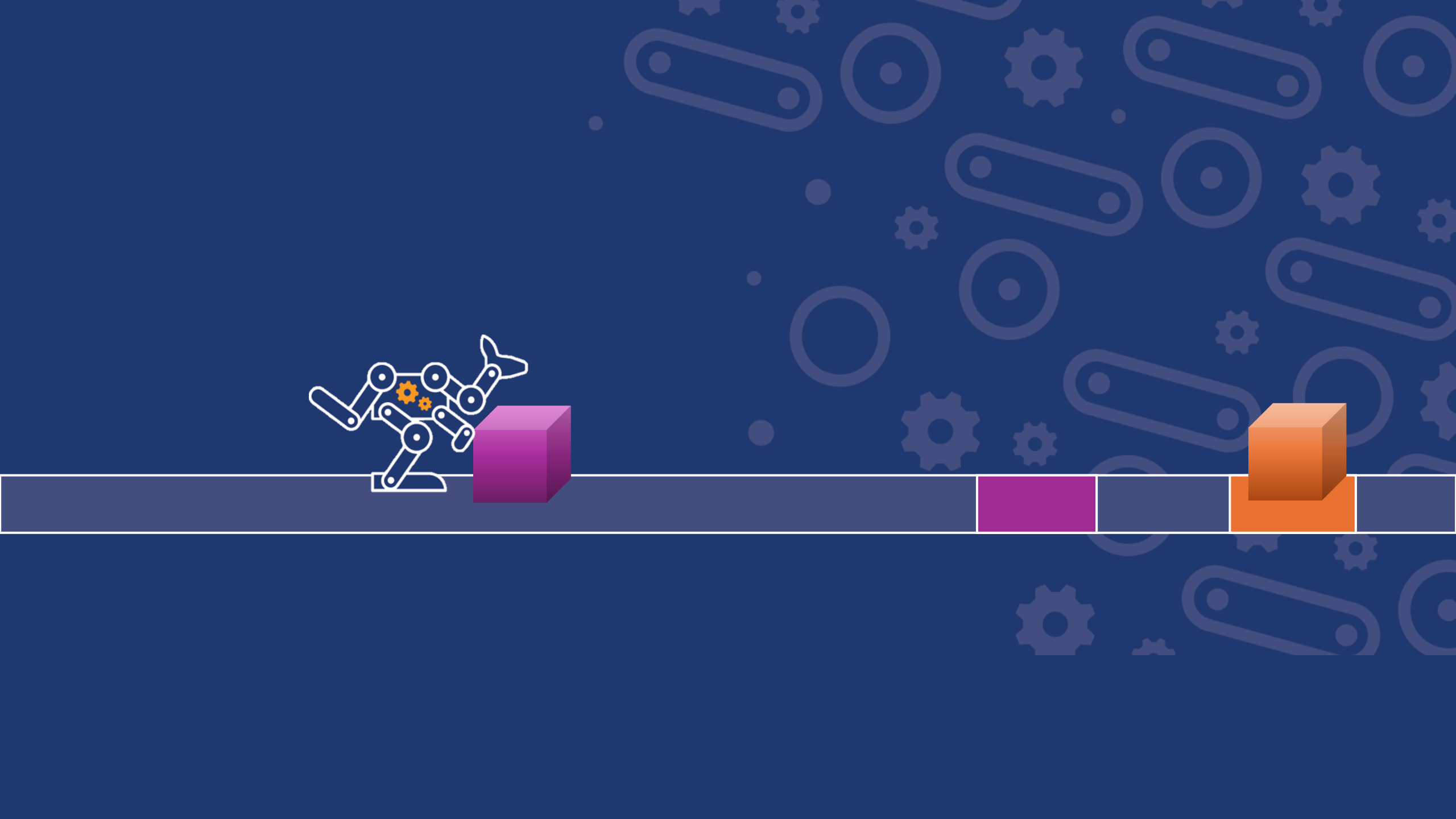


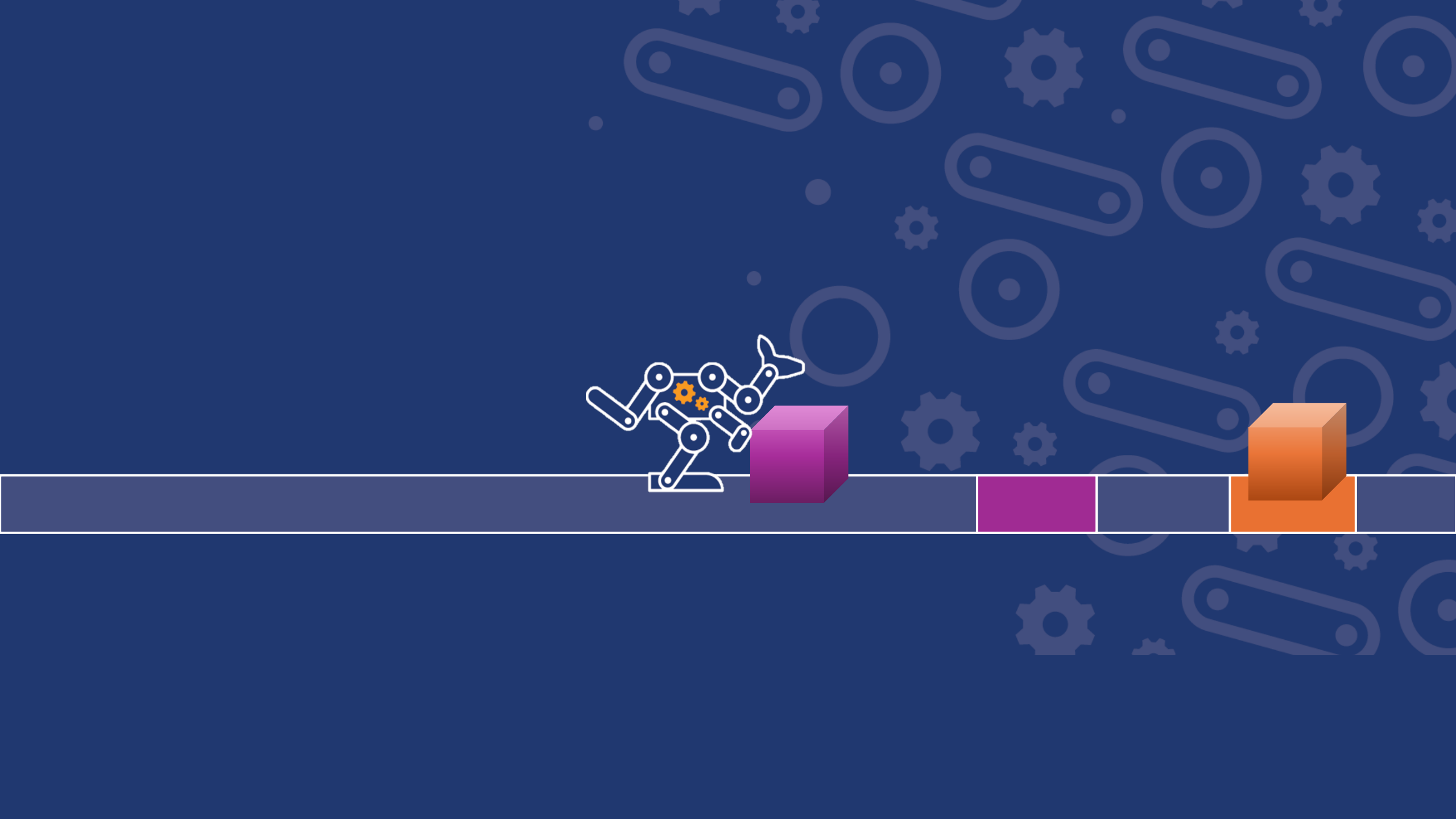


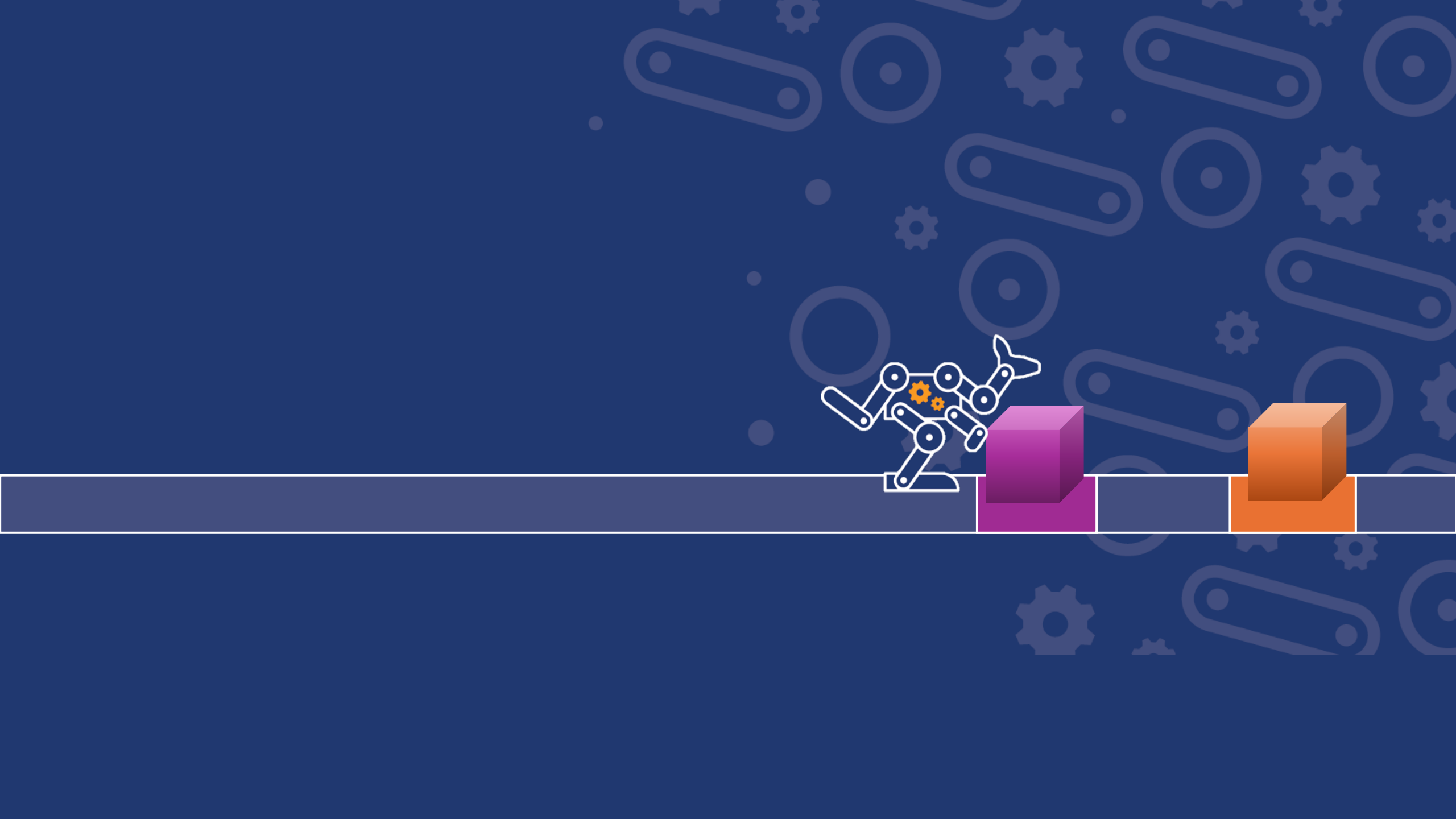


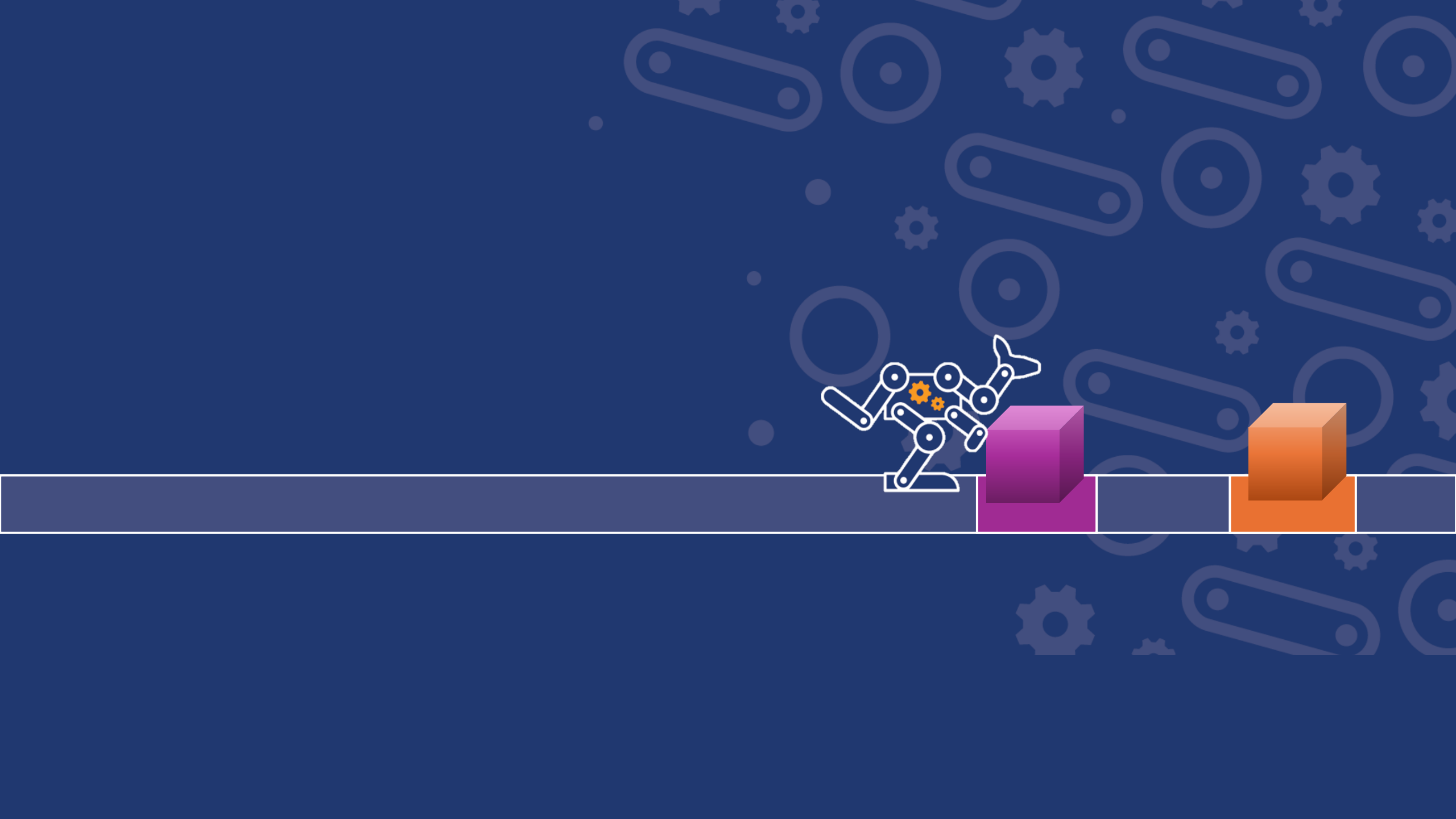






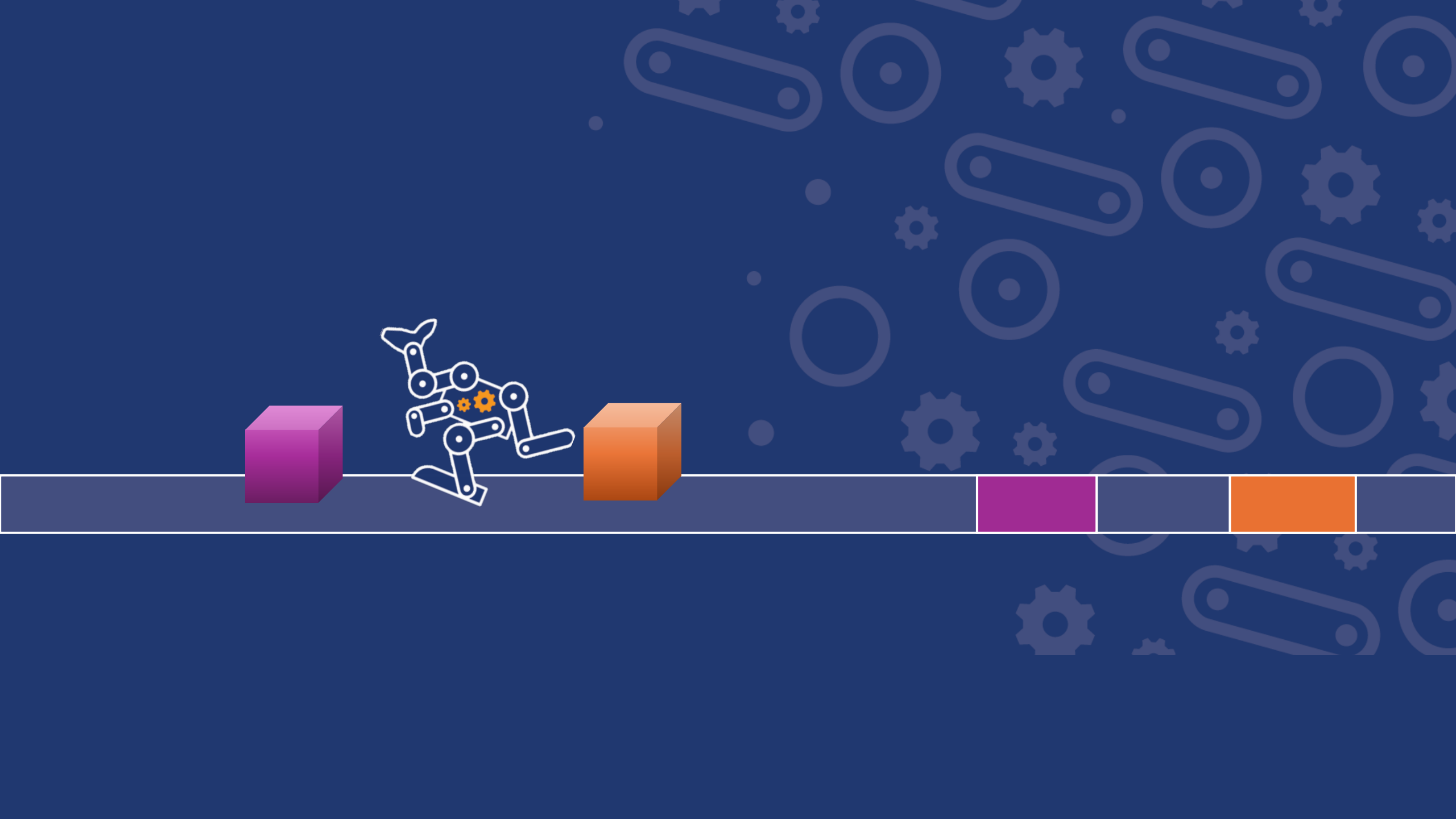


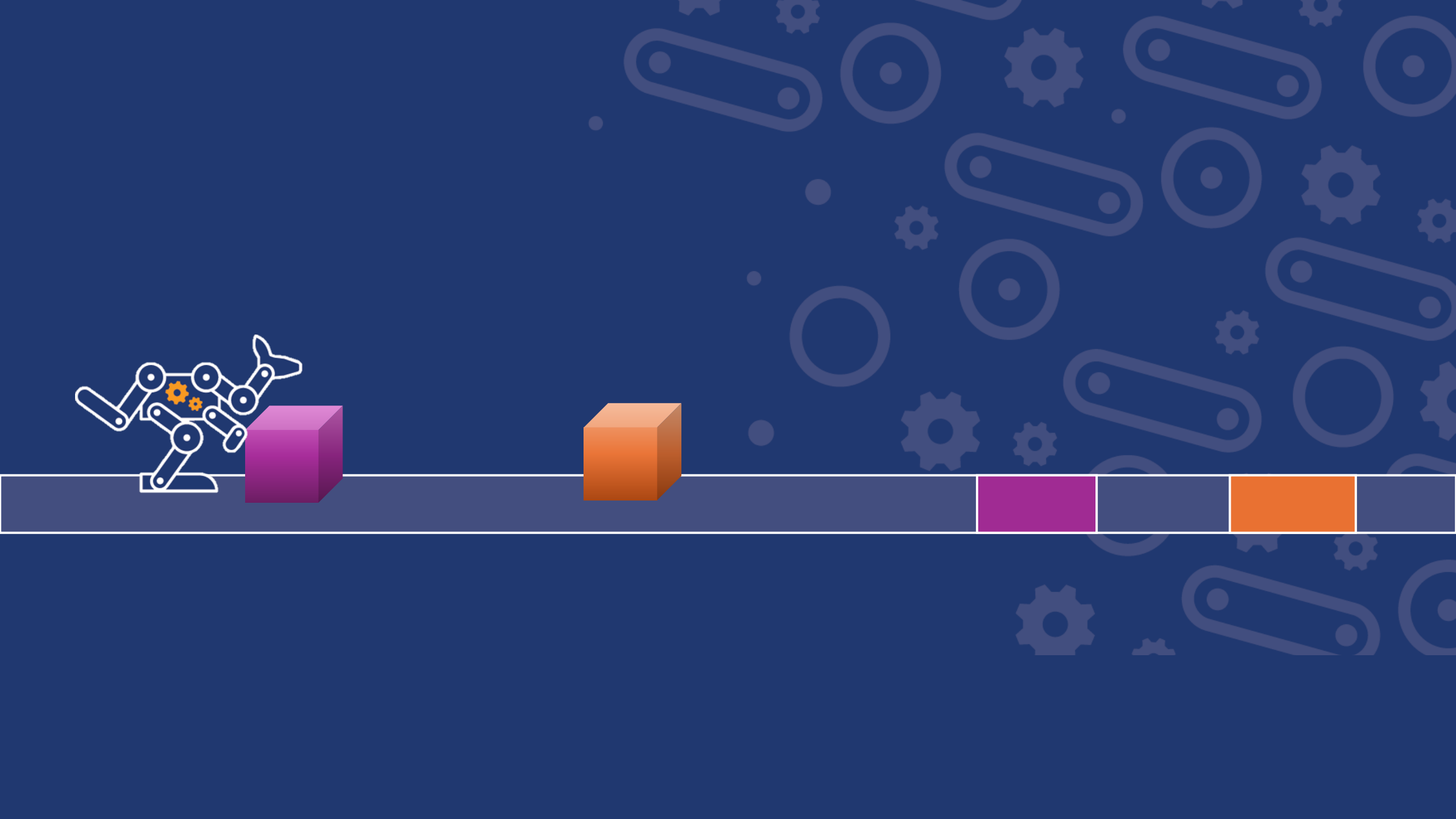


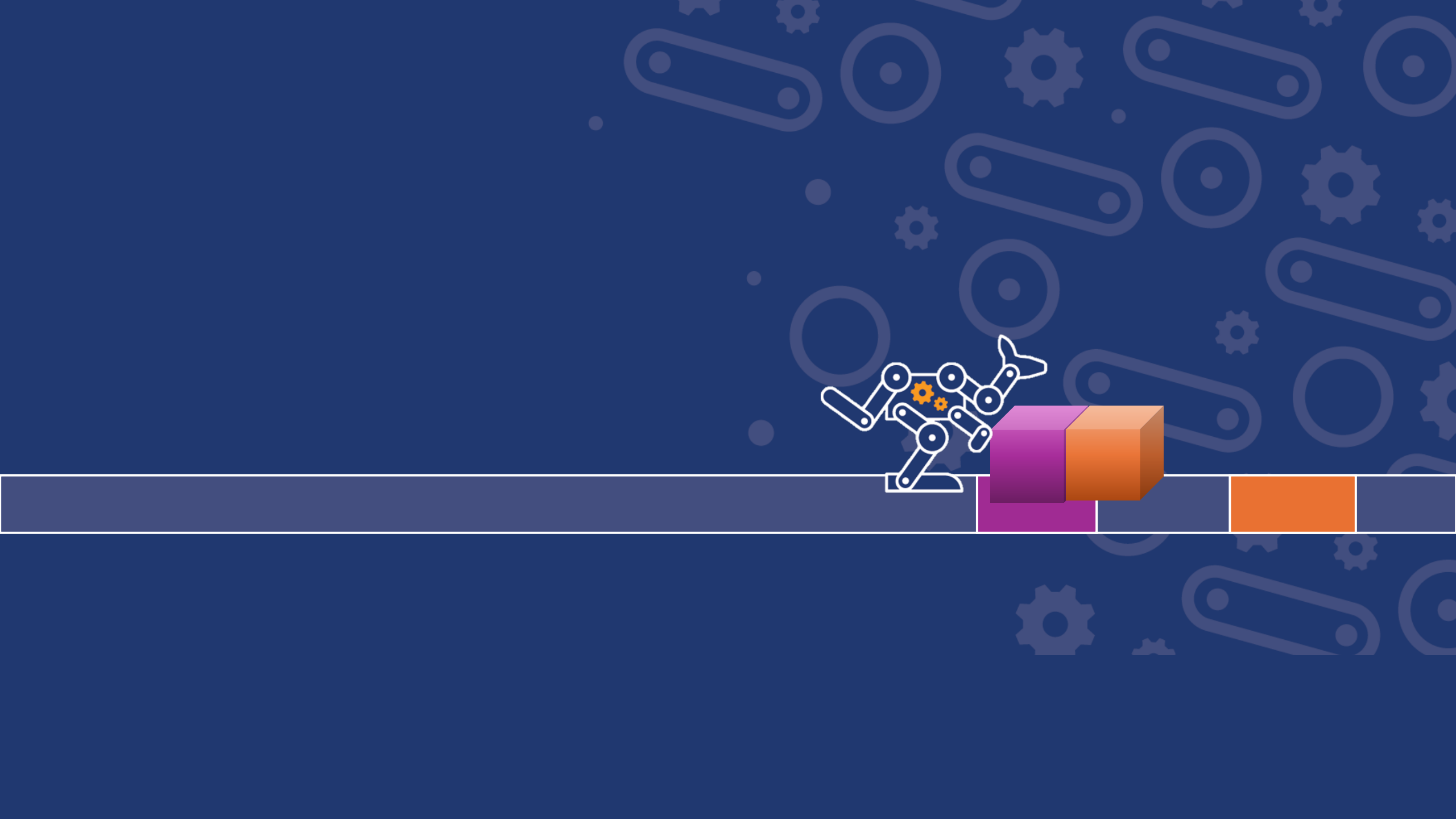


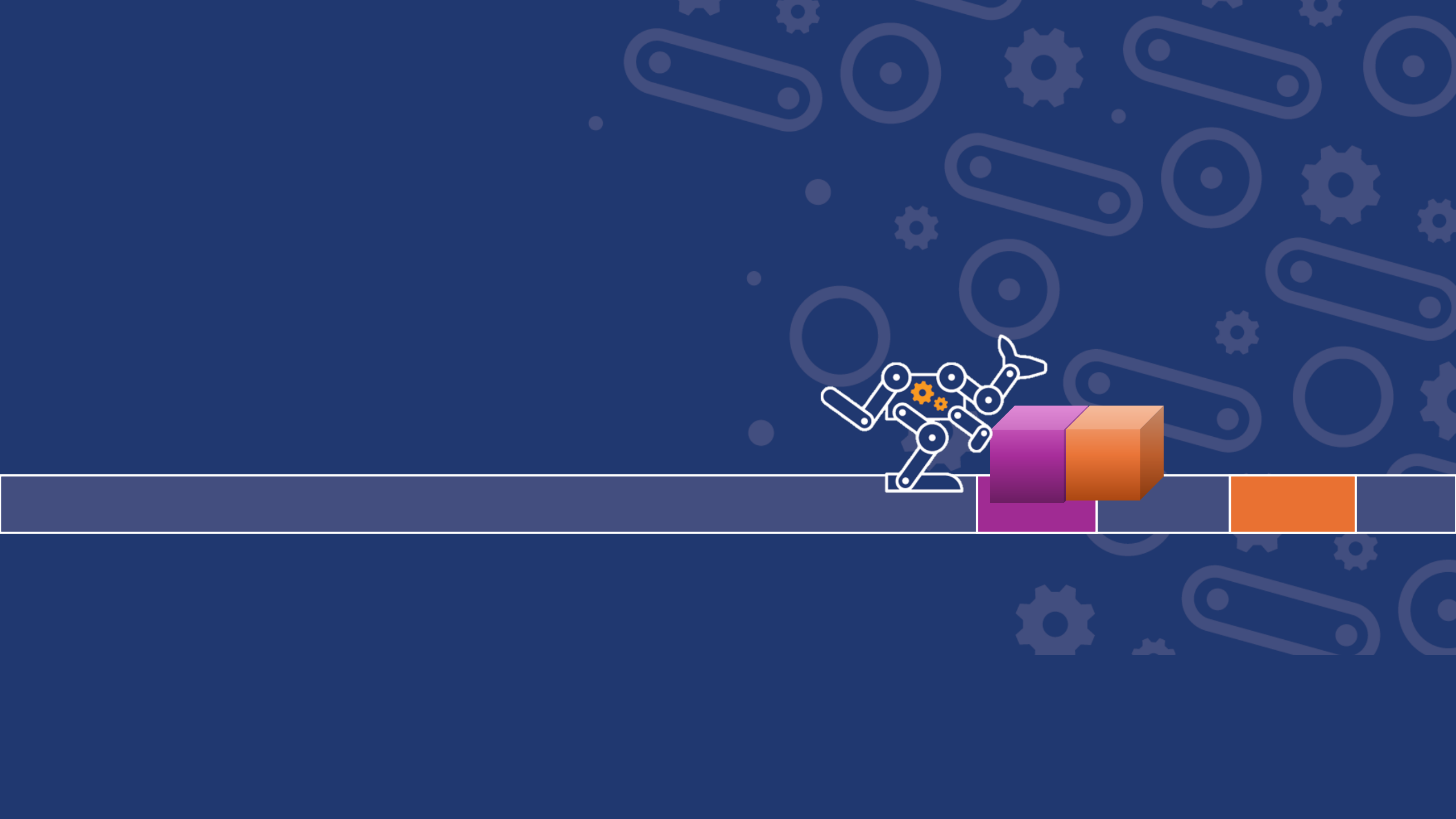
How to interact with and move the blocks?

Which block to move first?









How to interact with and move the blocks?

Which block to move first?

Manipulation

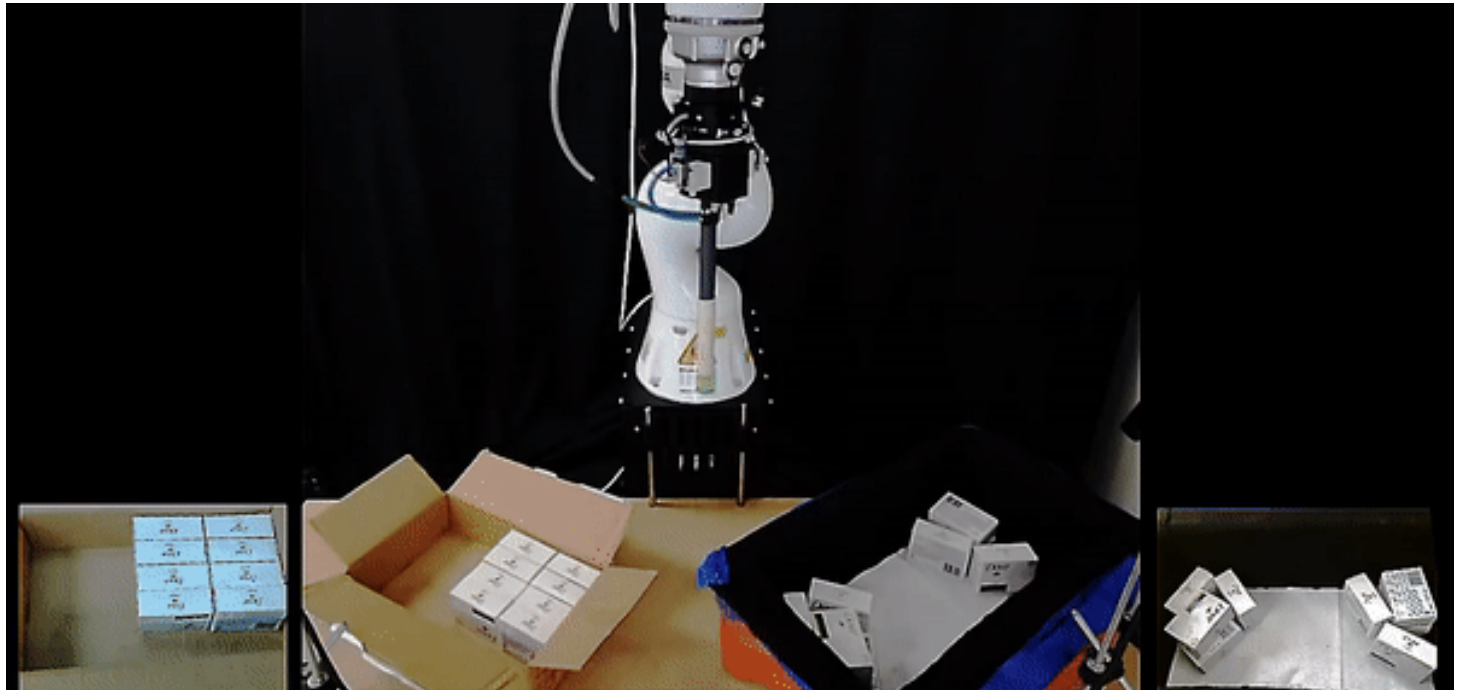
Manipulation

Manipulation is when an **agent moves things** other than itself through **selective contact**.

Mason, Matthew T. "Toward robotic manipulation." *Annual Review of Control, Robotics, and Autonomous Systems* 1, no. 1 (2018): 1-28.

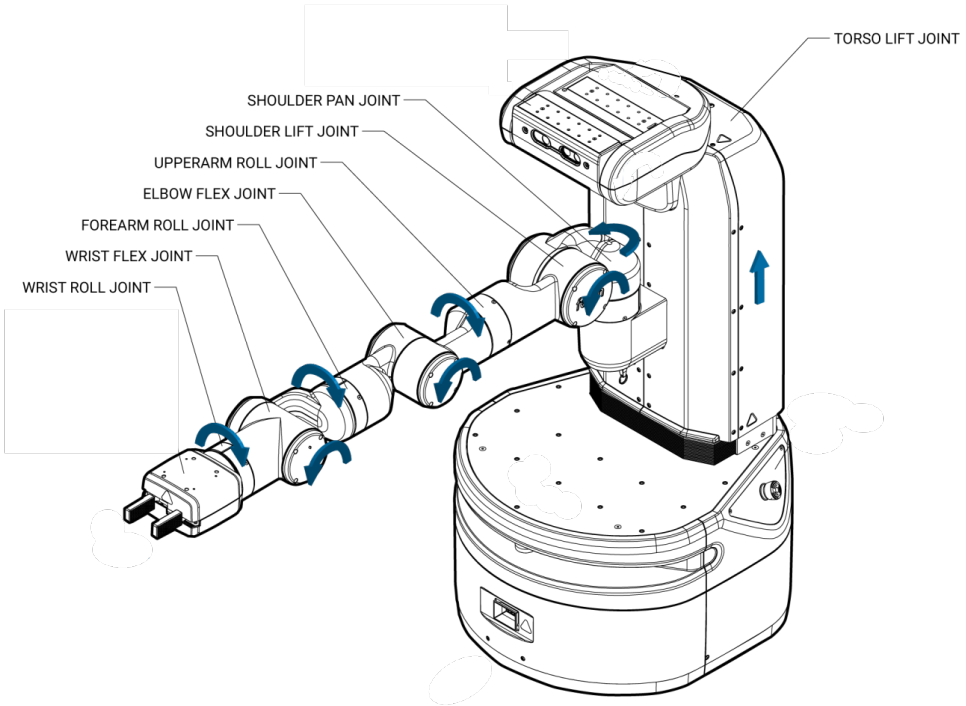
Manipulation

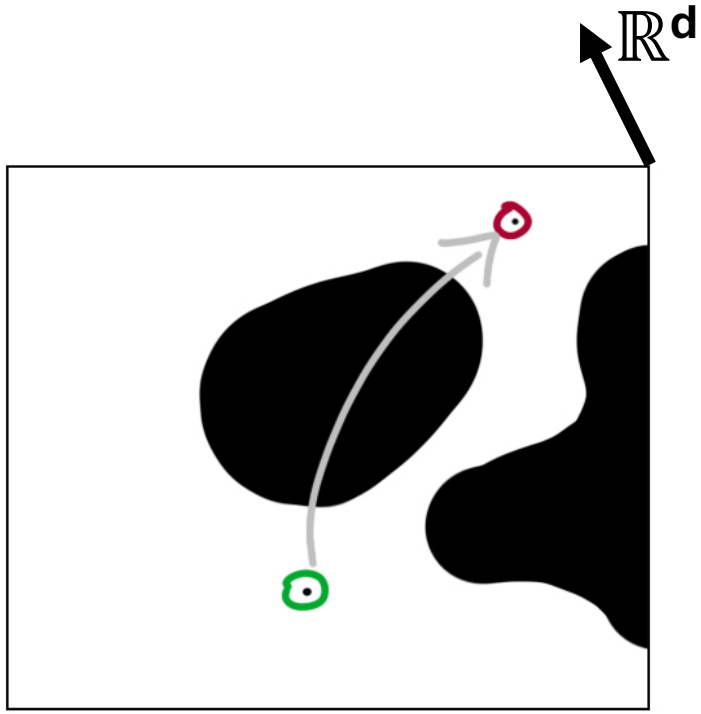
Manipulation is when an **agent moves things** other than itself through **selective contact**.



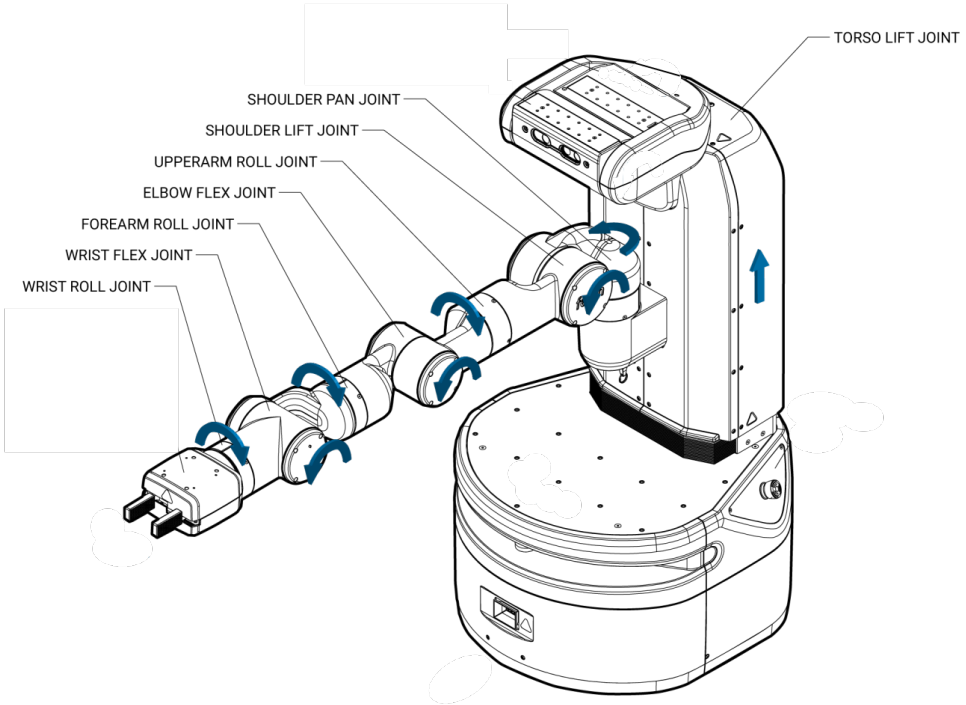
Shome, Rahul, Wei N. Tang, Changkyu Song, Chaitanya Mitash, Hristiyan Kourtev, Jingjin Yu, Abdeslam Boularias, and Kostas E. Bekris. "Towards robust product packing with a minimalistic end-effector." In *2019 International Conference on Robotics and Automation (ICRA)*, pp. 9007-9013. IEEE, 2019.

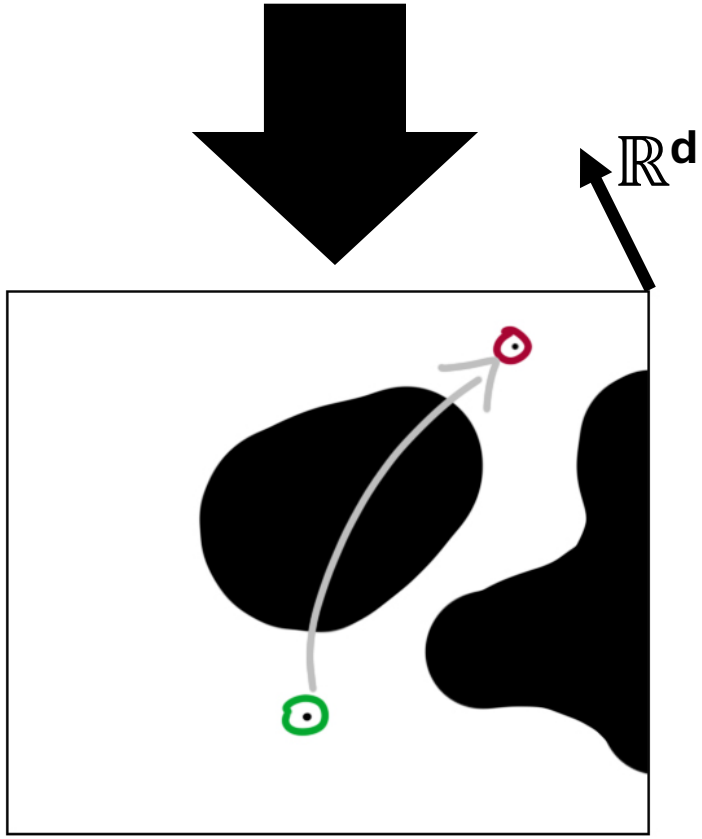
Spaces


TORSO LIFT JOINT
SHOULDER PAN JOINT
SHOULDER LIFT JOINT
UPPERARM ROLL JOINT
ELBOW FLEX JOINT
FOREARM ROLL JOINT
WRIST FLEX JOINT
WRIST ROLL JOINT


$\mathbb{R}^d$

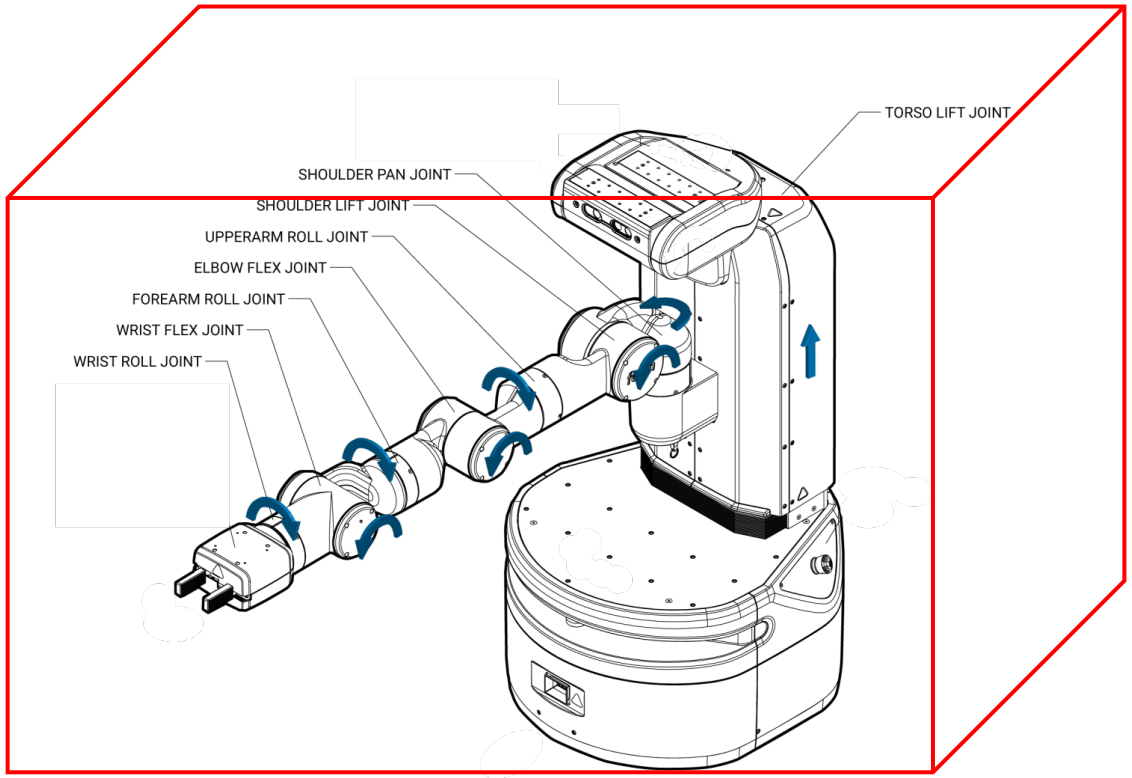
Configuration Space

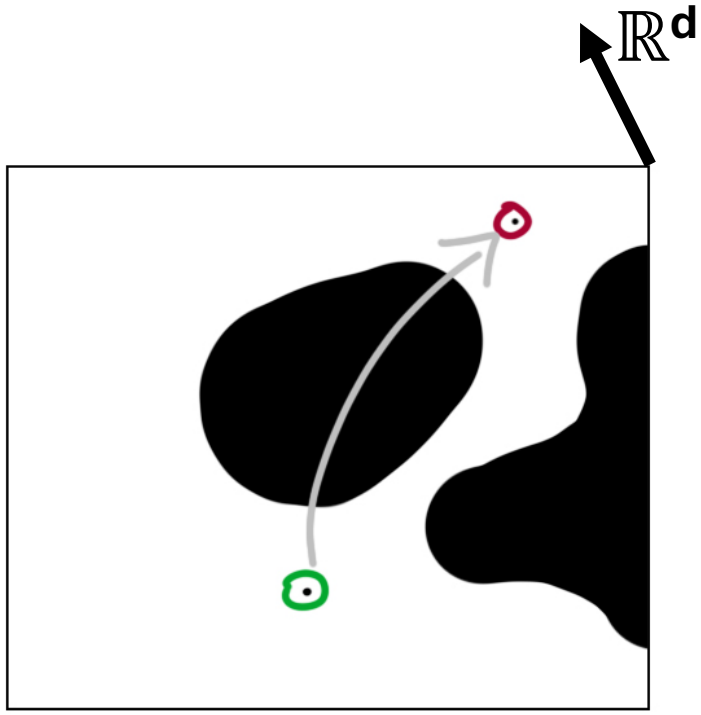




High-dimensional space where a point is a robot configuration.

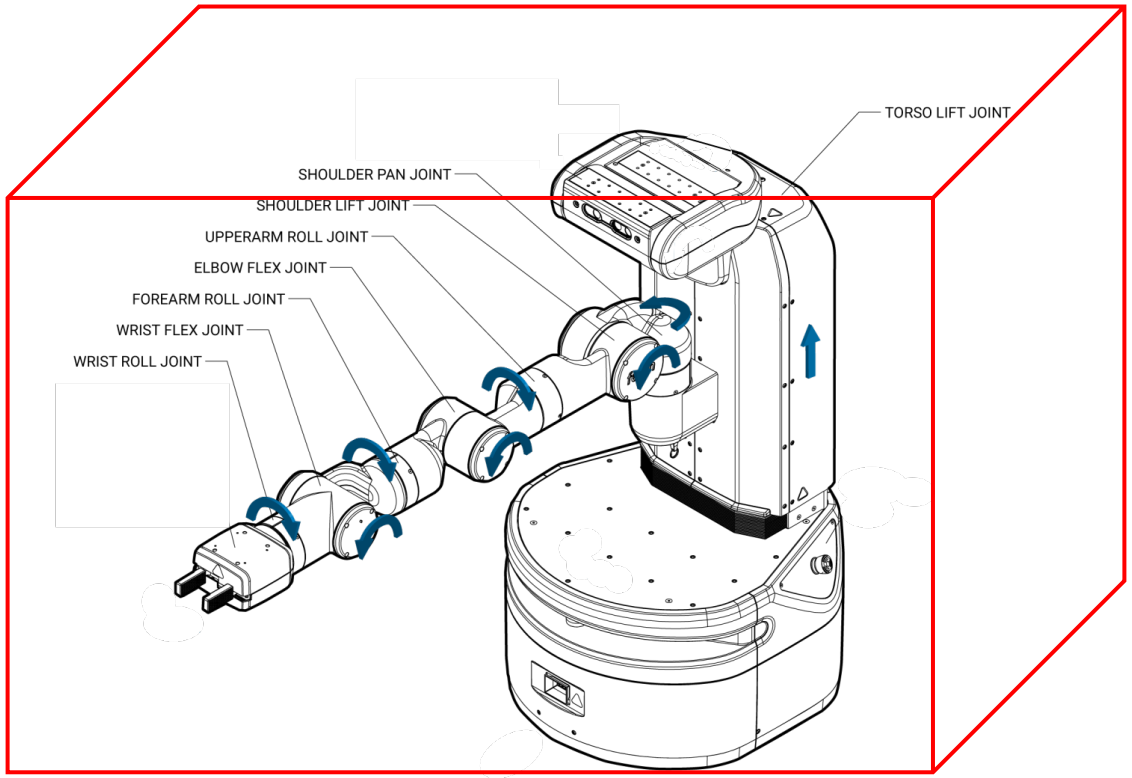
Workspace

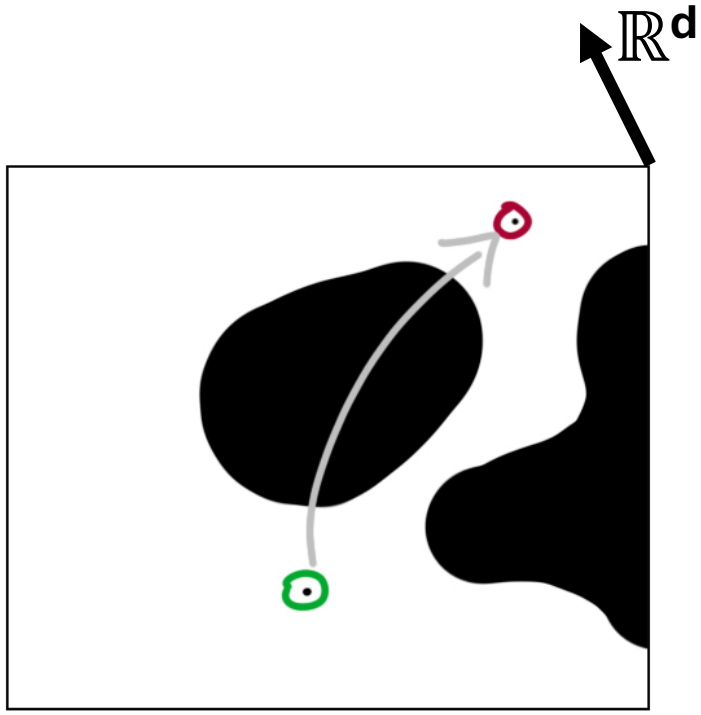




The space occupied by geometries of the robot and environment.
Here, it is 3D.

Workspace

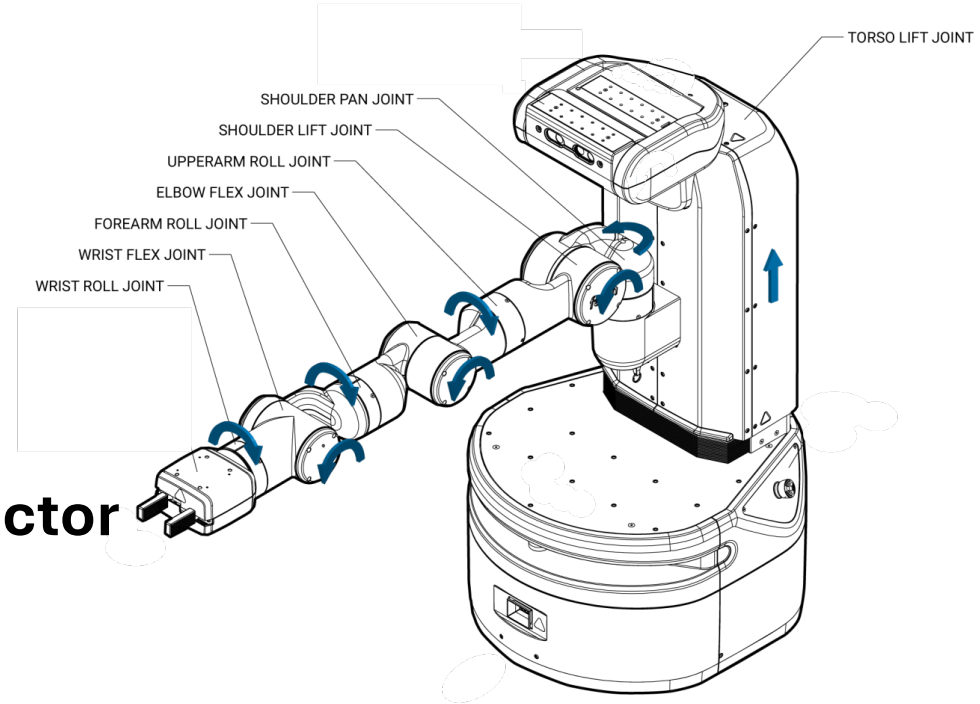




The space occupied by geometries of the robot and environment.
Here, it is 3D.

Manipulation

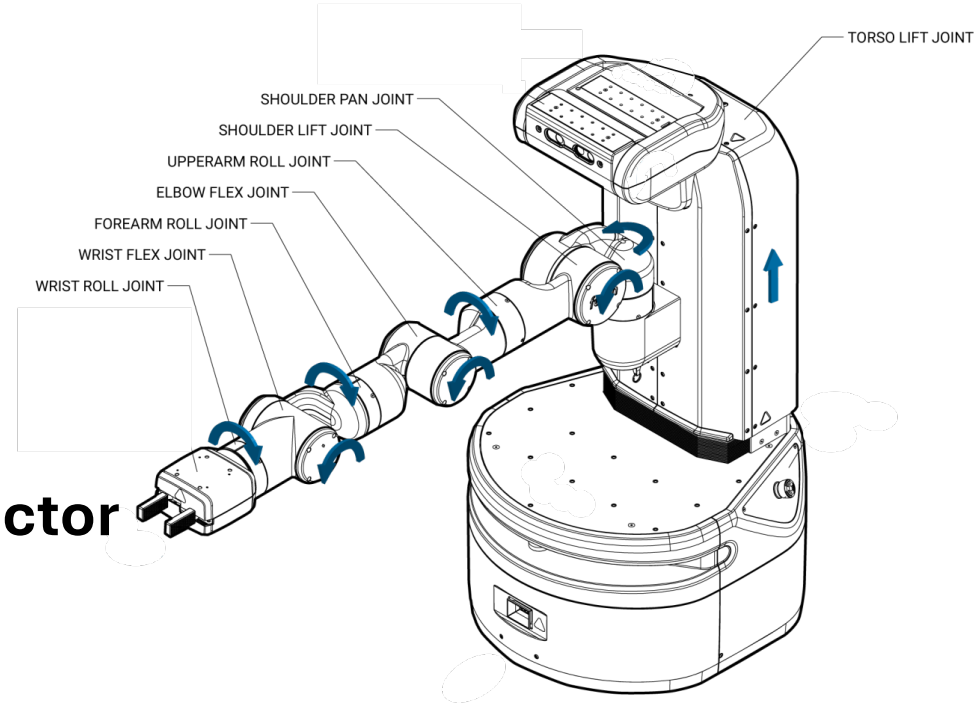
Manipulation is when an agent moves things other than itself through **selective contact**.



Mason, Matthew T. "Toward robotic manipulation." *Annual Review of Control, Robotics, and Autonomous Systems* 1, no. 1 (2018): 1-28.

Manipulation

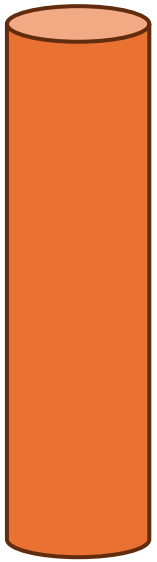
Manipulation is when an agent moves things other than itself through **selective contact**.

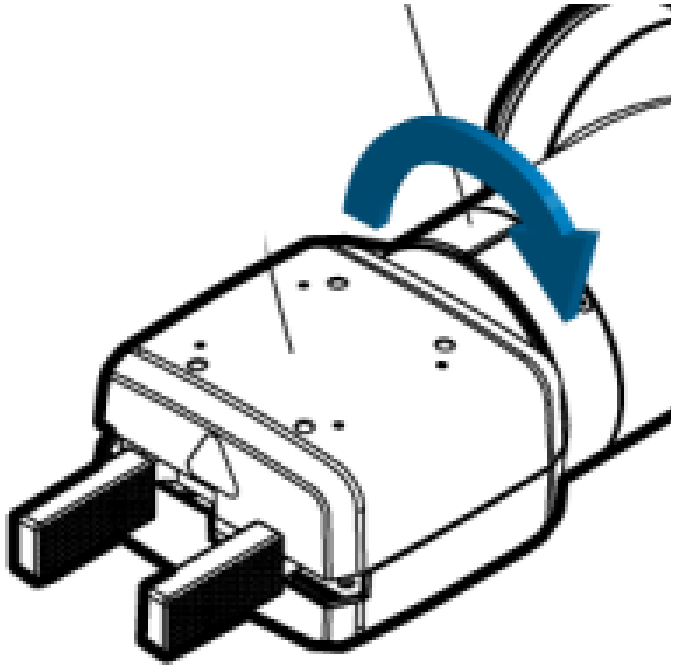


Mason, Matthew T. "Toward robotic manipulation." *Annual Review of Control, Robotics, and Autonomous Systems* 1, no. 1 (2018): 1-28.

Grasping

End-effector is the robot part making contact with an object.
The selective contact is a grasp.

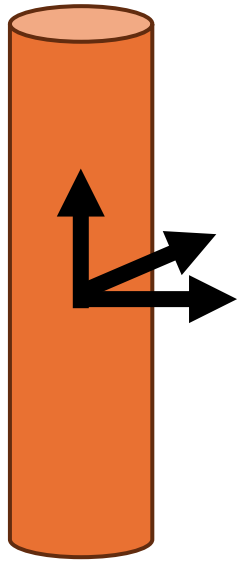


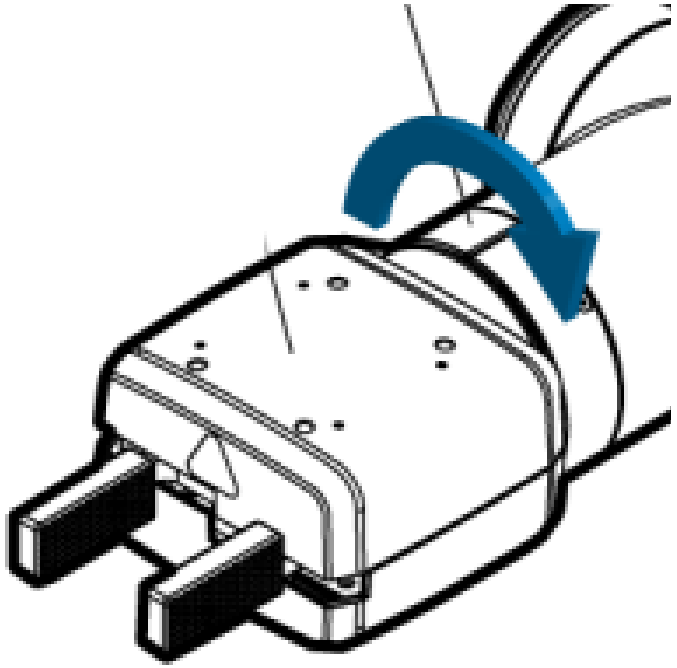


Grasping

End-effector is the robot part making contact with a **rigid object**.
The selective contact is a grasp.

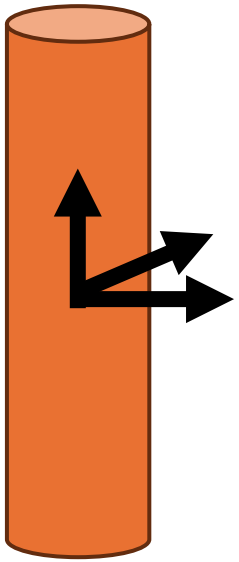
Pose of object

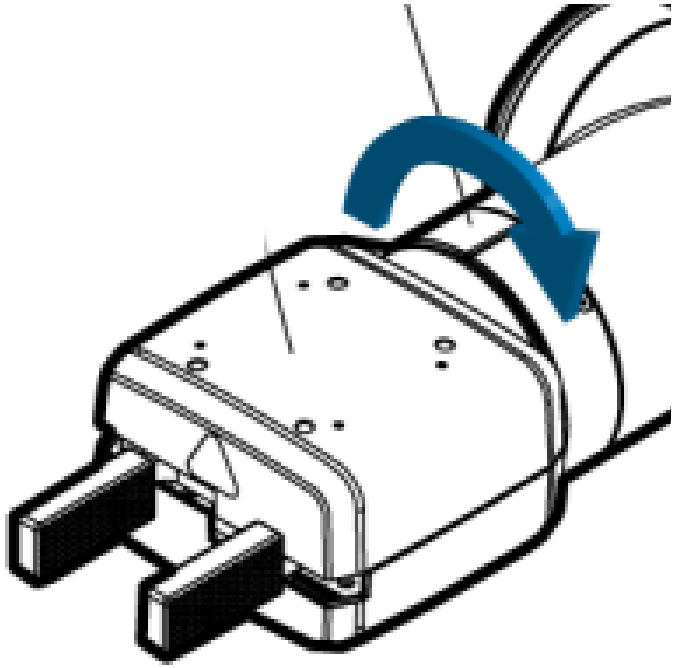




Grasping

End-effector is the robot part making contact with a rigid object.
The selective contact is a grasp.

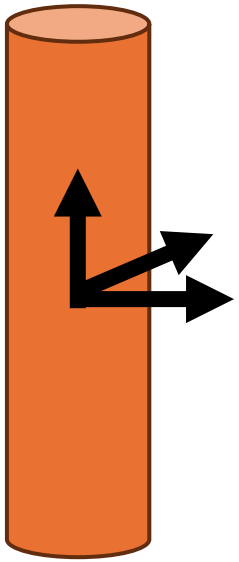


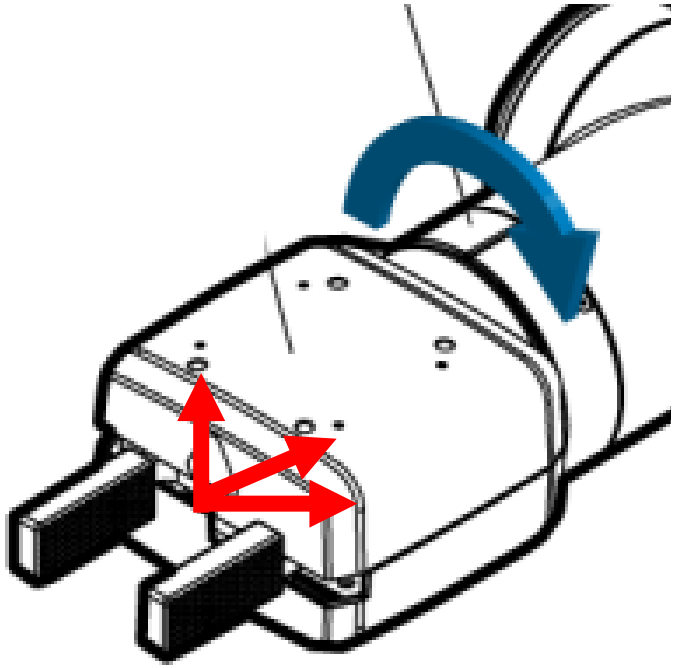


Where is the end-effector?

Grasping

End-effector is the robot part making contact with a rigid object.
The selective contact is a grasp.

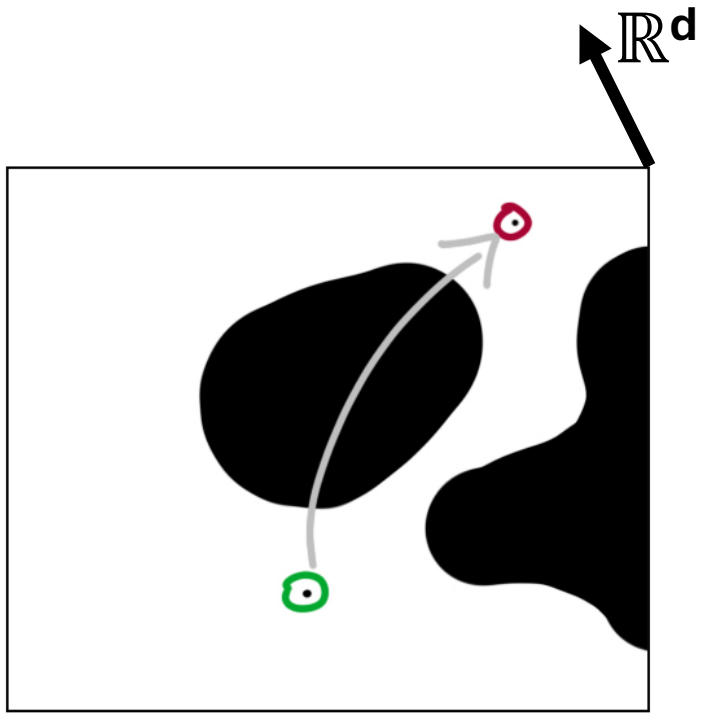


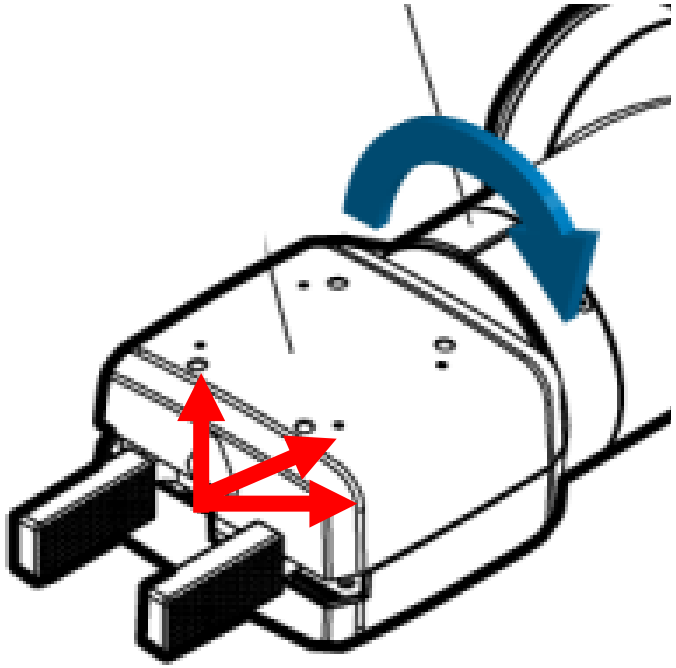


Where is the end-effector?

Grasping

End-effector is the robot part making contact with a rigid object.
The selective contact is a grasp.

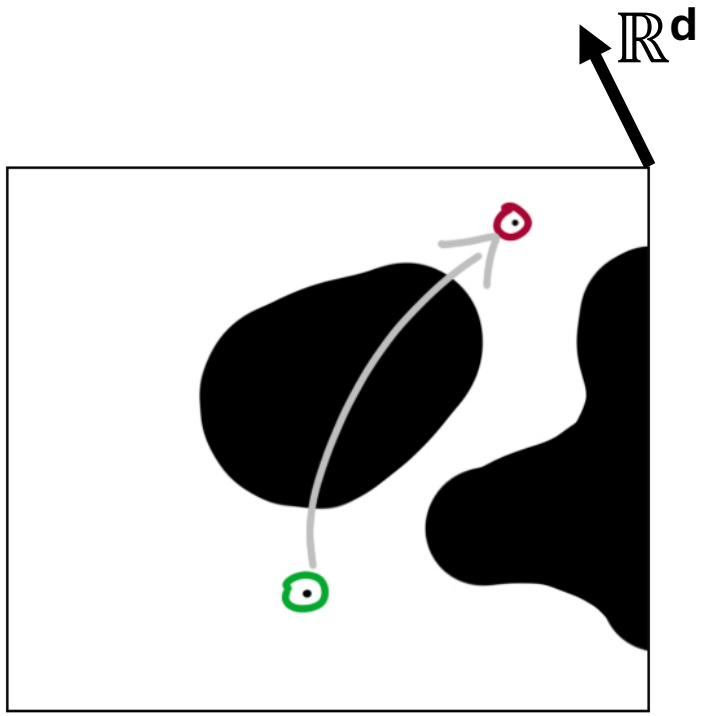




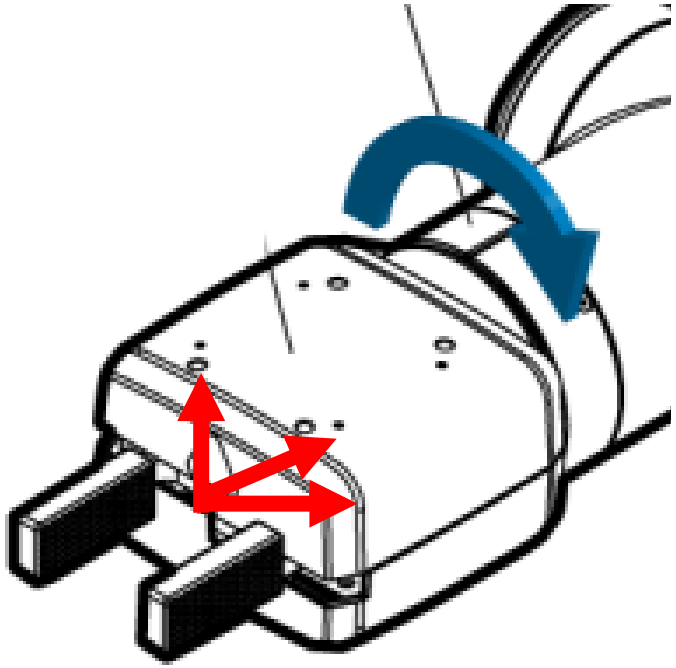
Where is the end-effector?

Grasping

End-effector is the robot part making contact with a rigid object.
The selective contact is a grasp.

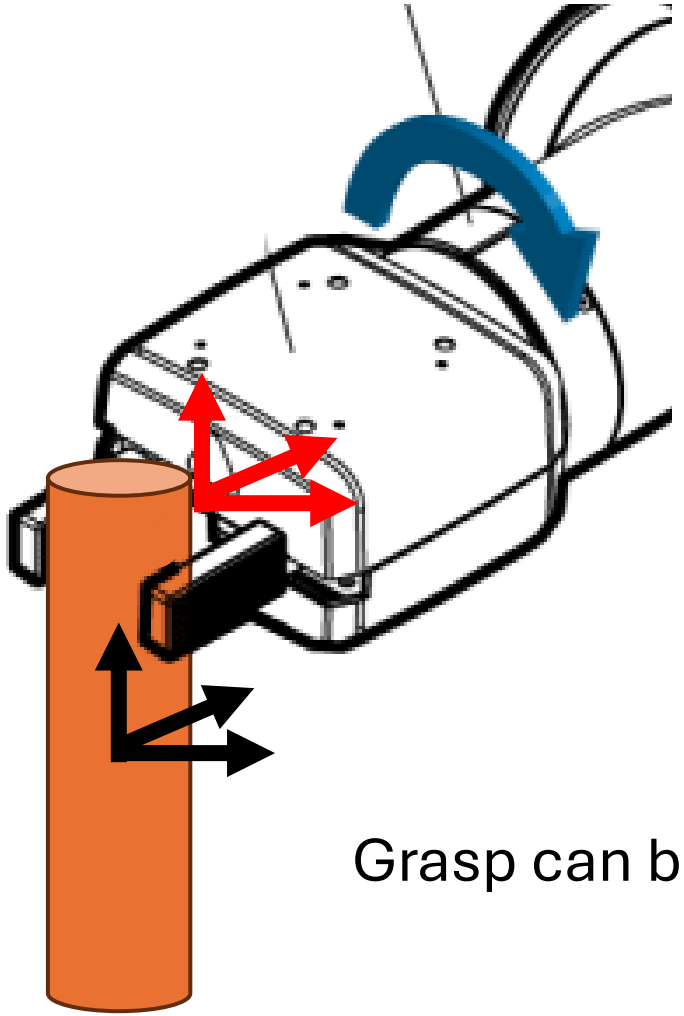


FK



End-effector pose from FK.

Grasp



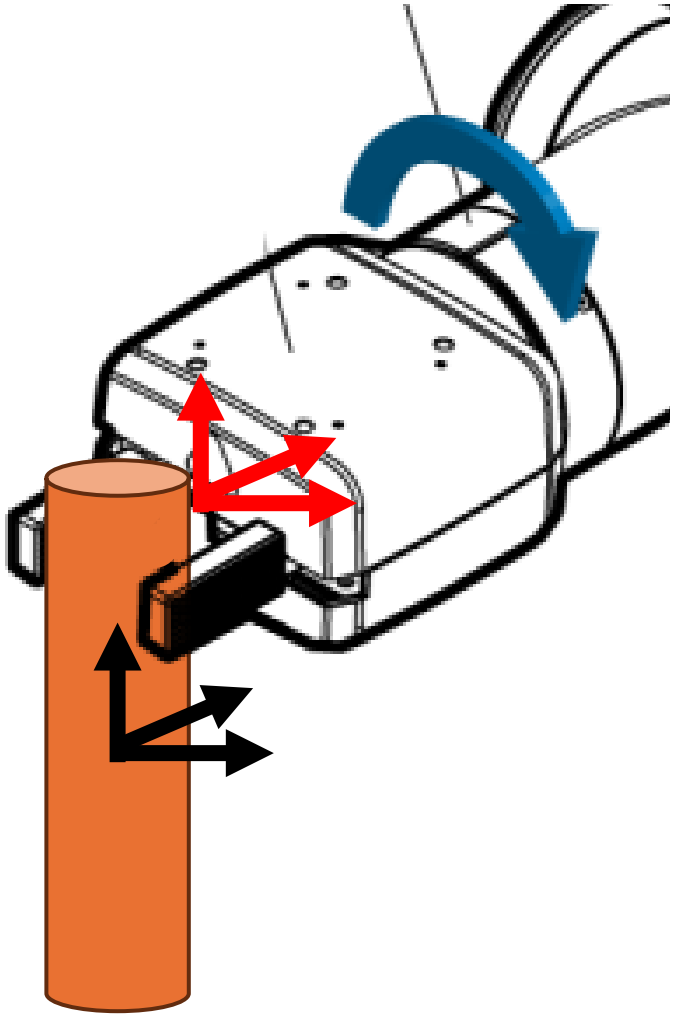
SE(3) Transformation or Relative Pose

End-effector pose at selective contact

Object pose

Grasp can be defined with the relative transformation from the object to the end-effector.

Grasp



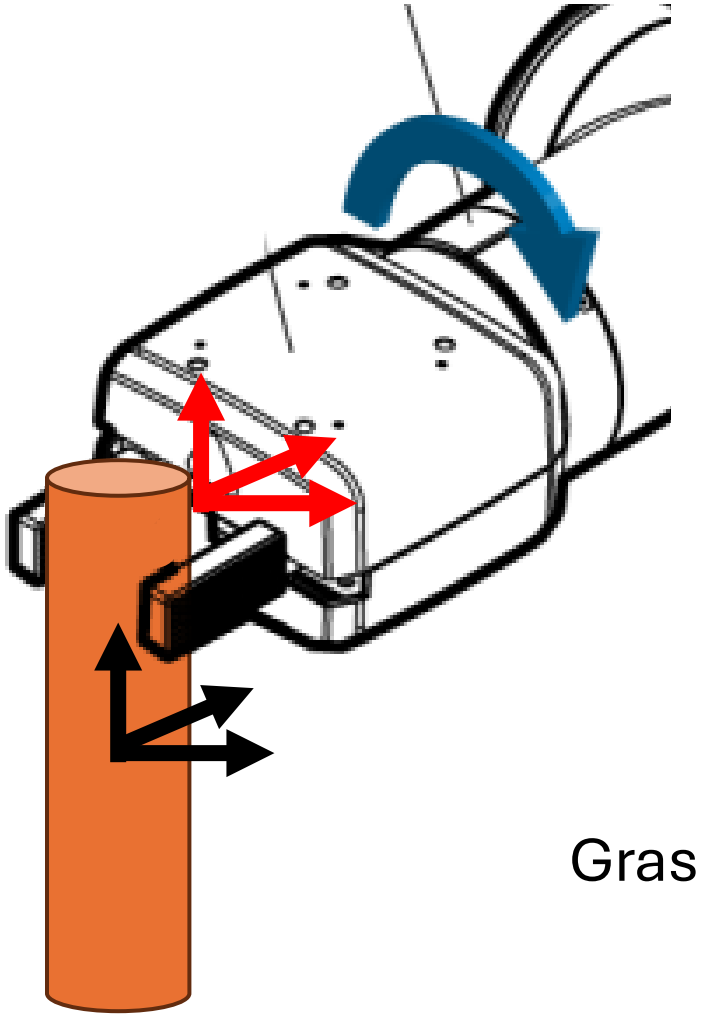
SE(3) Transformation or Relative Pose

End-effector pose at selective contact

Object pose

Grasp can be defined with the relative transformation from the object to the end-effector.

Grasp



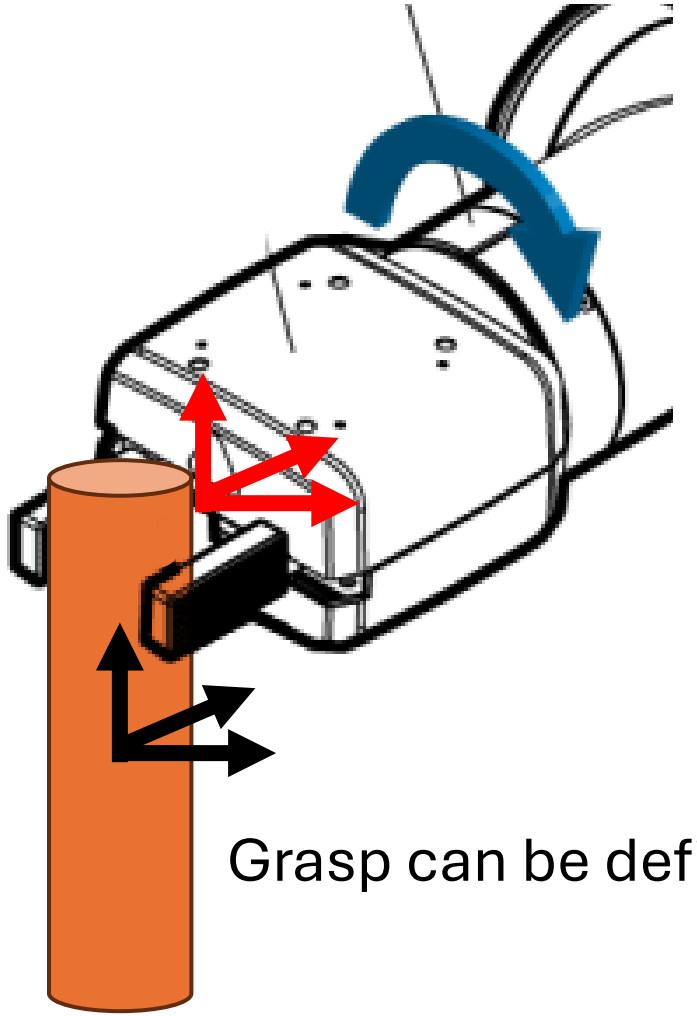
SE(3) Transformation or Relative Pose

End-effector pose at selective contact

Object pose

Grasp can be defined with the relative transformation from the object to the end-effector.

Grasp



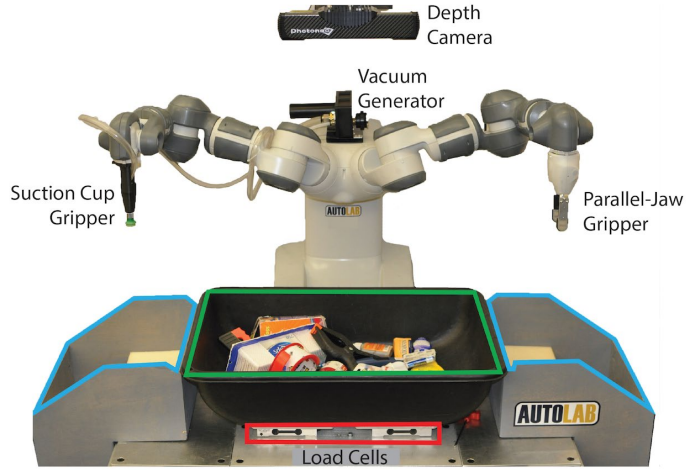
SE(3) Transformation or Relative Pose

End-effector pose at selective contact

Object pose

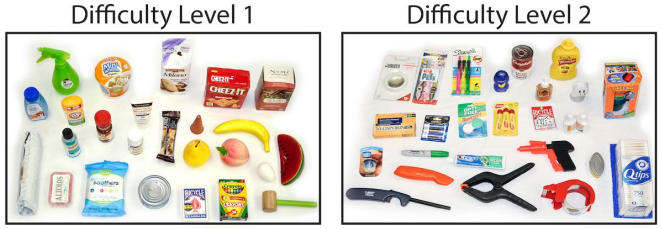
Grasp can be defined with the relative transformation from the object to the end-effector.

Grasp Generation



Model-based methods use known geometric information about objects (graspit!).

Model-free methods can operate directly on sensing information (dex-net, kpam)



Dex-Net 4.0

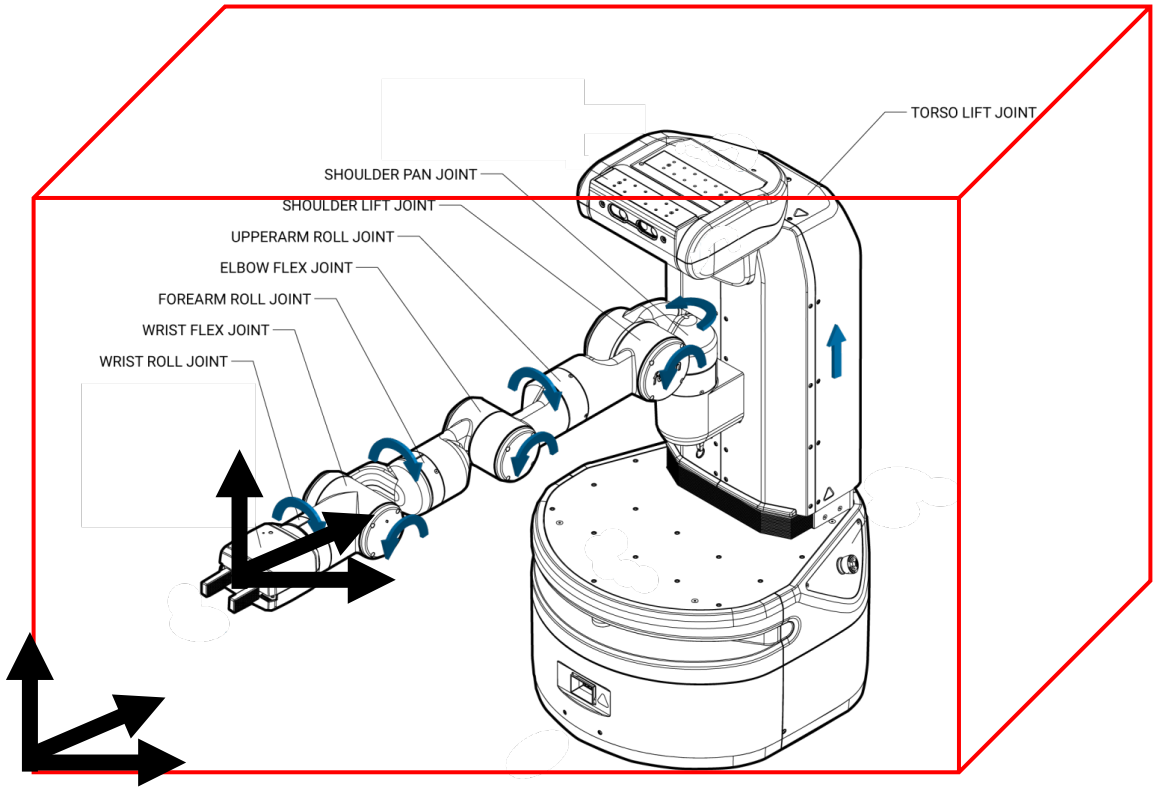
Miller, Andrew T., and Peter K. Allen. "Graspit! a versatile simulator for robotic grasping." *IEEE Robotics & Automation Magazine* 11, no. 4 (2004): 110-122.

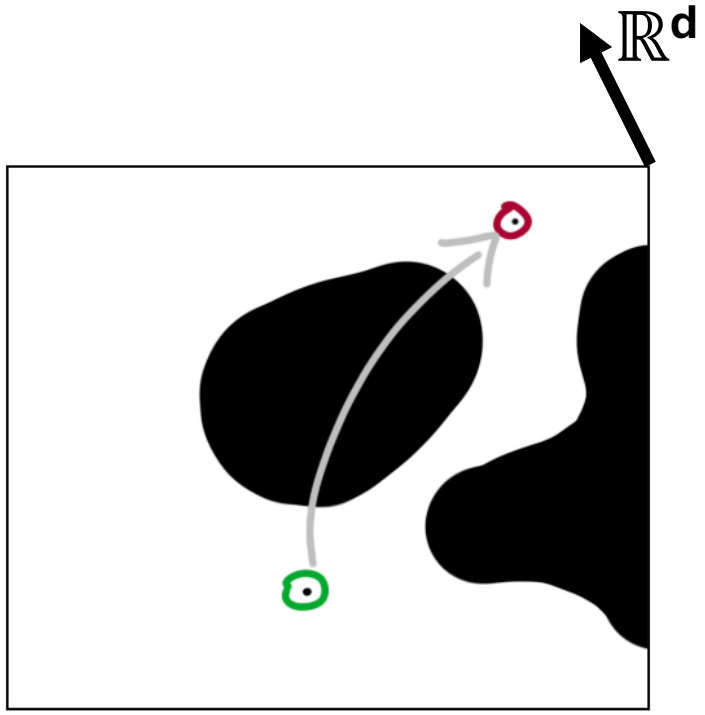
Mahler, Jeffrey, Matthew Matl, Xinyu Liu, Albert Li, David Gealy, and Ken Goldberg. "Dex-net 3.0: Computing robust vacuum suction grasp targets in point clouds using a new analytic model and deep learning." In *2018 IEEE International Conference on robotics and automation (ICRA)*, pp. 5620-5627. IEEE, 2018.

Manuelli, Lucas, Wei Gao, Peter Florence, and Russ Tedrake. "kpam: Keypoint affordances for category-level robotic manipulation." In *The International Symposium of Robotics Research*, pp. 132-157. Cham: Springer International Publishing, 2019.

Mahler, Jeffrey, Matthew Matl, Vishal Satish, Michael Danielczuk, Bill DeRose, Stephen McKinley, and Ken Goldberg. "Learning ambidextrous robot grasping policies." *Science Robotics* 4, no. 26 (2019): eaau4984.

Task Space

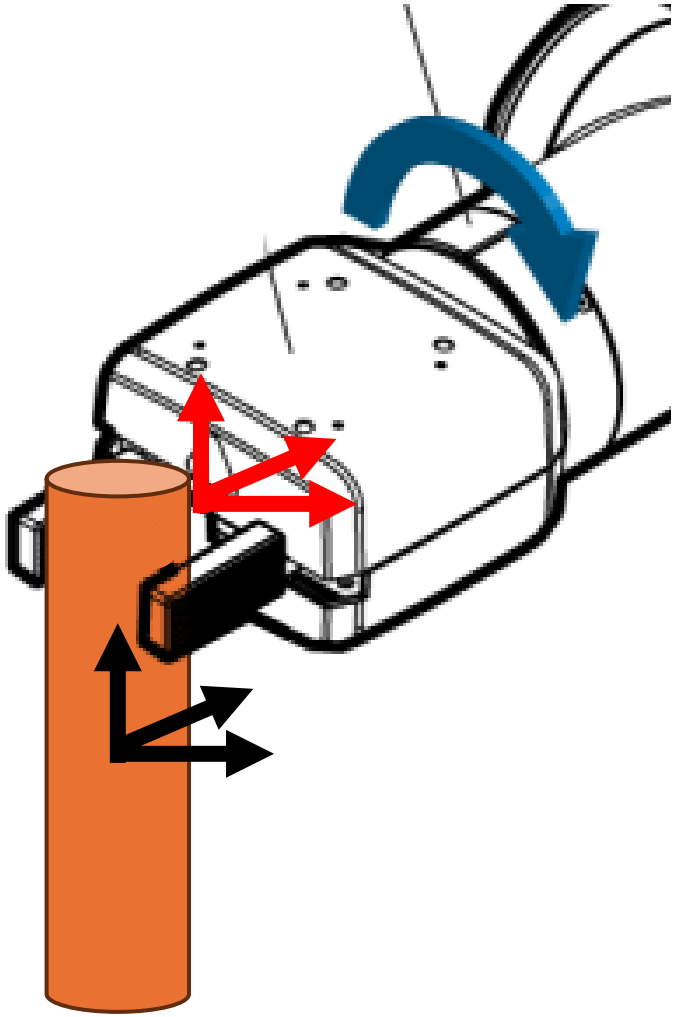




The space where the task will be defined wrt an end-effector.
Here, SE(3). Closely related to operation space.

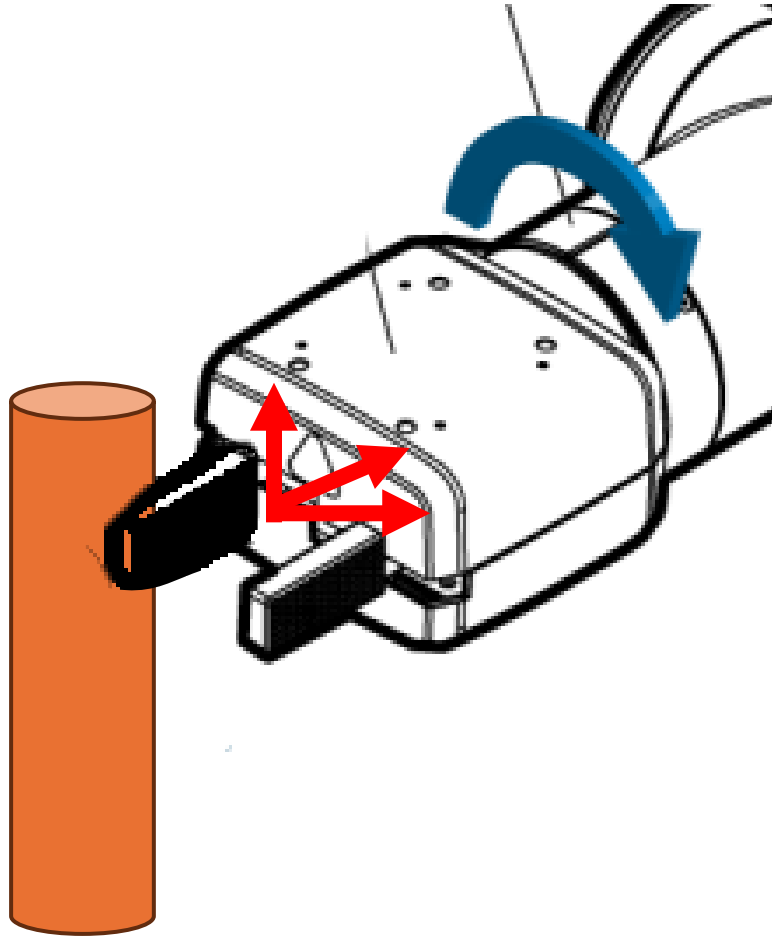
Prehensile Manipulation

The relative grasping pose does not change while the grasp is engaged.



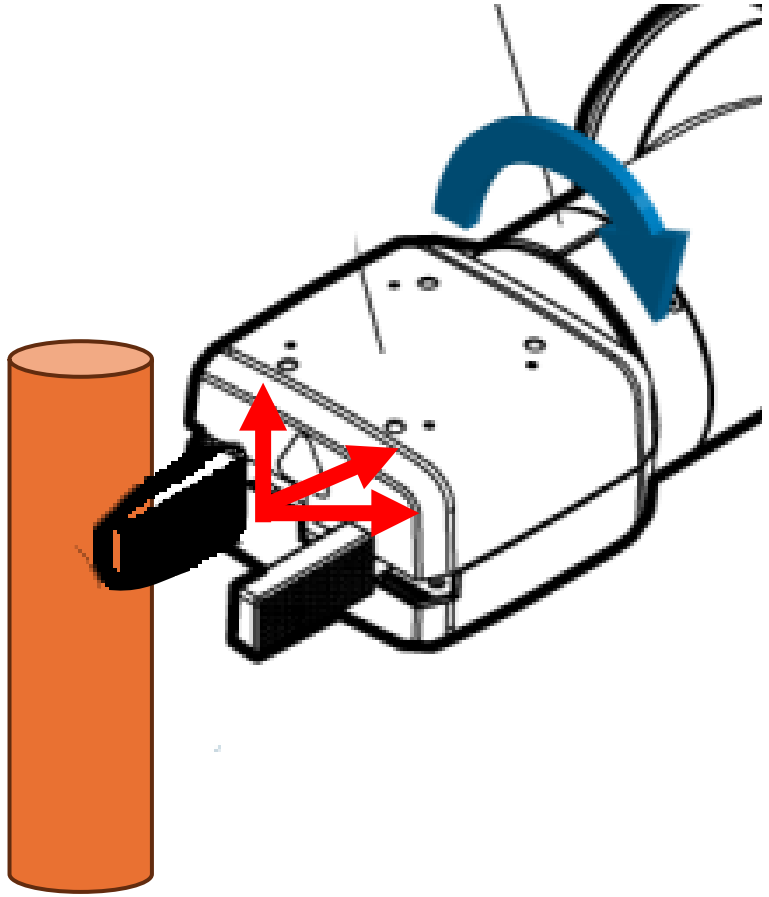
Non-prehensile Manipulation

The relative grasping pose can change while the contact is engaged.



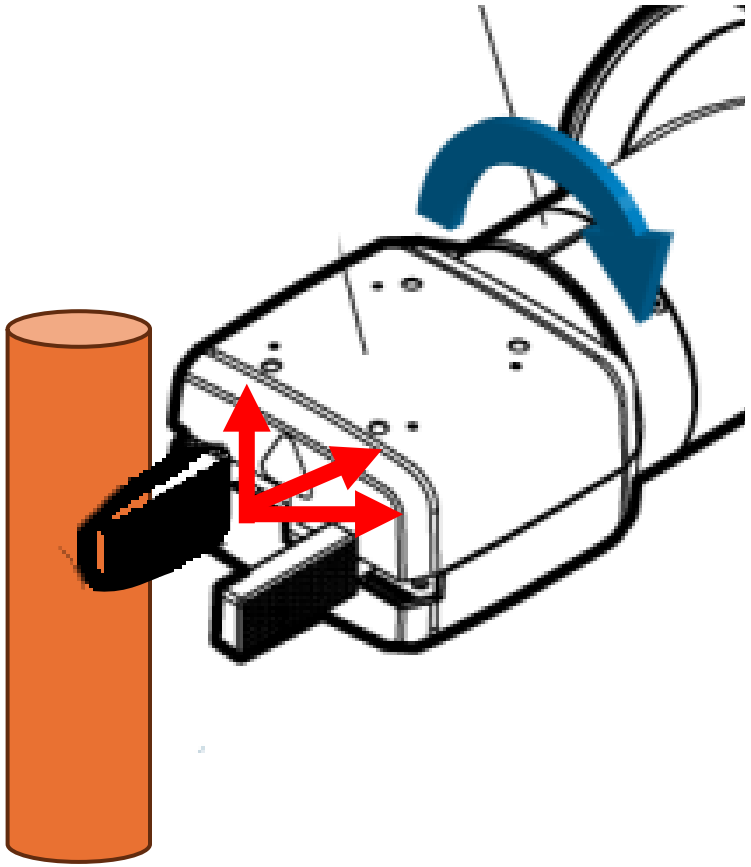
Non-prehensile Manipulation

The relative grasping pose can change while the contact is engaged.



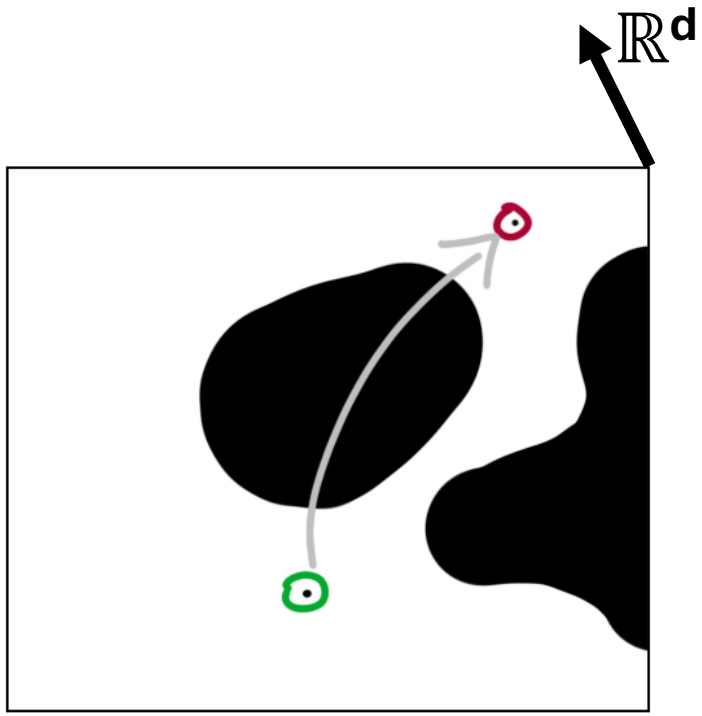
Non-prehensile Manipulation

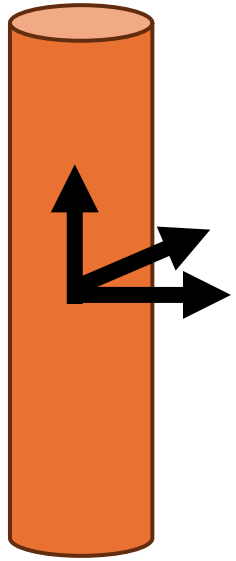
The relative grasping pose can change while the contact is engaged.



Grasping Configurations From Object Poses

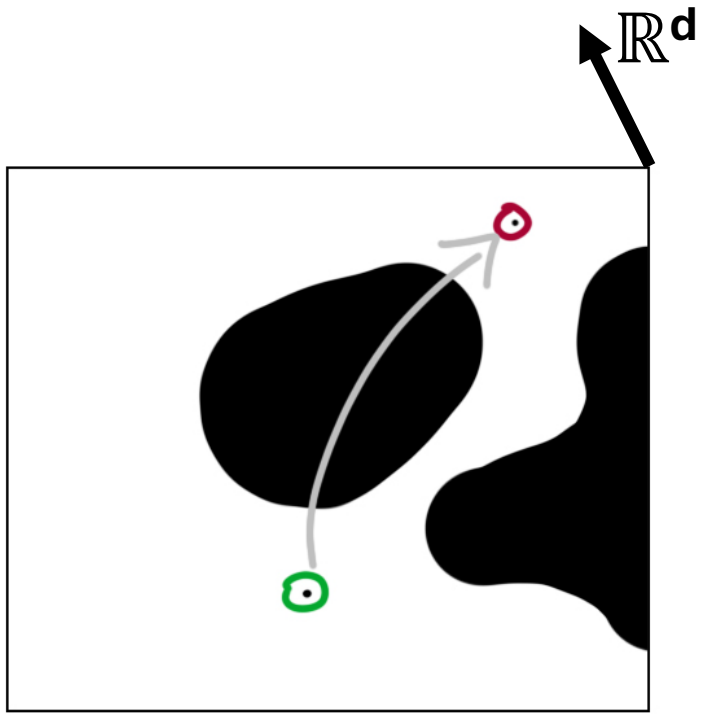
For manipulation planning we need a configuration to plan to.

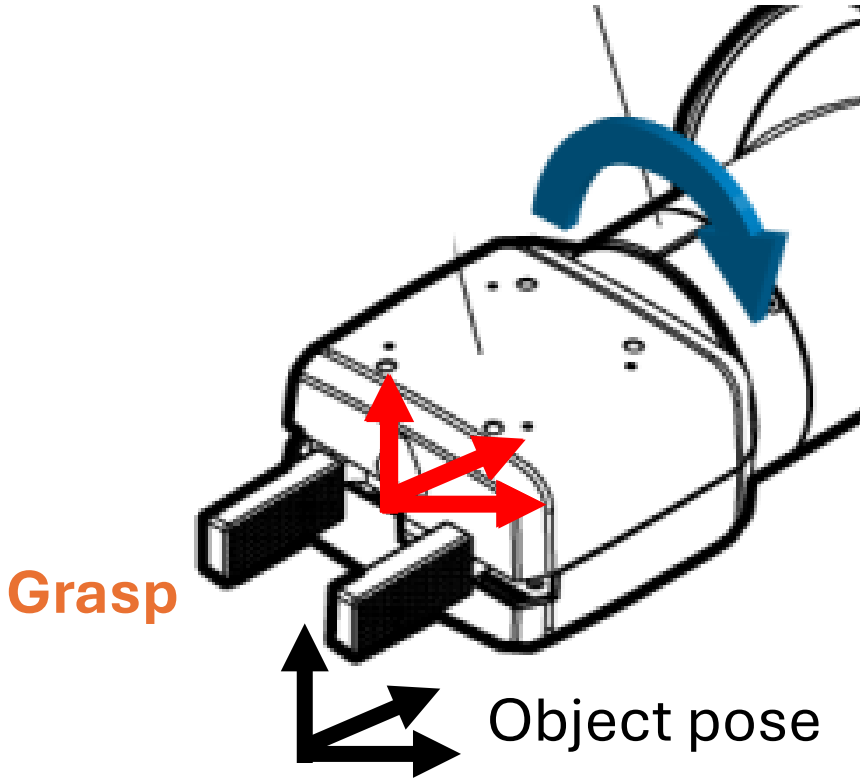




Grasping Configurations From Object Poses

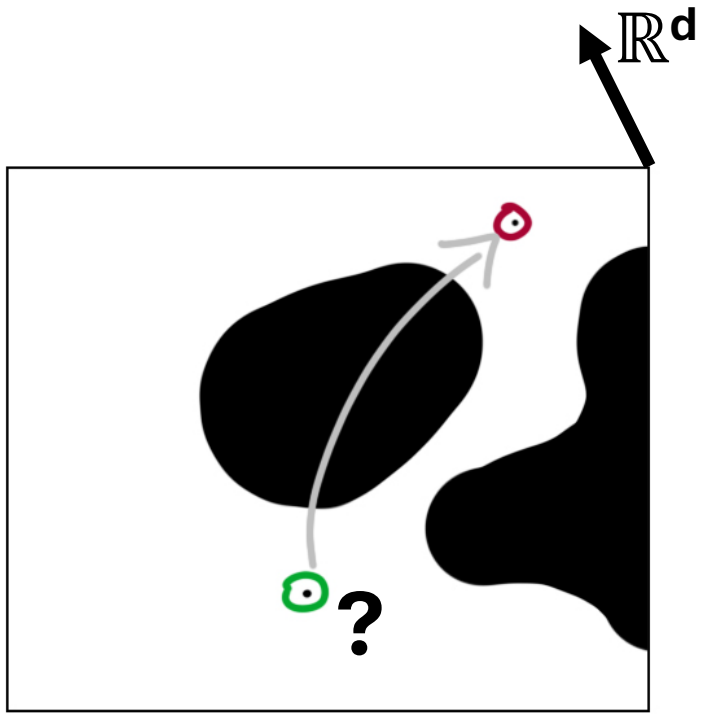
For manipulation planning we need a configuration to plan to.

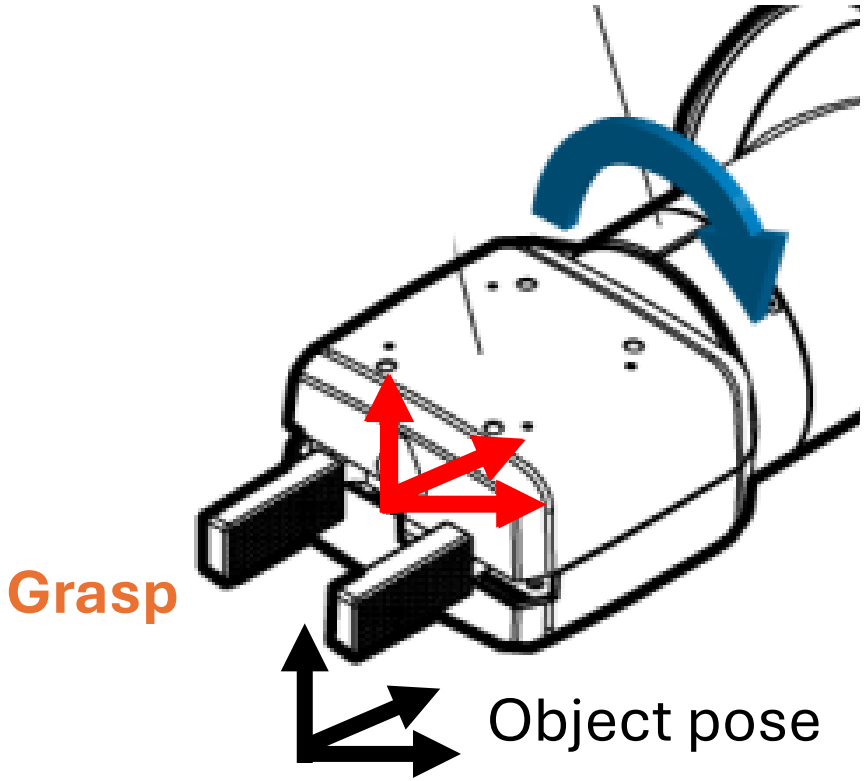




Grasping Configurations From Object Poses

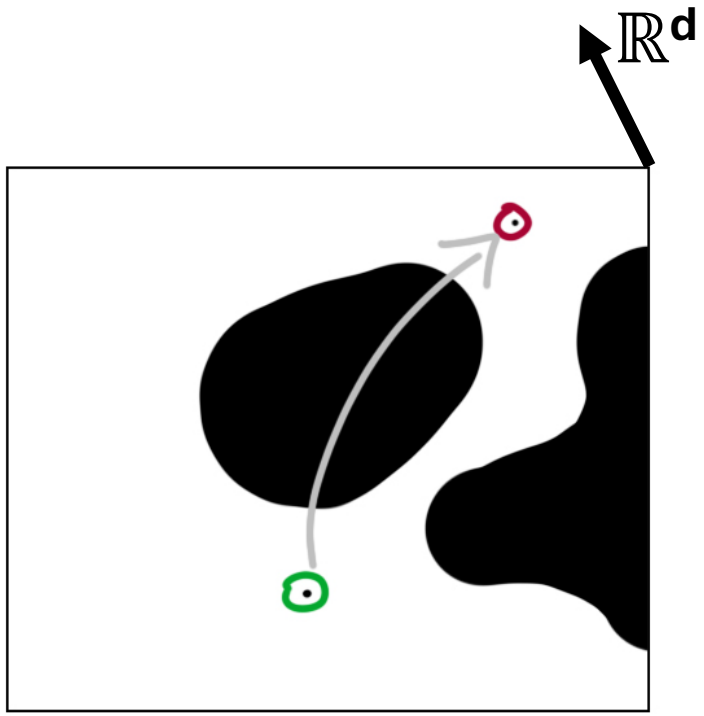
For manipulation planning we need a configuration to plan to.



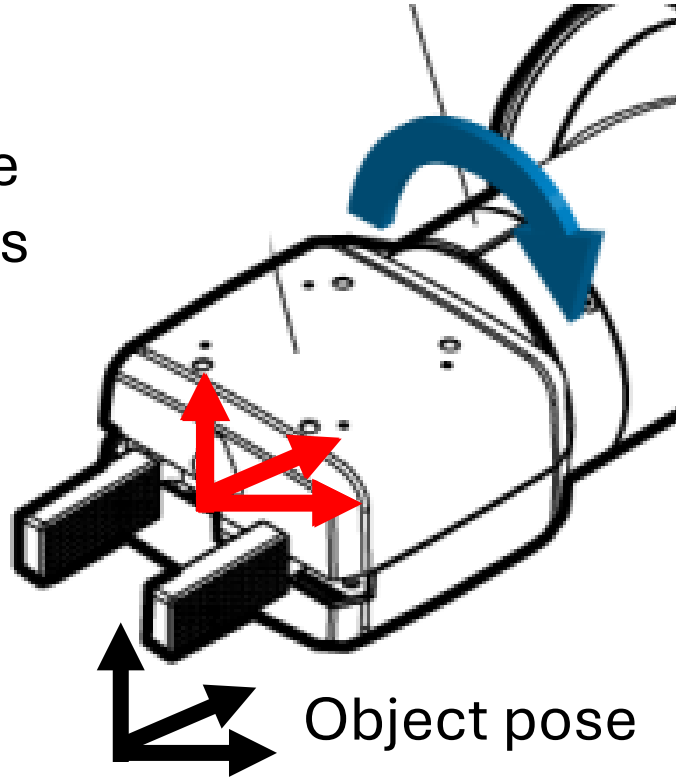


Grasping Configurations From Object Poses

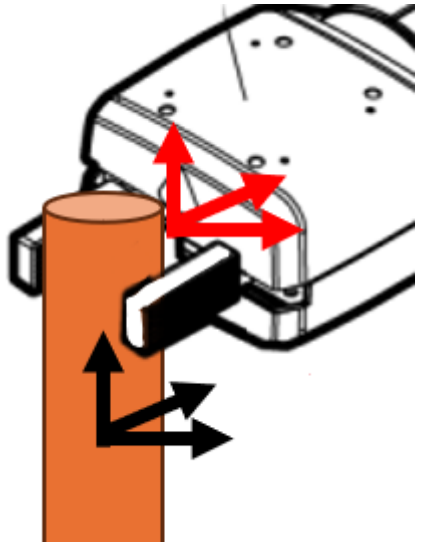
For manipulation planning we need a configuration to plan to.



IK - Inverse Kinematics

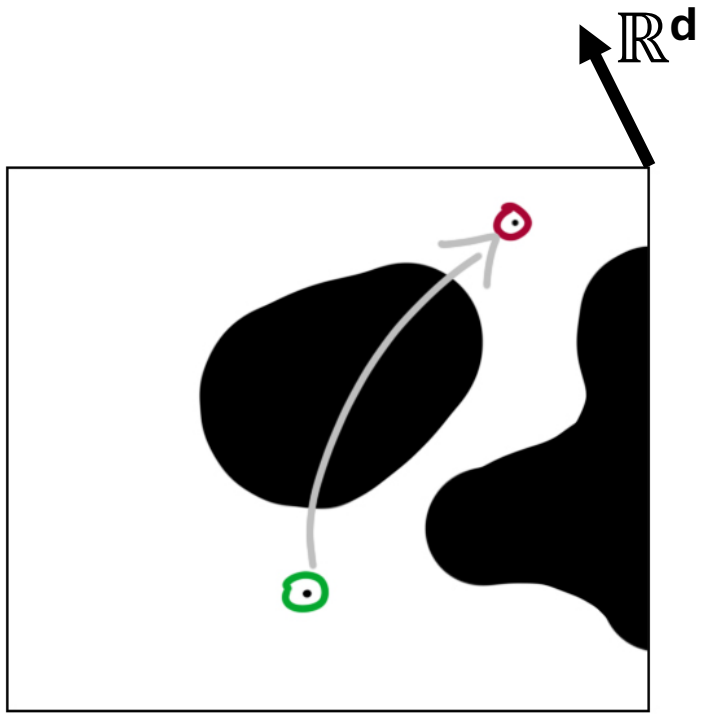


Does this configuration look correct?

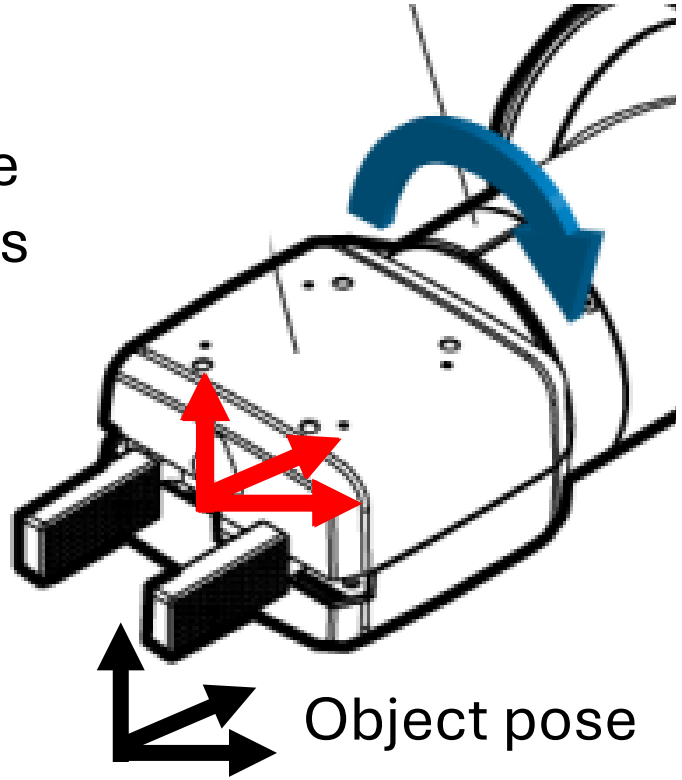


Grasping Configurations From Object Poses

For manipulation planning we need a configuration to plan to.

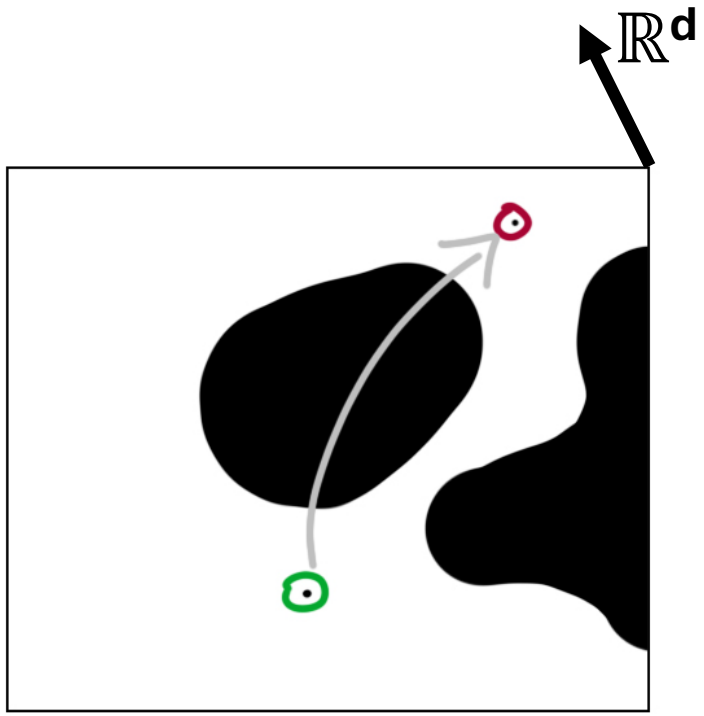


IK - Inverse Kinematics

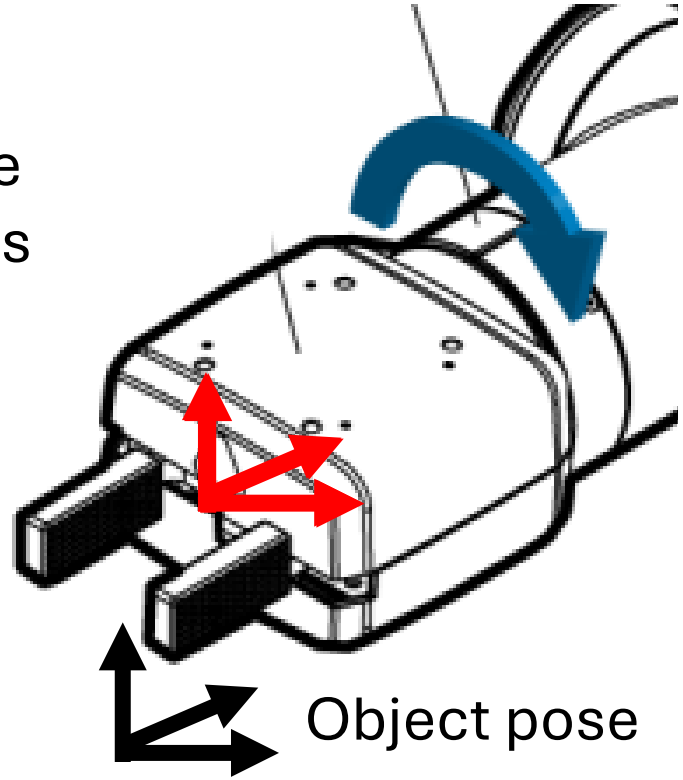


Pick and Place Manipulation Planning

Motion plan between manipulation configurations
- grasping and stable placements

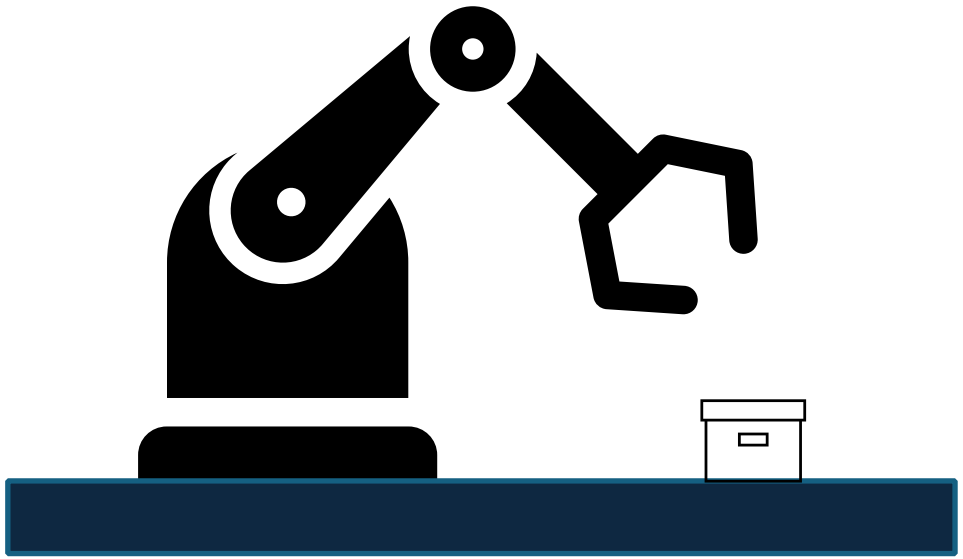


IK - Inverse Kinematics



Planning Perspective

Modes (Manipulation)

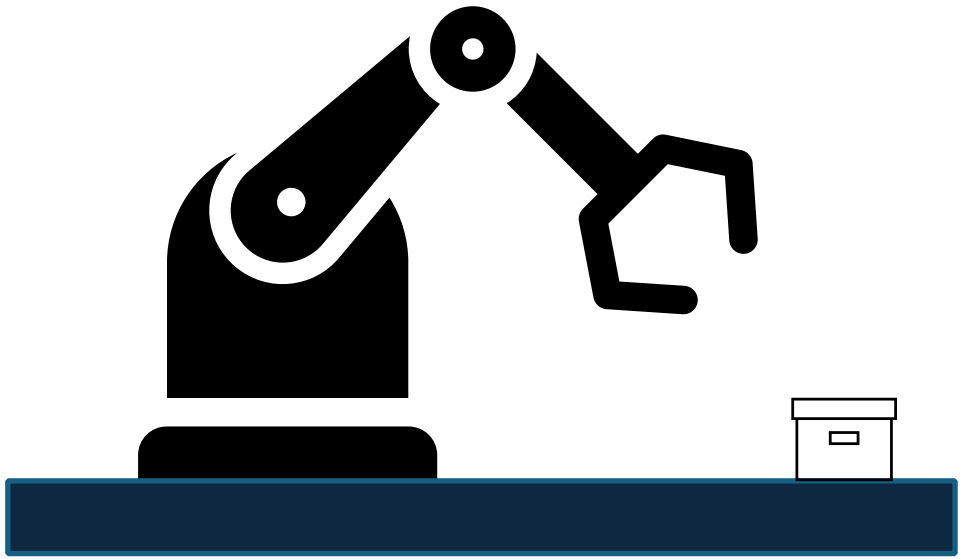


Brock O., Kuffner J., Xiao J. (2008) Motion for Manipulation Tasks. In: Siciliano B., Khatib O. (eds) Springer Handbook of Robotics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-30301-5_27

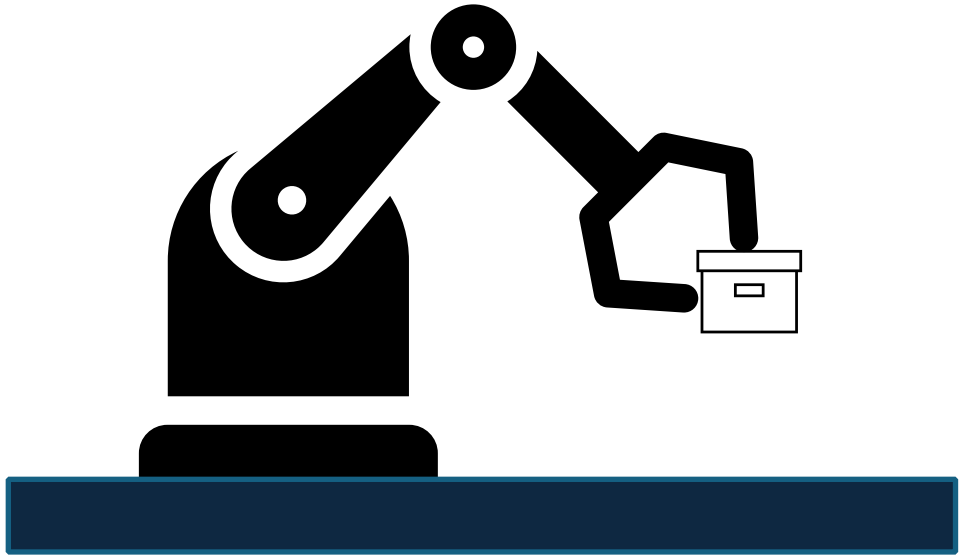
Modes (Manipulation)

Brock O., Kuffner J., Xiao J. (2008) Motion for Manipulation Tasks. In: Siciliano B., Khatib O. (eds) Springer Handbook of Robotics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-30301-5_27

Modes (Manipulation)



the manipulator moves alone
(transit mode)

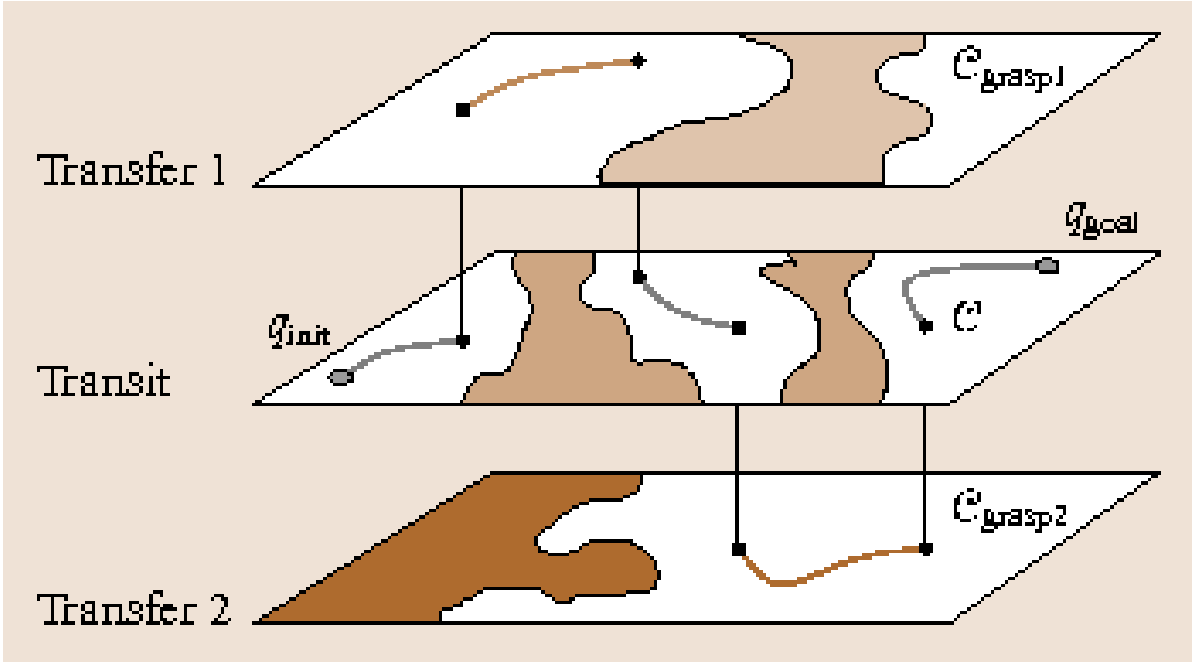


the manipulator moves with grasped object
(transfer mode)

Brock O., Kuffner J., Xiao J. (2008) Motion for Manipulation Tasks. In: Siciliano B., Khatib O. (eds) Springer Handbook of Robotics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-30301-5_27

Modes (Manipulation)

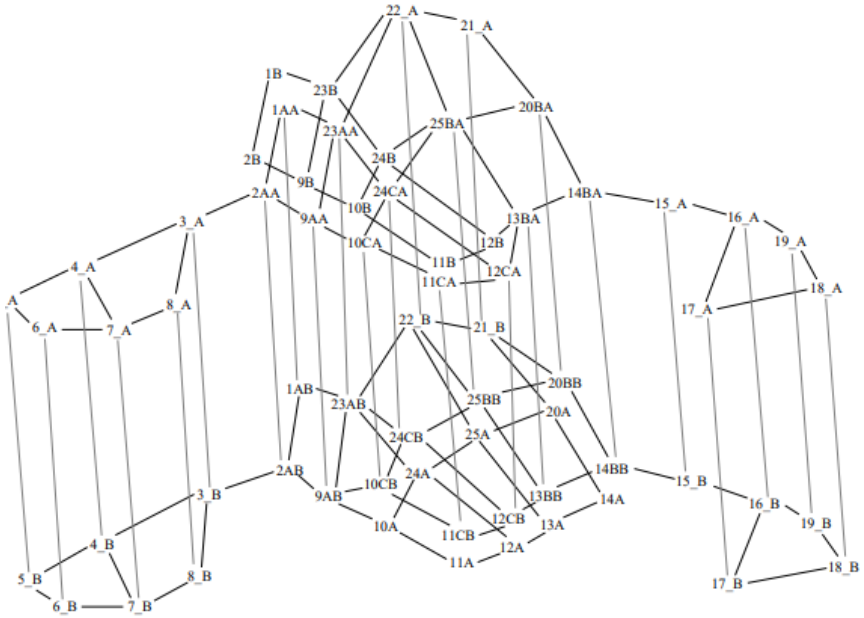
- Transit and transfer modes create a a set of hybrid continuous configuration spaces. In this example, transfer paths in different $\mathcal{C}$-spaces arise from different ways of rigidly grasping the object

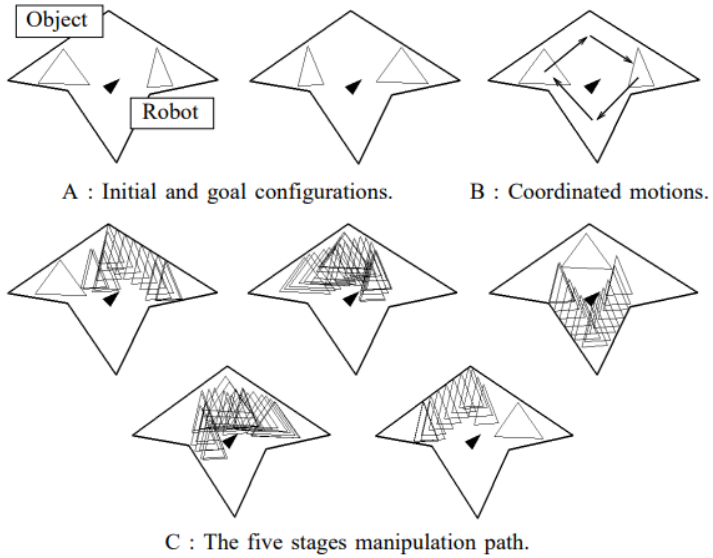


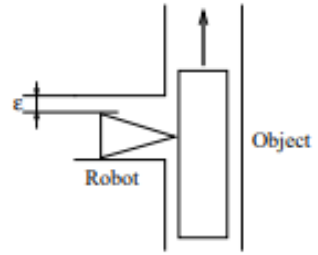
Brock O., Kuffner J., Xiao J. (2008) Motion for Manipulation Tasks. In: Siciliano B., Khatib O. (eds) Springer Handbook of Robotics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-30301-5_27

Manipulation Graph

- **Manipulation planning problem**: Find a finite sequence of transit-paths and transfer-paths to reach the final configuration.

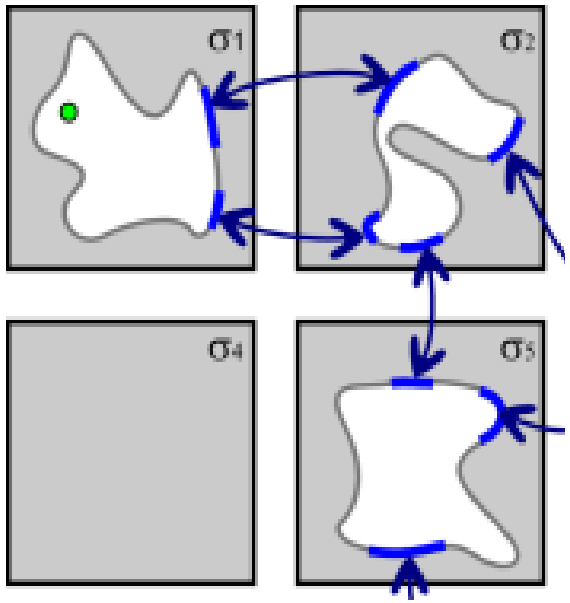


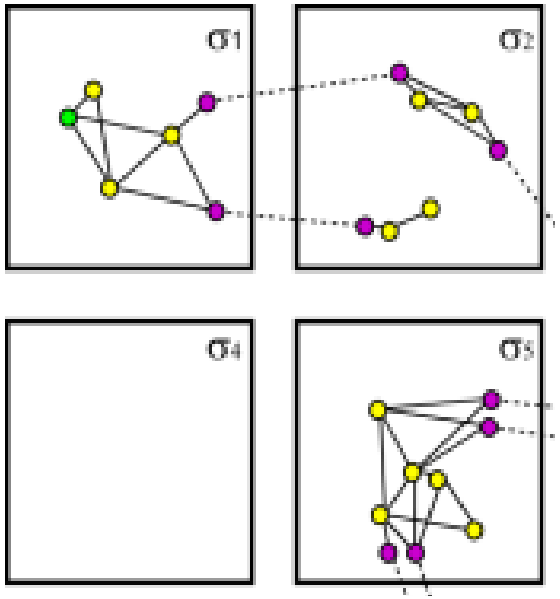


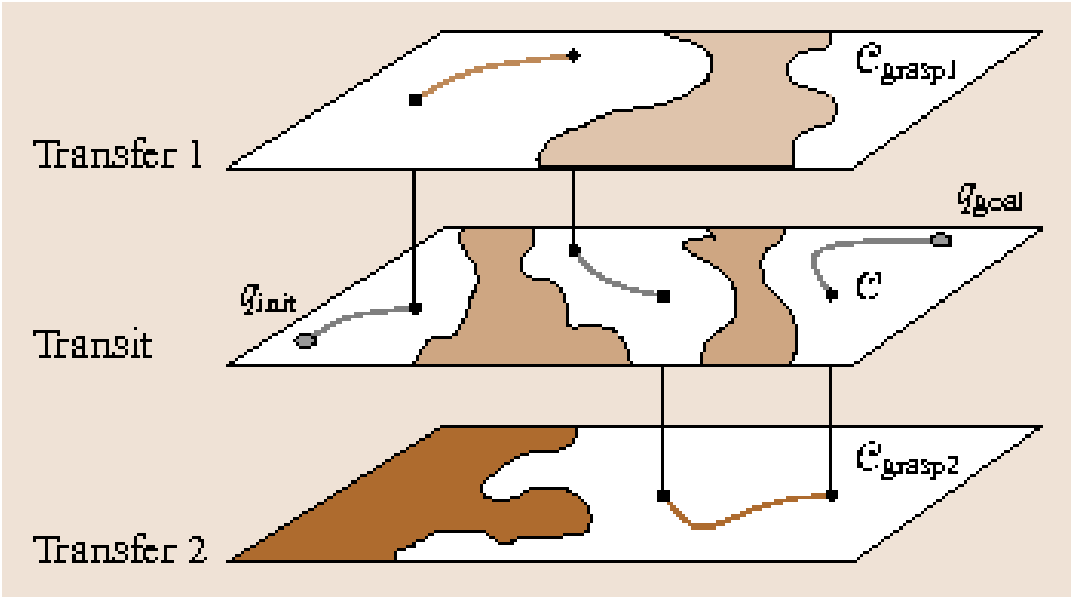


- Alami, Rachid, Jean-Paul Laumond, and Thierry Siméon. "Two manipulation planning algorithms." In WAFR Proceedings of the workshop on Algorithmic foundations of robotics, pp. 109-125. AK Peters, Ltd. Natick, MA, USA, 1994.

Abstractions for discrete search space





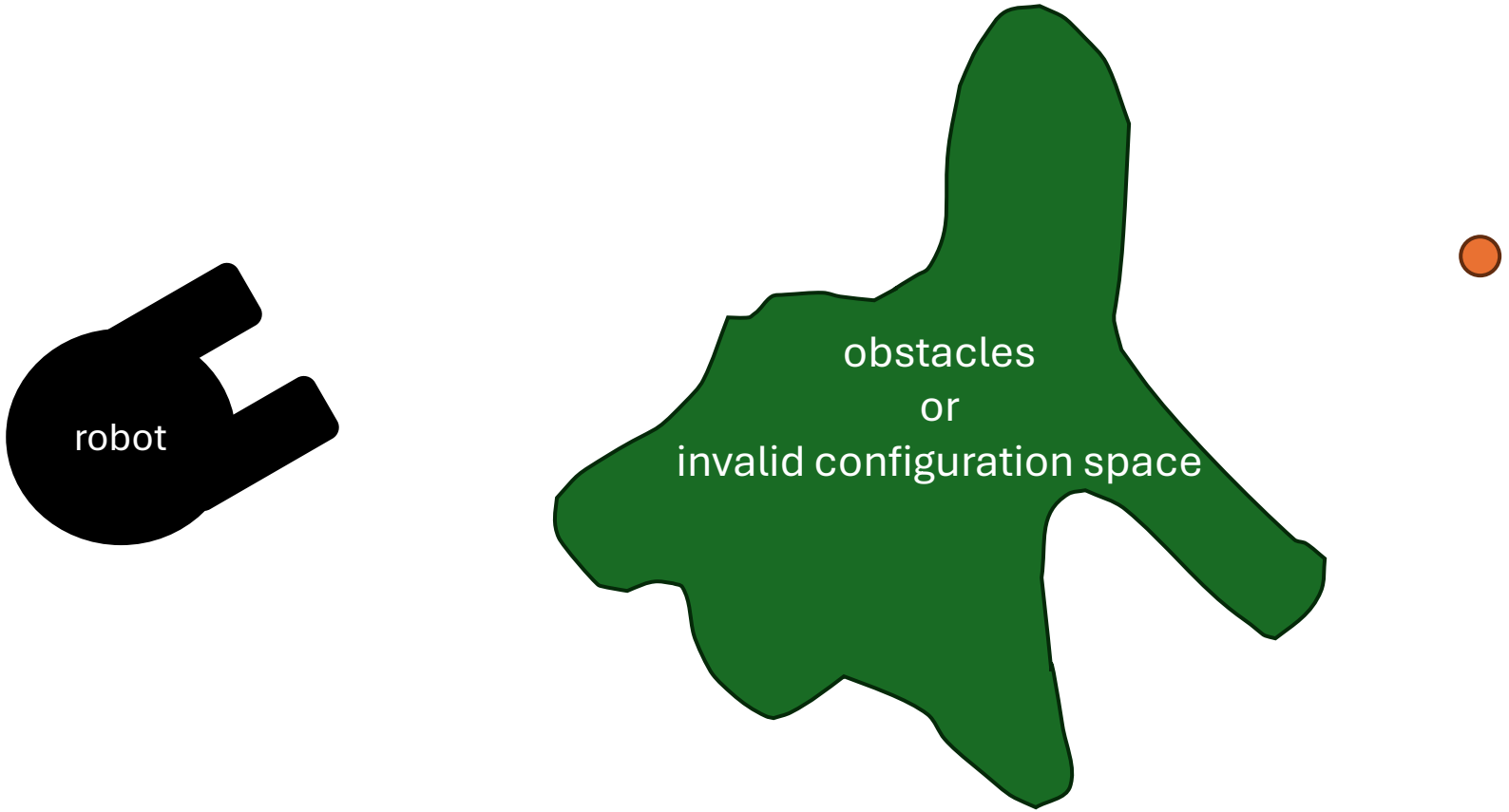


Transit Transfer
PICK PLACE

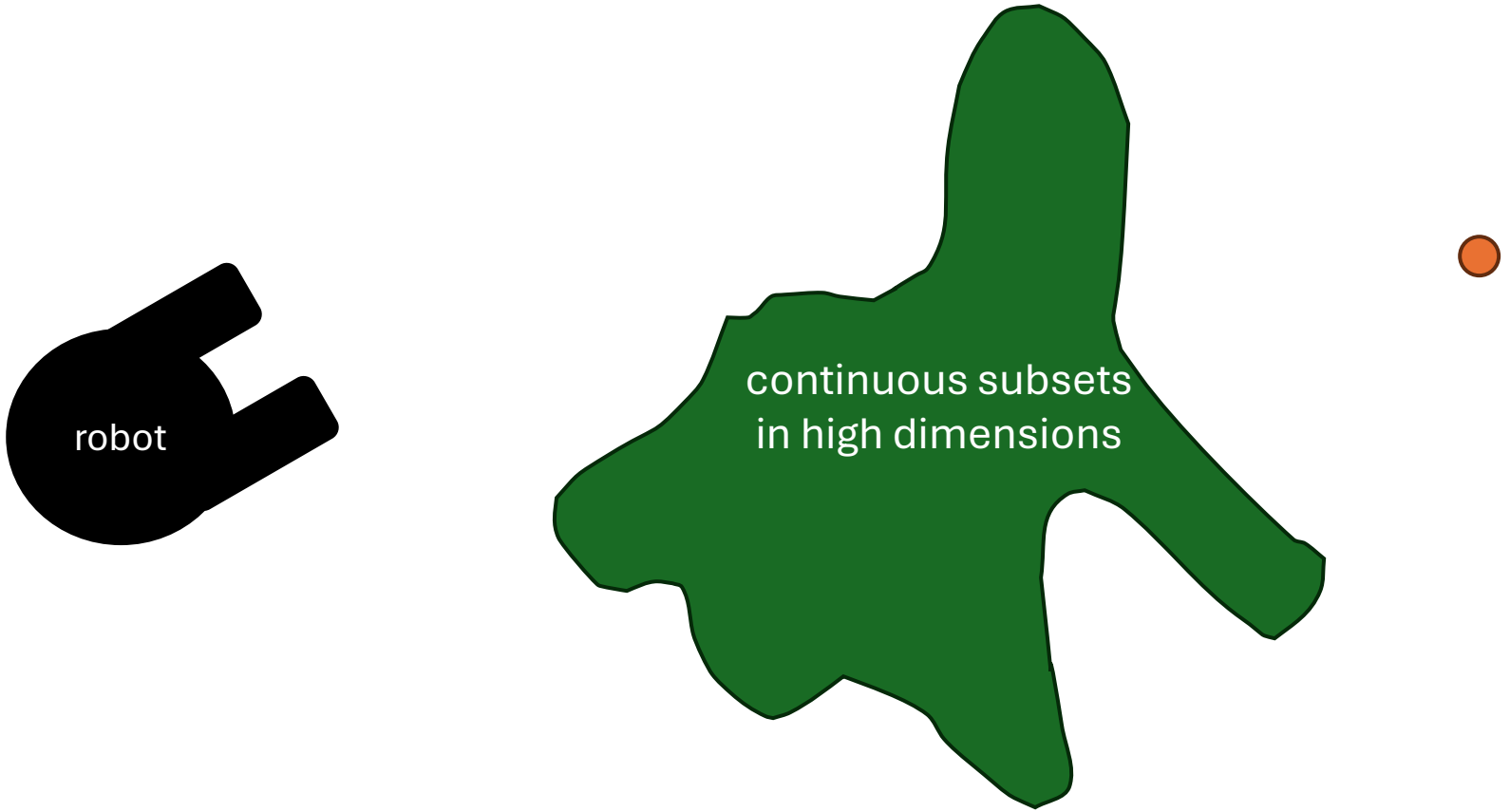
Hauser, Kris, and Jean-Claude Latombe. "Multi-modal motion planning in non-expansive spaces." *The International Journal of Robotics Research* 29, no. 7 (2010): 897-915.

Brock O., Kuffner J., Xiao J. (2008) Motion for Manipulation Tasks. In: Siciliano B., Khatib O. (eds) Springer Handbook of Robotics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-30301-5_27

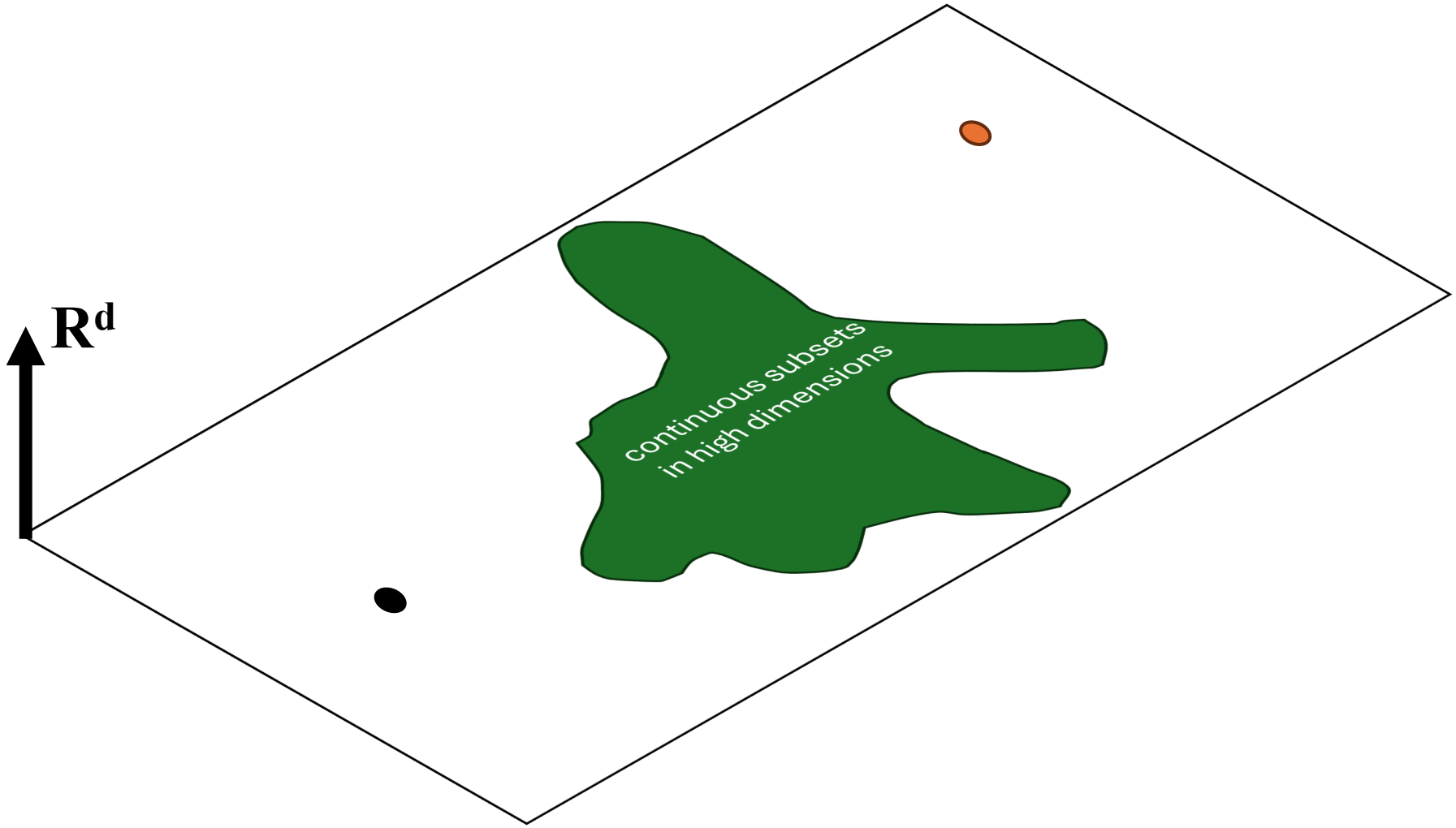
Recap: Robot Motion Planning



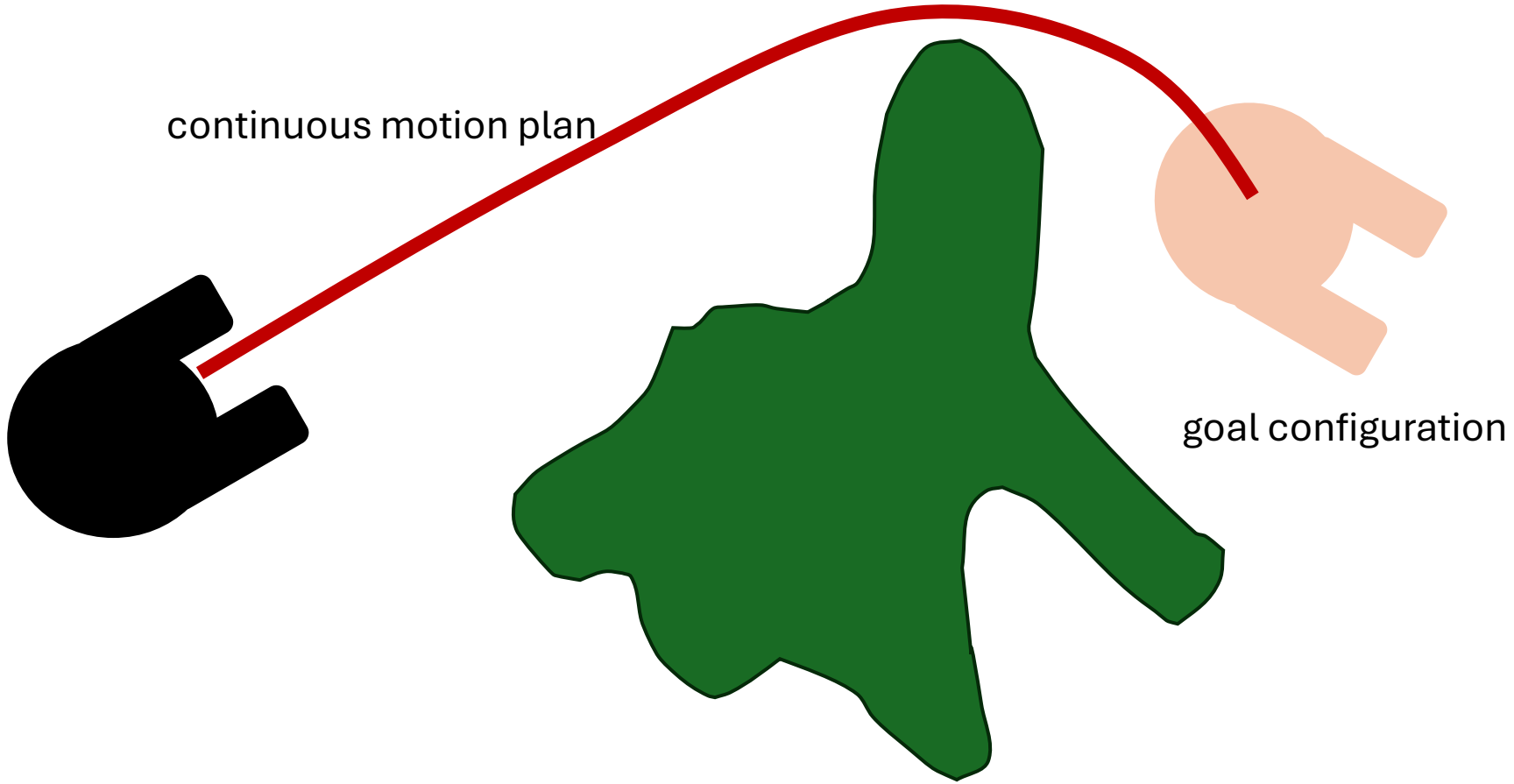
Robot Motion Planning



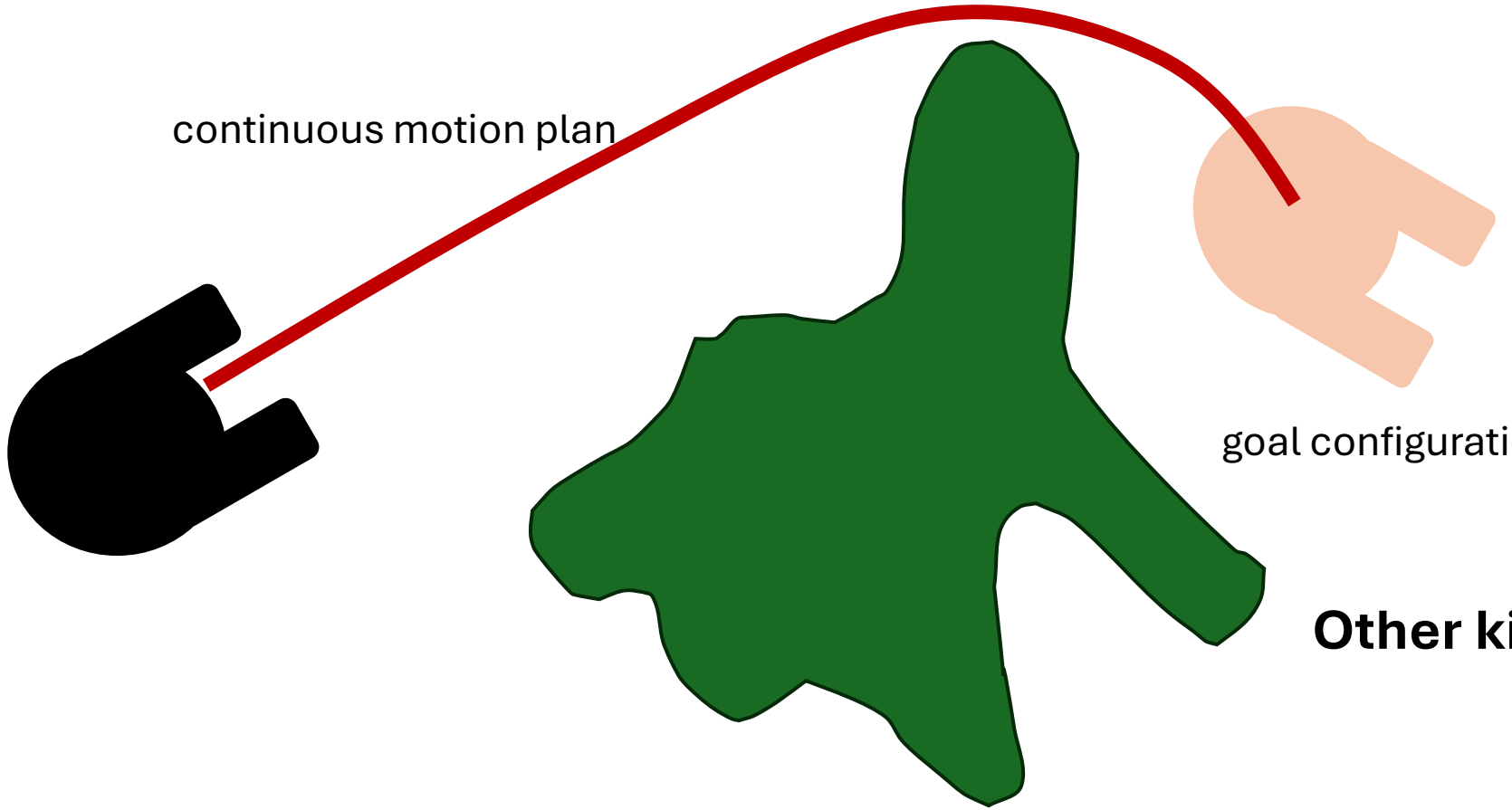
Robot Motion Planning



Robot Motion Planning

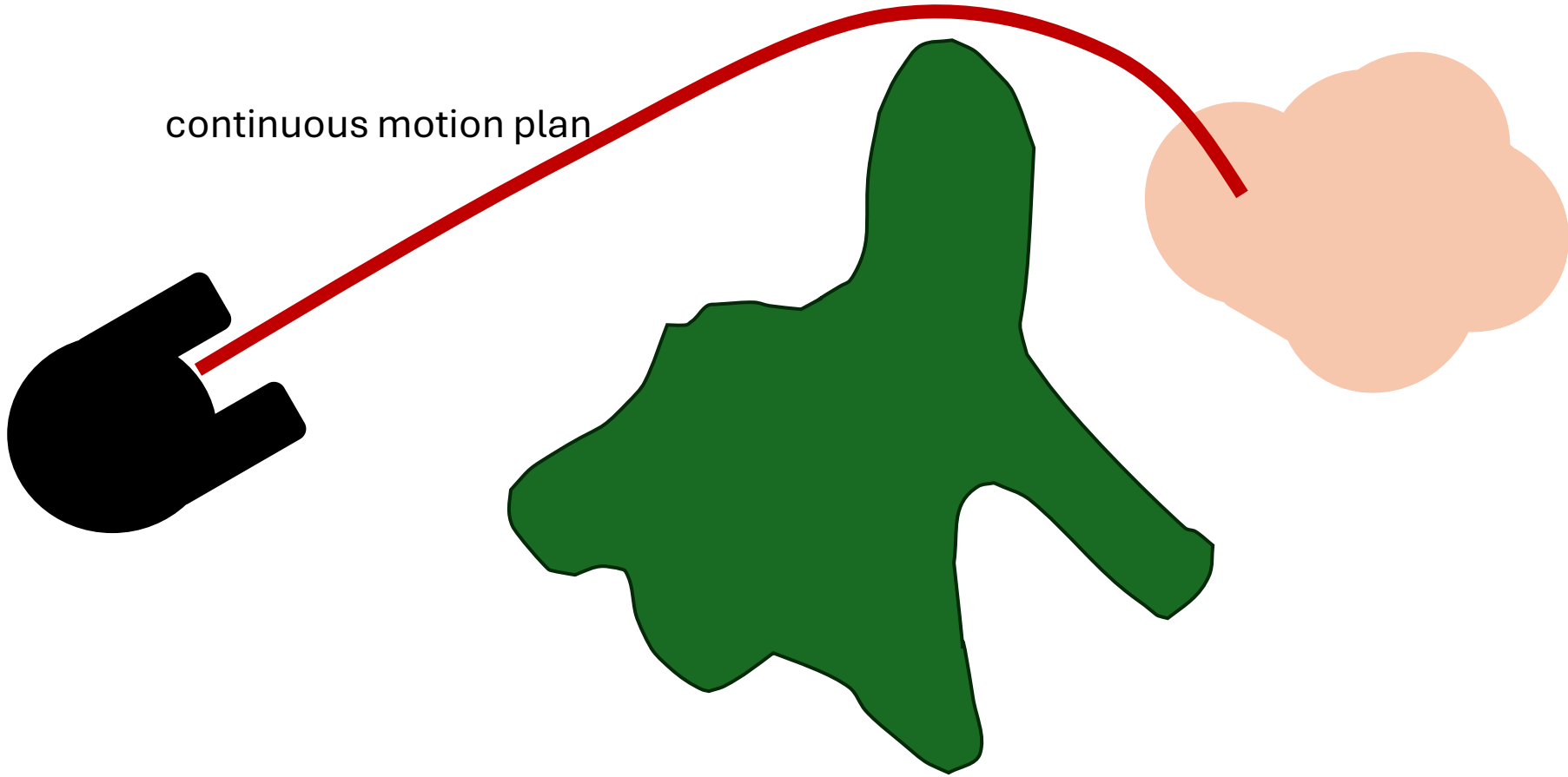


Robot Motion Planning

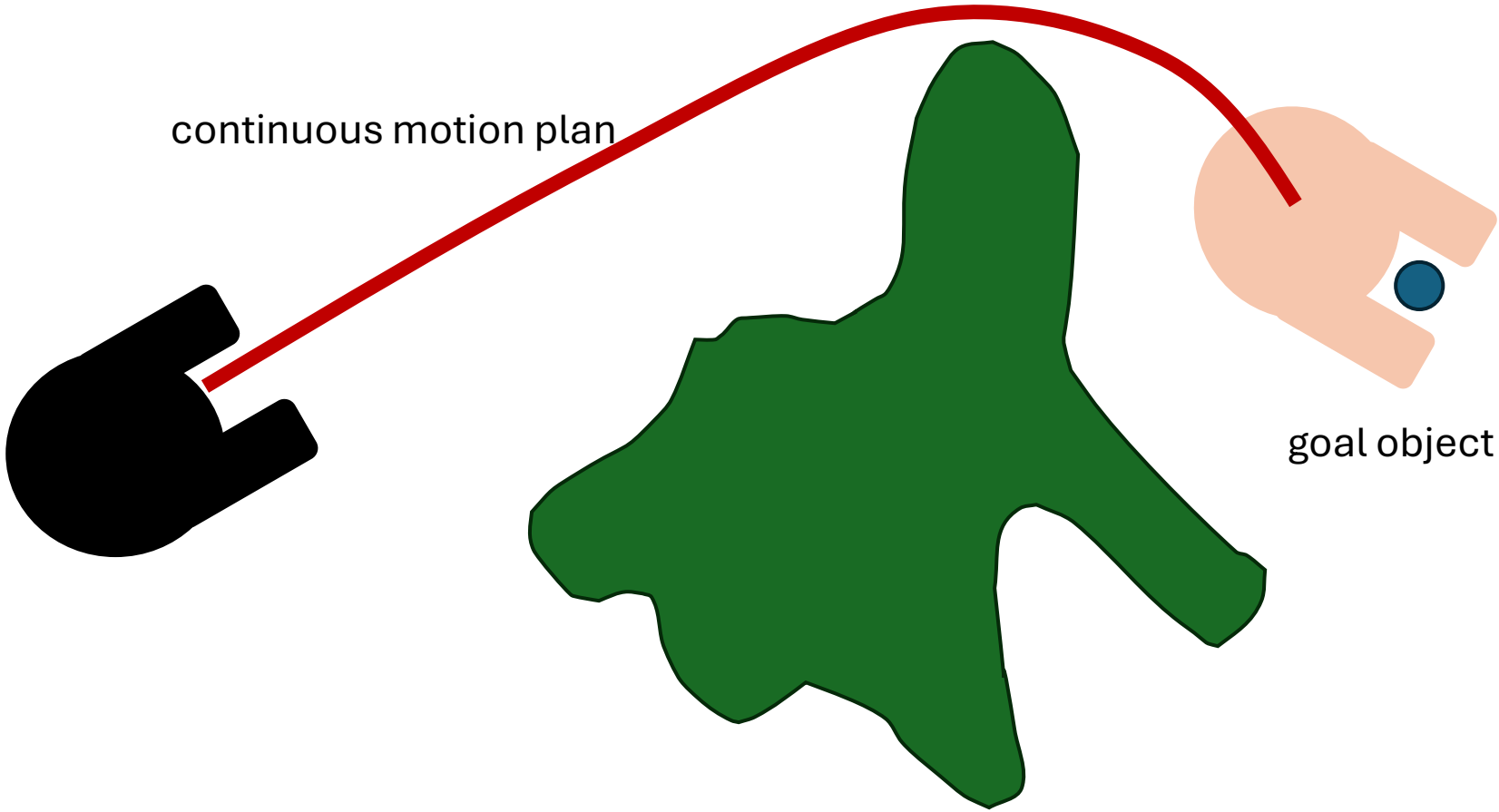


Other kinds of goals?

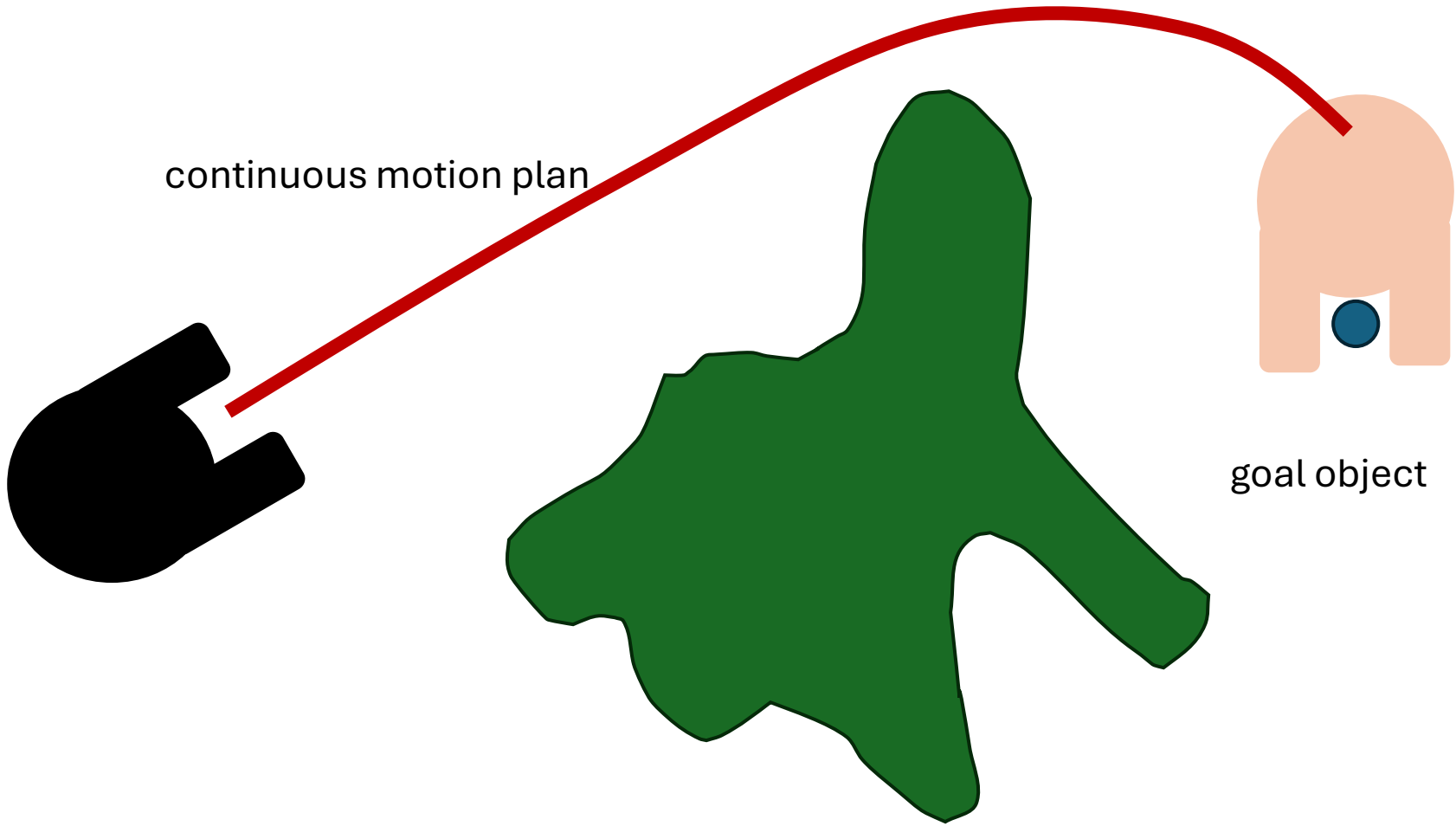
Goal Sets



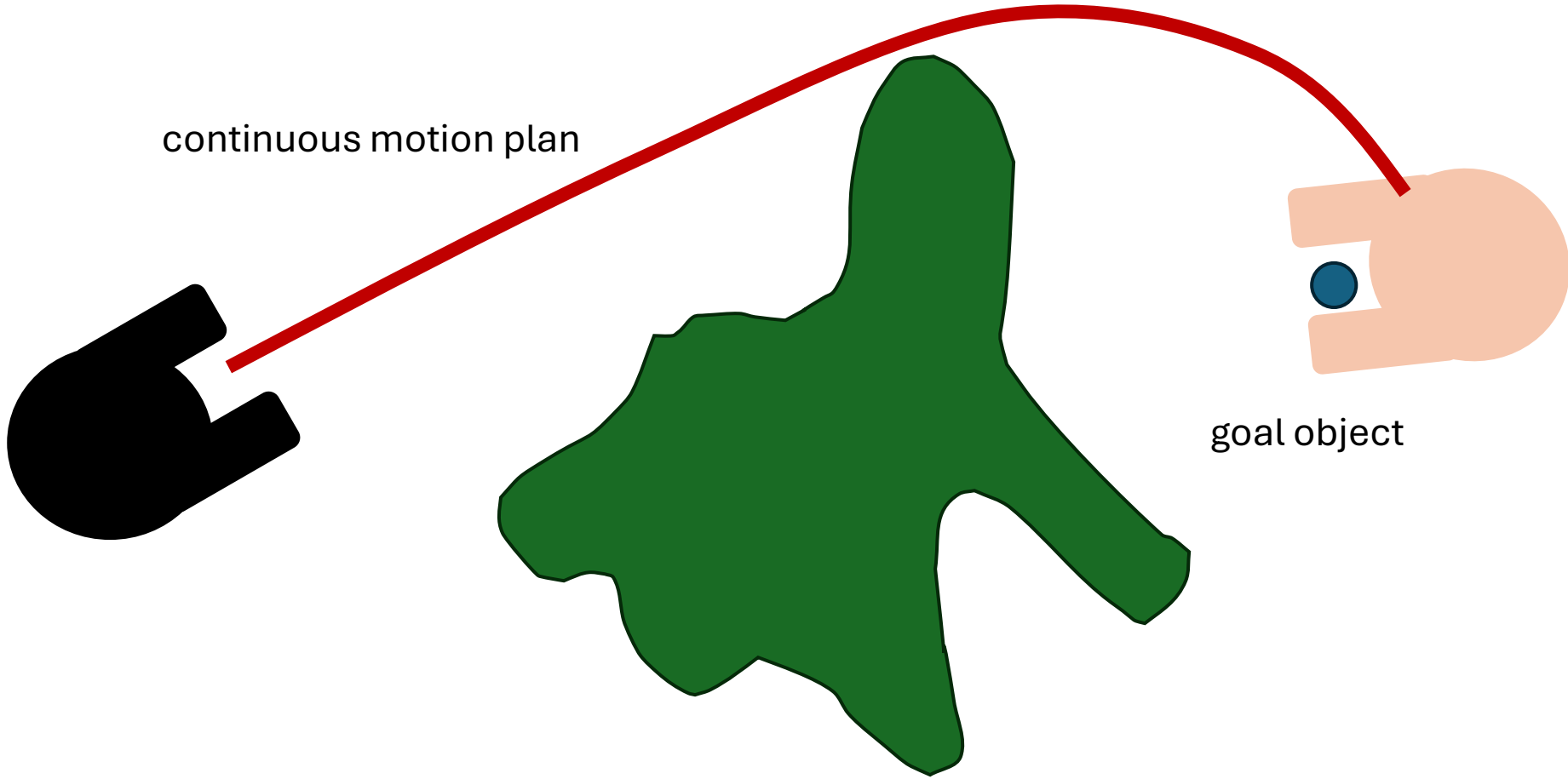
Goal: PICK the object



Goal: PICK the object

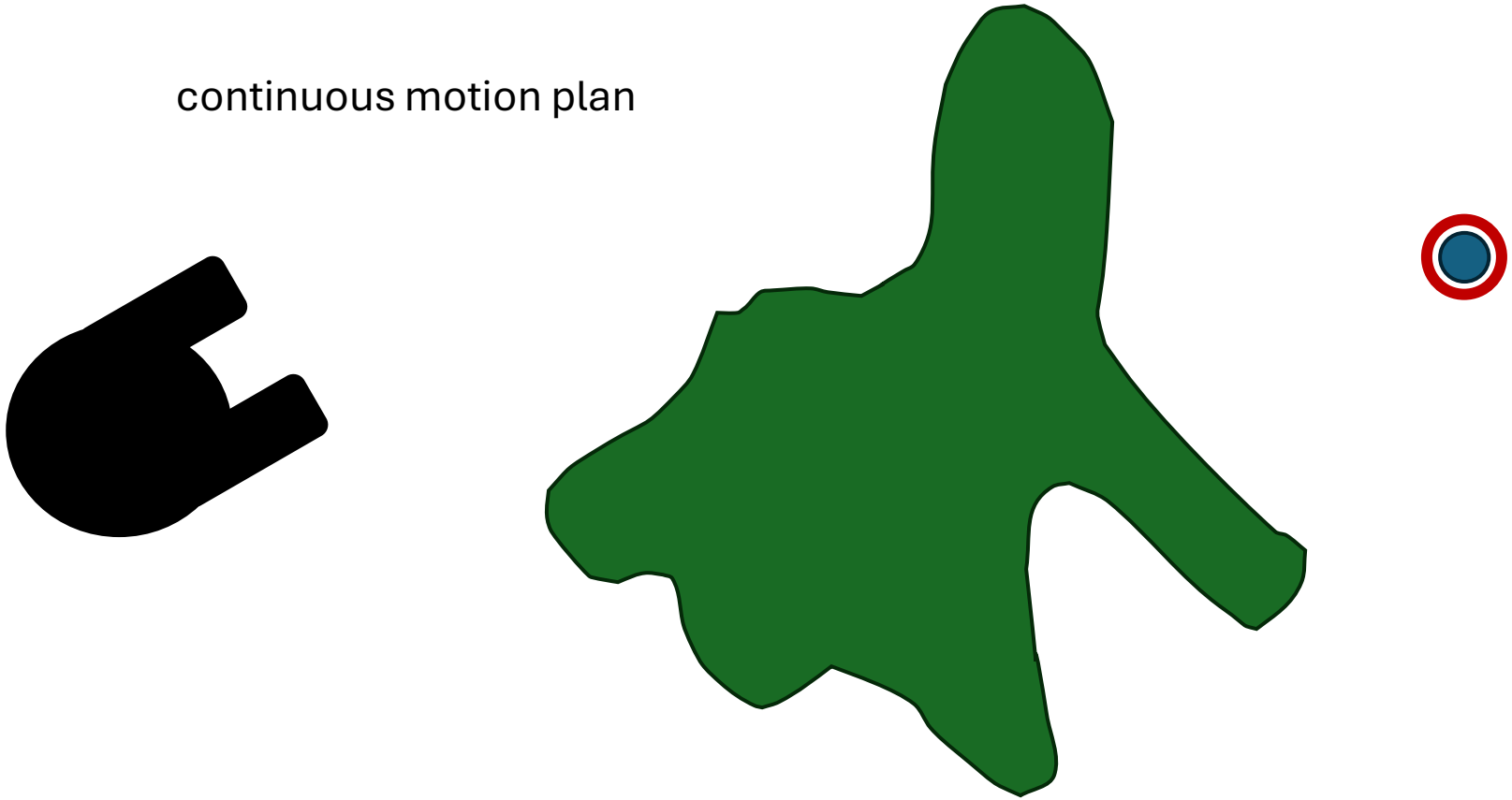


Goal: PICK the object



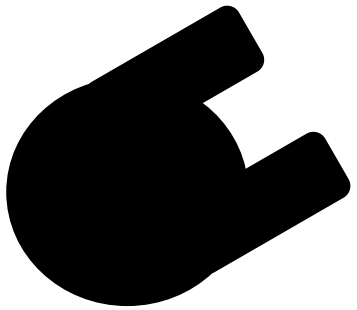
Goal set: PICK the object

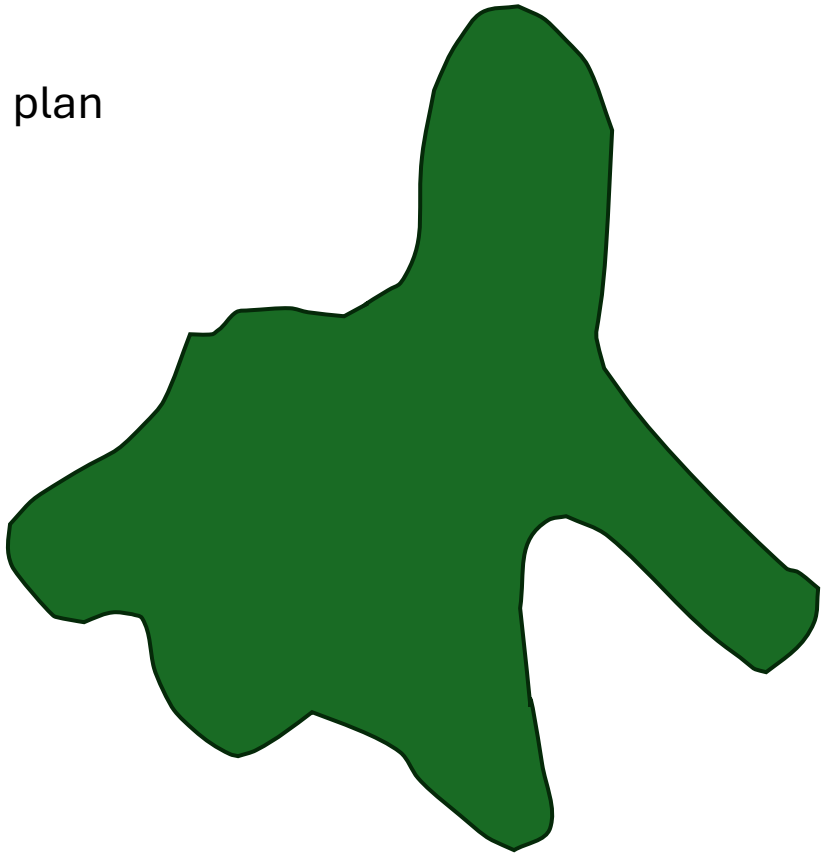
continuous motion plan



Goal set: PICK the object

continuous motion plan

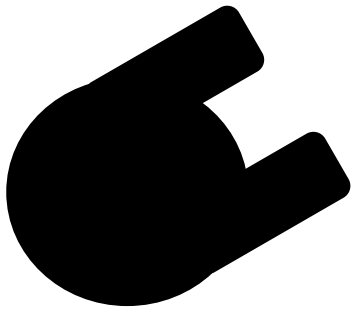


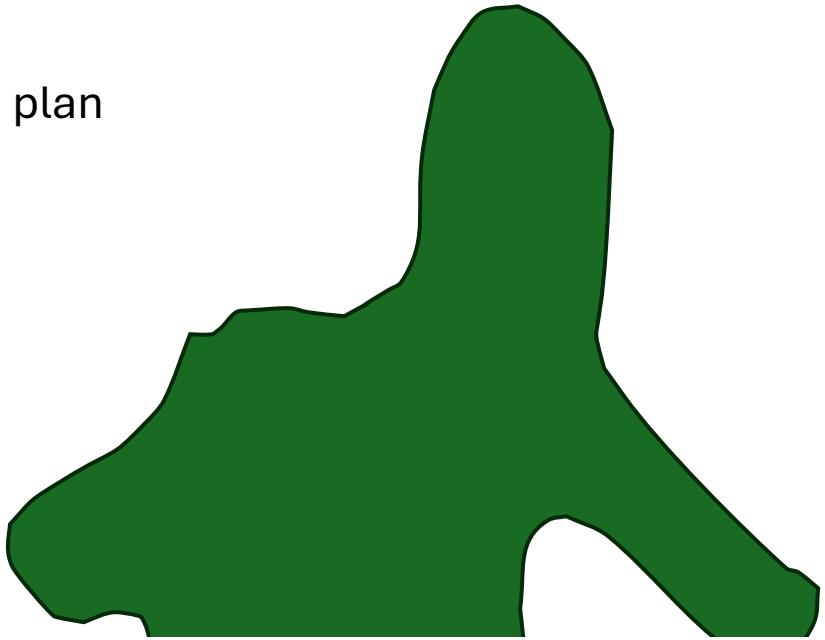


The ring is a lower-dimensional manifold

Actions as Constraint Manifolds

continuous motion plan



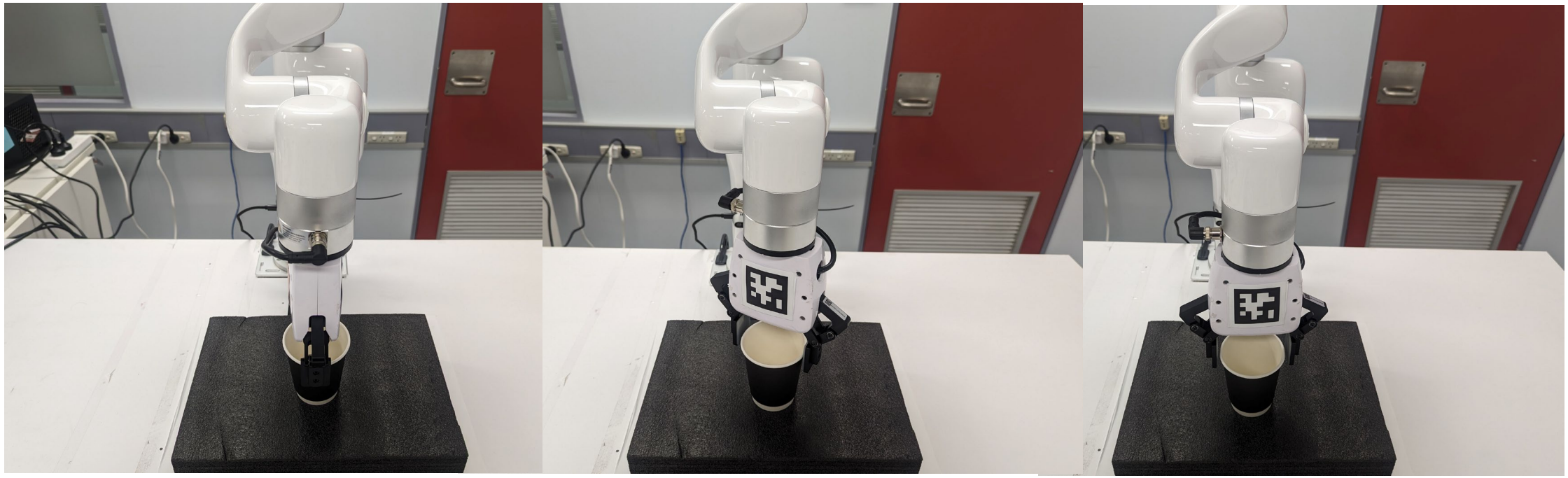


The ring is a lower-dimensional manifold

Actions as Constraints

PICK()

Actions as Constraint Manifolds

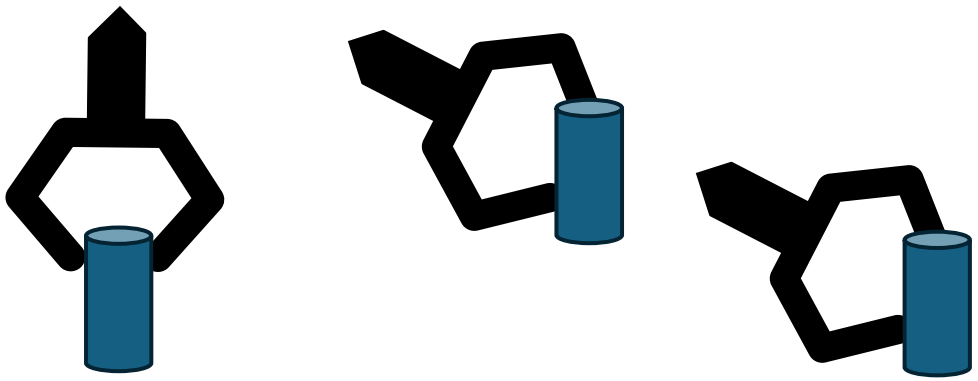


Actions as Constraints

PICK( )

Actions as Constraint Manifolds

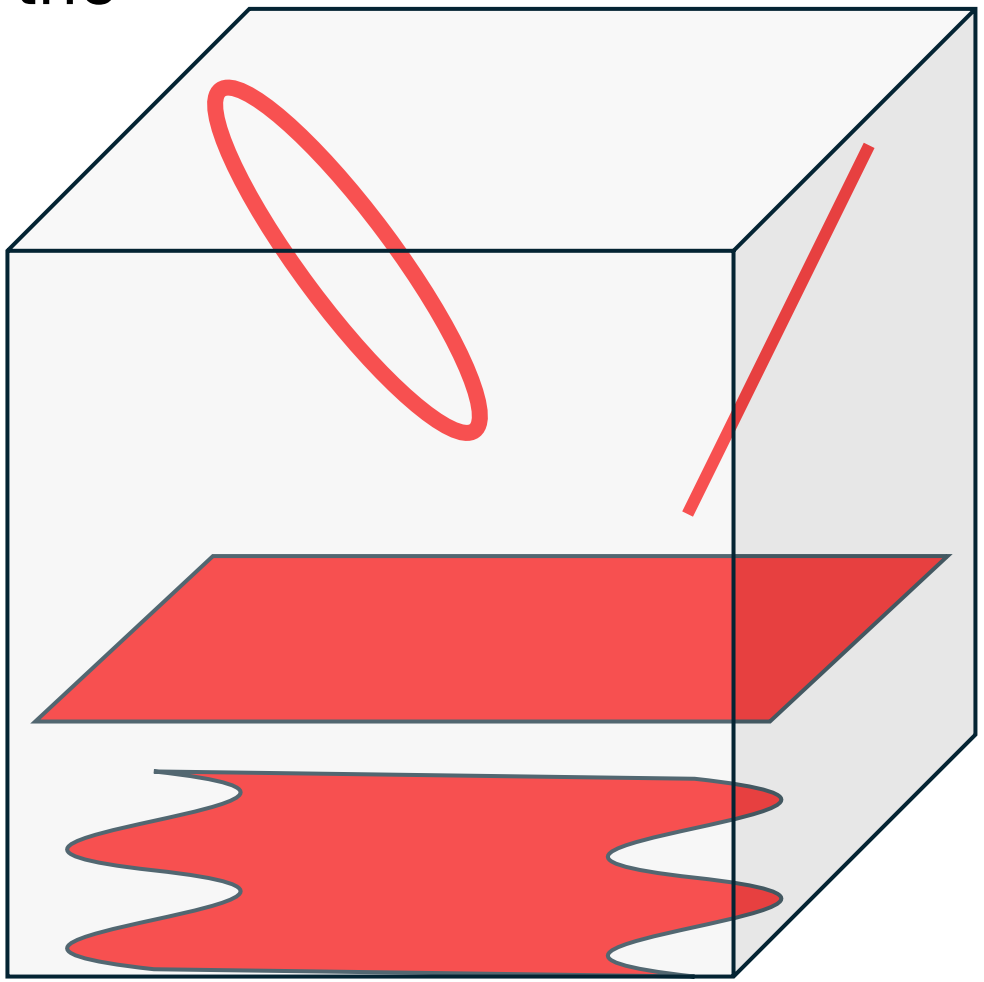
- Configuration Space – all the ways the robot can move
- Constraint manifold – subset in space which can be zero volume and lower dimensional



Pick up

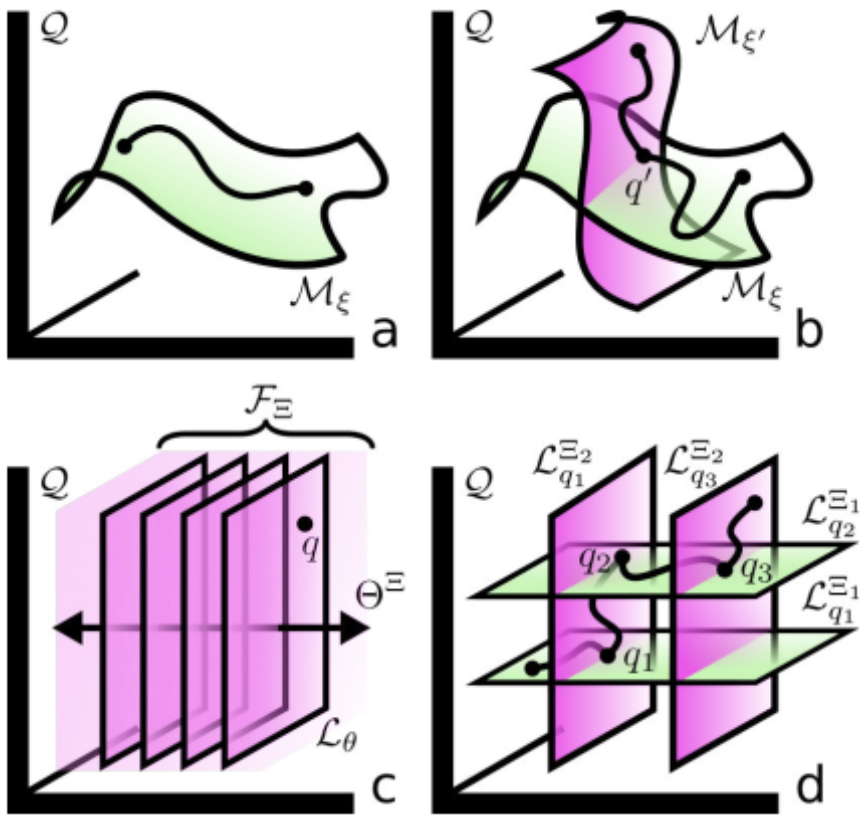
Keep upright

Place



Planning through Sequences of Constraints

- Multi-modal Planning

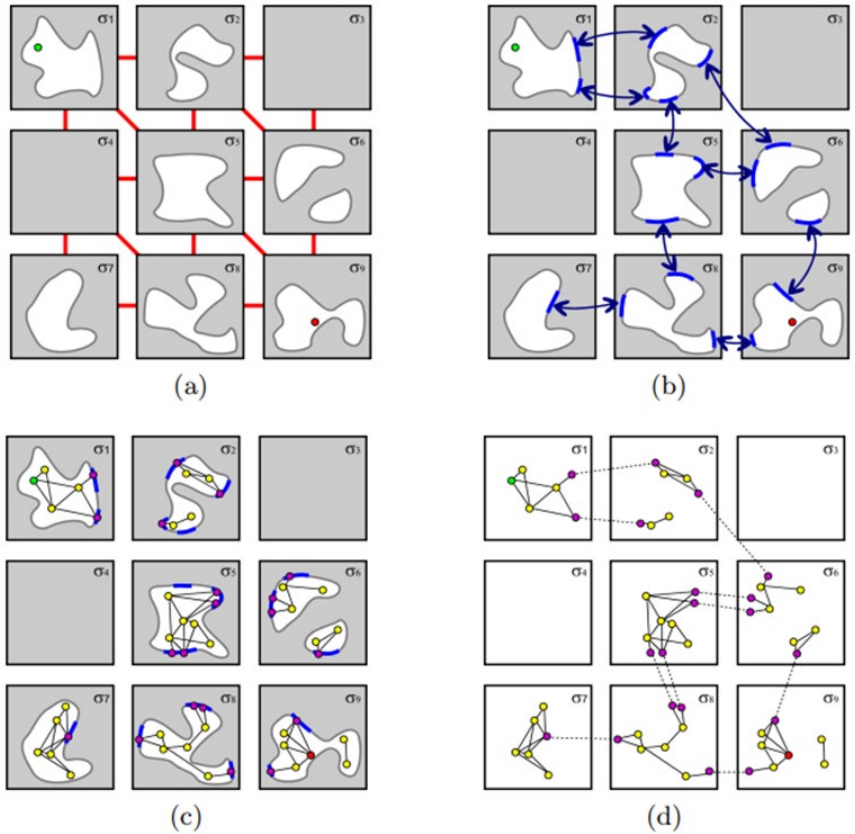


Kingston, Zachary, Andrew M. Wells, Mark Moll, and Lydia E. Kavraki. "Informing multi-modal planning with synergistic discrete leads." In *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 3199-3205. IEEE, 2020.

Kingston, Zachary, Mark Moll, and Lydia E. Kavraki. "Decoupling constraints from sampling-based planners." In *Robotics Research*, pp. 913-928. Springer, Cham, 2020.

Planning through Sequences of Constraints

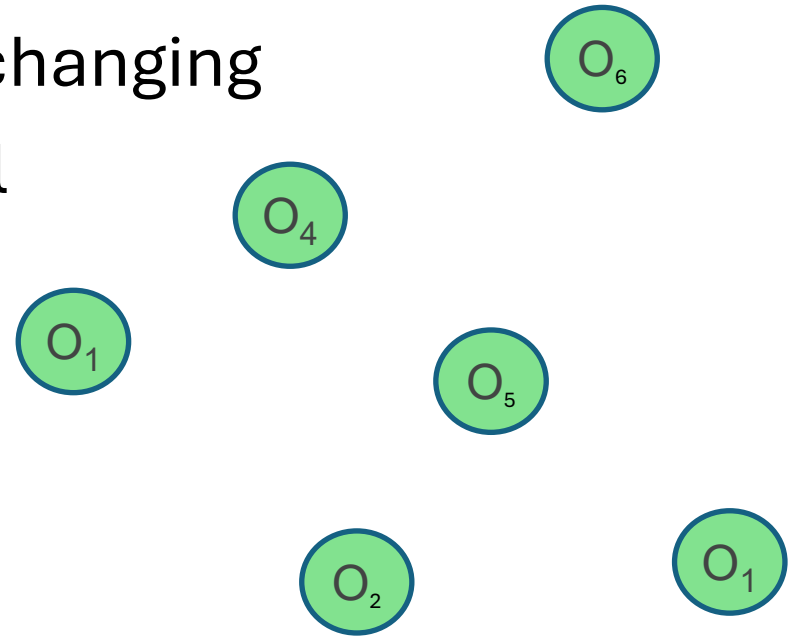
- Multi-modal Planning

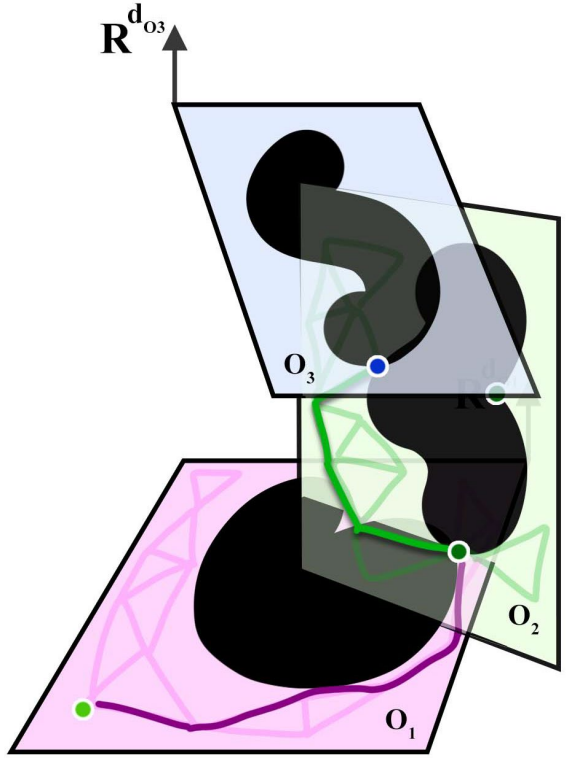


Hauser, Kris, and Jean-Claude Latombe. "Multi-modal motion planning in non-expansive spaces." *The International Journal of Robotics Research* 29, no. 7 (2010): 897-915.

Planning through Sequences of Constraints

- These search spaces are hybrid
- These search spaces are massive
- Dimensions keep changing
- Lower dimensional components cannot be sampled naively
- Need for guidance



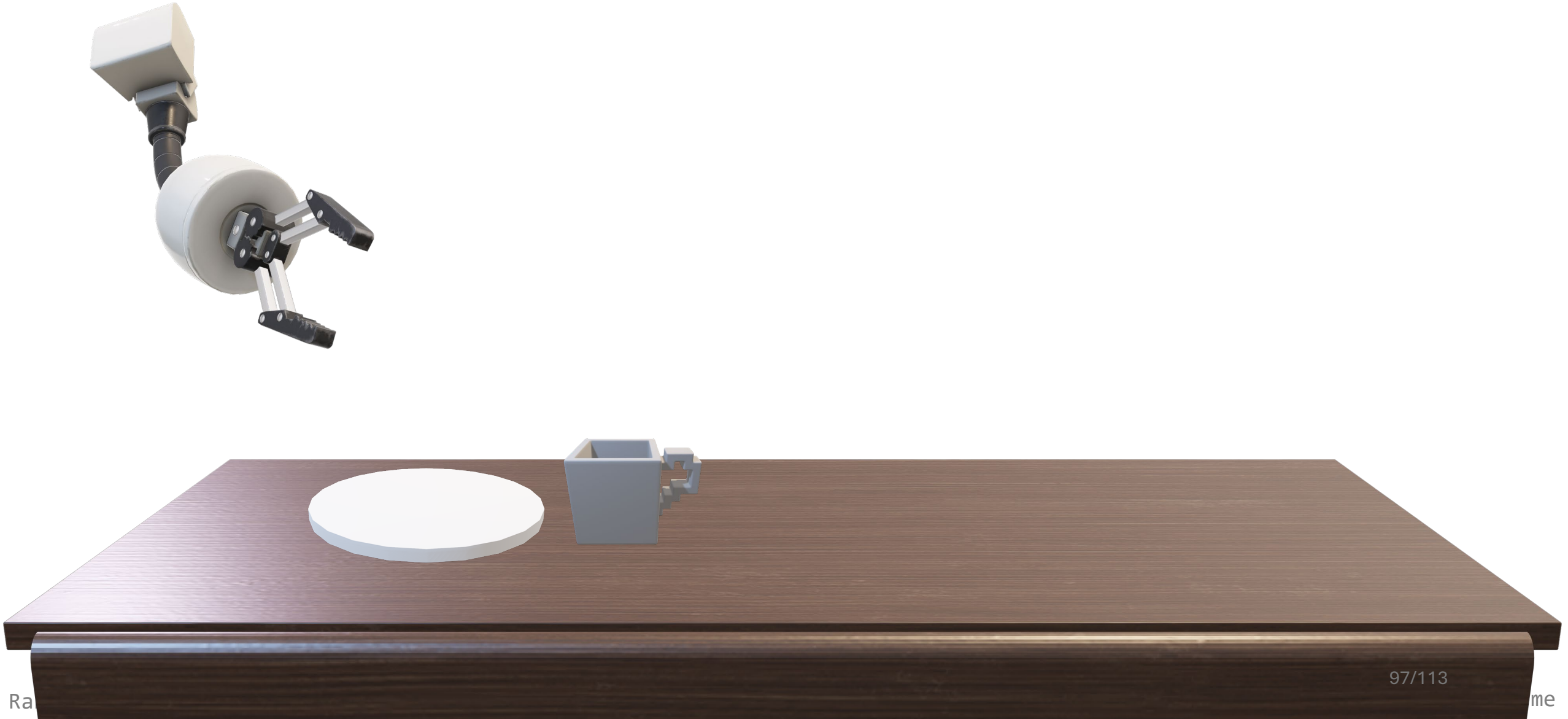


Vega-Brown, William, and Nicholas Roy. "Asymptotically optimal planning under piecewise-analytic constraints." In *Algorithmic Foundations of Robotics XII*, pp. 528-543. Springer, Cham, 2020.

Shome, Rahul, Daniel Nakhimovich, and Kostas E. Bekris. "Pushing the boundaries of asymptotic optimality in integrated task and motion planning." In *International Workshop on the Algorithmic Foundations of Robotics*, pp. 467-484. Springer, Cham, 2020.

Task and Motion Planning

Logic Beyond Motion Planning



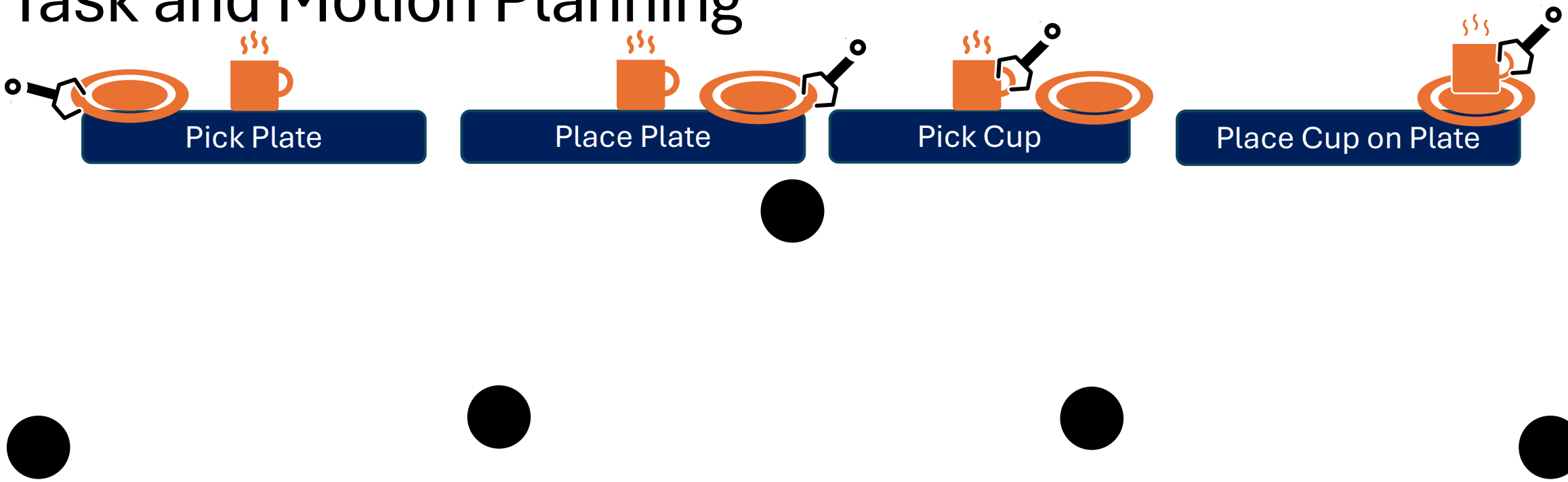
Logic Beyond Motion Planning

Logic Beyond Motion Planning

start configuration

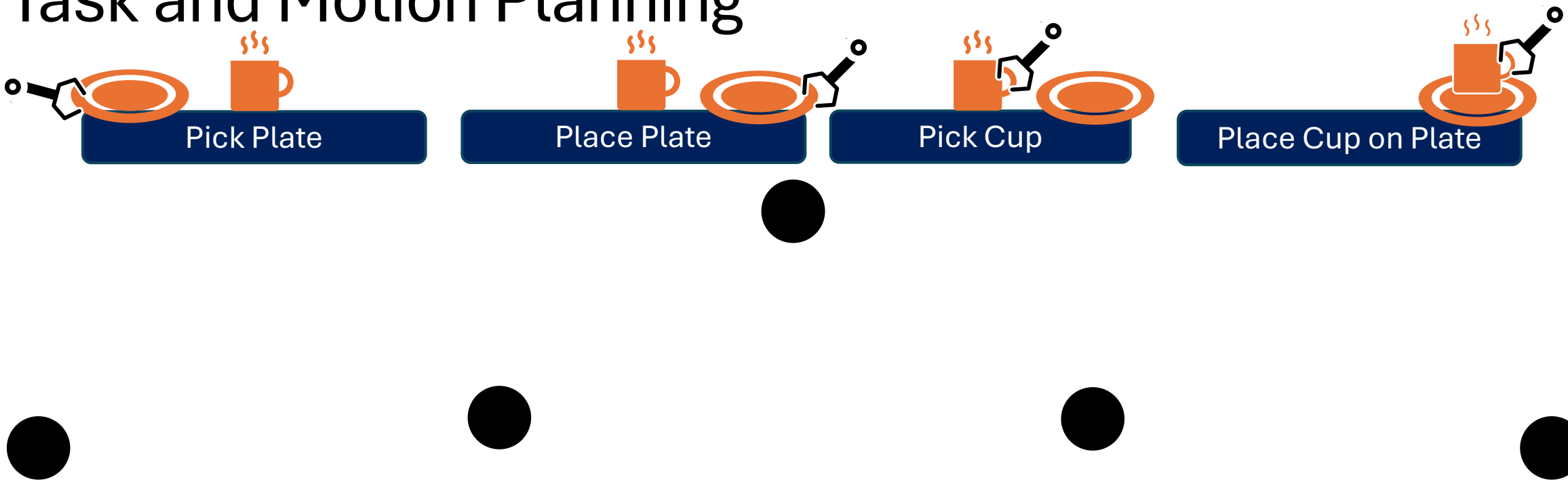
task goal

Task and Motion Planning



- Sequence of **deliberate motions or actions** that achieve task goal

Task and Motion Planning

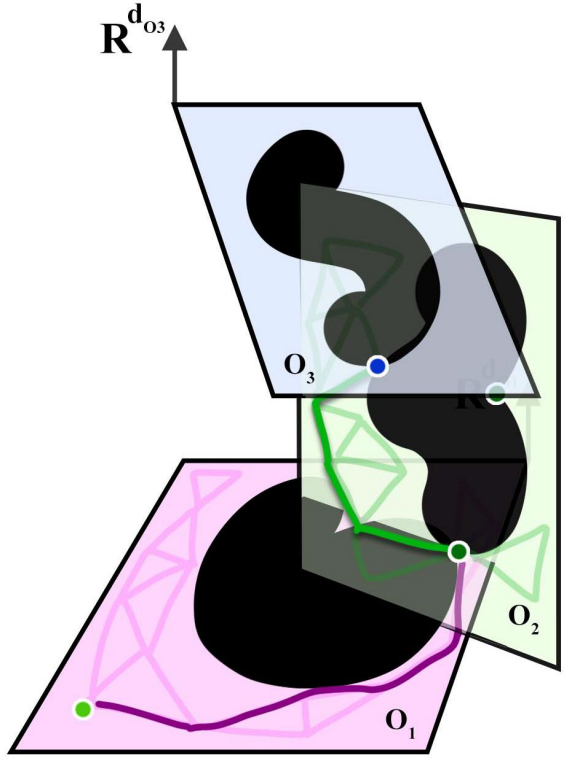


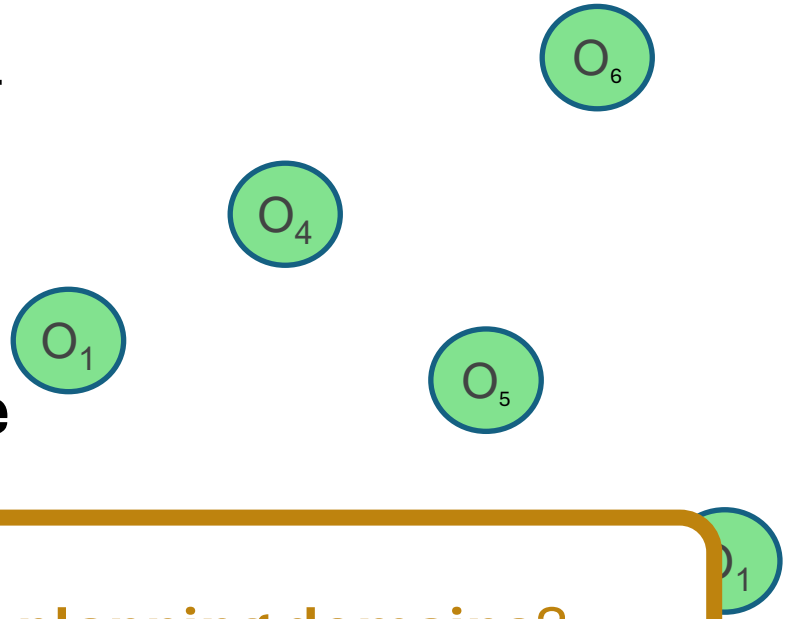
Each of these is a motion planning problem

- Sequence of **deliberate motions or actions** that achieve task goal

Planning through Sequences of Constraints

- These search spaces are massive
- Dimensions keep changing
- Lower dimensional components cannot be sampled naively
- **Need for guidance**



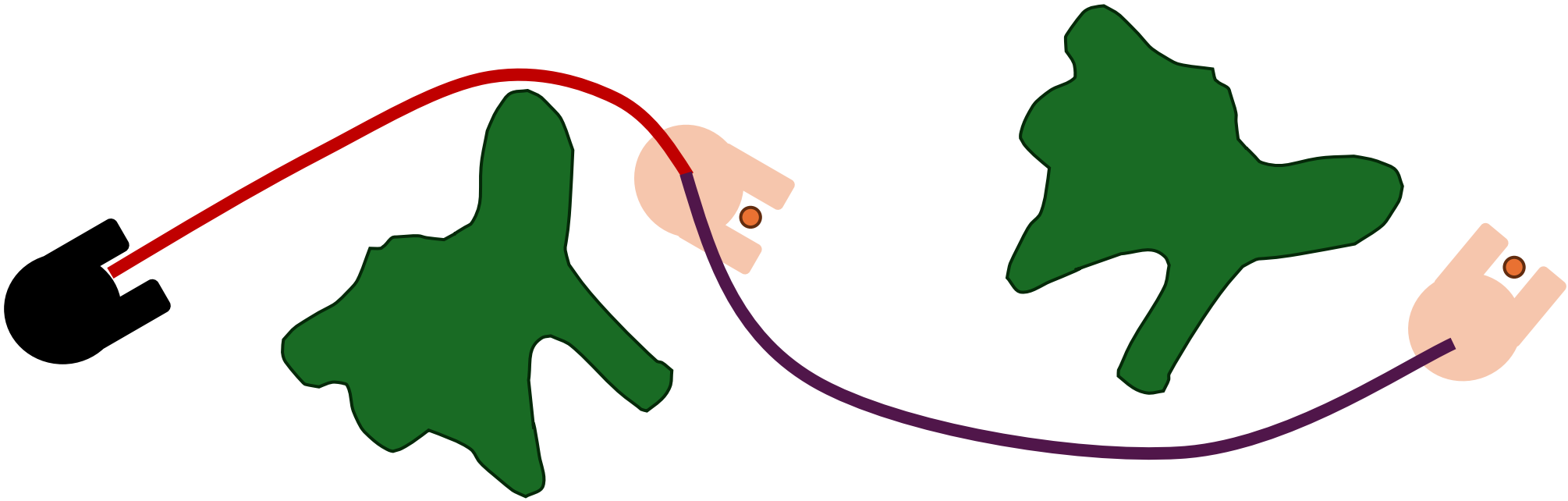


Task Plans in **discrete planning domains**?

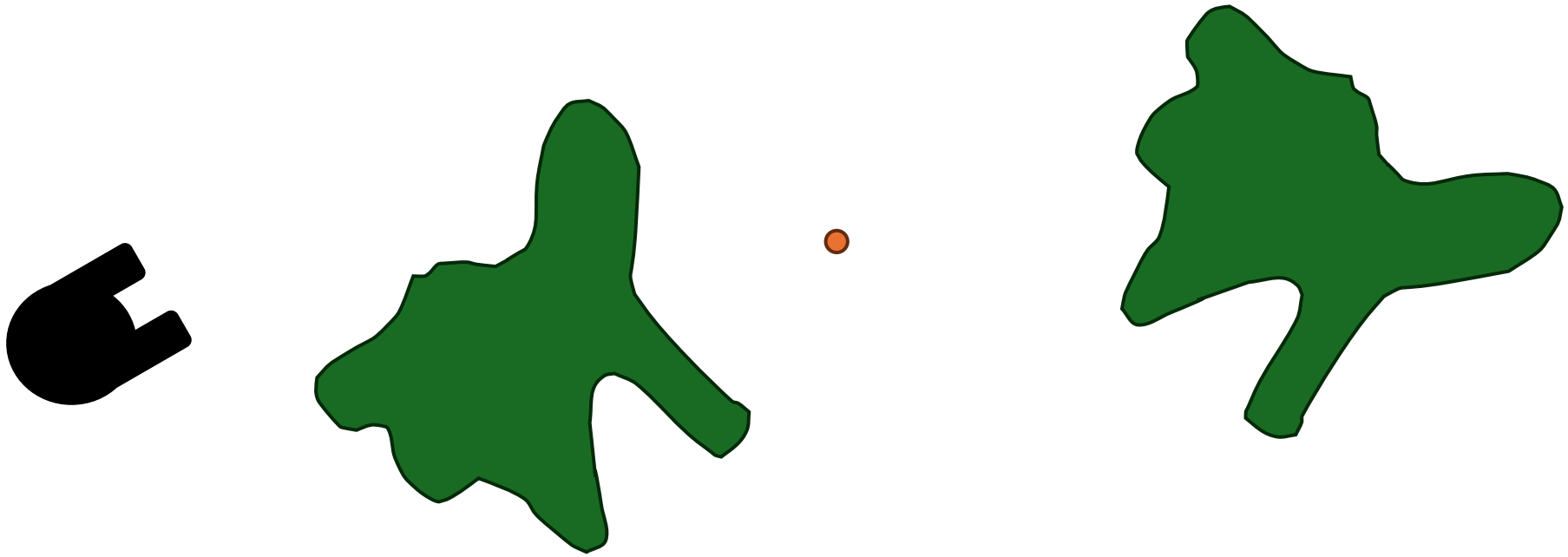
V c constraints." In *Algorithmic Foundations of Robotics XII*, pp. 528-543. Springer, Cham, 2020.

Shome, Rahul, Daniel Nakhimovich, and Kostas E. Bekris. "Pushing the boundaries of asymptotic optimality in integrated task and motion planning." In *International Workshop on the Algorithmic Foundations of Robotics*, pp. 467-484. Springer, Cham, 2020.

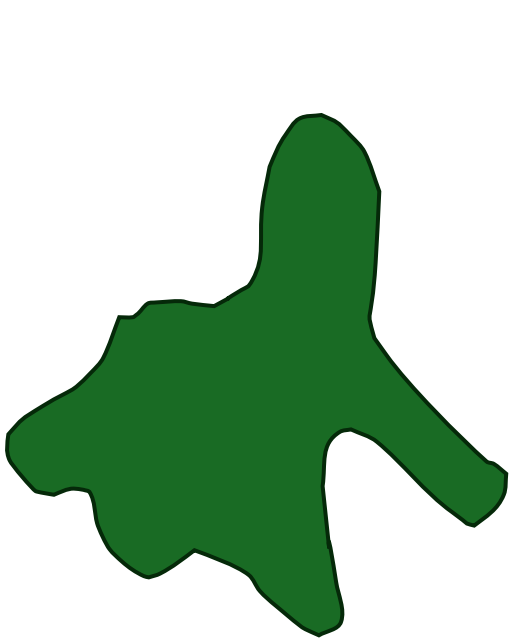
Motion Plans for Actions

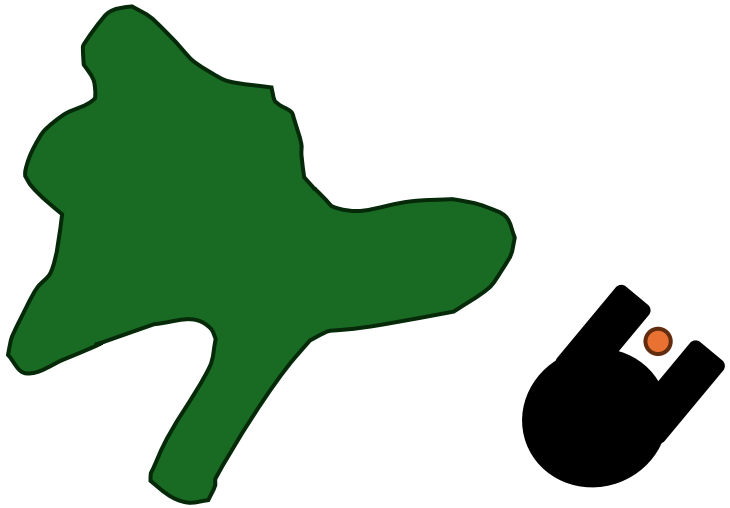


Start state and configuration



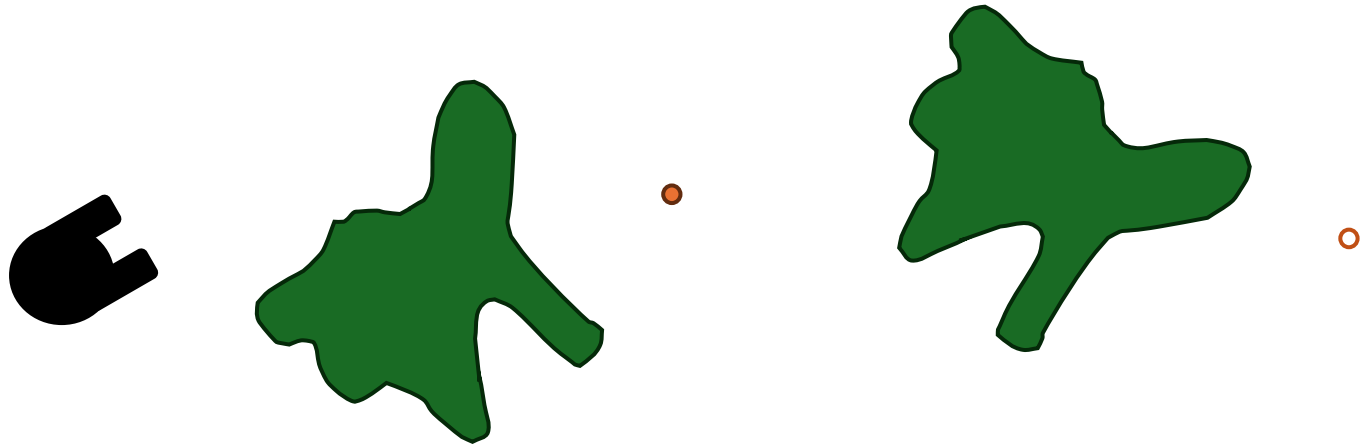
Goal state and configuration





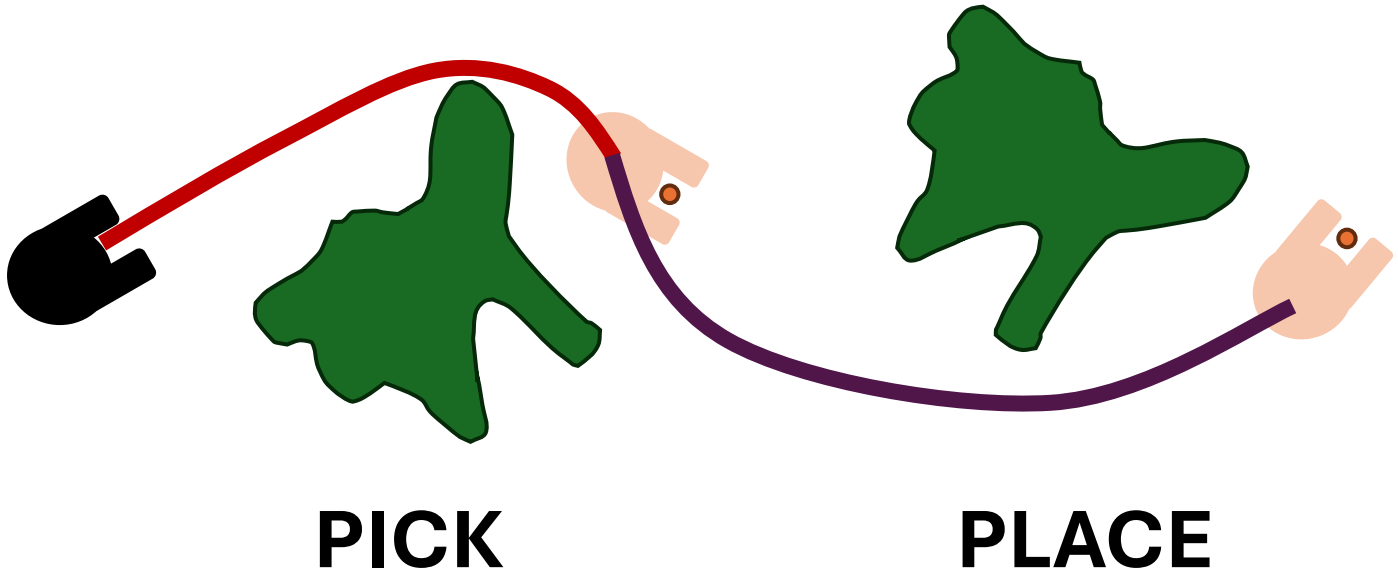
Elements of the problem

- Compute discrete actions to goal state
- Compute feasible motions for actions



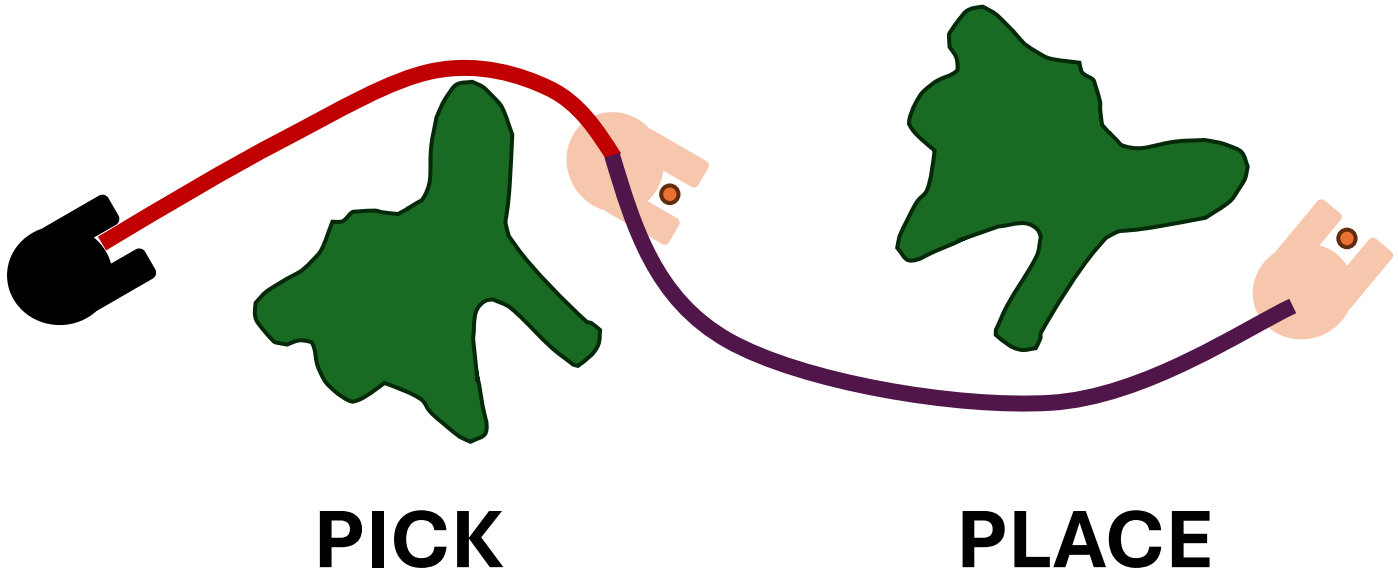
Elements of the problem

- Compute discrete actions to goal state
- Compute feasible motions for actions



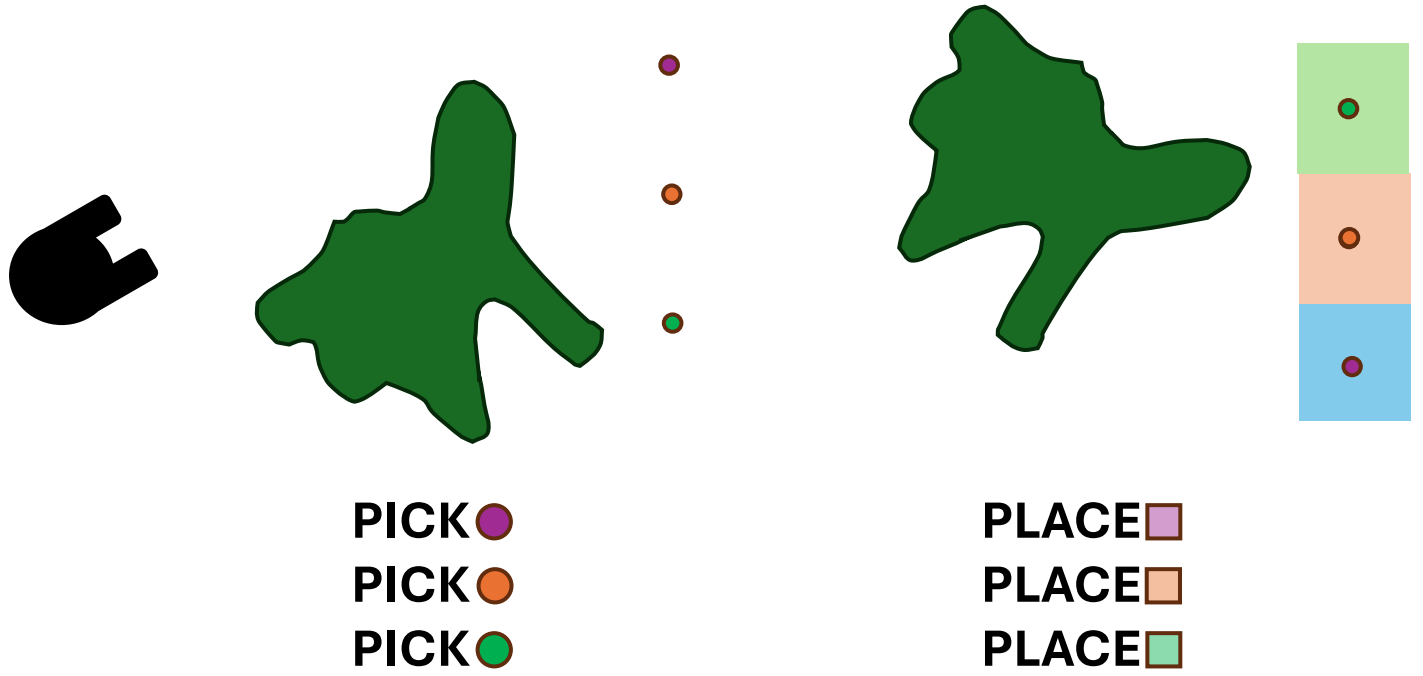
Elements of the problem

- **Task Planning:** Compute discrete actions to goal state
- **Motion Planning:** Compute feasible motions for actions



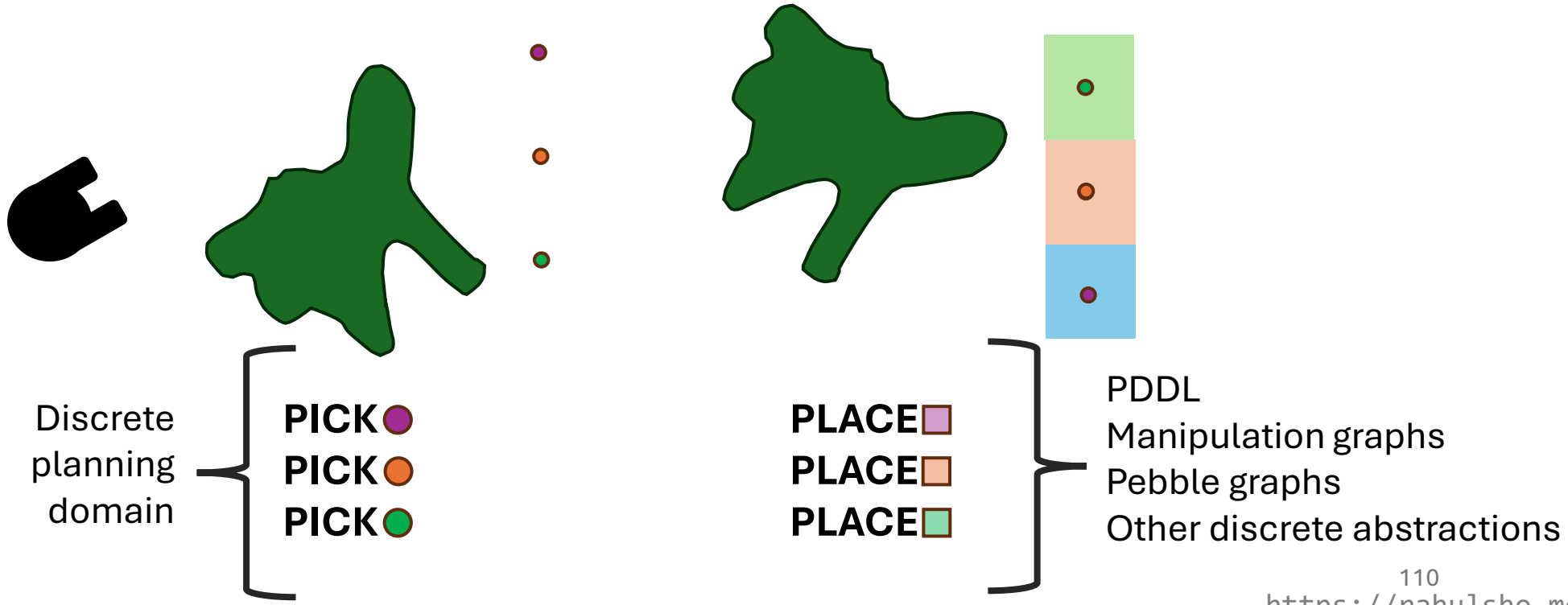
Elements of the problem

- **Task Planning:** Compute discrete actions to goal state
- **Motion Planning:** Compute feasible motions for actions



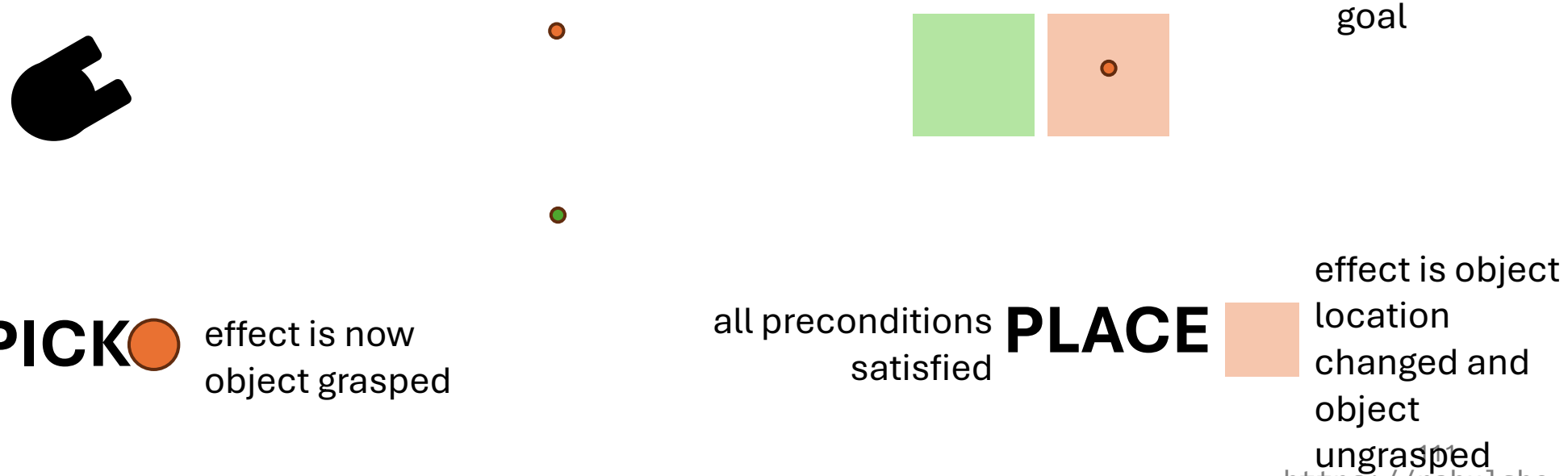
Elements of the problem

- **Task Planning:** Compute discrete actions to goal state
- **Motion Planning:** Compute feasible motions for actions



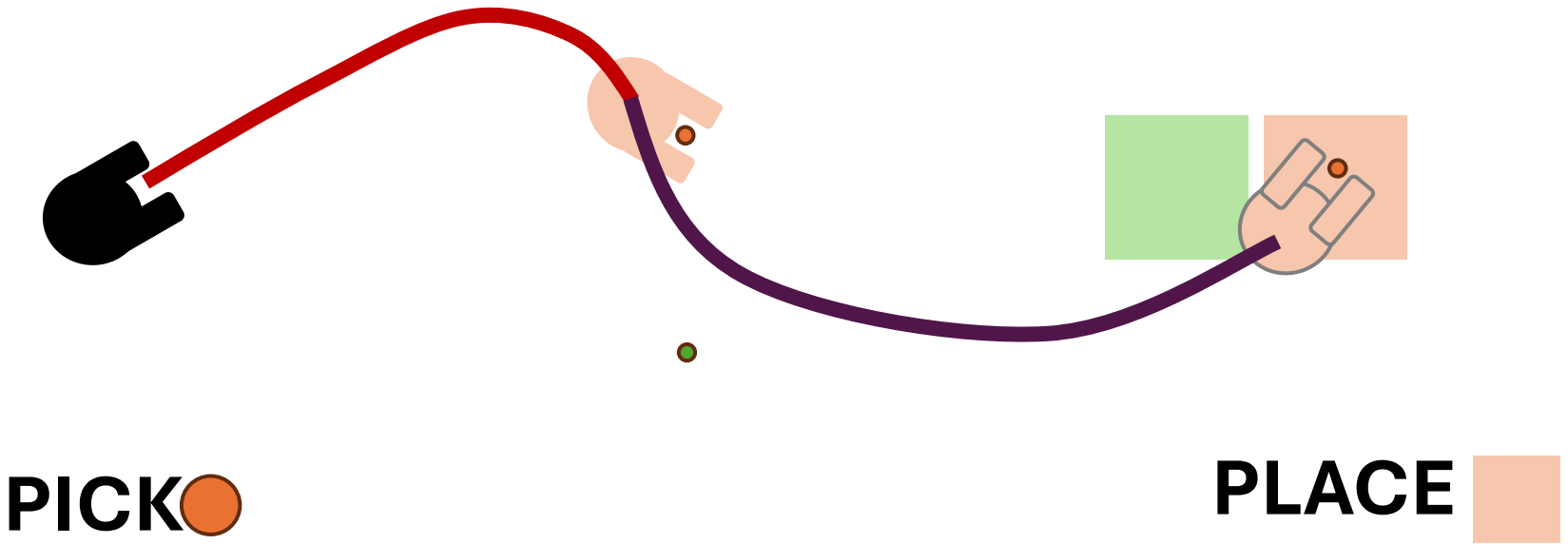
Task Planning, Motion Planning

- Find task plan (task planner query)
- Find motion plans (sequence of motion planner queries)



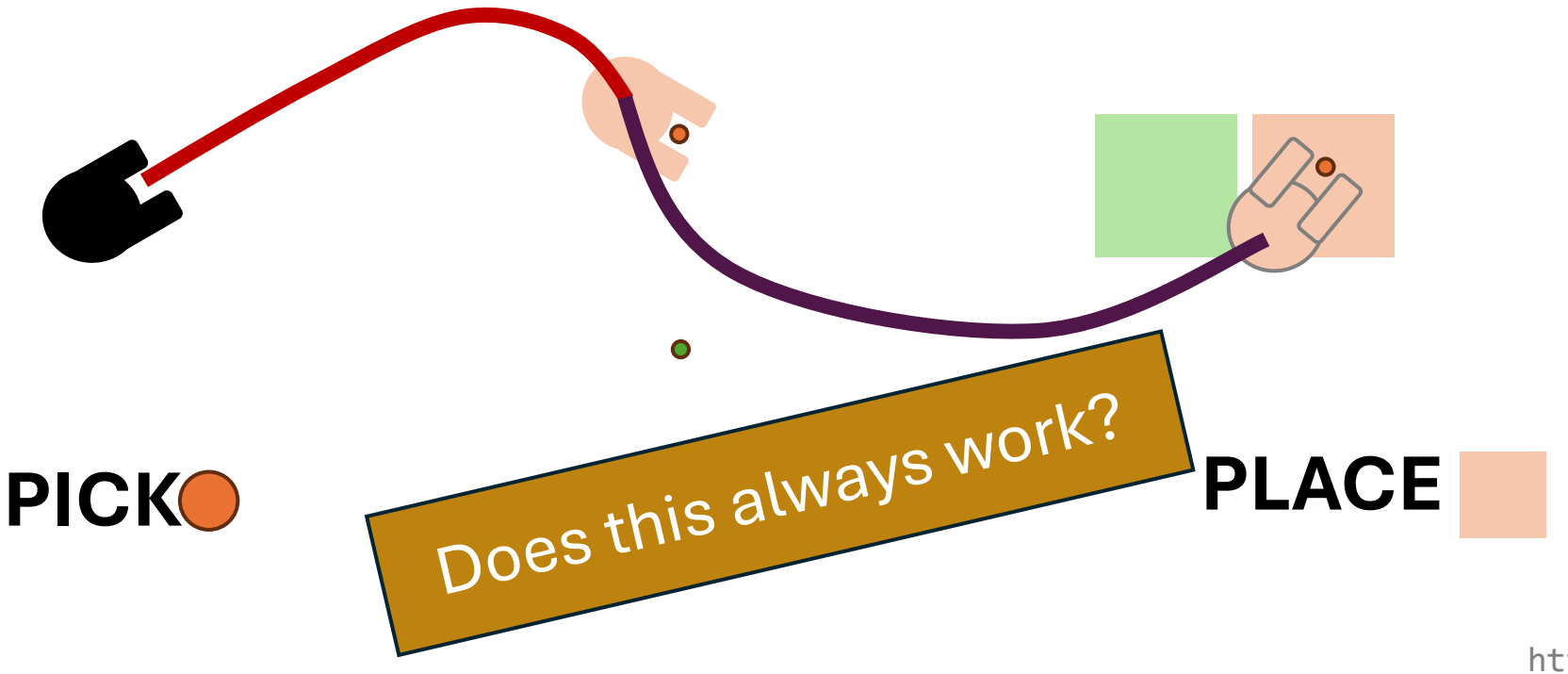
Task Planning THEN Motion Planning

- Find task plan (task planner query)
- **THEN** Find motion plans (sequence of motion planner queries)



Task Planning THEN Motion Planning

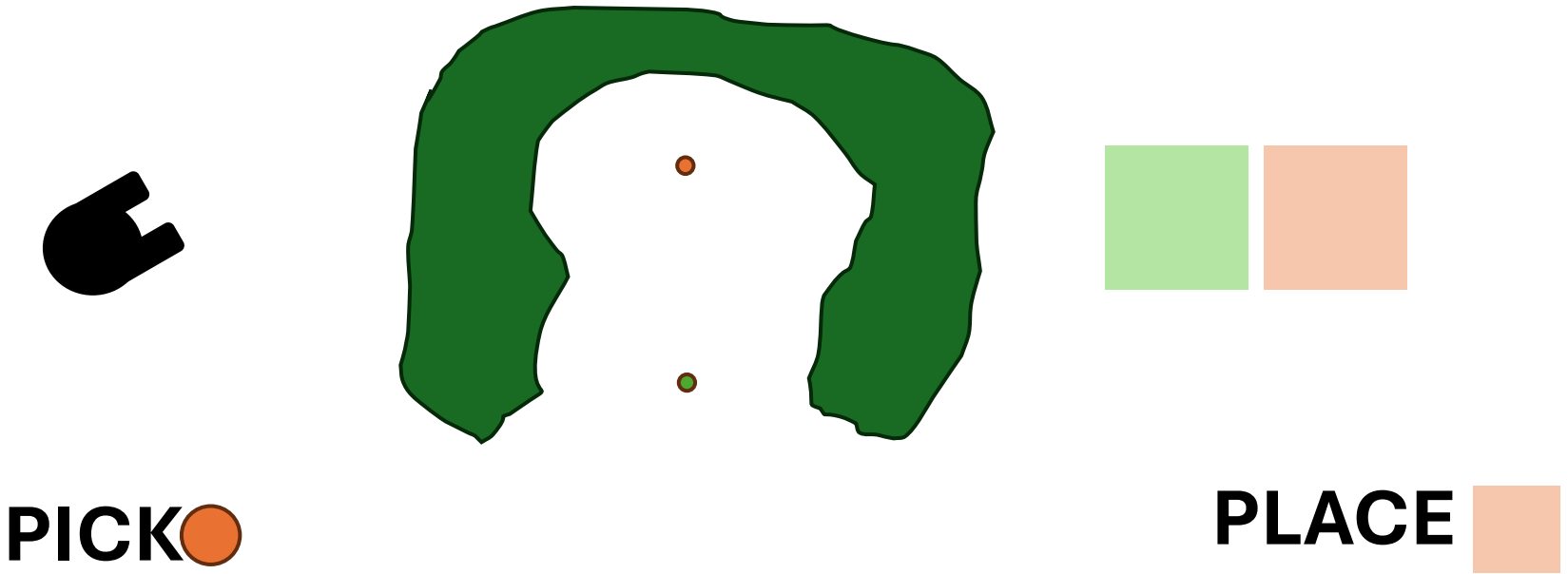
- Find task plan (task planner query)
- **THEN** Find motion plans (sequence of motion planner queries)



Task Planning THEN Motion Planning

- Find task plan (task planner query)
- Then find motion plans (sequence of motion planner queries)

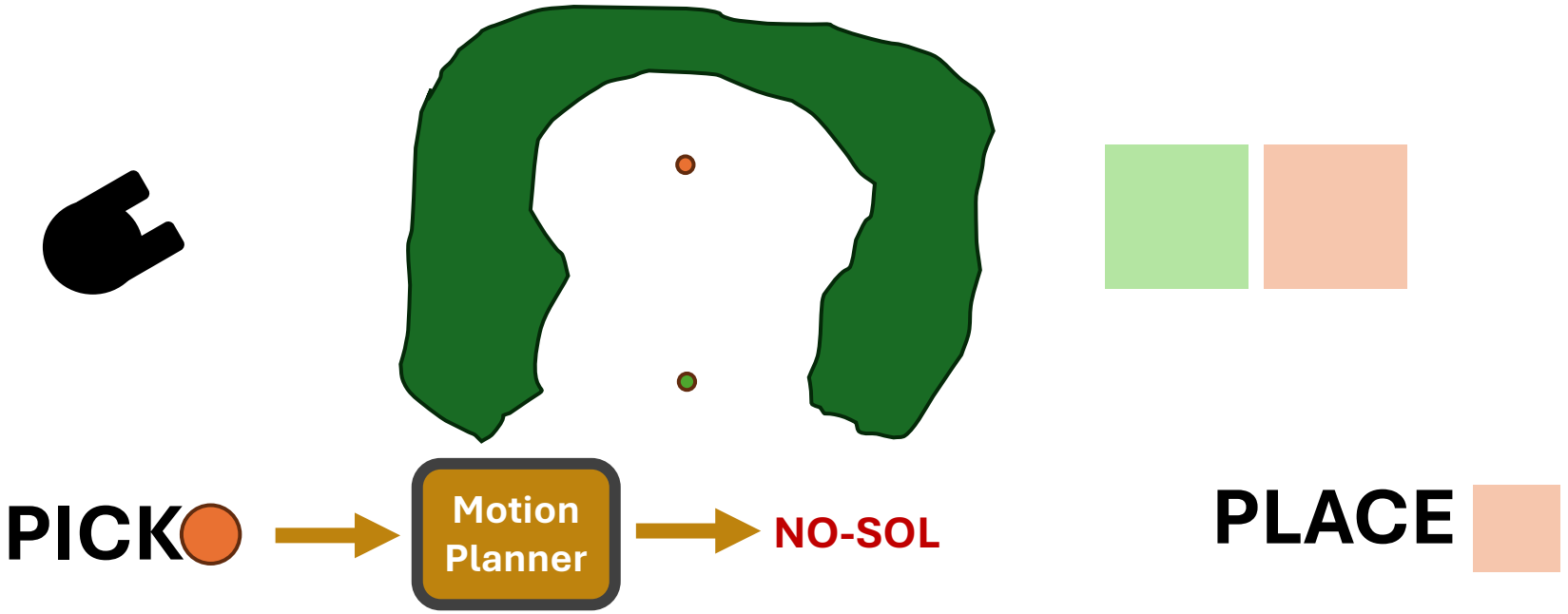
Motion infeasibility in high-dimensional configuration space is not known beforehand



Task Planning AND Motion Planning

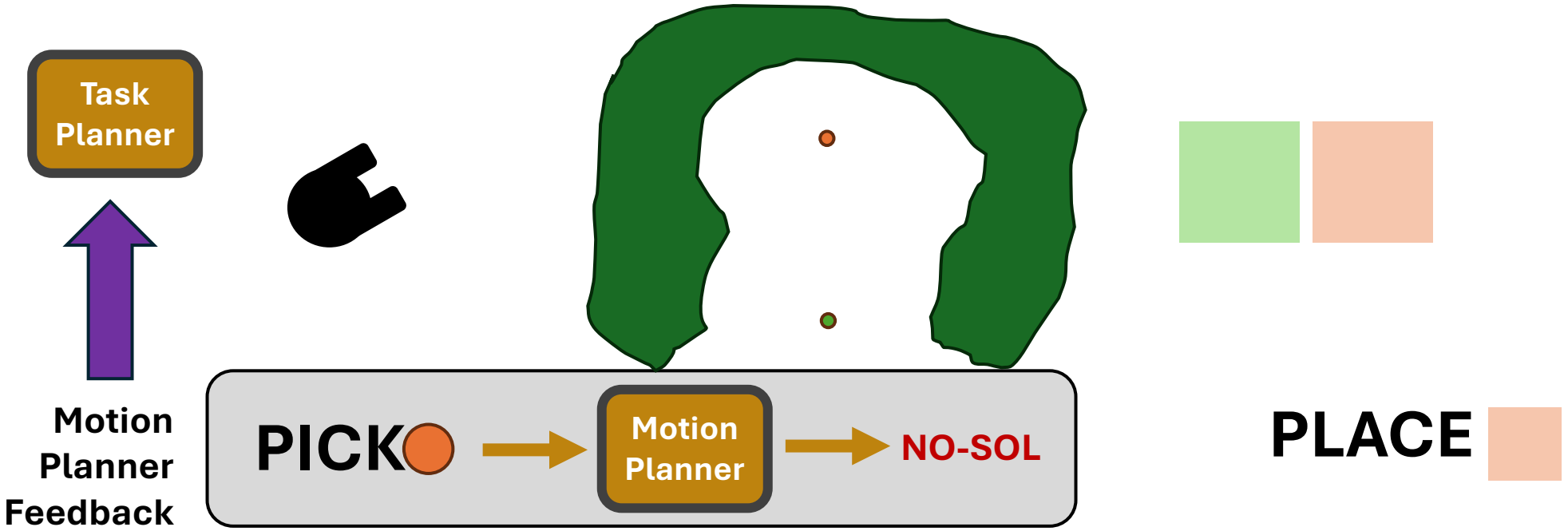
- Find task plan (task planner query)
- Find motion plans (sequence of motion planner queries)

Motion infeasibility in high-dimensional configuration space is not known beforehand

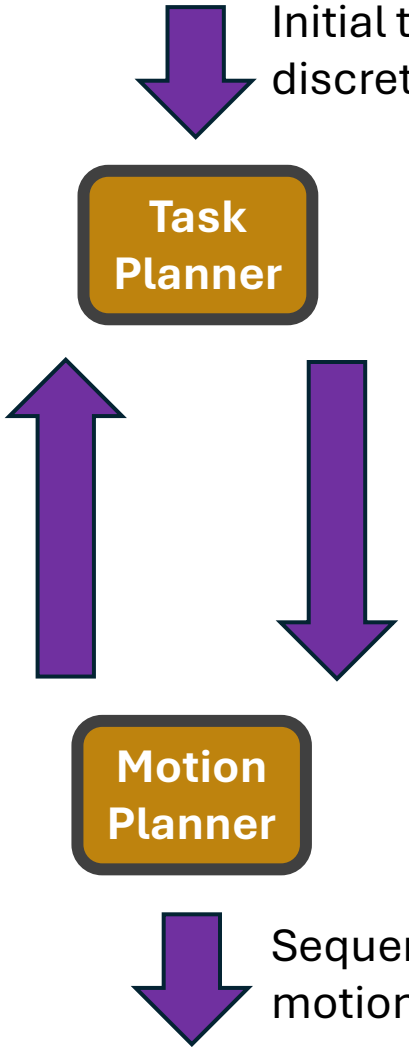


Task Planning AND Motion Planning

- Find task plan (task planner query)
- Find motion plans (sequence of motion planner queries)

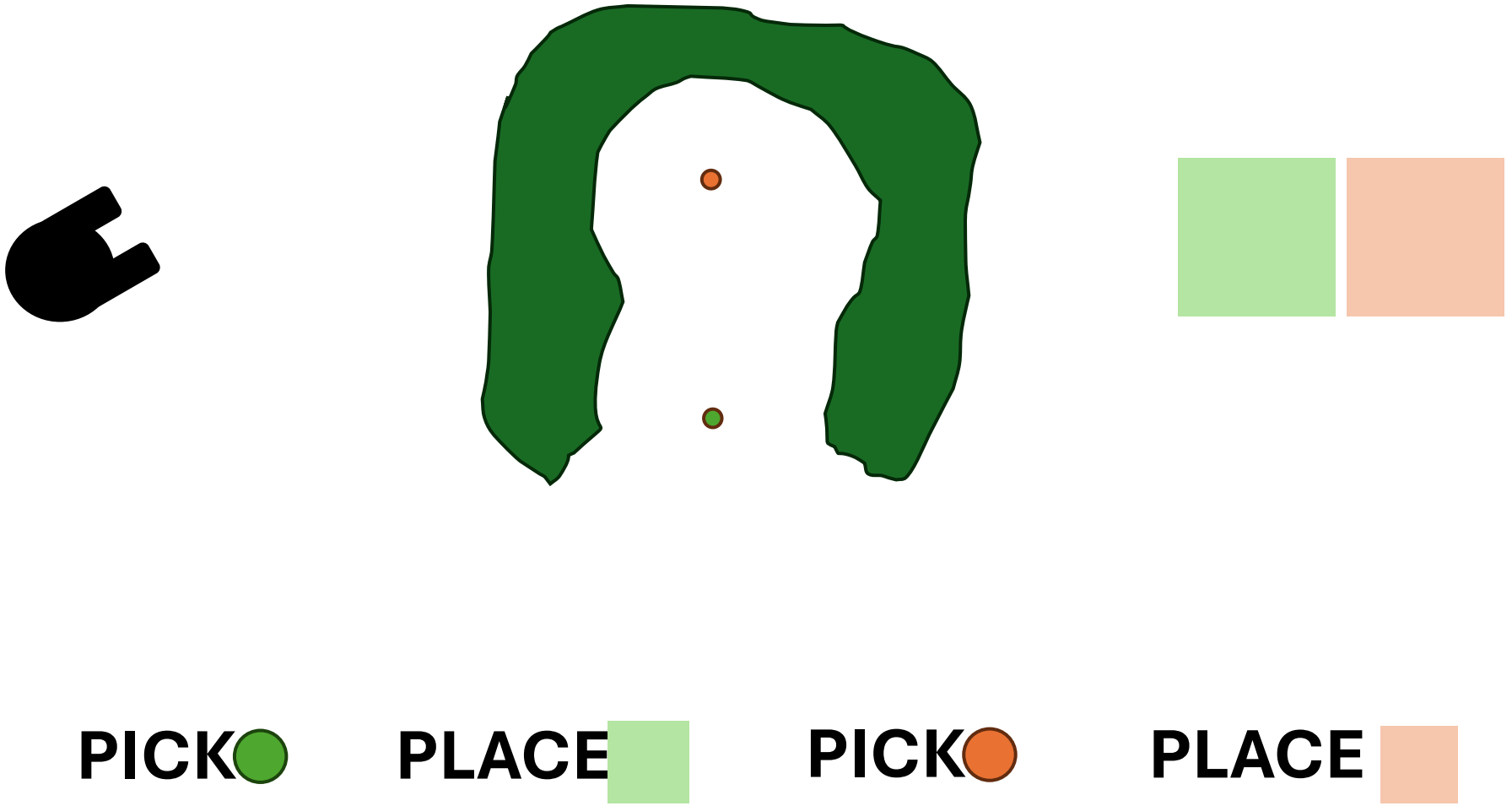


Task and Motion Planning

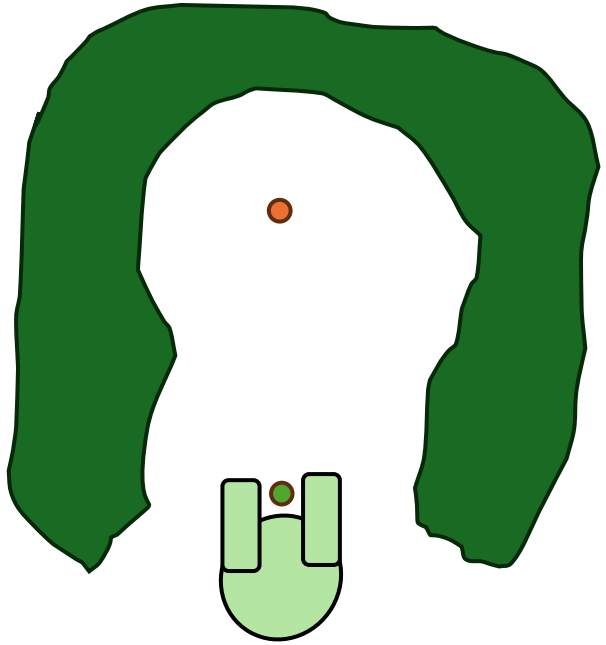


Dantam, Neil T., Zachary K. Kingston, Swarat Chaudhuri, and Lydia E. Kavraki. "Incremental task and motion planning: A constraint-based approach." In *Robotics: Science and systems*, vol. 12, p. 00052. 2016.

Task and Motion Planning

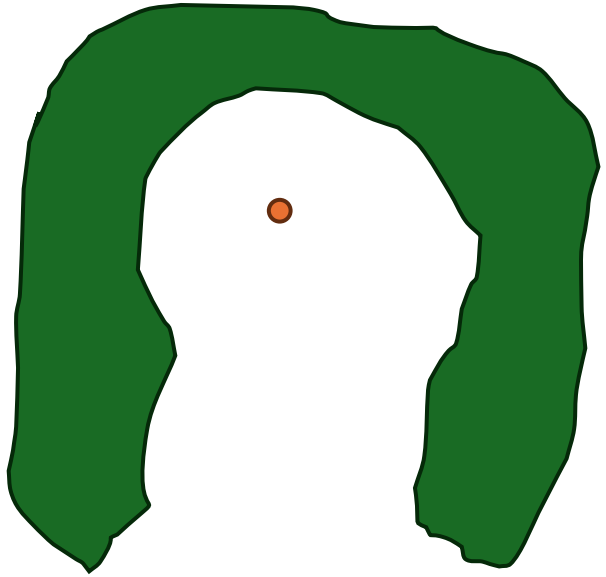


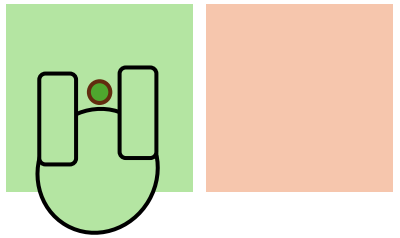
Task and Motion Planning



PICK PLACE PICK PLACE

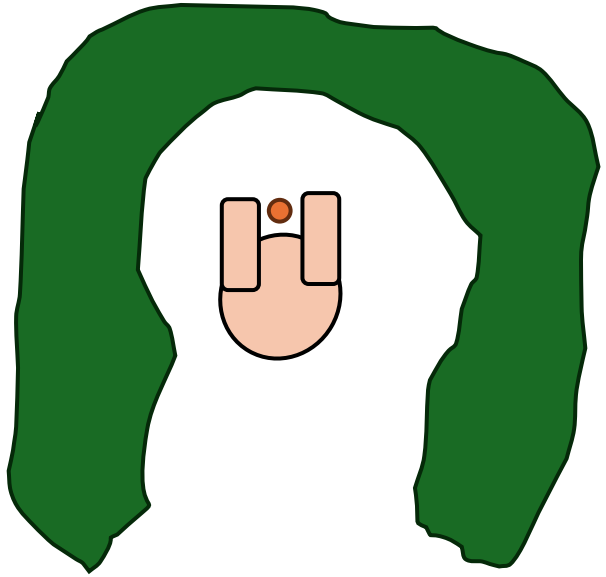
Task and Motion Planning





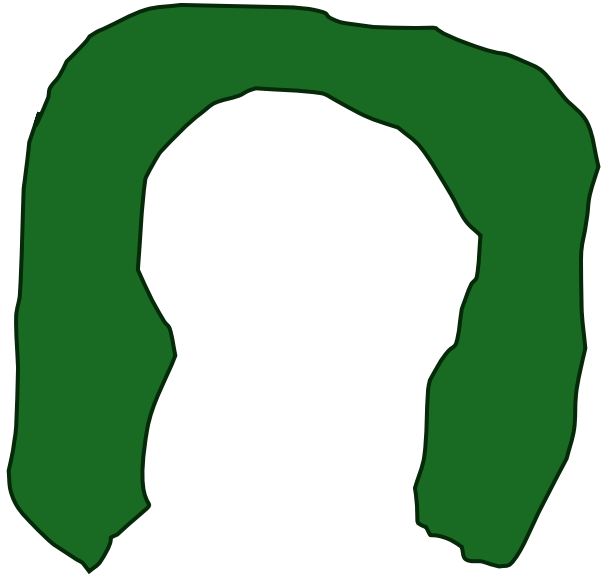
PICK PLACE PICK PLACE

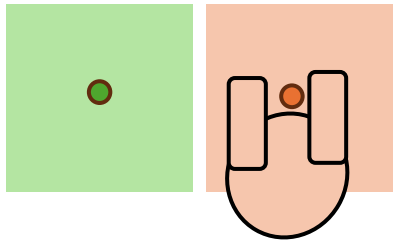
Task and Motion Planning



PICK PLACE PICK PLACE

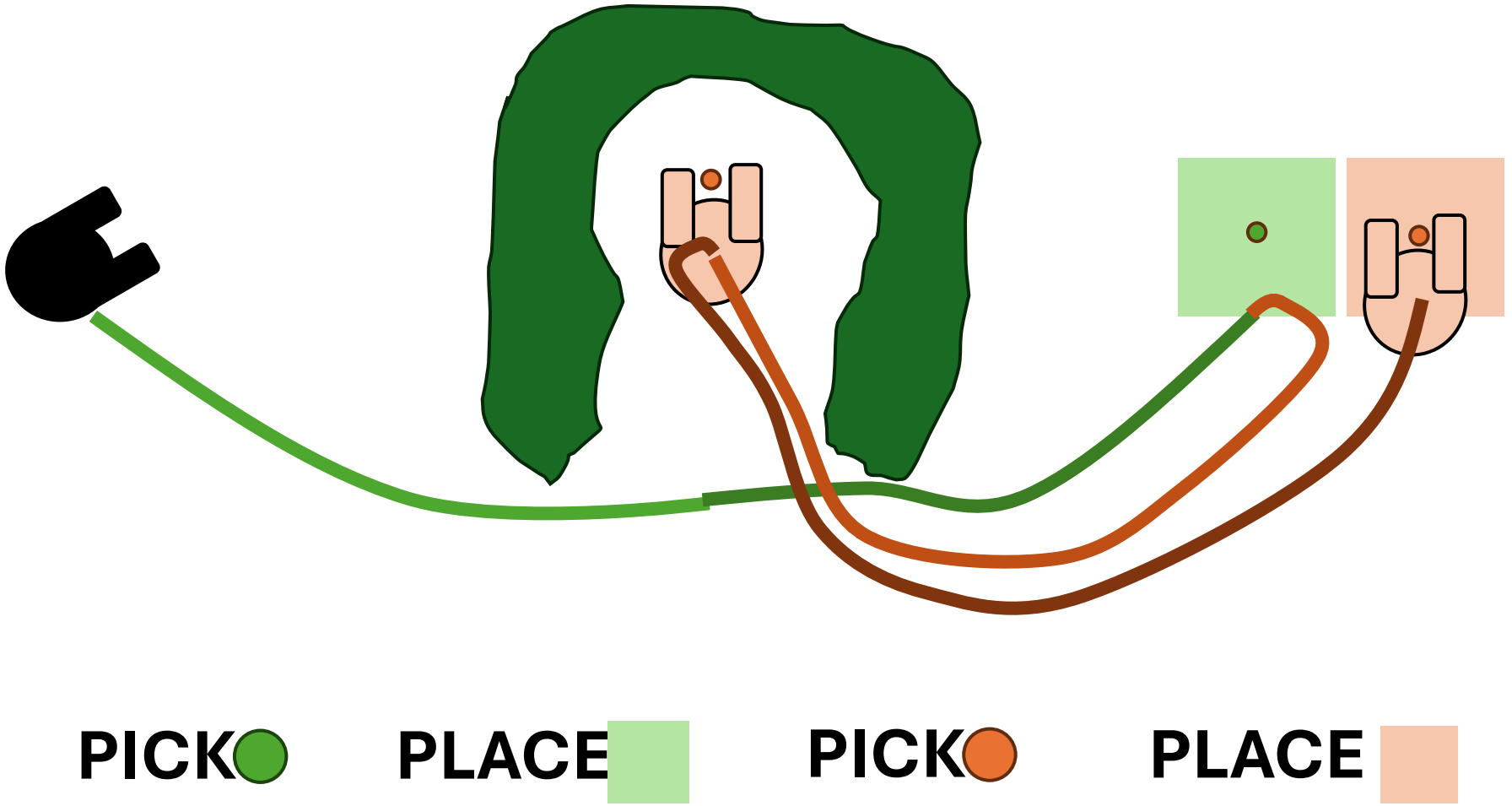
Task and Motion Planning



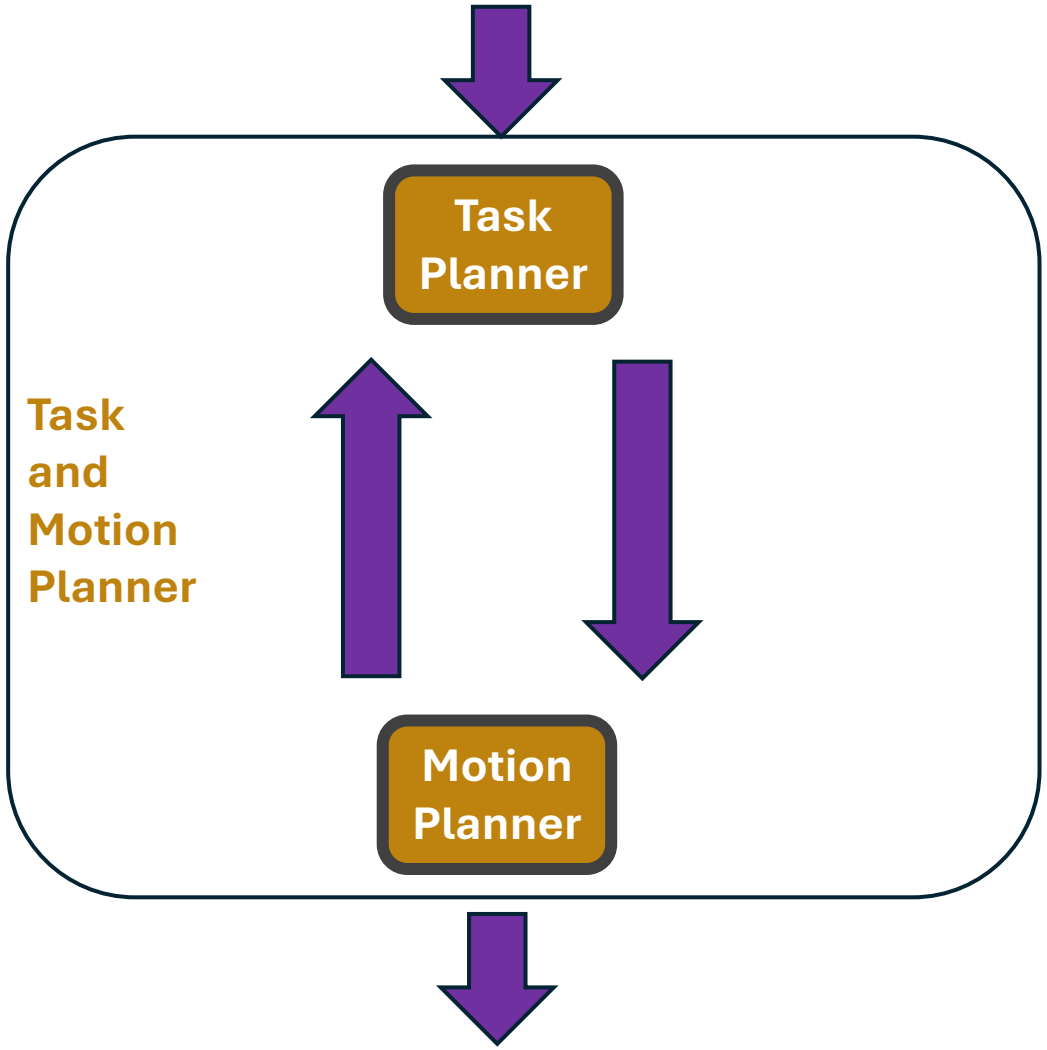


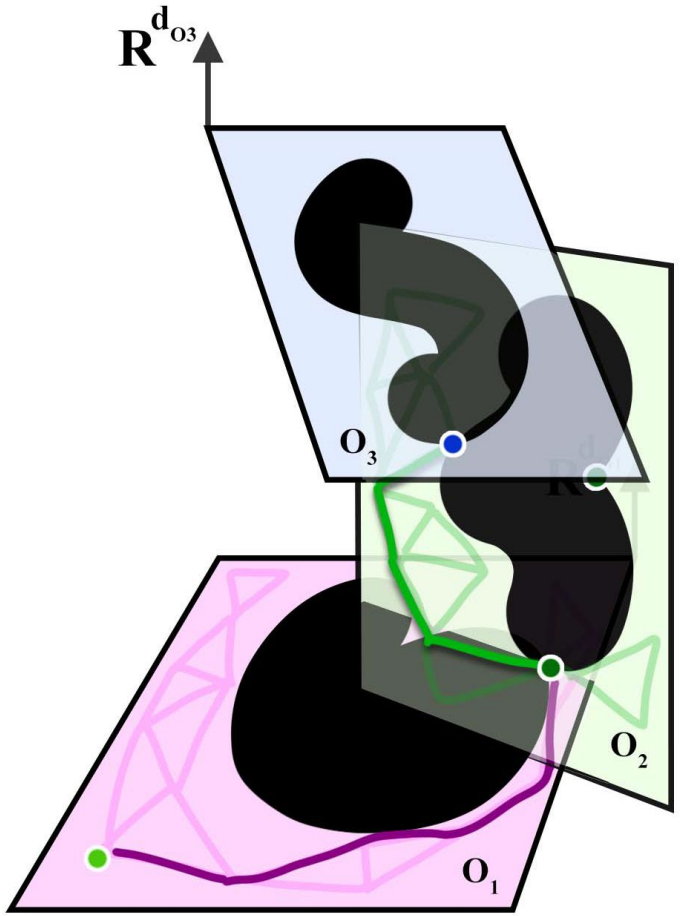
PICK PLACE PICK PLACE

Task and Motion Planning



Task and Motion Planning

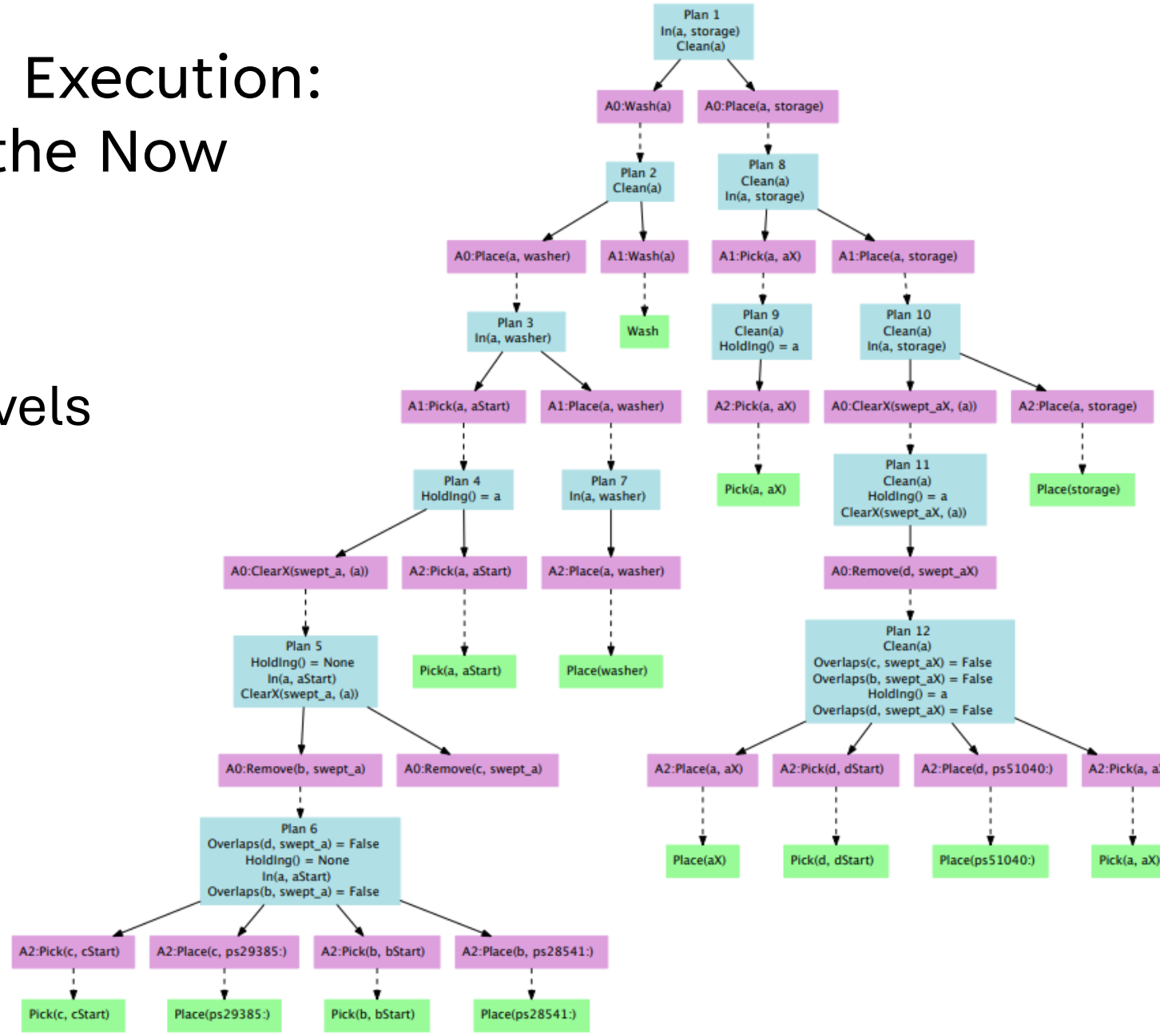




TAMP Variants

Interleaved Planning and Execution: Hierarchical Planning in the Now

- Recursively plan across refinement (abstraction) levels of actions
  -- ***then motion plan then execute***



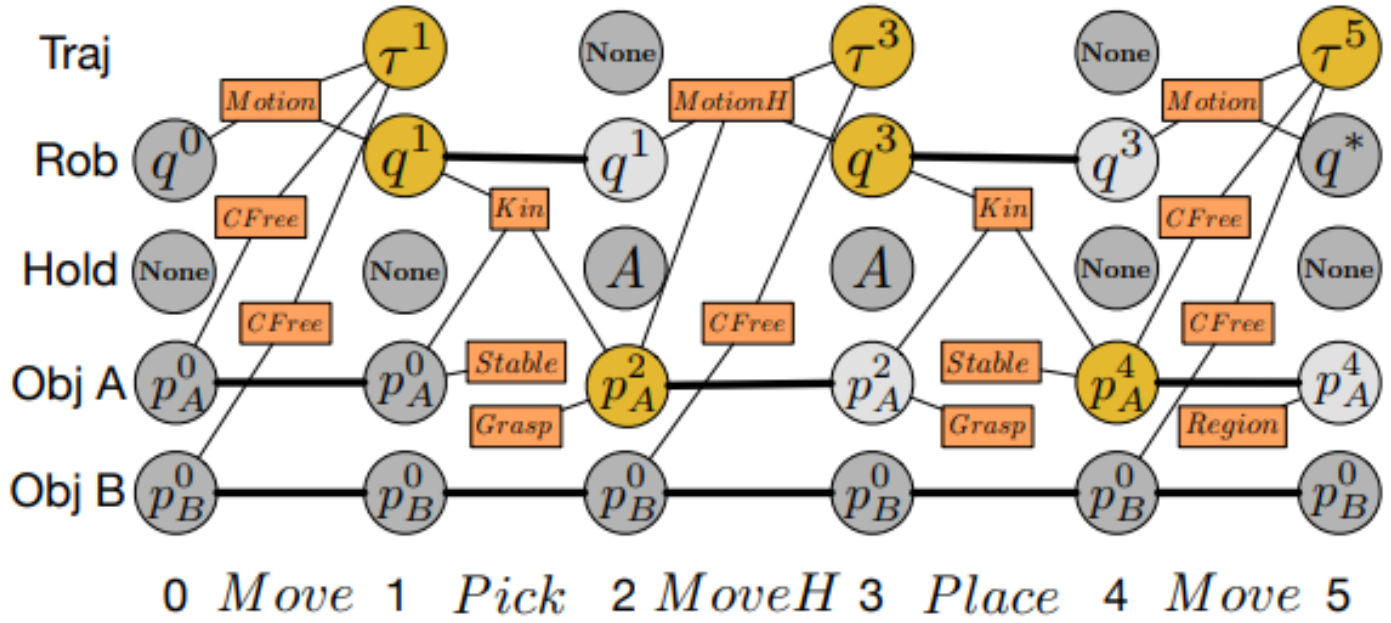
Kaelbling, Leslie Pack, and Tomás Lozano-Pérez. "Hierarchical planning in the now." In *Workshops at the Twenty-Fourth AAAI Conference on Artificial Intelligence*. 2010.

Composing Samplers

- Factored transition system
  - factored search space

arm	$C_{manipulator}$ X
objects	P_{objA} X P_{objB} X
grasped?	{ϕ, objA, objB}

Pick-and-place sampler and constraint network



Garrett, Caelan Reed, Tomás Lozano-Pérez, and Leslie Pack Kaelbling. "Ffrob: An efficient heuristic for task and motion planning." In *Algorithmic Foundations of Robotics XI*, pp. 179-195. Springer, Cham, 2015.

Garrett, Caelan Reed, Tomás Lozano-Pérez, and Leslie Pack Kaelbling. "Sample-Based Methods for Factored Task and Motion Planning." In Robotics: Science and Systems, vol. 13. 2017.

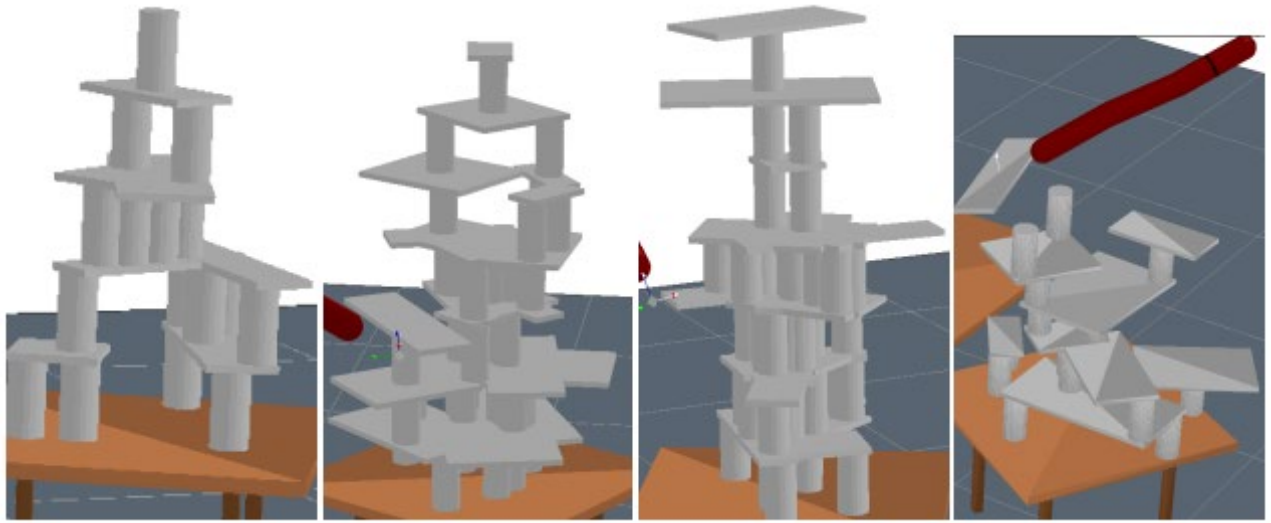
Garrett, Caelan Reed, Tomas Lozano-Perez, and Leslie Pack Kaelbling. "FFRob: Leveraging symbolic planning for efficient task and motion planning." The International Journal of Robotics Research 37, no. 1 (2018): 104-136.

Garrett, Caelan Reed, Tomás Lozano-Pérez, and Leslie Pack Kaelbling. "PDDLStream: Integrating symbolic planners and blackbox samplers via optimistic adaptive planning." In *Proceedings of the International Conference on Automated Planning and Scheduling*, vol. 30, pp. 440-448. 2020.

Garrett, Caelan Reed, Chris Paxton, Tomás Lozano-Pérez, Leslie Pack Kaelbling, and Dieter Fox. "Online replanning in belief space for partially observable task and motion problems." In *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5678-5684. IEEE, 2020.

Optimization: Logic-geometric Programming

- Find plan skeleton (sequence of actions)
- Then optimize
- While not violating constraints
- With some objective function



Build the tallest structure

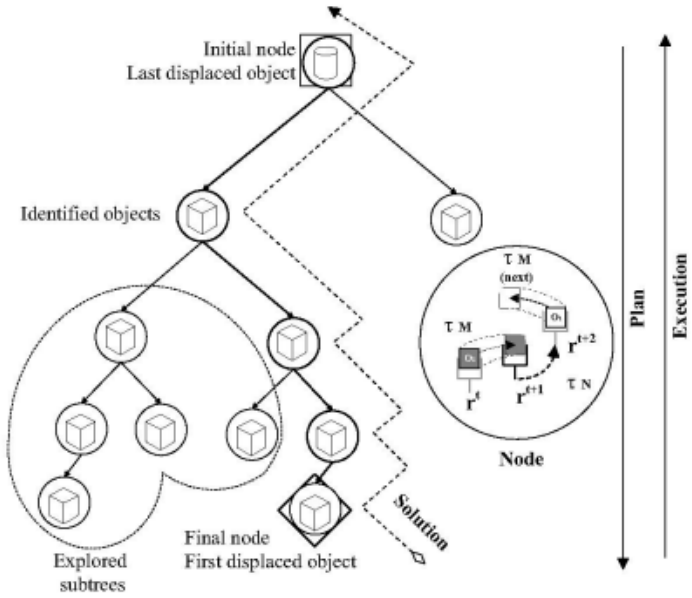
Toussaint, Marc. "Logic-geometric programming: An optimization-based approach to combined task and motion planning." In *Twenty-Fourth International Joint Conference on Artificial Intelligence*. 2015.

Manipulation Among Movable Obstacles

- Movable object:

Geometry	One closed triangular mesh.
Center of Gravity	A given point.
Motion Constraints	One vector specifying allowable motion in generalized coordinates.
Grasps	A set of workspace transforms for the end effector in the local object frame.

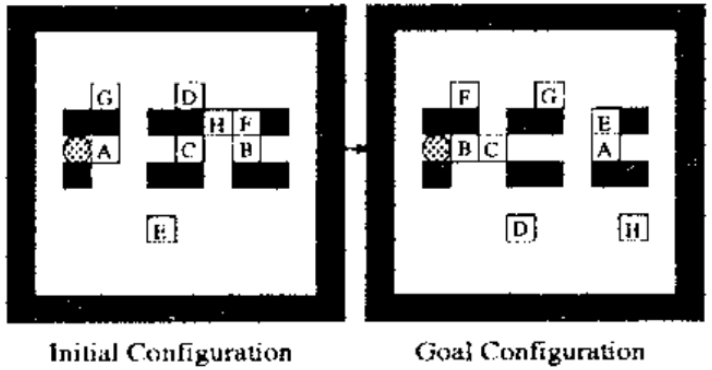
- Monotone: each object moved **once**



- Stilman, Mike, Jan-Ullrich Schamburek, James Kuffner, and Tamim Asfour. "Manipulation planning among movable obstacles." In Proceedings 2007 IEEE international conference on robotics and automation, pp. 3327-3332. IEEE, 2007.

Pushing Advances

- Non-prehensile actions: pushing
- Rearranging objects to accomplish a task

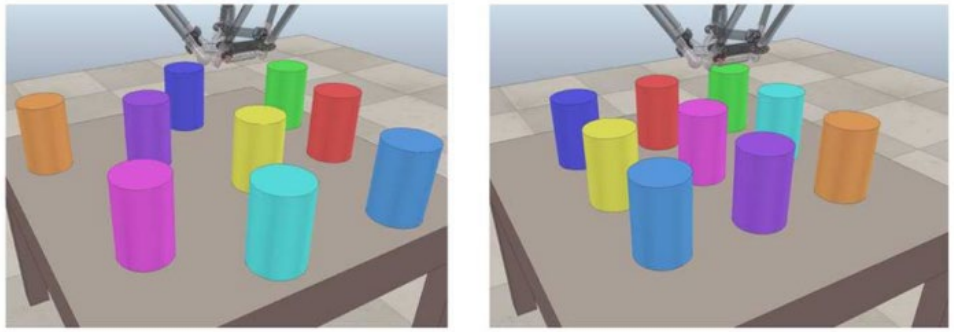


Initial Configuration Goal Configuration

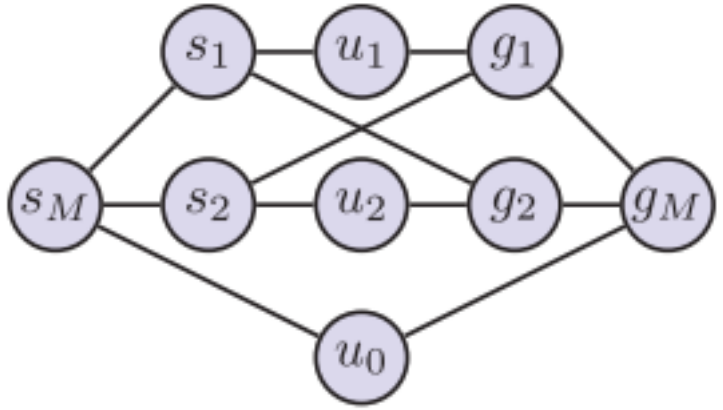
- Dogar, Mehmet R., and Siddhartha S. Srinivasa. "A planning framework for non-prehensile manipulation under clutter and uncertainty." Autonomous Robots 33, no. 3 (2012): 217-236..

Optimal Tabletop Rearrangement

- **Monotone**
  (single grasp per object -> find the best ordering)
- **The optimal solution is a Travelling Salesperson Problem**



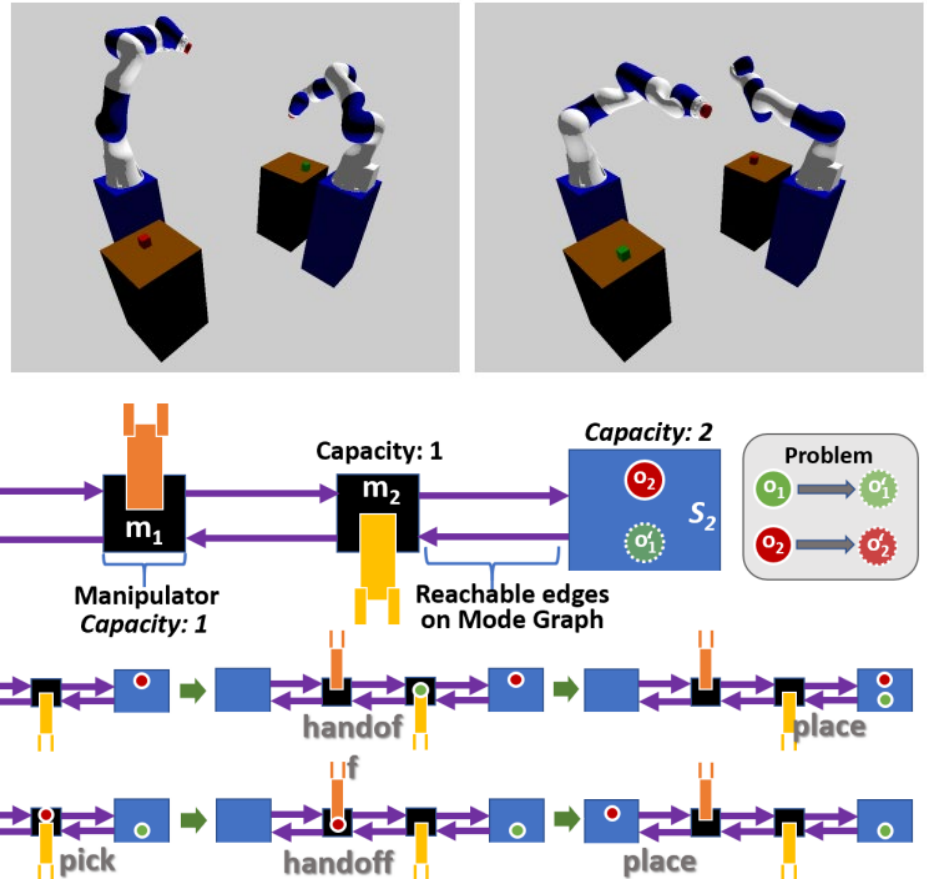
Costs here are closely related to object locations



- Han, Shuai D., Nicholas M. Stiffler, Athanasios Krontiris, Kostas E. Bekris, and Jingjin Yu. "Complexity results and fast methods for optimal tabletop rearrangement with overhand grasps." The International Journal of Robotics Research 37, no. 13-14 (2018): 1775-1795.

Many-arm Tabletop Rearrangement

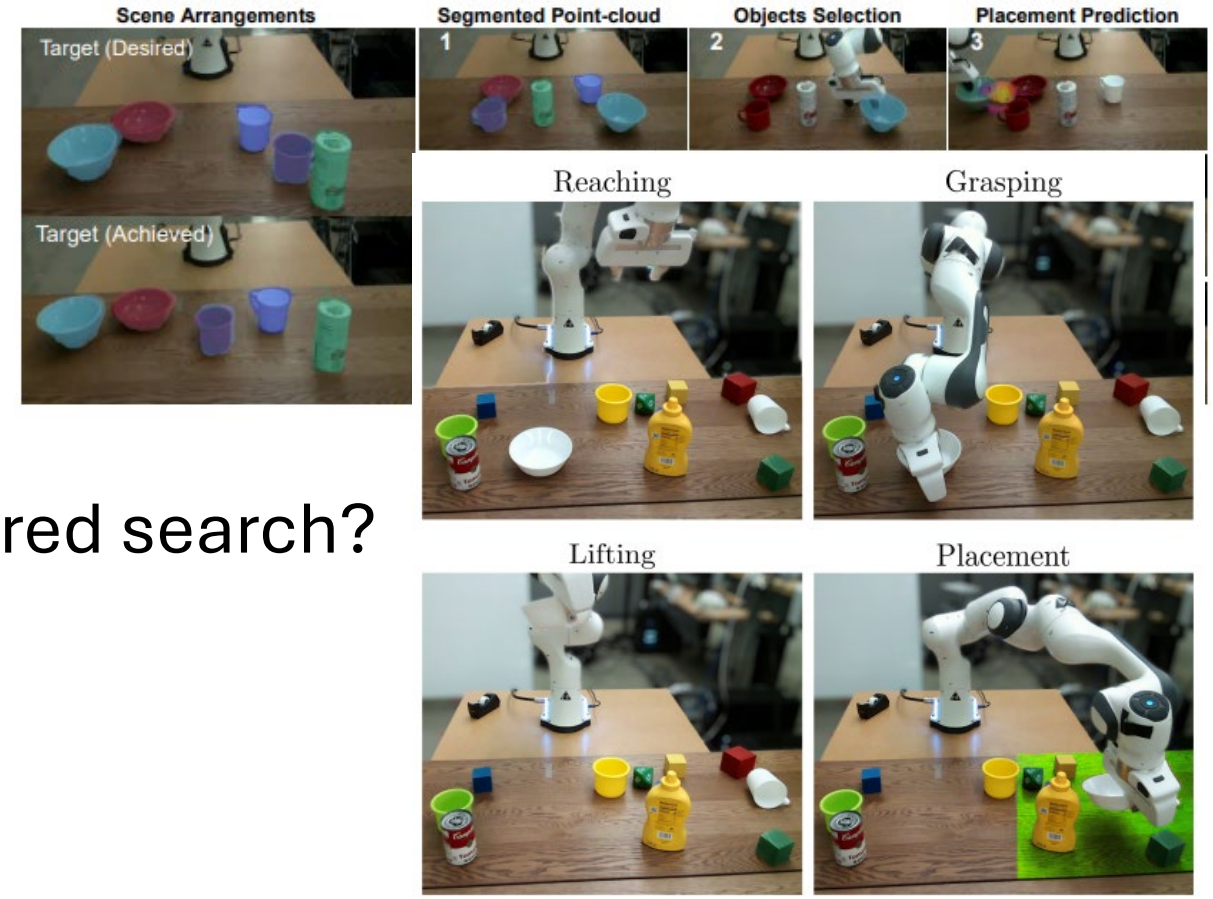
- High-level TAMP search
- Arm x Object-centric guidance reducible to **network flow problem**



- Shome, Rahul, and Kostas E. Bekris. "Synchronized multi-arm rearrangement guided by mode graphs with capacity constraints." WAFR (2020).

What Abstraction is the Best Abstraction?

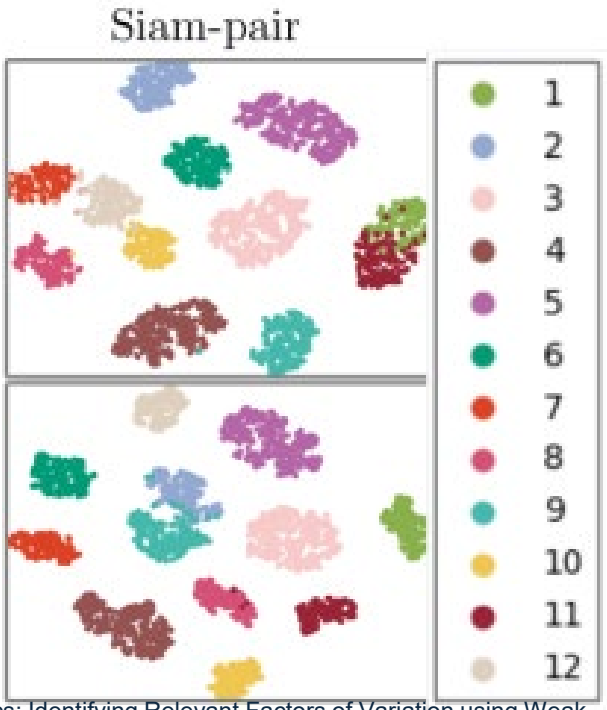
- Continuous robot reasoning?
- Object-centric reasoning?
- Manipulation mode reasoning?
- Mode x grasp x IK x pose – factored search?
- Learn it all?



- Qureshi, Ahmed H., Arsalan Mousavian, Chris Paxton, Michael C. Yip, and Dieter Fox. "NeRP: Neural Rearrangement Planning for Unknown Objects." arXiv preprint arXiv:2106.01352 (2021).
- Danielczuk, Michael, Arsalan Mousavian, Clemens Eppner, and Dieter Fox. "Object rearrangement using learned implicit collision functions." In 2021 IEEE International Conference on Robotics and Automation (ICRA), pp. 6010-6017. IEEE, 2021.

Learning

- Learn abstractions of the discrete space
  -- states
  -- actions
  -- transitions
- Learn symbolic states from sensing
- Learn action parametrizations
- Learn heuristics, objectives, rewards, constraints...

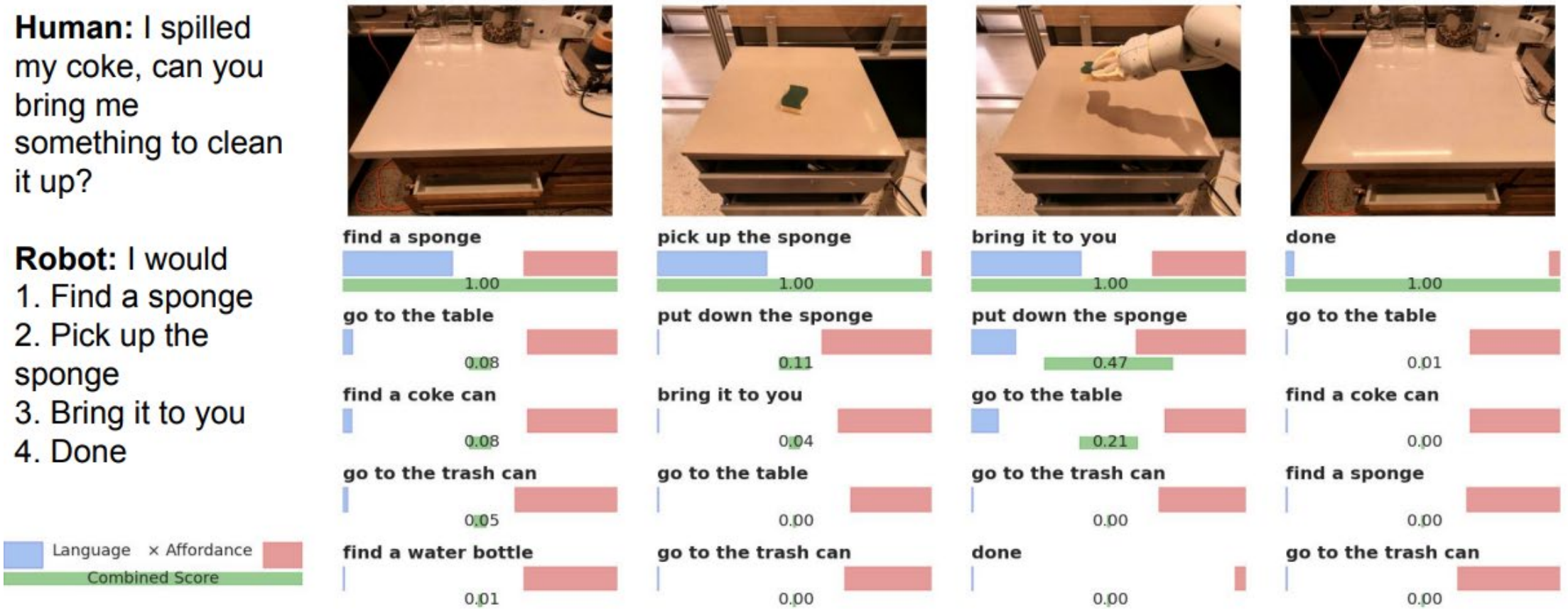


Chamzas, Constantinos, Martina Lippi, Michael C. Welle, Anastasiia Varava, Alessandro Marino, Lydia E. Kavraki, and Danica Kragic. "State Representations in Robotics: Identifying Relevant Factors of Variation using Weak Supervision." In *Robot Learning Workshop, Neurips*. 2020.
Curtis, Aidan, Xiaolin Fang, Leslie Pack Kaelbling, Tomás Lozano-Pérez, and Caelan Reed Garrett. "Long-Horizon Manipulation of Unknown Objects via Task and Motion Planning with Estimated Affordances." *arXiv preprint arXiv:2108.04145* (2021).
Wang, Zi, Caelan Reed Garrett, Leslie Pack Kaelbling, and Tomás Lozano-Pérez. "Learning compositional models of robot skills for task and motion planning." *The International Journal of Robotics Research* 40, no. 6-7 (2021): 866-894.

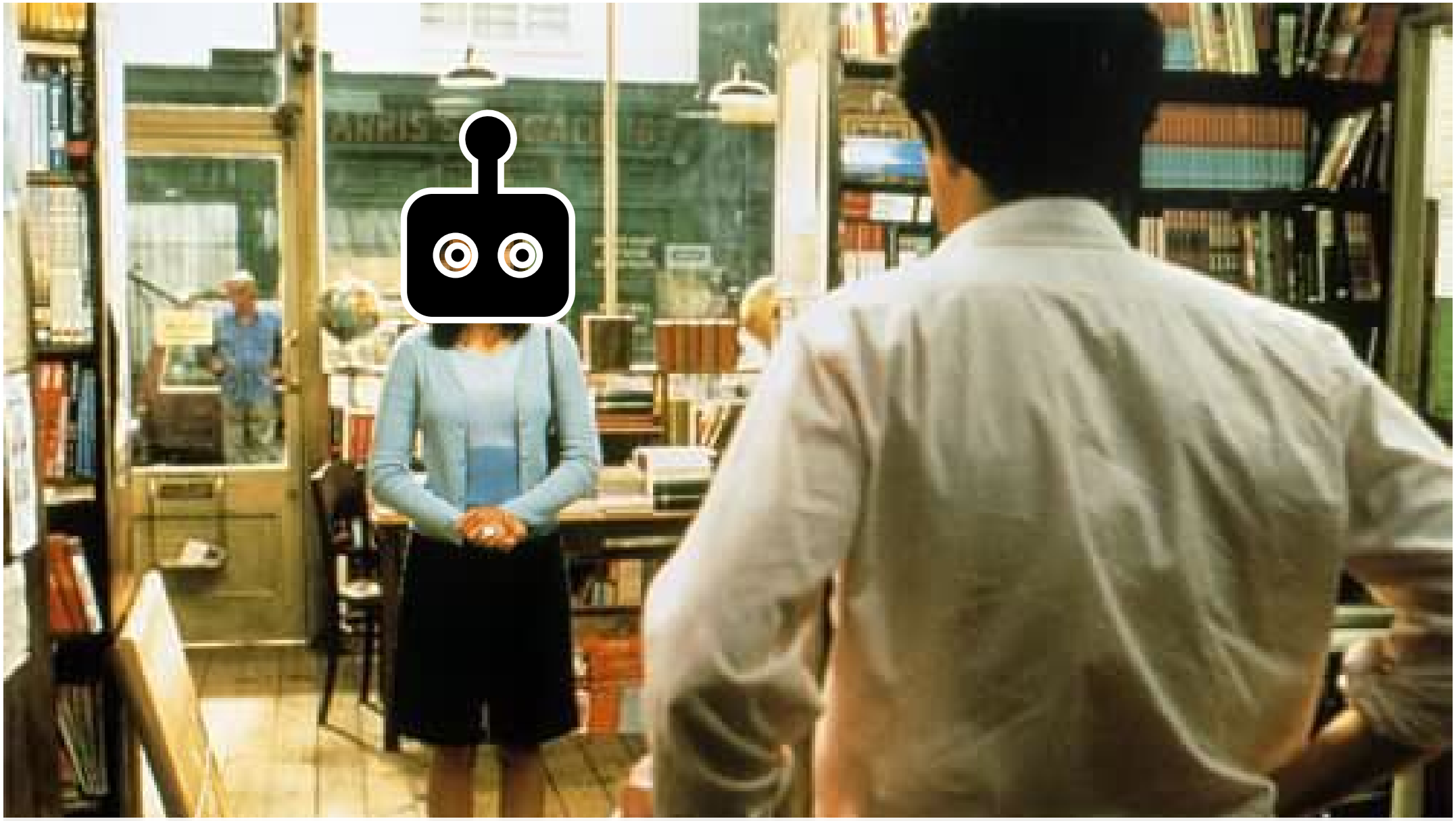
LLM-ephant in the Room

Human: I spilled my coke, can you bring me something to clean it up?

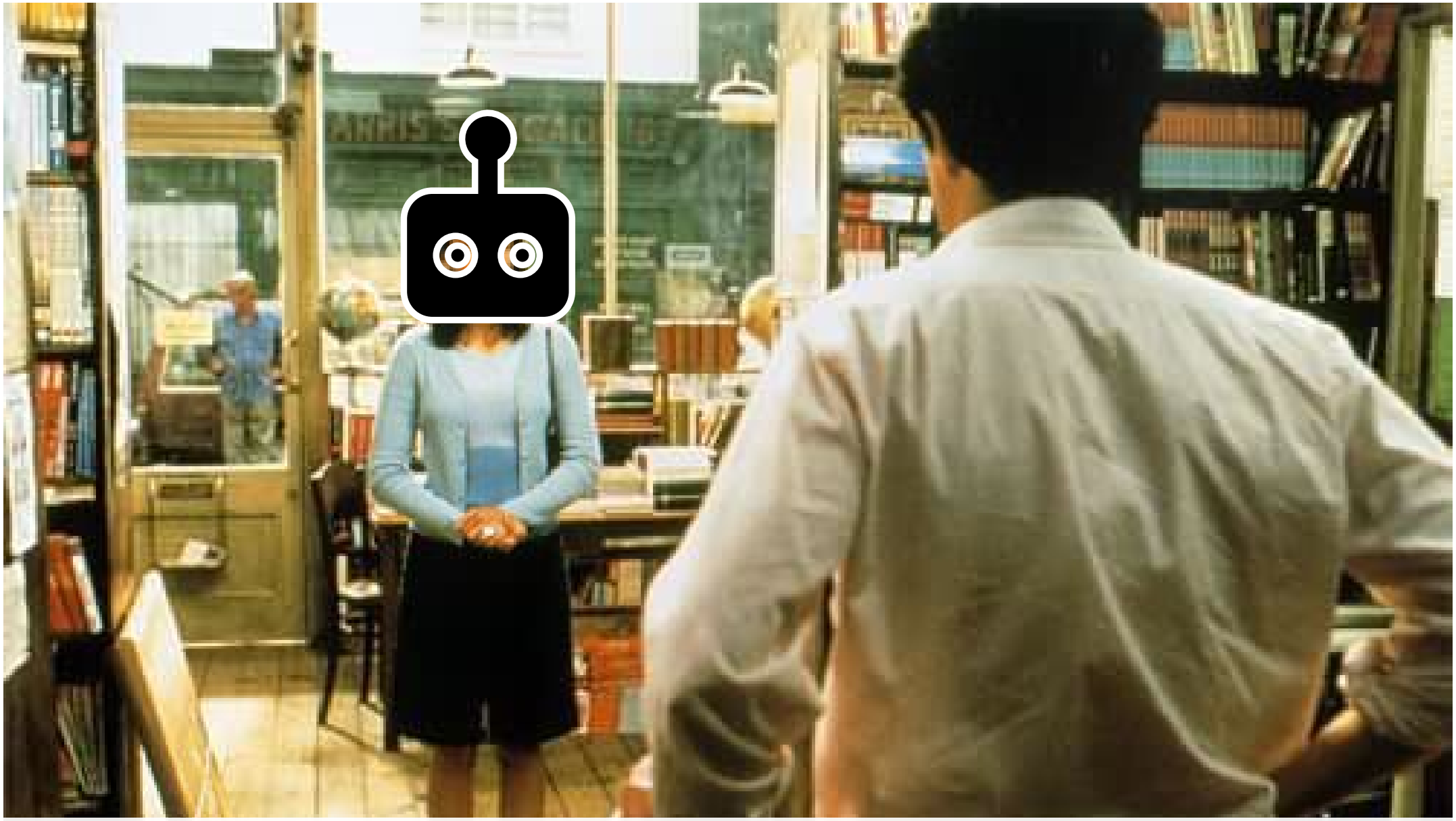
Robot: I would
1. Find a sponge
2. Pick up the sponge
3. Bring it to you
4. Done



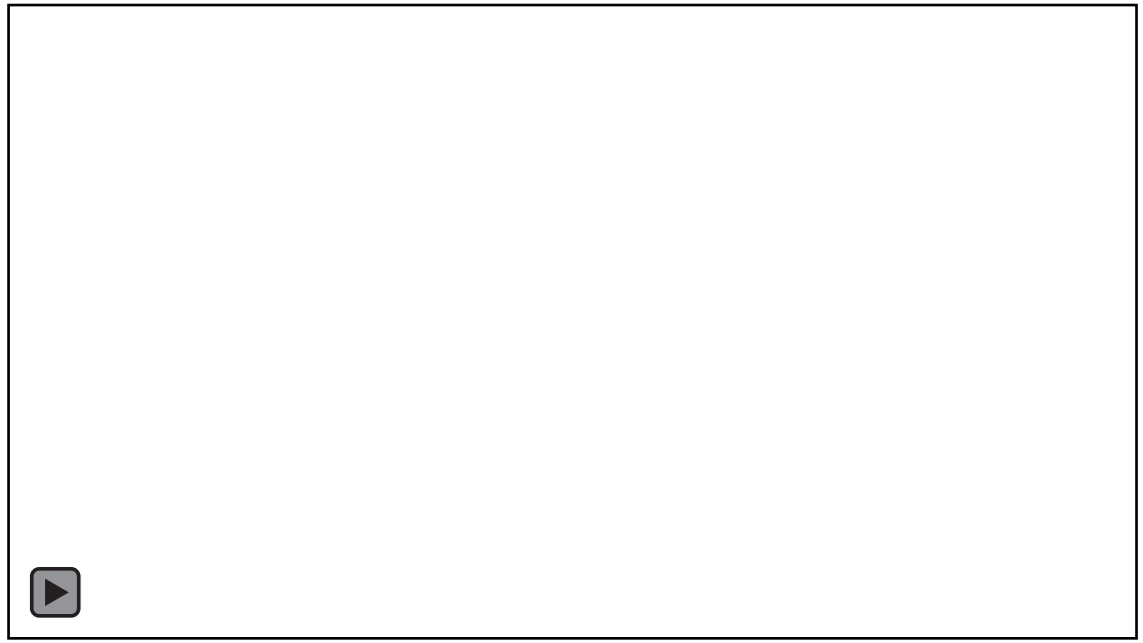
Ahn, Michael, Anthony Brohan, Noah Brown, Yevgen Chebotar, Omar Cortes, Byron David, Chelsea Finn et al. "Do as i can, not as i say: Grounding language in robotic affordances." *arXiv preprint arXiv:2204.01691* (2022).

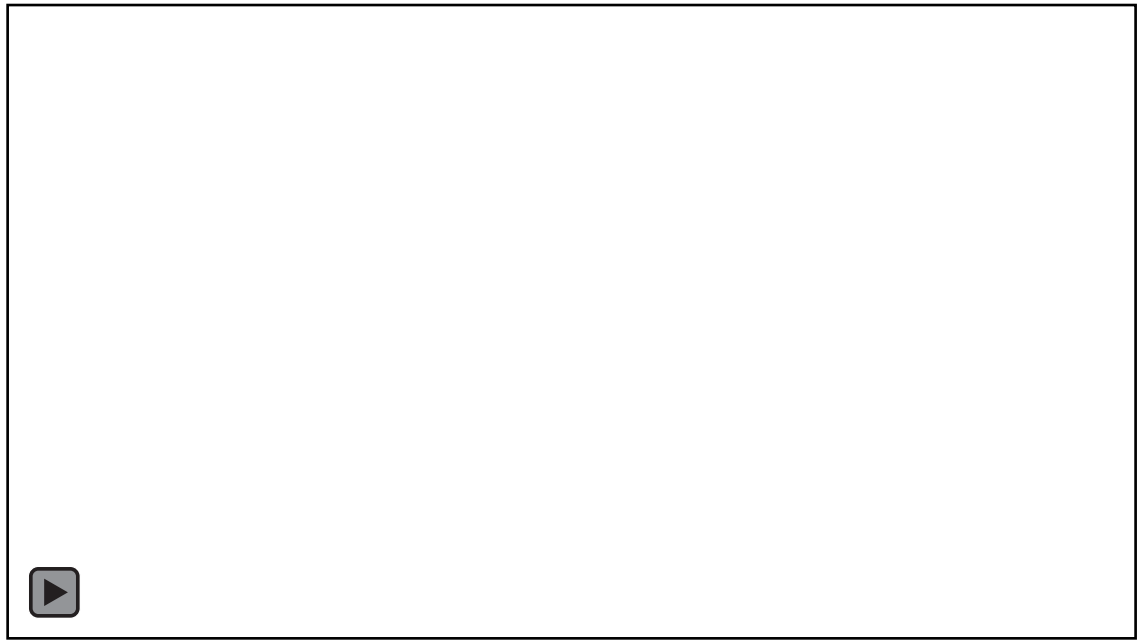


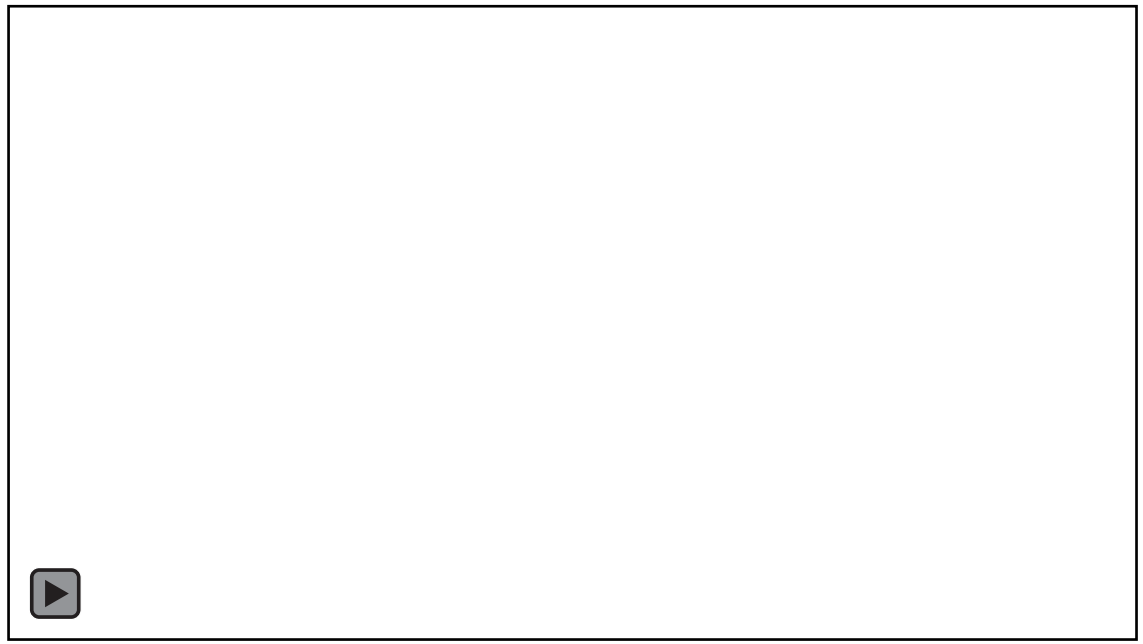
I’m just a point in a high-dimensional hybrid space trying to reach the goal.

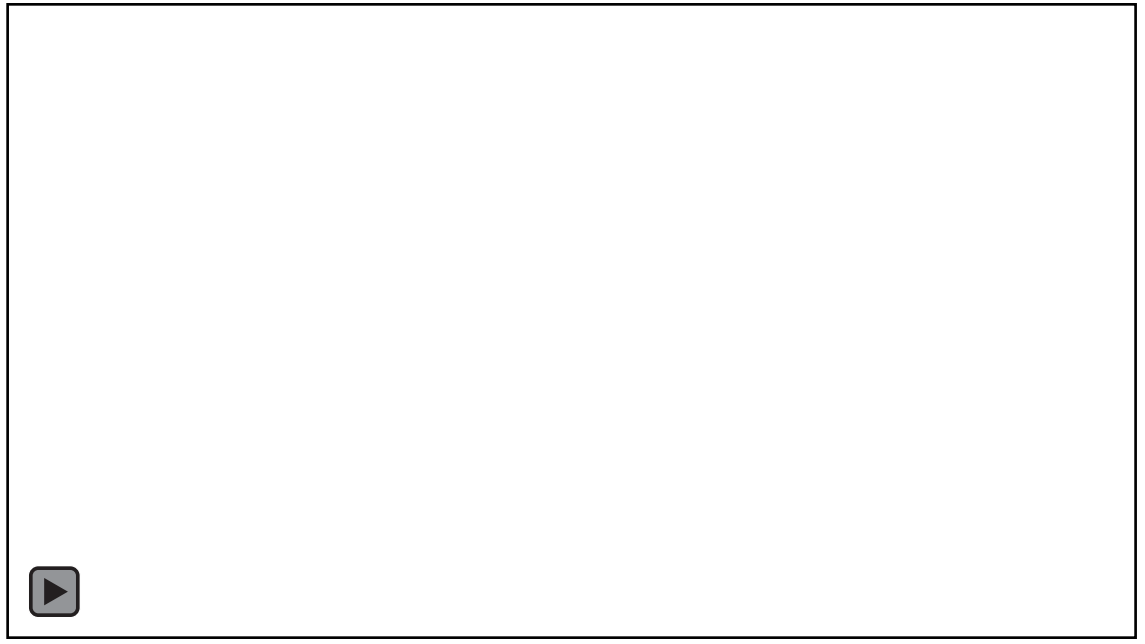


I’m just a point in a high-dimensional space trying to reach the goal.









Task and Motion Planning for Execution in the Real, Pan Tianyang and Shome, Rahul and Kavraki, Lydia E. 2024 IEEE Transactions on Robotics