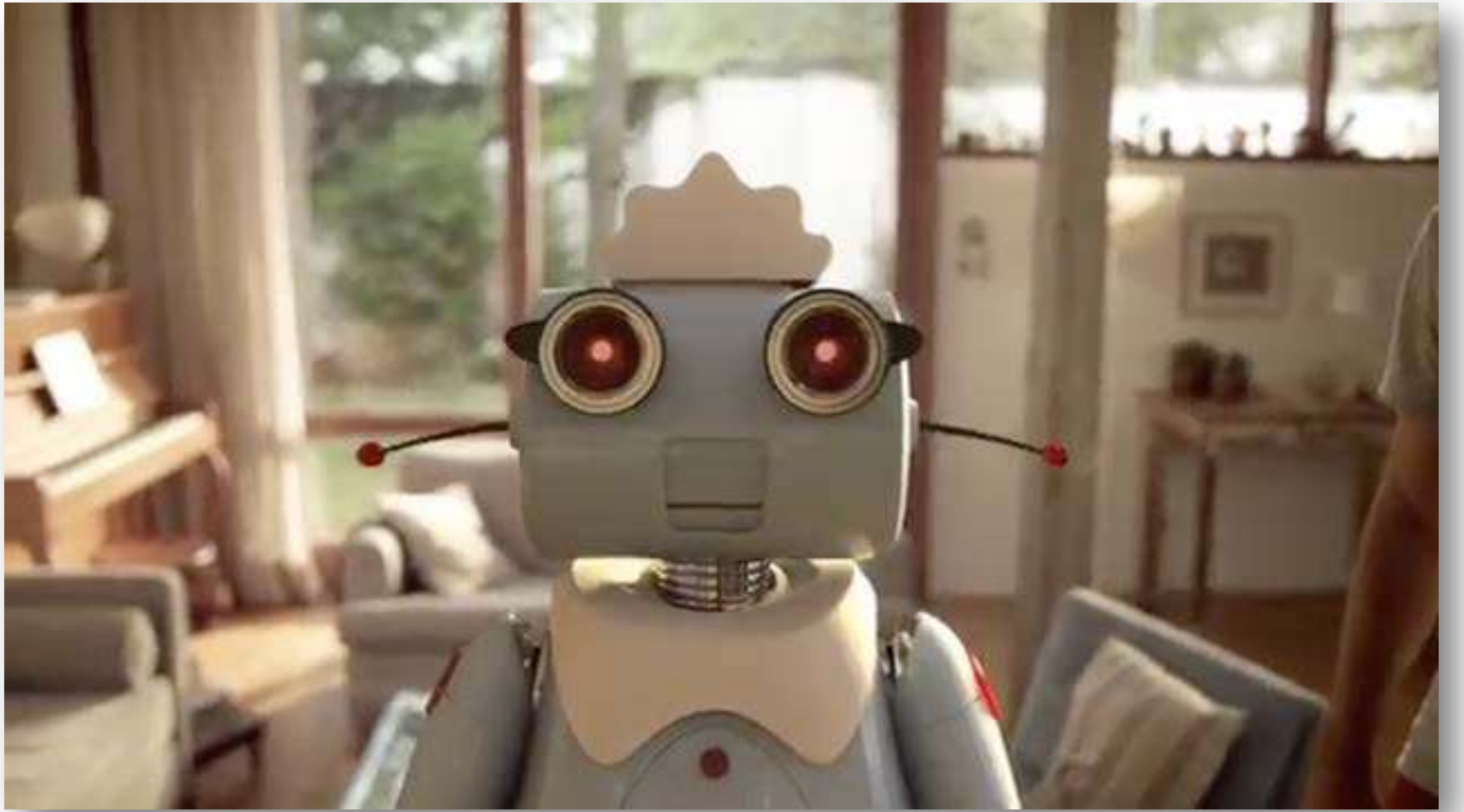
Generalizable Autonomy in Robot Manipulation

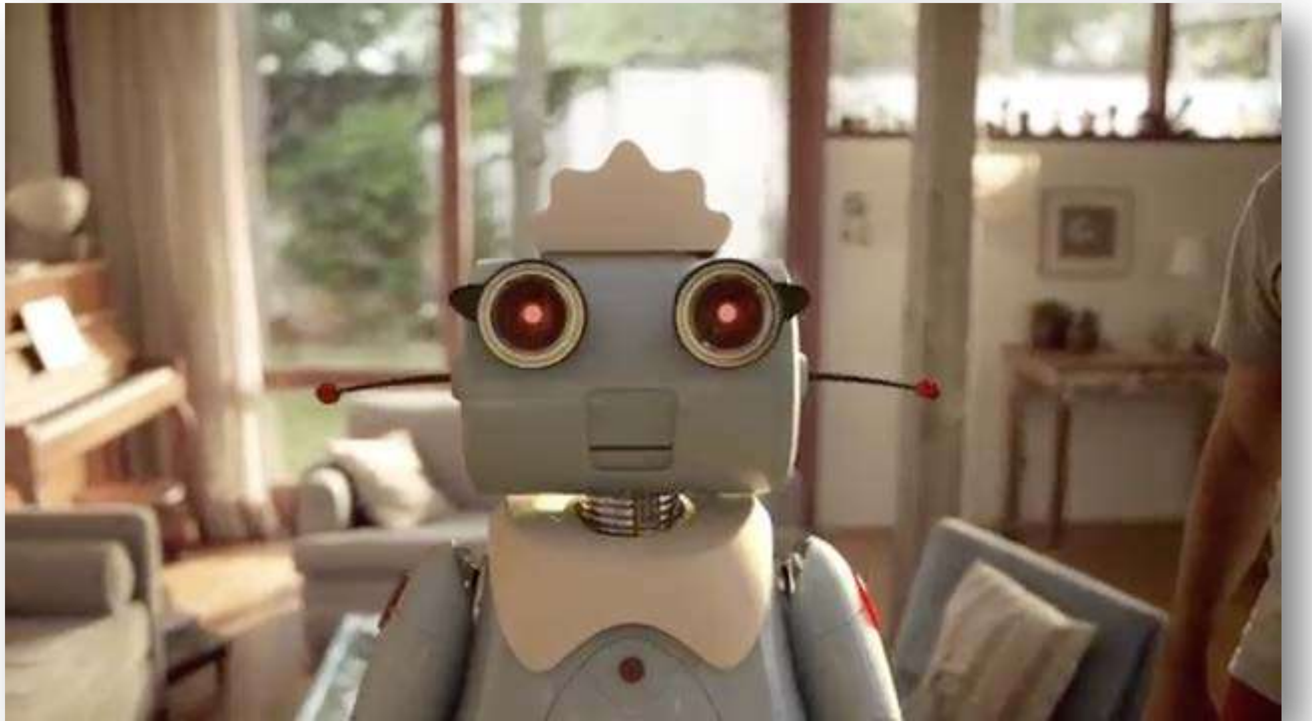


Animesh Garg | UNIVERSITY OF TORONTO VECTOR INSTITUTE NVIDIA

Generalizable Autonomy in Robot Manipulation

...     ...

Vacuuming | Sweeping/Mopping | Cooking | Laundry



Generalizable Autonomy in Robot Manipulation

Vacuuming

Sweeping/Mopping

Cooking

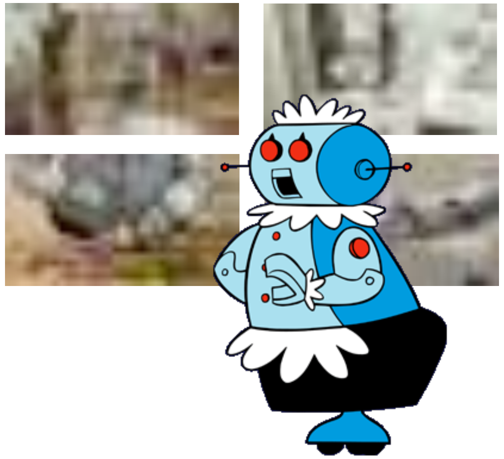
Laundry

Diversity: New Scenes, Tools,…

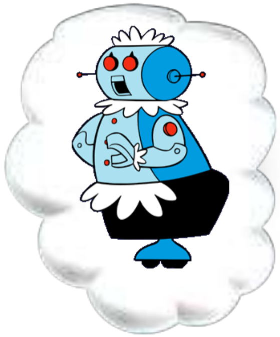
Complexity: Long-term Settings

Generalizable Autonomy in Robot Manipulation

Vision: Build Intelligent Robotic Companions towards Human Enrichment and Augmentation



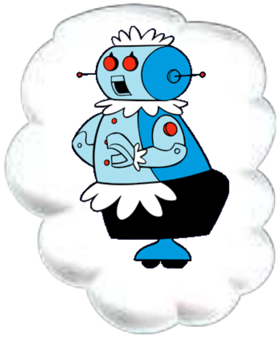
Generalizable Autonomy in Robot Manipulation



1956 Dartmouth AI Project

1956

Generalizable Autonomy in Robot Manipulation

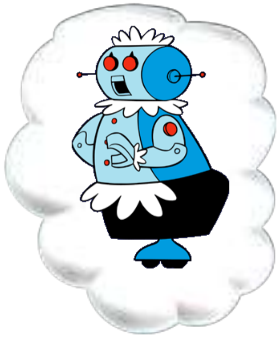


Dartmouth AI Meeting

UNIMATE
1st Industrial robot

1956 ‘61 1968

Generalizable Autonomy in Robot Manipulation

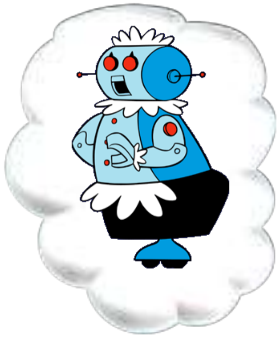


Dartmouth AI Me

UNIM
1st Indus

1956 ‘61 1968 2013

Generalizable Autonomy in Robot Manipulation



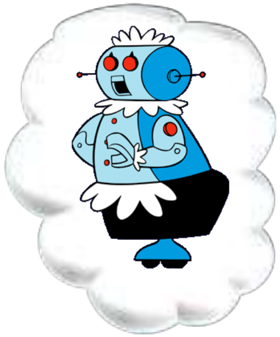
Dartmouth AI Meet

UNIMA
1st Industri

P

1956 ‘61 1968 2013 2018

Generalizable Autonomy in Robot Manipulation



Dartmouth AI Me

UNIM

1st Indus

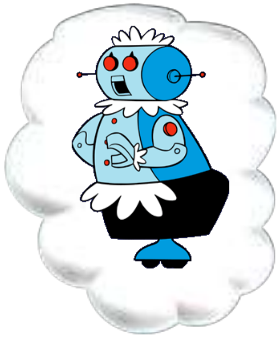
1956 ‘61 1968 2013 2018 2019

Generalizable Autonomy in Robot Manipulation

Then

Now

How to Generalize to Unstructured Scenarios?



Dartmouth AI Meeting — 1956

UNIMATE 1st Industrial robot — '61

Personal Robot Assistant — 1968

Atlas Robot Humanoid — 2013

Staged Repeated Tasks — 2018

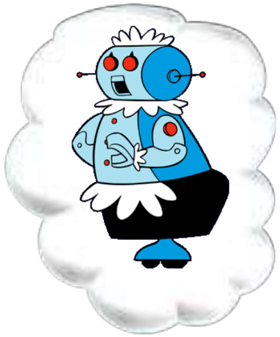
Structured Environments — 2019

Generalizable Autonomy in Robot Manipulation

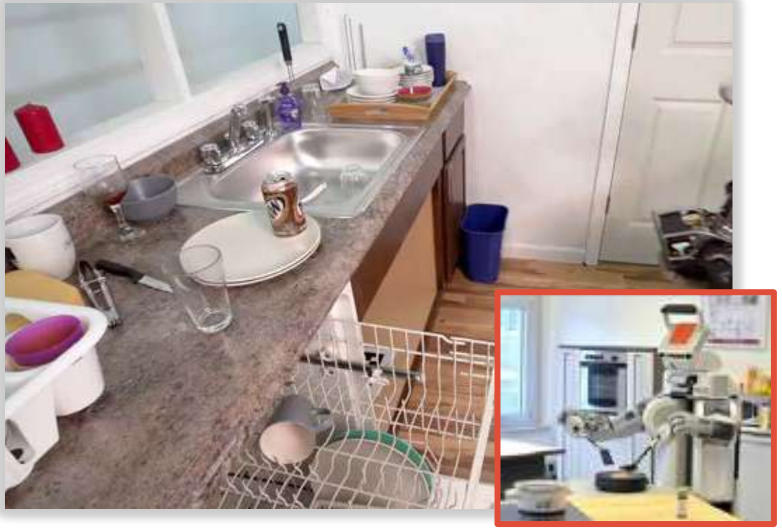
Then

Now

How to Generalize to Unstructured Scenarios?



Manufacturing/Retail



Personal/Service

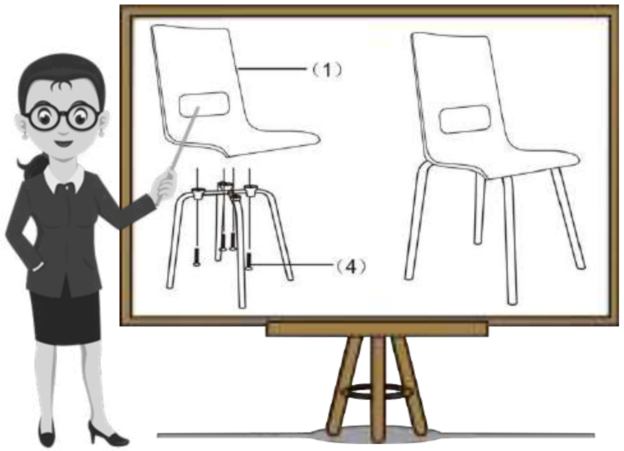
Healthcare/Medicine

Generalizable Autonomy in Robot Manipulation

Vision: Build Intelligent Robotic Companions

Approach: Learning with Structured Inductive Bias and Priors

Demonstration



Instructional Input
(Teleoperation, Video, Language)

Task Imitation

Learn to do the task in
Same Environment

Generalization

New Task Variations
in Novel Environments

Layers of Imitation

Movement Skills

Control

Skill Sequencing

Planning

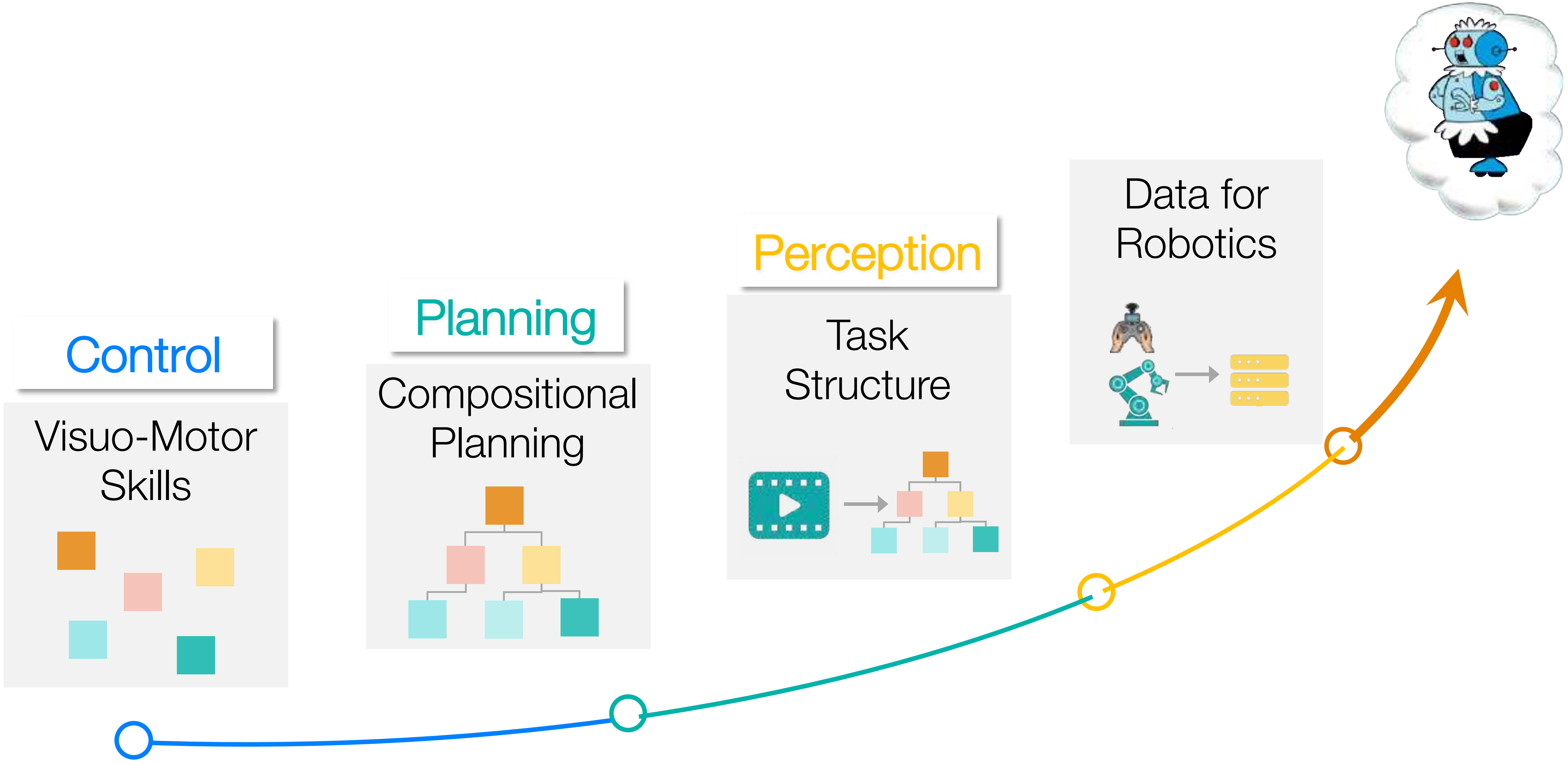
Semantic Purpose

Perception

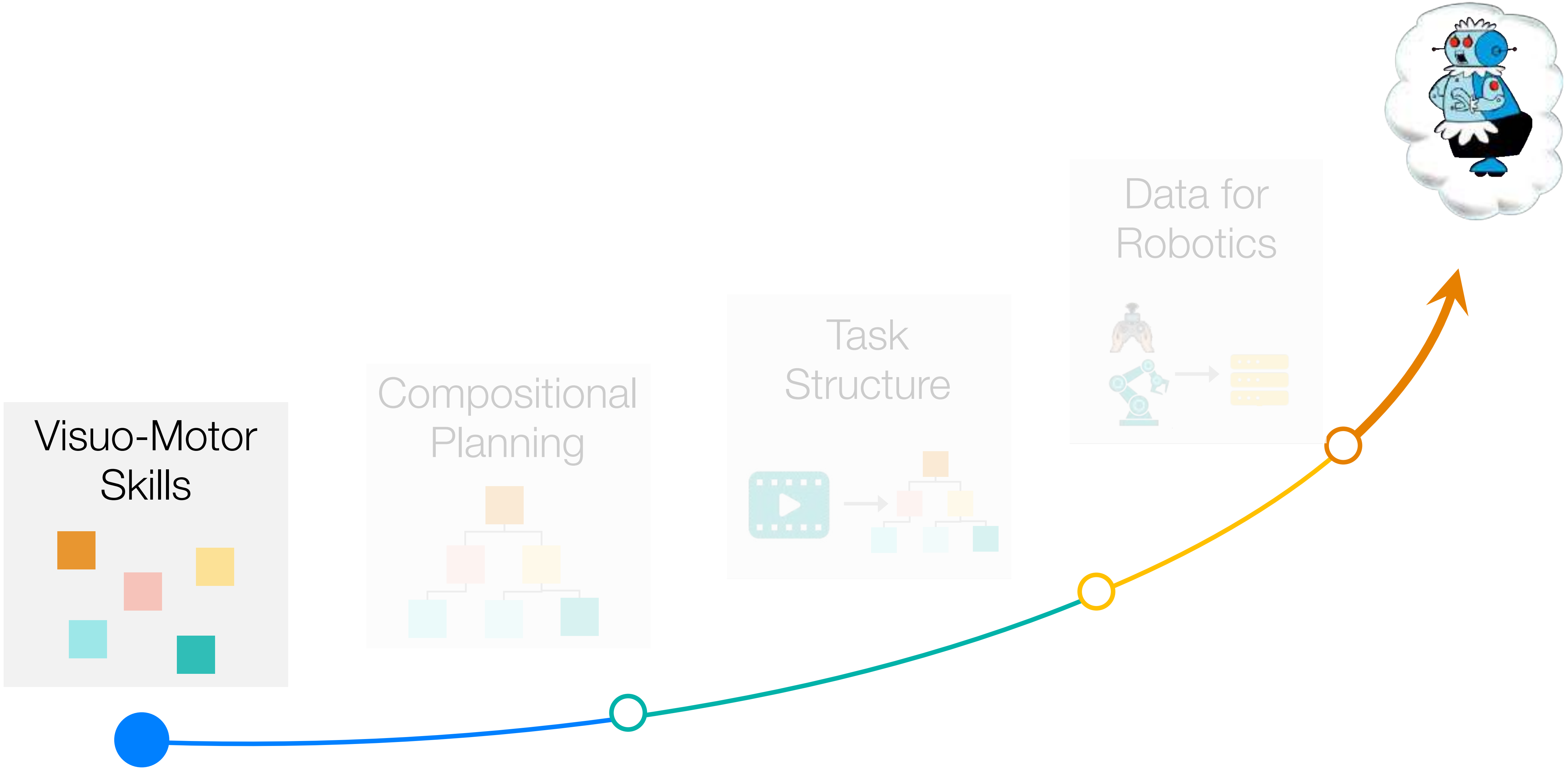
Task Specification

Cheng et al. Sci.Rob. 2019

Generalizable Autonomy in Robot Manipulation



Generalizable Autonomy in Robot Manipulation



Visuo-Motor Skills

Challenge: Algorithmic frameworks to learn a diversity of skills

Approach: Close the Visuo-Motor Loop with Learning based Control

• • •

Vacuuming

Sweeping/Mopping

Cooking

Cleaning

• • •

Visuo-Motor Skills: Generalization

Cleaning

Skills: Surface Wiping

Hard Stains – Push Harder?

Different Surfaces – Be Gentle?

Generalization

Visuo-Motor Skills: Current Paradigm

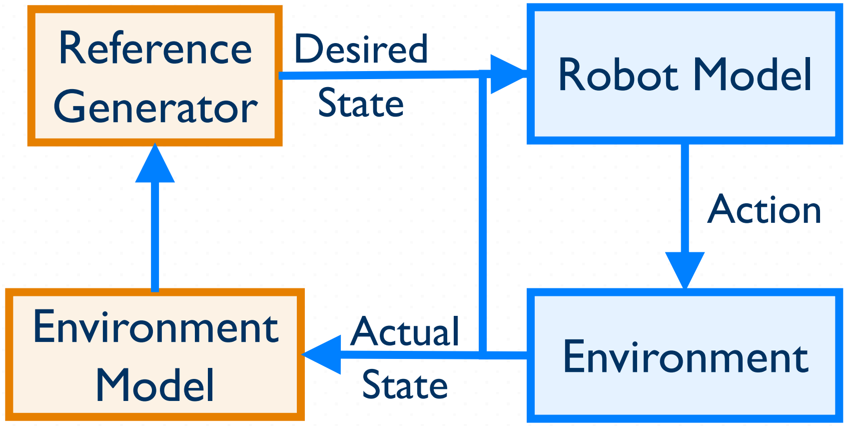
Model Based Task (Operational) Space Control

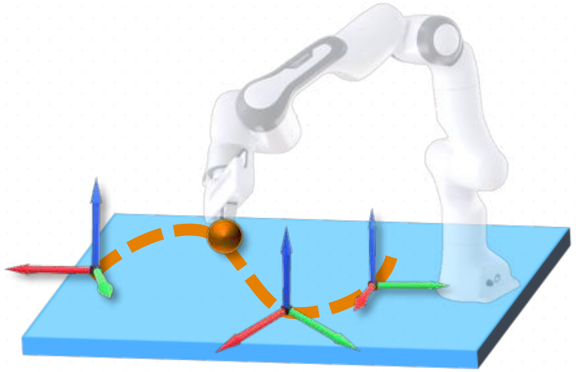
Actual State: Image, Force, Joint Enc.

Desired State: x_d

Robot Model Parameters: M, J

Action: τ





Robot Model

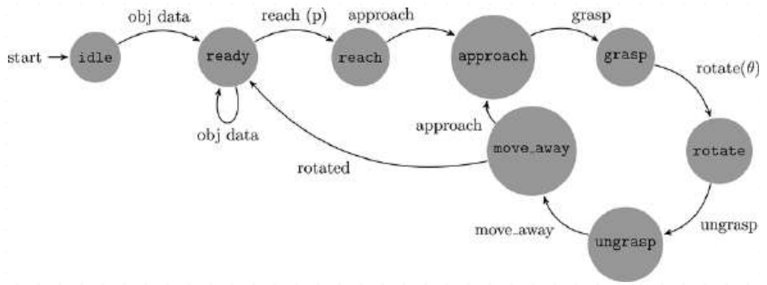
$$\ddot{x}_{ref} = K_p(x_d - x) + K_v(\dot{x}_d - \dot{x}) + \ddot{x}_d$$

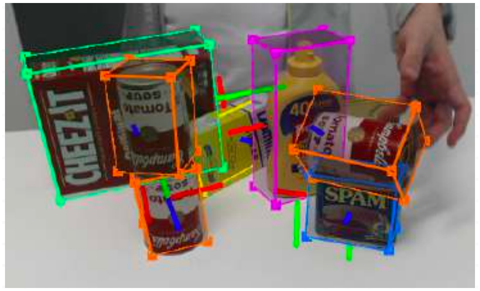
$$M(q,\dot{q}) + C(q,\dot{q}) + G(q) + \varepsilon(q,\dot{q}) = \tau$$

$$\tau = J^T\,(JM^{-1}J^T)^{-1}(\ddot{x}_{ref} - \dot{J}\dot{q} + JM^{-1}F)$$

+ Leverages Robot Model
+ Compliant Control

Environment Model + Reference Generator





- Needs Environment (Task) Model

- Task Dependent State
- Explicit State Estimation

[Khatib.1987], [Bruyninckx et al. , '96], [Schaal '03], [Rodriguez et al. 2012], [Vijaykumar et al. '11],[Ijspreet et al. '13]][Li, Billard, et al. '14], [Lee, Abbeel et al. '15]

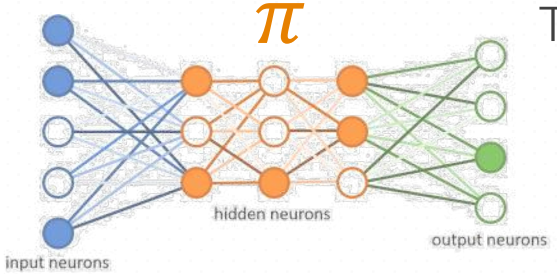
Visuo-Motor Skills: Current Paradigm

Deep Reinforcement Learning

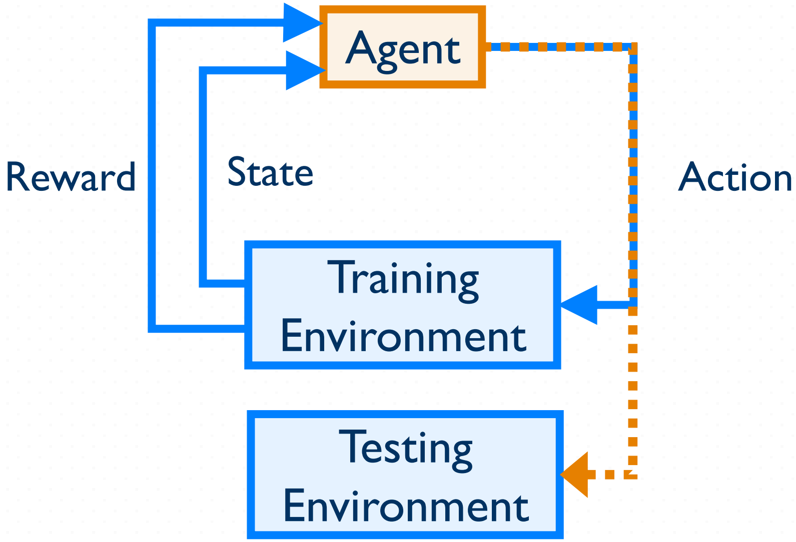
State: Image

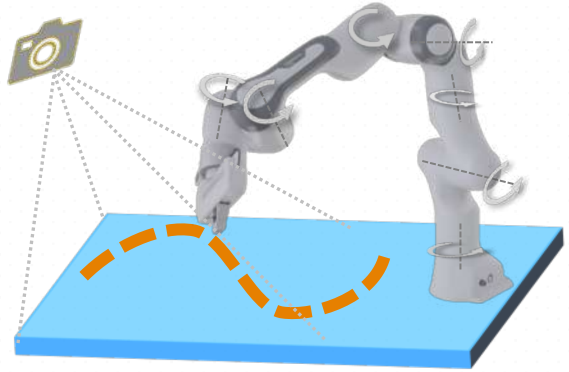
Policy π

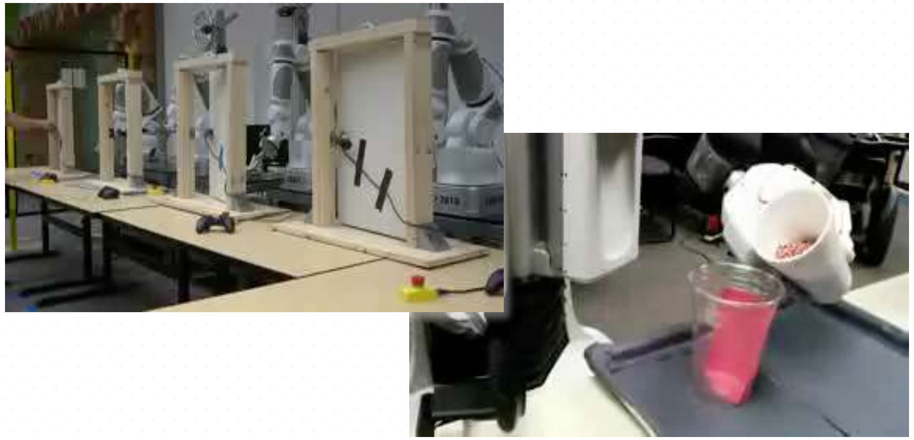
Action: Torque



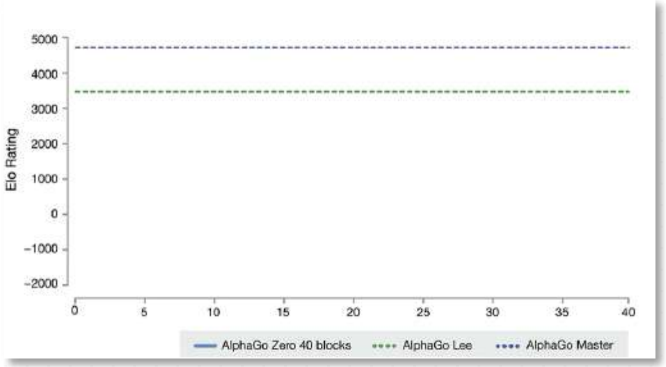
τ



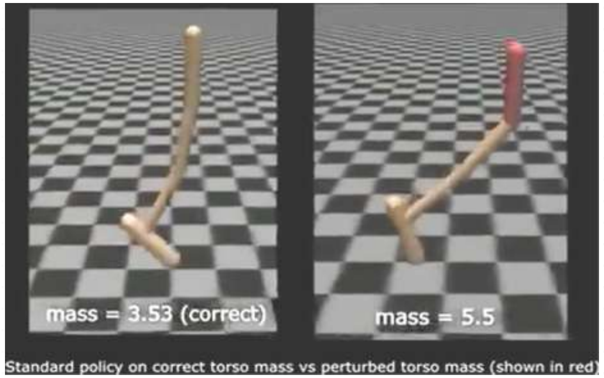




+ Model Free: No Environment Model
+ State is Image



- Sample Inefficient
- Learn robot model (implicitly)

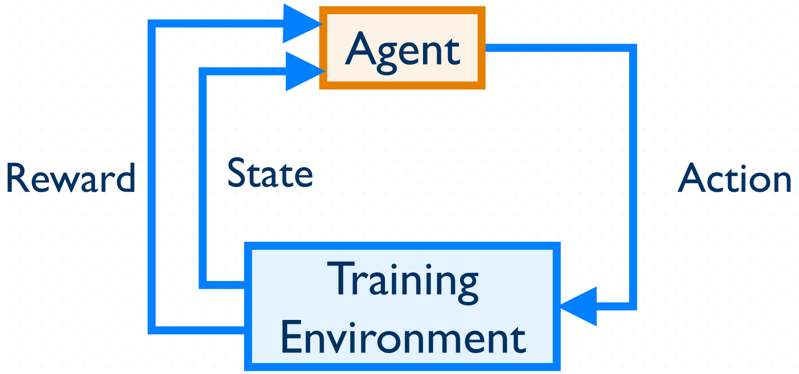


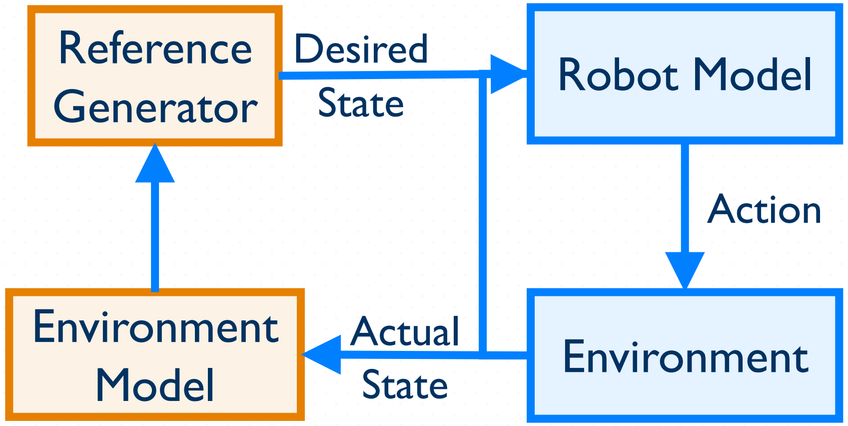
- If Training ≉ Testing: Policy Fails!

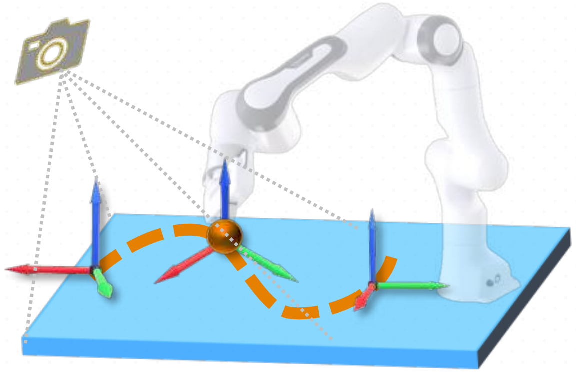
[Agrawal et al., '16], [Levine et al., '16], [Peng et al., '17], [Gu et al., '16], [Chebotar et al., '17], [Yahya et al., '16], [James et al., '17], [Popov et al., '17]

Visuo-Motor Skills: Our Approach

RL with Variable Impedance Task-Space

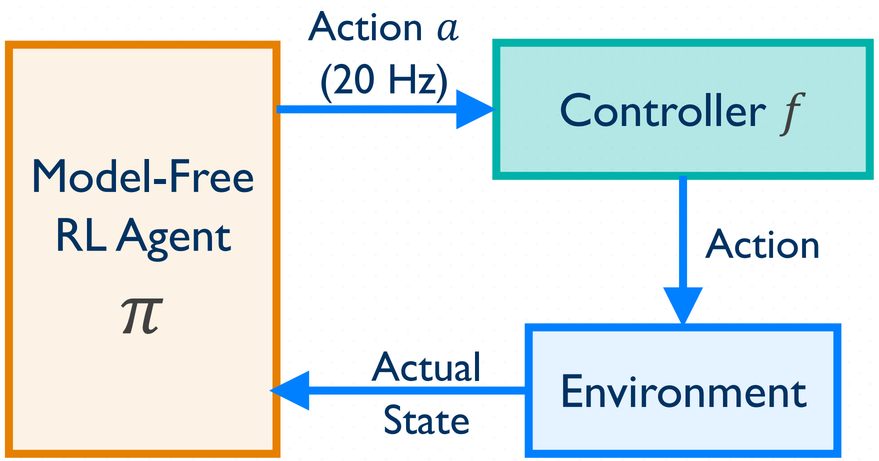






Visuo-Motor Skills: Our Approach

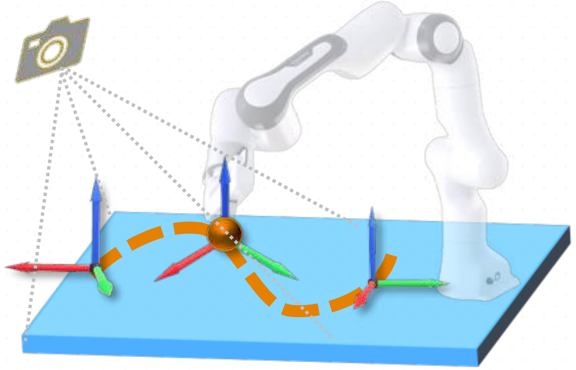
RL with Variable Impedance Task-Space



Reference Generator
(learned)

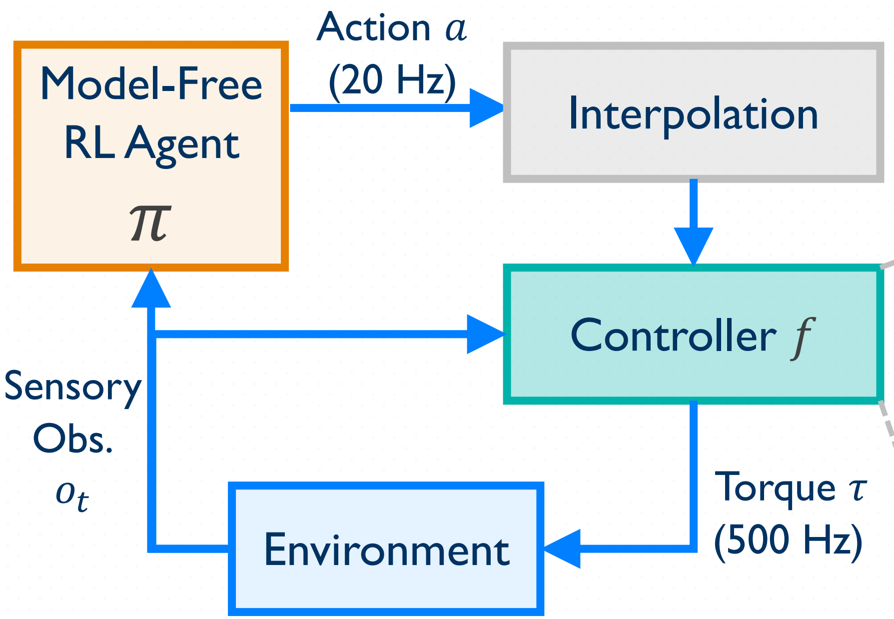
$$\tau = f(\pi(o_t))$$

Robot Model
(Deterministic)



Visuo-Motor Skills: Our Approach

RL with Variable Impedance Task-Space



$$\tau = f(\pi(o_t))$$

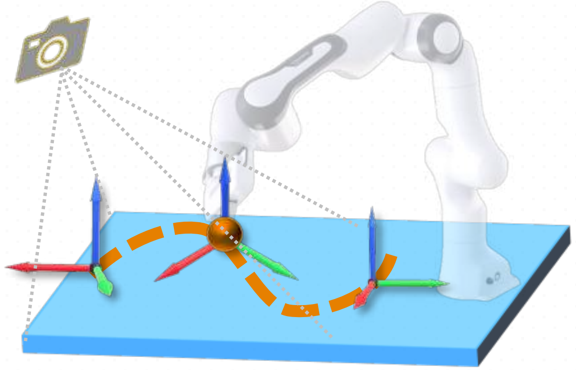
$$\pi(o_t) = a\colon [\boxed{x_d, \dot{x}_d}, \boxed{K_p, K_v}]$$

Pose and Velocity

Impedance Gains

$$\tau = \boxed{f}(x_d, \dot{x}_d, K_p, K_v)$$

Deterministic Position-Velocity Control Jacobian J and Inertia M



+ Model Free: No Environment Model
+ State is Image
+ Leverages Robot Model
+ Compliant Control
+ Sample Efficient
+ Transferable

Visuo-Motor Skills: Action Representation

Surface Wiping

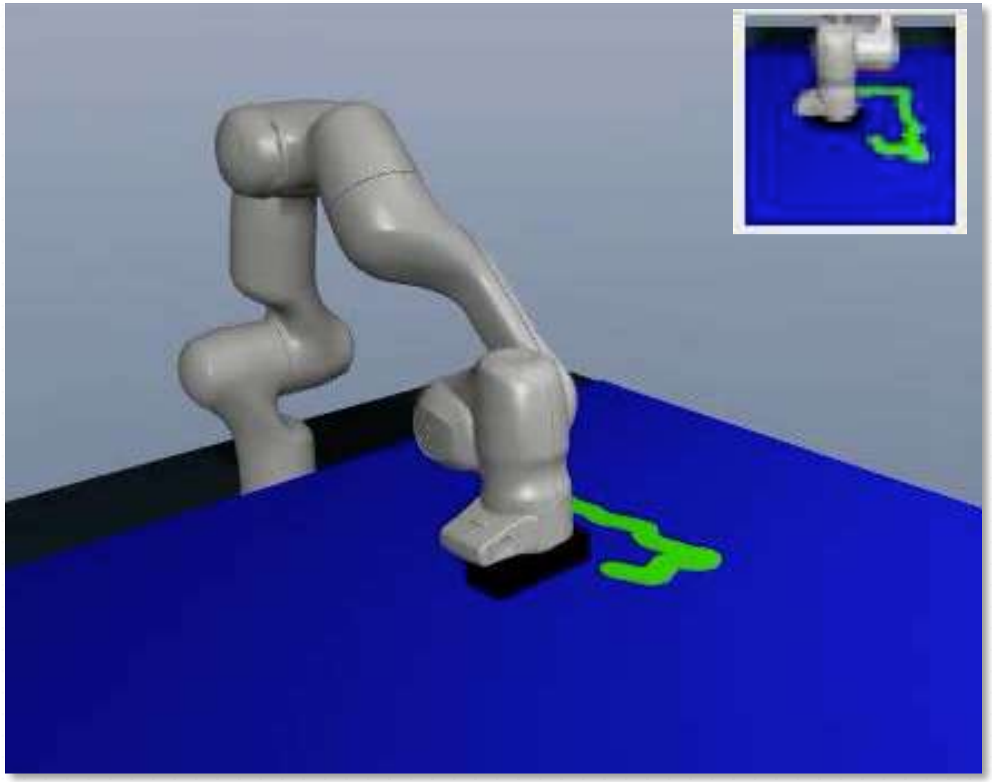
Input: Image (48x48)

Minimize the number of Dirty Tiles

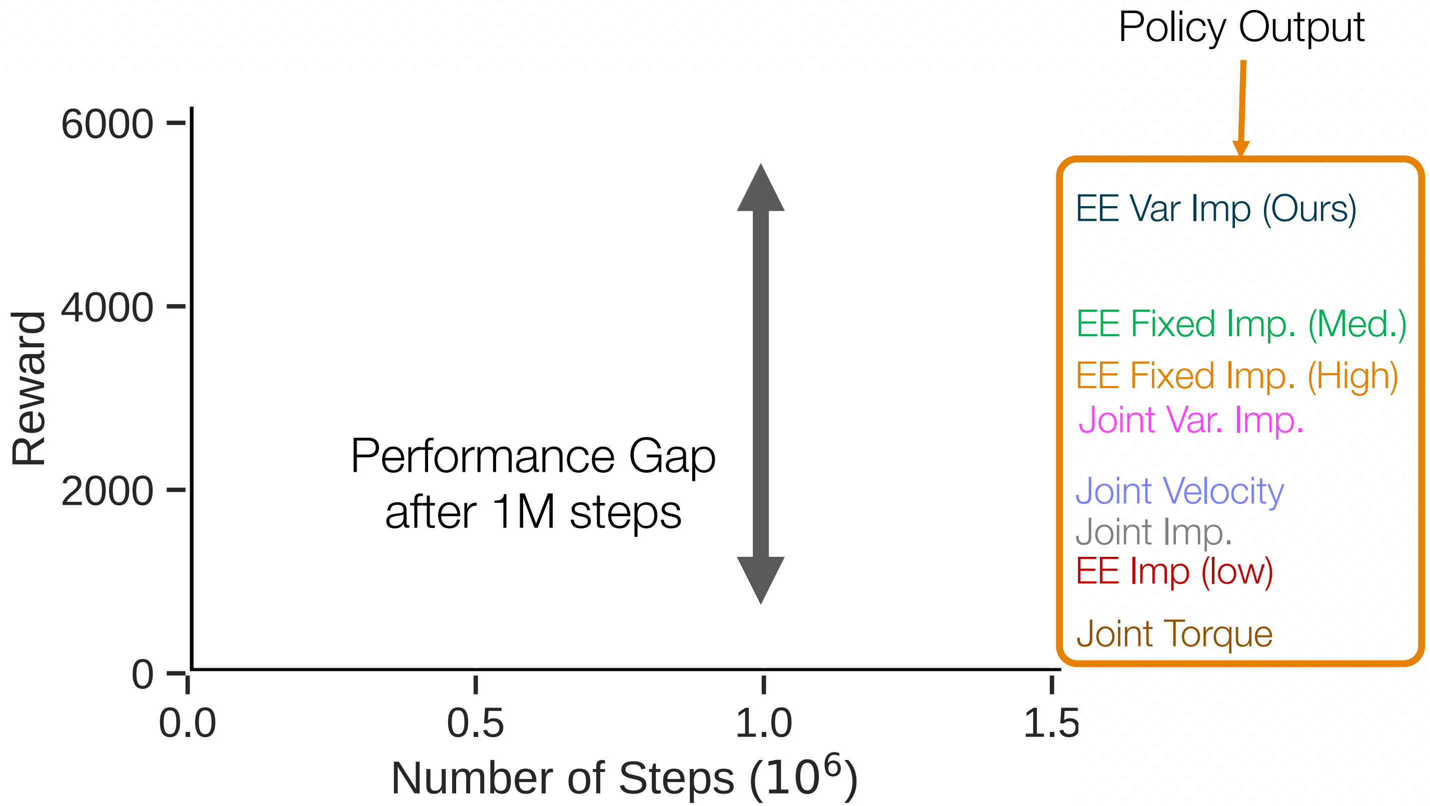
Maintain Contact with the Table

Don't push with more than Robot Payload

Reward: $\lambda_1 \sum(dirt\_on\_table) + \lambda_2(distance\_to\_table) - \lambda_3 \mathbb{I}\,(F \geq 40N)$



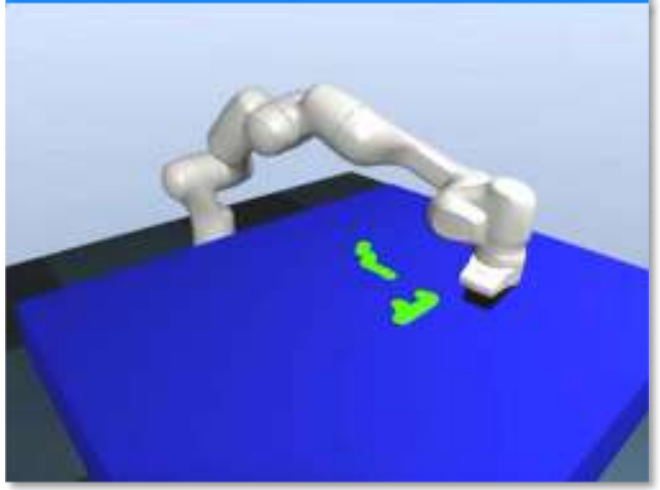
Trained Policy Rollout (Ours)



Evaluation During Training (PPO)

Visuo-Motor Skills: Action Representation

Training on Panda



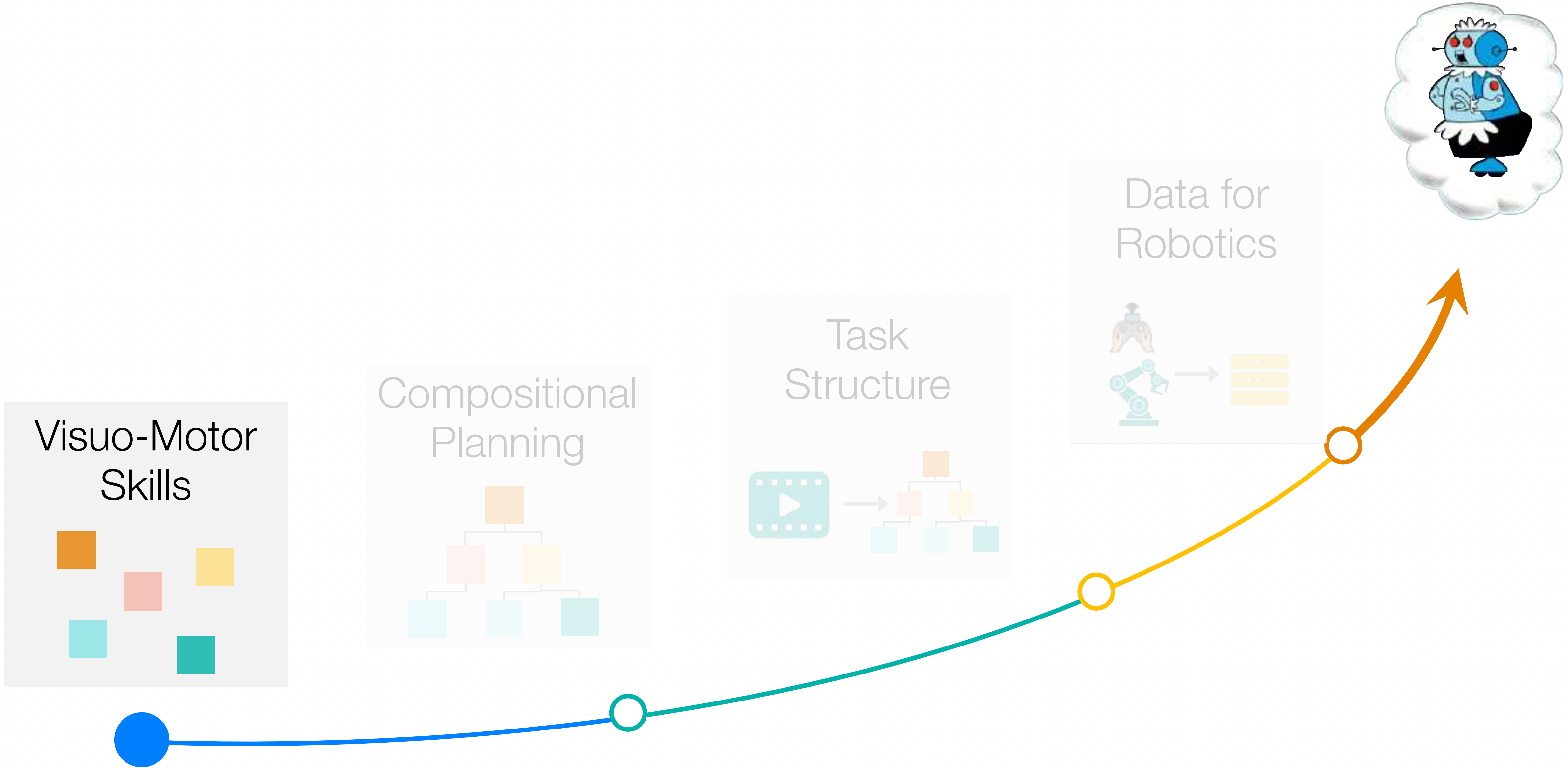
$\tau = f_{Sim}(\pi(o_t))$

Evaluation on Real Robot without Fine-Tuning

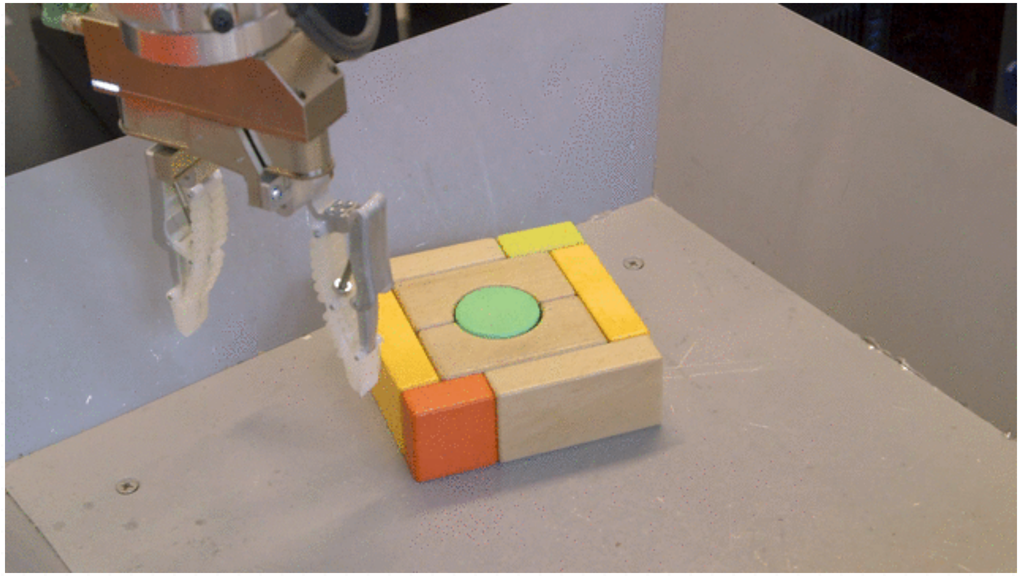
$\tau = f_{Real}(\pi(o_t))$

Success 80% (10 Trials)

Generalizable Autonomy in Robot Manipulation



Skills: Imitation from Heuristics



Promise of Deep RL
closed loop-control with images

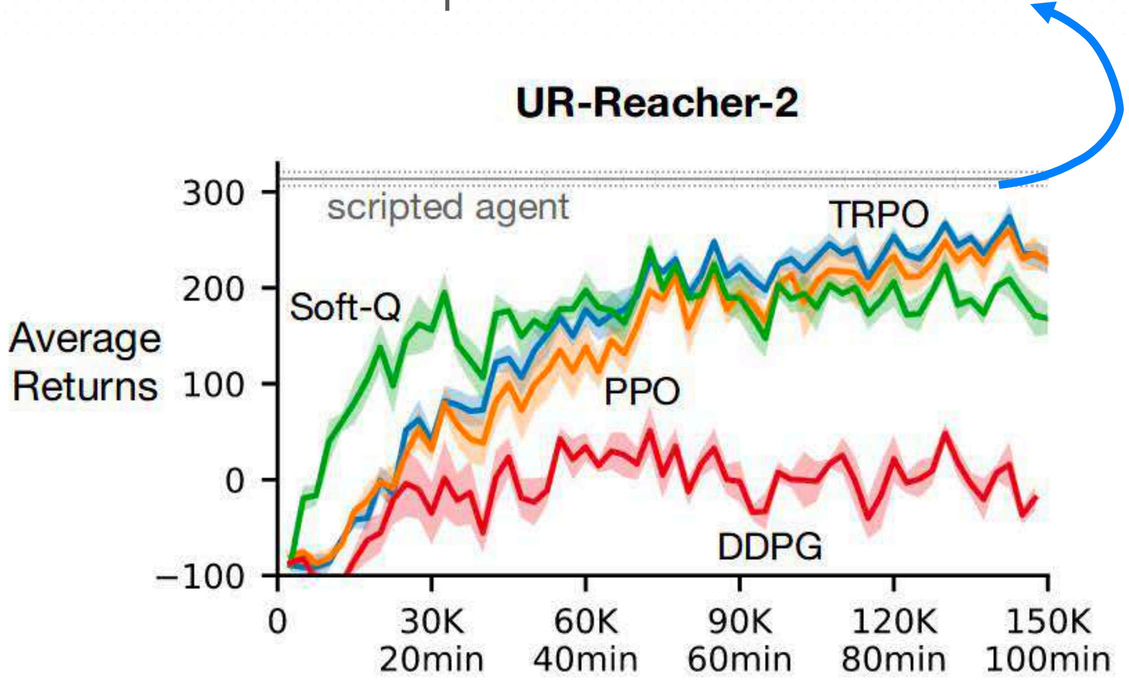
…albeit, with a lot of training

[Kalashnikov et al (2018). Levine et al. (2016), Pinto et al. (2016), Kalashnikov et al. (2018), Yu et al. (2016), Haarnoja et al. (2018), Lee et al. (2019), Vecerik et al. (2017)]

Skills: Heuristics often beat RL

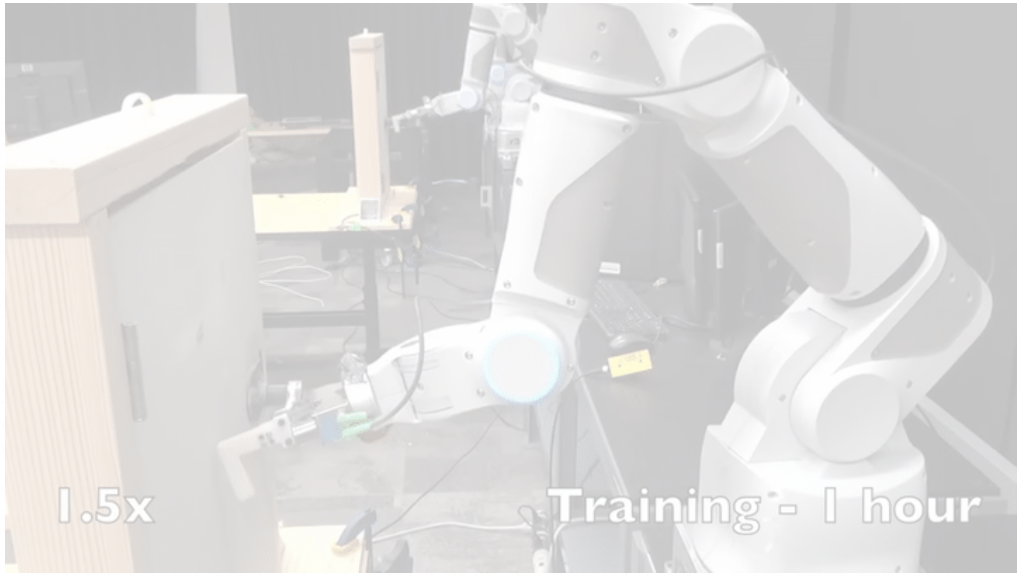
RL struggles with structured, multi-step skills

Even simple heuristics beat RL

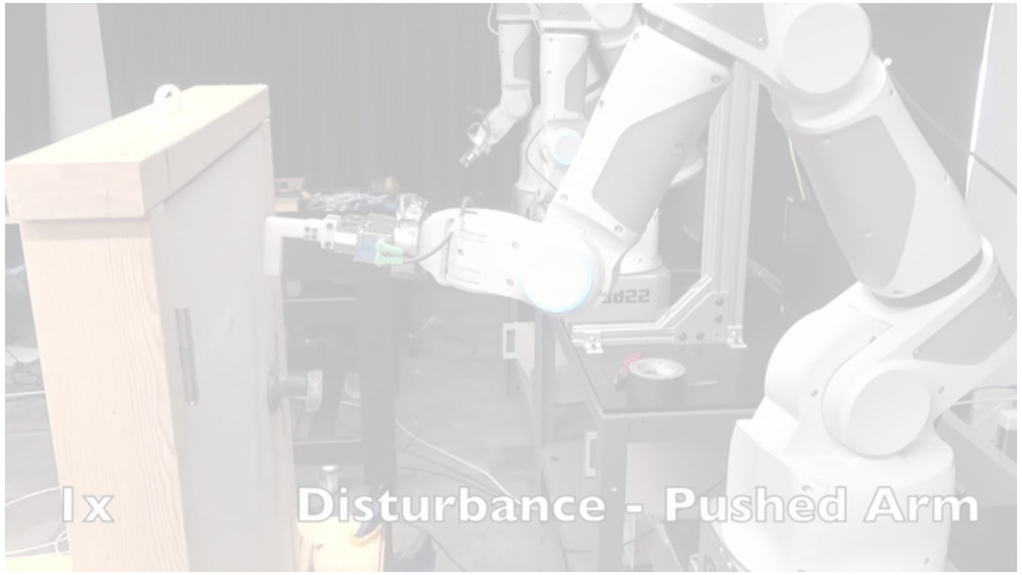


IROS 2019, Mahmood et al. 2018

Skills: Exploration without Guidance



Random Exploration is slow



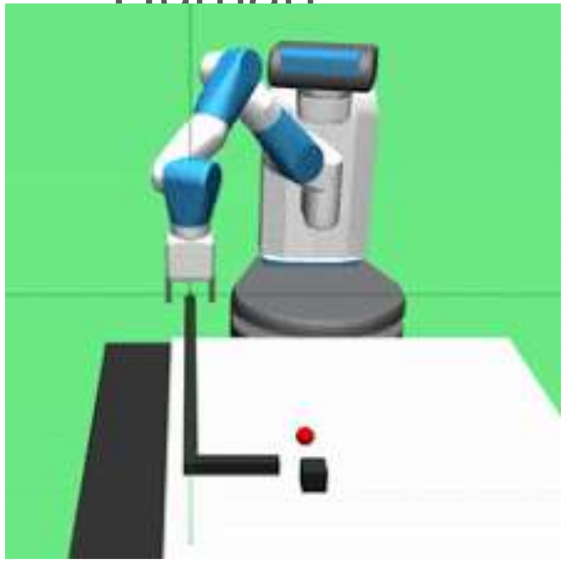
…even when first steps are obvious

Can Human Intuition Guide Exploration?

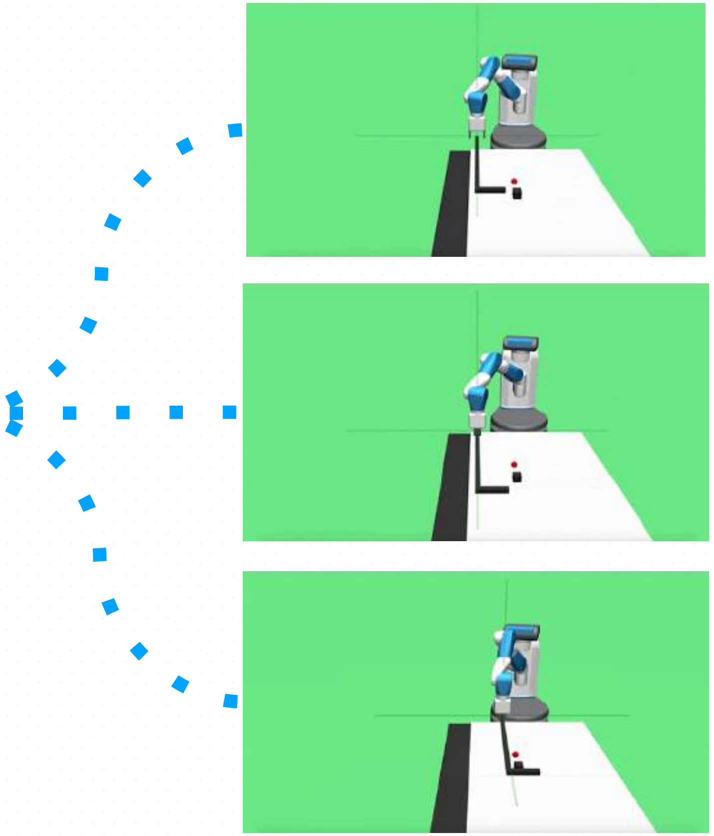
Gu et al. 2017

Skills: Imitation from Heuristics

Human
RL Task



Teachers



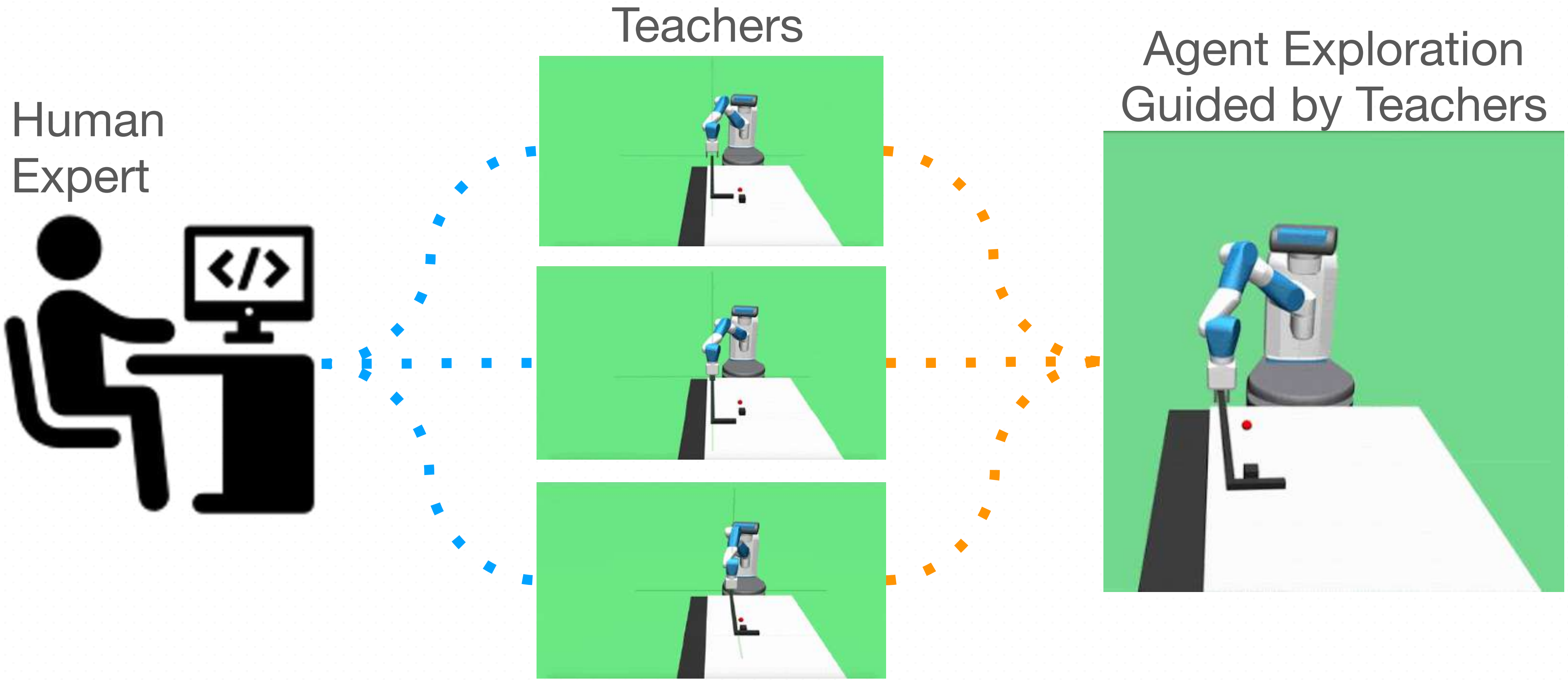
Intuition

Implement Useful Skills
...but not full solution

Teachers

Black-box controllers
solving parts of the task

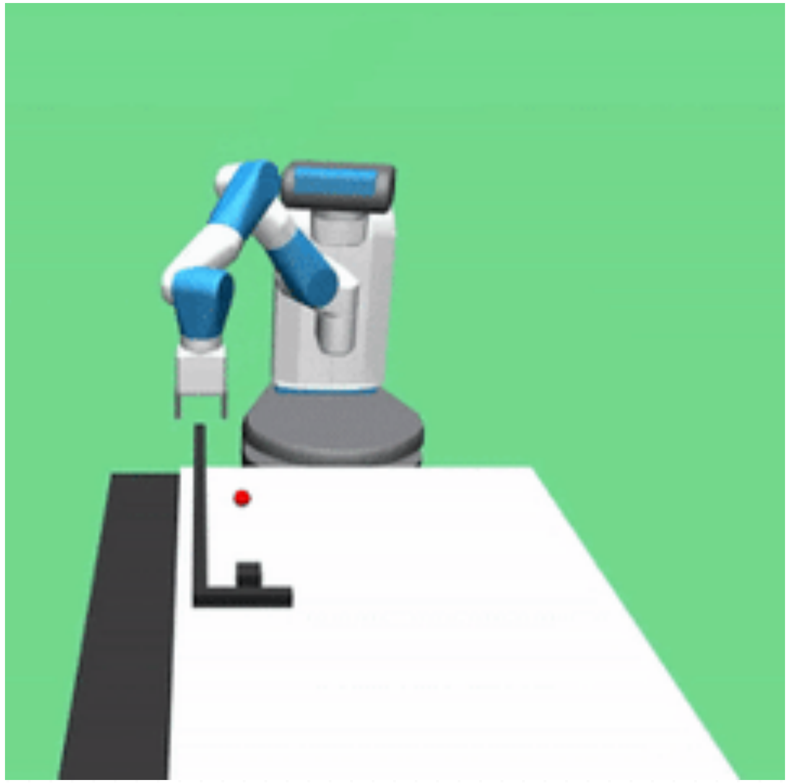
Skills: Imitation from Heuristics

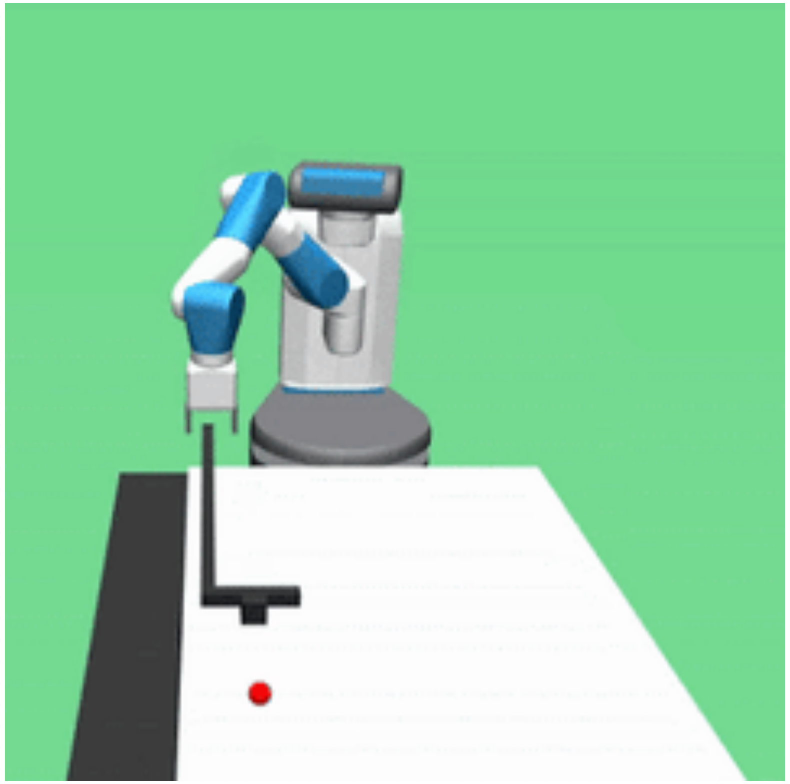


Goals: A) **faster** agent training B) **optimal** test-time agent performance

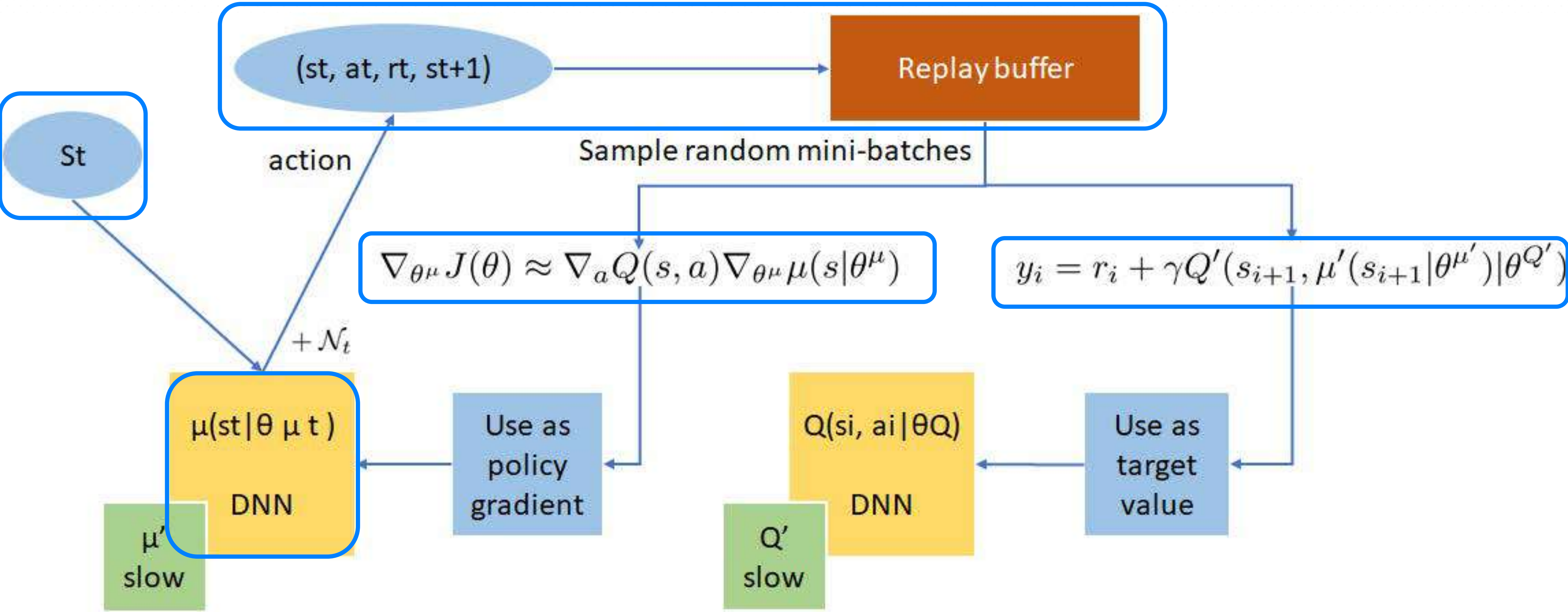
Skills: Imitation from Heuristics

Naive action choice might not work well!



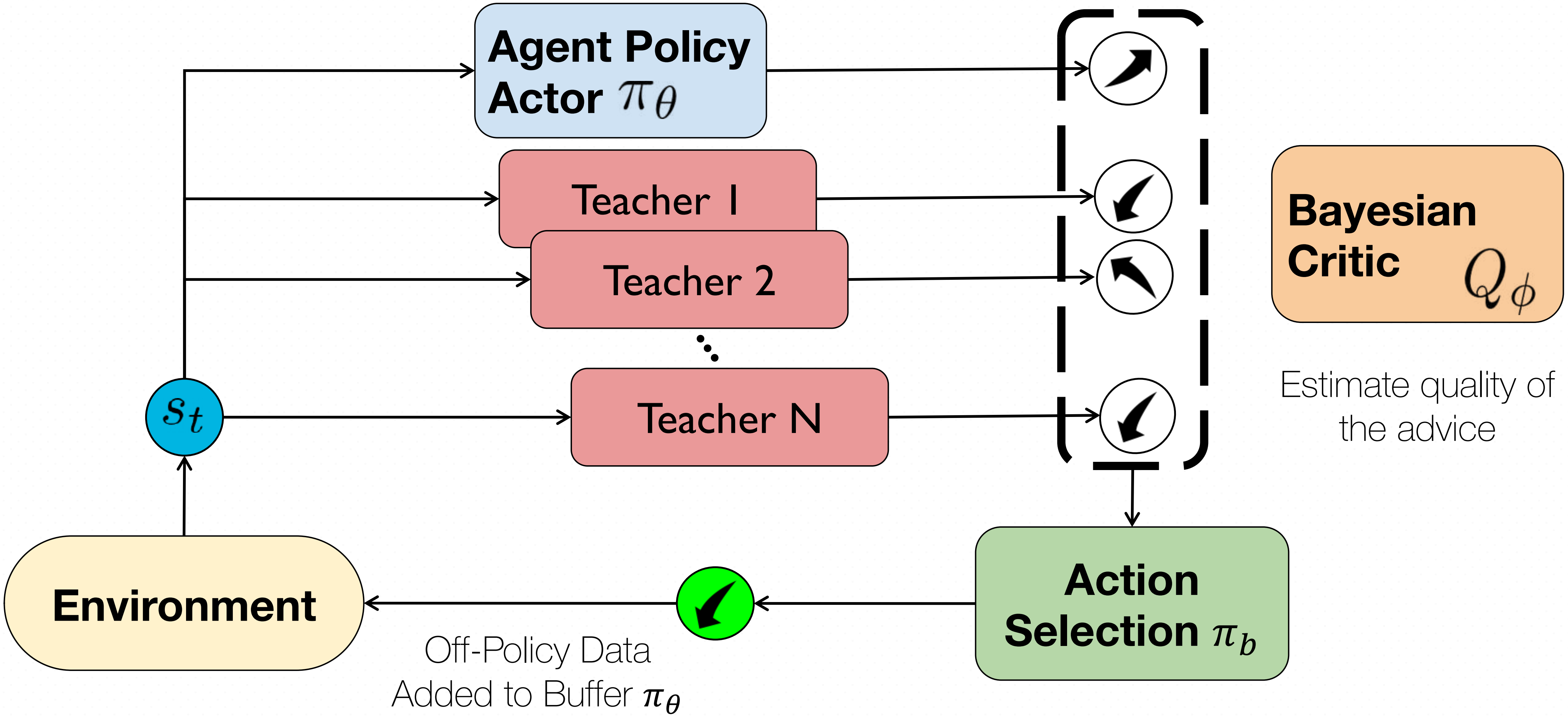


Off-Policy RL: DDPG Review



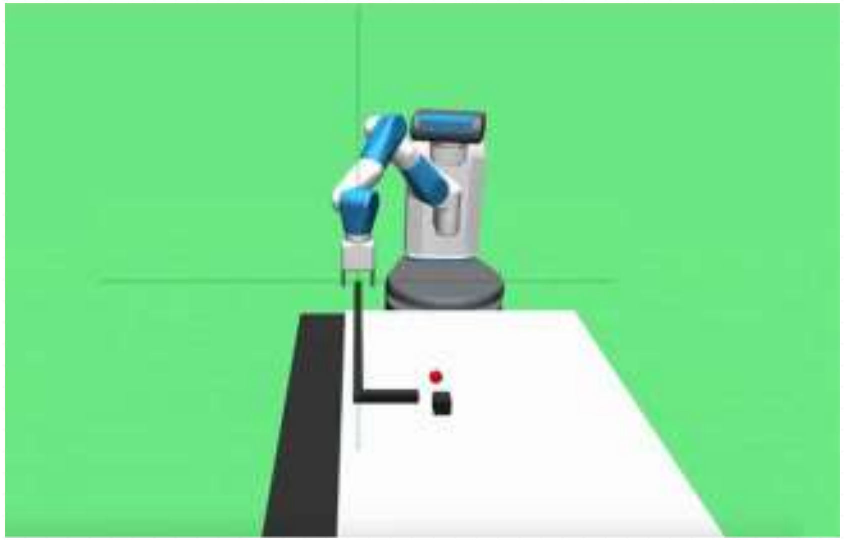
Lillicrap et al. 2015

AC-Teach: Actor-Critic with Teachers

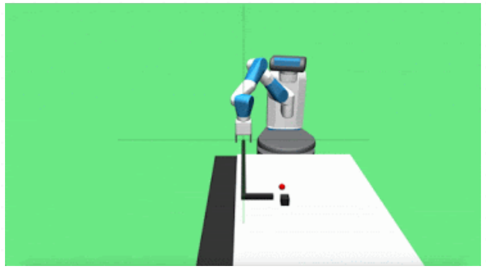


Experiments

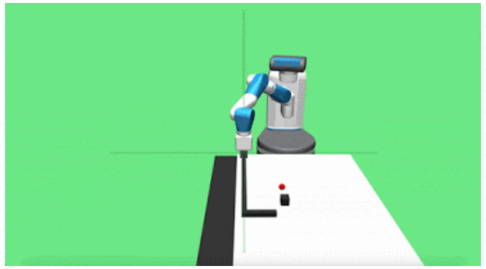
Task:



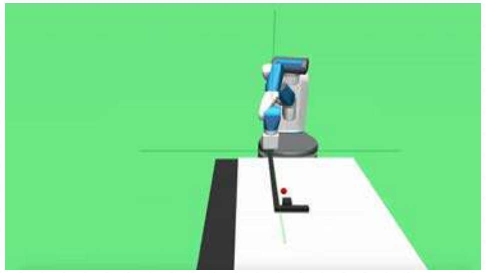
Teachers:



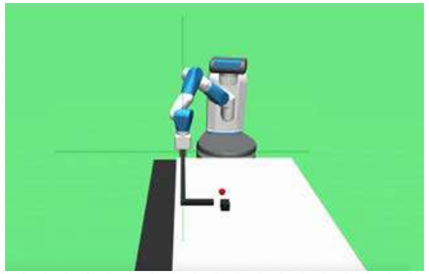
grab hook



position hook



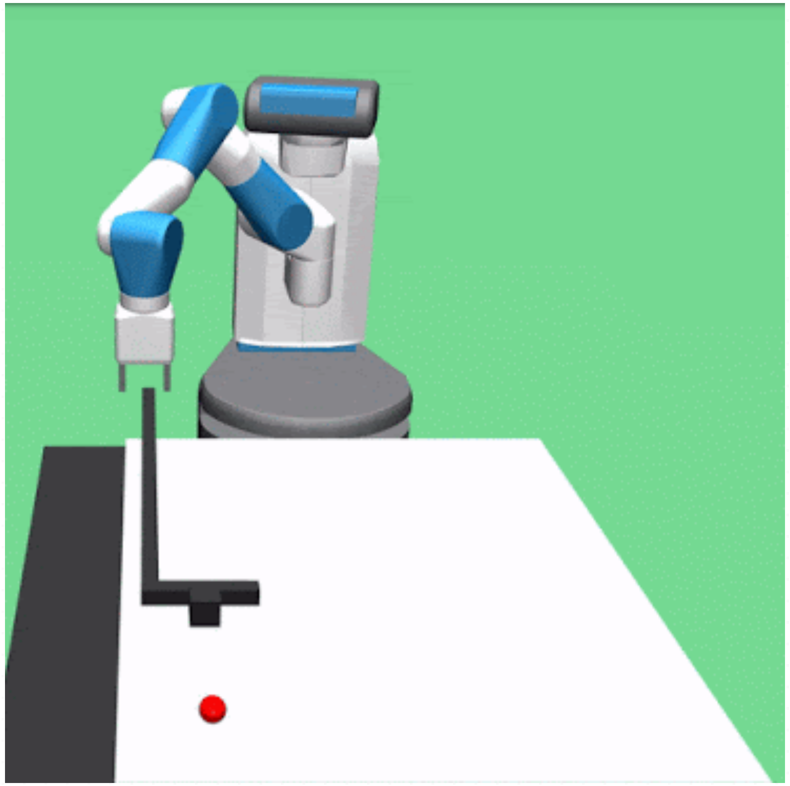
pull

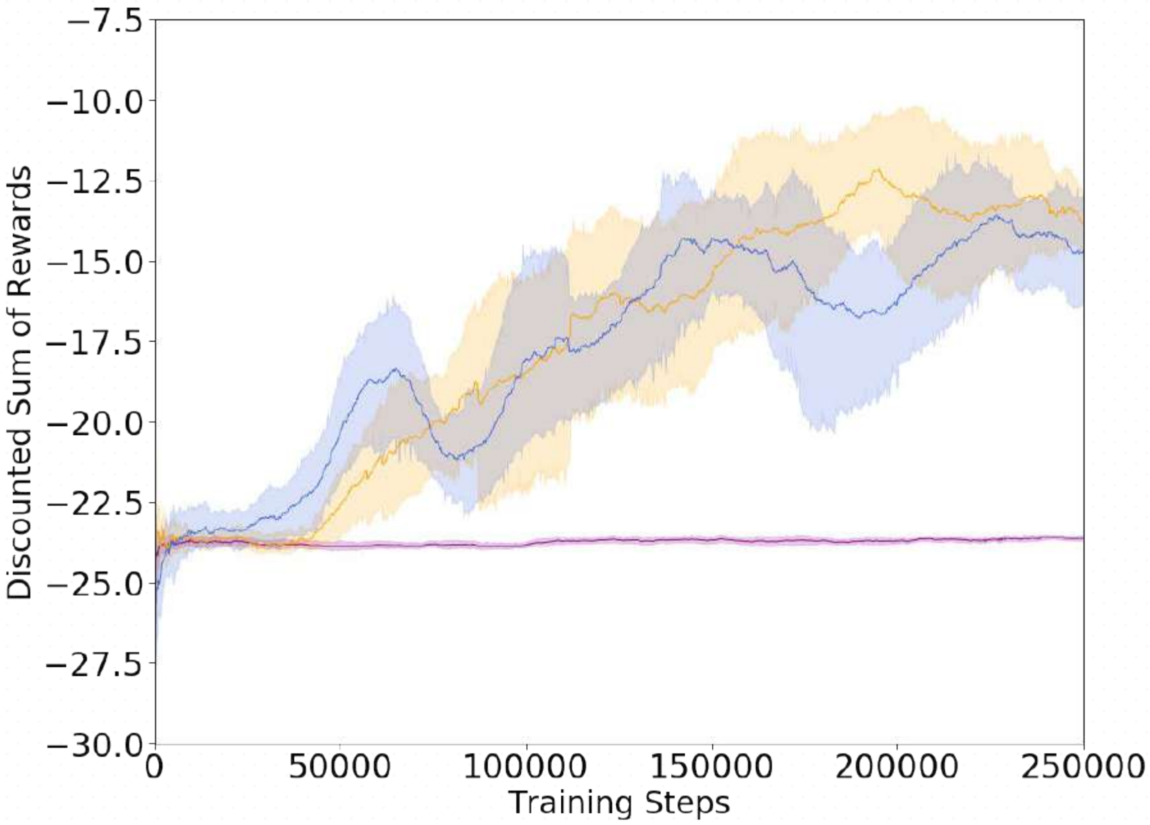


push

Results

B-DDPG + AC-Teach (ours) B-DDPG + DQN B-DDPG (no teachers)

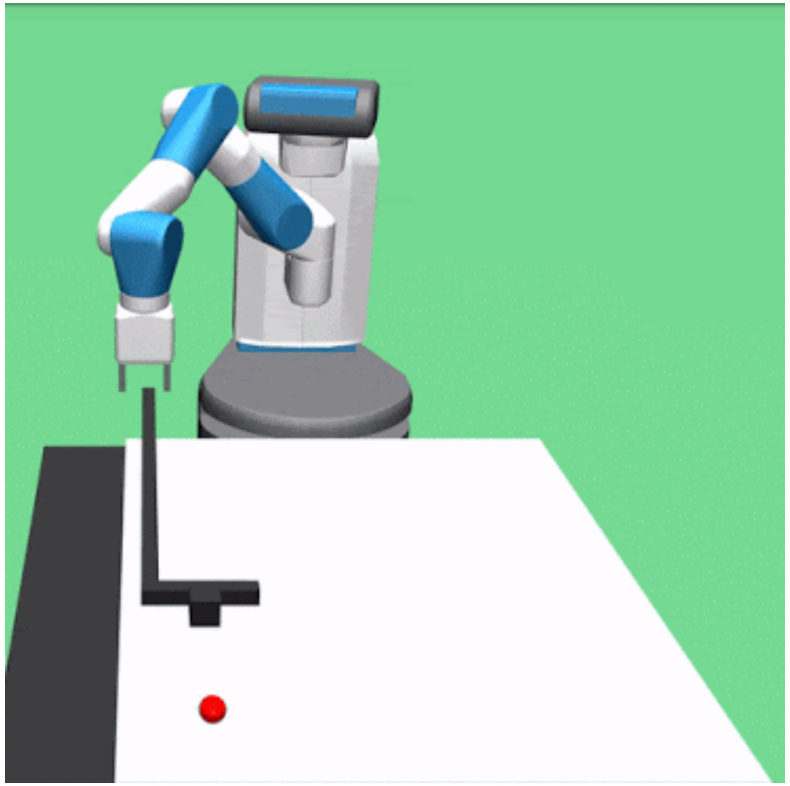


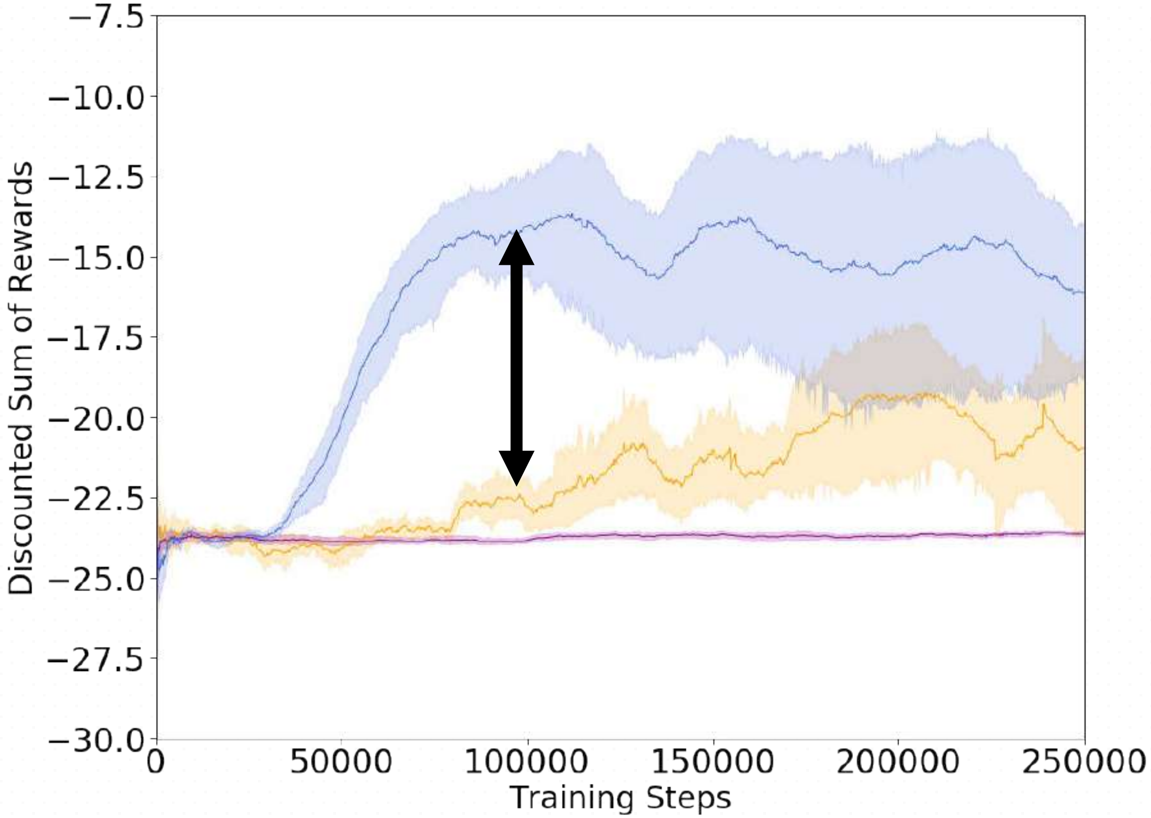


AC-Teach is able to leverage a single teacher well

Results

B-DDPG + AC-Teach (ours) | B-DDPG + DQN | B-DDPG (no teachers)

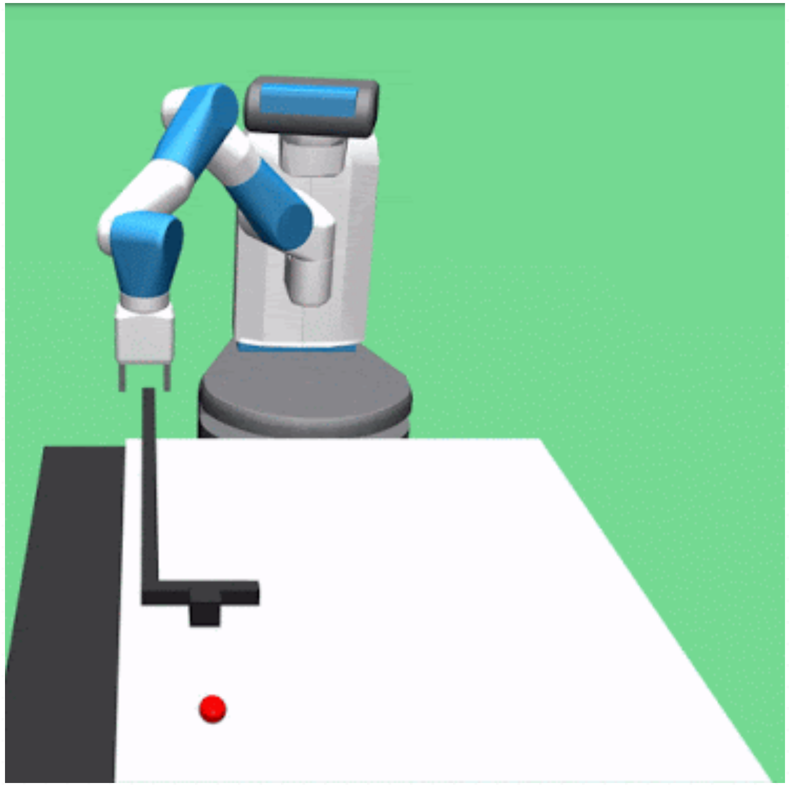


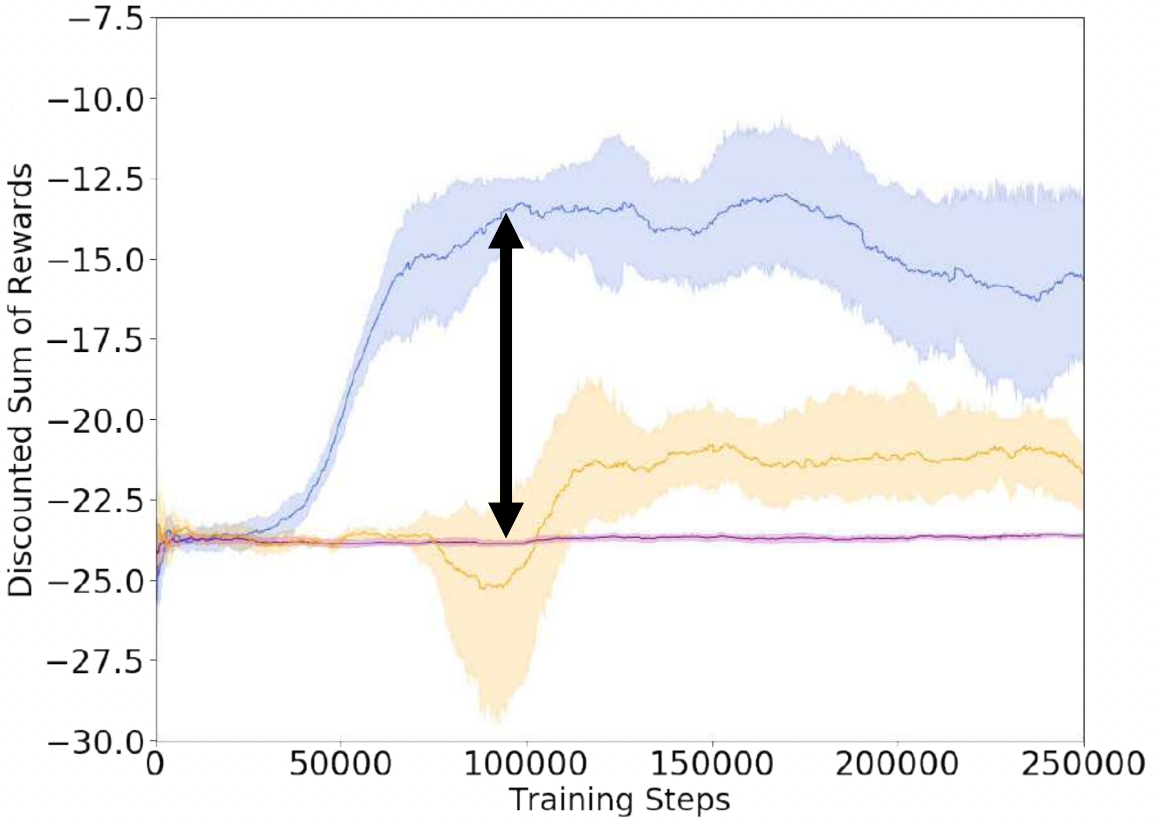


AC-Teach speeds up training given multiple teachers

Results

B-DDPG + AC-Teach (ours) — B-DDPG + DQN — B-DDPG (no teachers)





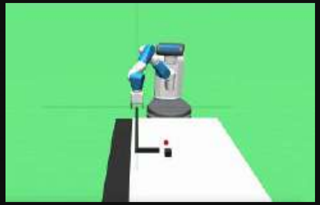
AC-Teach has agent learn behaviors not in teacher set

AC-Teach: CoRL 2019

Visuo-Motor Skills

- Grasping
- Pushing
- Picking
- Wiping
- Open door

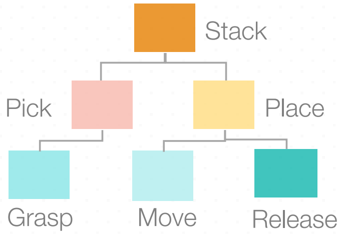
IROS 2019



CoRL 2019

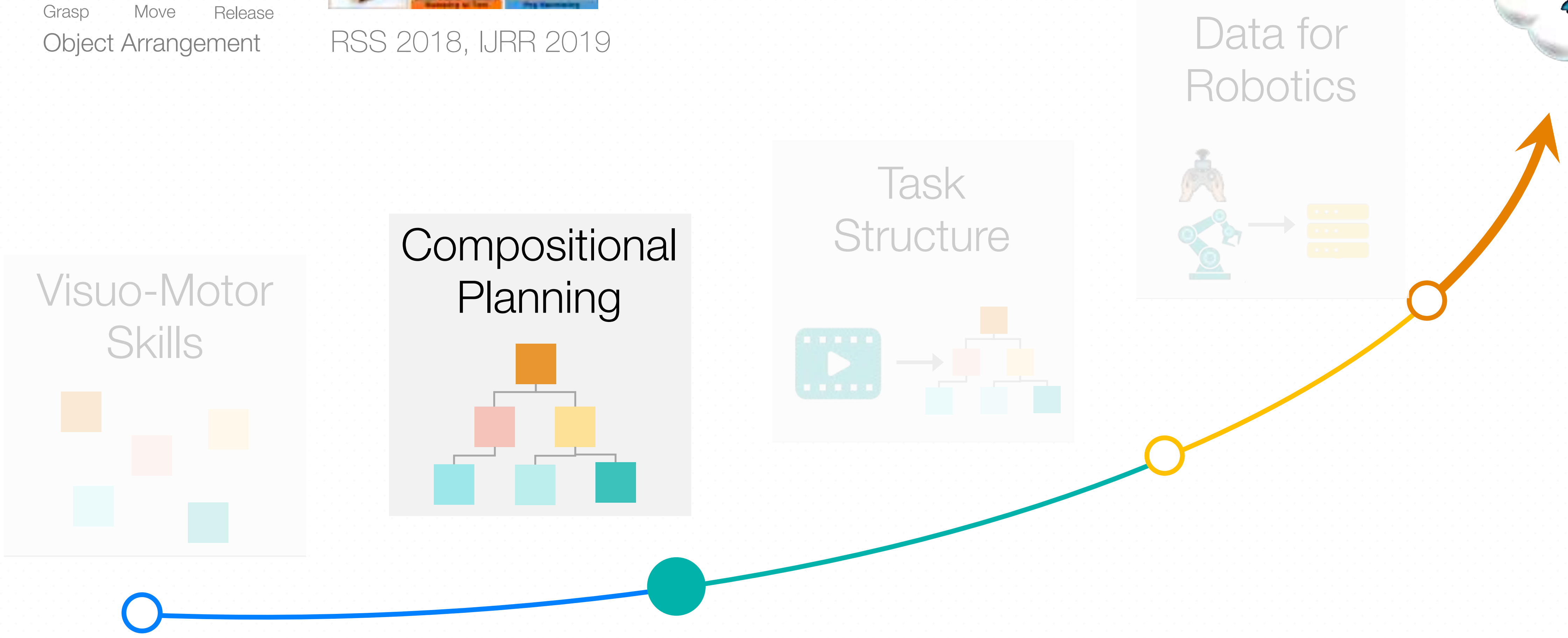
Action Representations and Weak-Supervision provide structure to enable learning efficiency and generalization

Generalizable Autonomy in Robot Manipulation



Object Arrangement


RSS 2018, IJRR 2019



Sequential Skills

Skills: Surface Wiping

Skills: Tool Use

Primitive Skills

Grasping

Pushing

Picking

Wiping

Open door

Sequential Skills

Hammering (with unknown objects)

Cutting (with new knife)

Sweeping (with new broom)

Sequential Skills: Manipulation with Tools

Tool-Use

Initial State

Unknown Object

Task-Agnostic Grasping[1]

Optimizes for Grasp Success Only

Suboptimal for Task!

Task-Oriented Grasping

Sweeping

Hammering

[1] Pinto et al. '16, Levine et al. '16, Mahler et al. '18, Kalashnikov et al. '18

Visuo-Motor Skills: Task-Oriented Grasping

Input =  

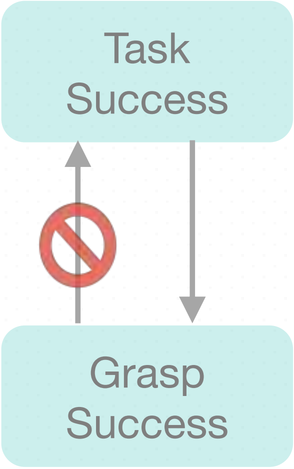
Depth Image o | Task T

Output =    

Hammering

Grasp Parameters $g = (g_x, g_y, g_z, g_\phi)$

Policy $a = \pi(o, g)$



$$g^*, \pi^* = \underset{g,\pi}{\operatorname{argmax}}\; Q_T^\pi(o, g)$$

Score Function

$$Q_T^\pi(o, g) = P_\pi(S_T = 1 \mid S_G = 1, o, g)\, P(S_G = 1 \mid o, g)$$

$$Q_T^\pi(o, g) = Q_{T|G}^\pi(o, g)\, Q_G(o, g)$$

Task Success

Task Conditioned Grasp Success

Grasp Success

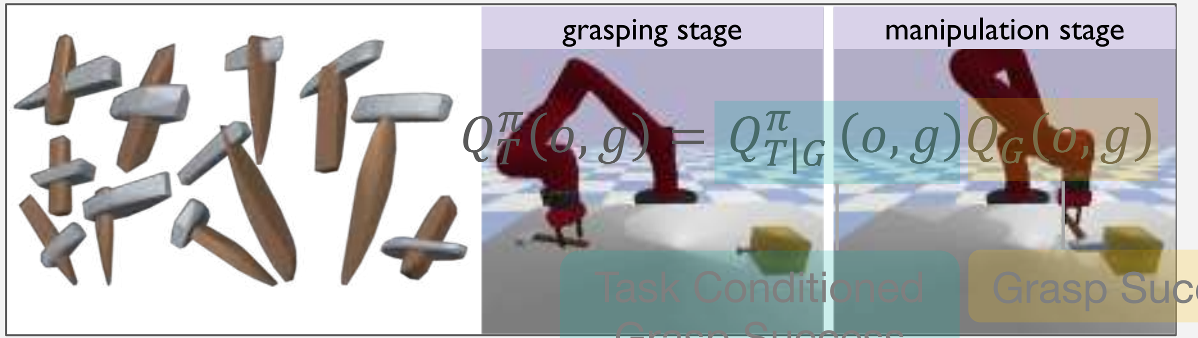
RSS 2018, IJRR 2019

Visuo-Motor Skills: Task-Oriented Grasping

Input: Depth Image (64x64)

CNN Model	Output	Loss Function
grasping model	$Q_G(o, g)$	$\mathcal{L}(S_G, Q_G(o, g; \theta_1))$
task-oriented grasping model	$Q^{\pi}_{T\|G}(o, g)$	$\mathbb{I}(S_G = 1)\mathcal{L}(S_T, Q^{\pi}_{T\|G}(o, g; \theta_2))$
Manipulation	$\pi(a \mid o, g; \theta_3)$	$\nabla_{\theta_3} \log \pi(a \mid o, g; \theta_3)$

Training



$$Q^{\pi}_{T}(o, g) = Q^{\pi}_{T|G}(o, g)\, Q_G(o, g)$$

Task Conditioned Grasp Success

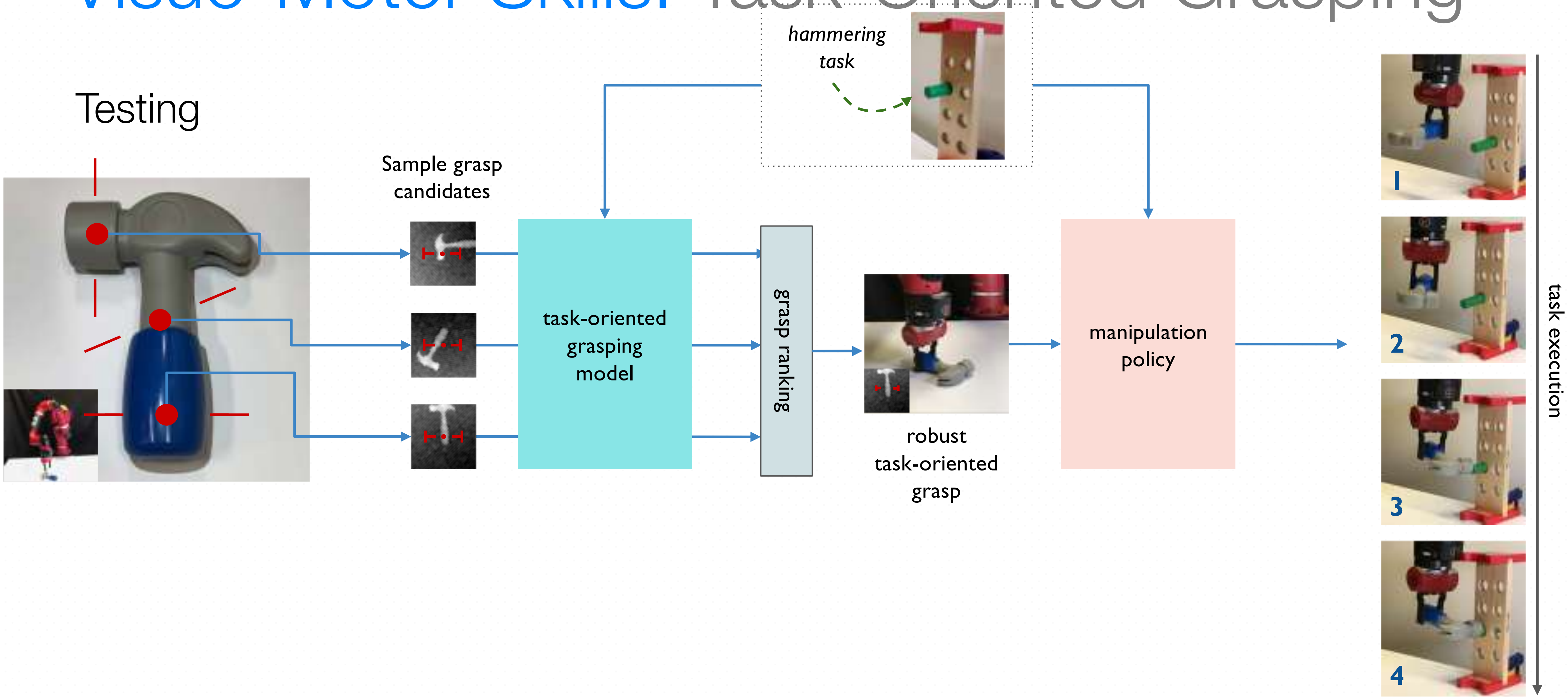
Grasp Success

18K diverse training objects

large-scale data collection (1.5m Episodes)

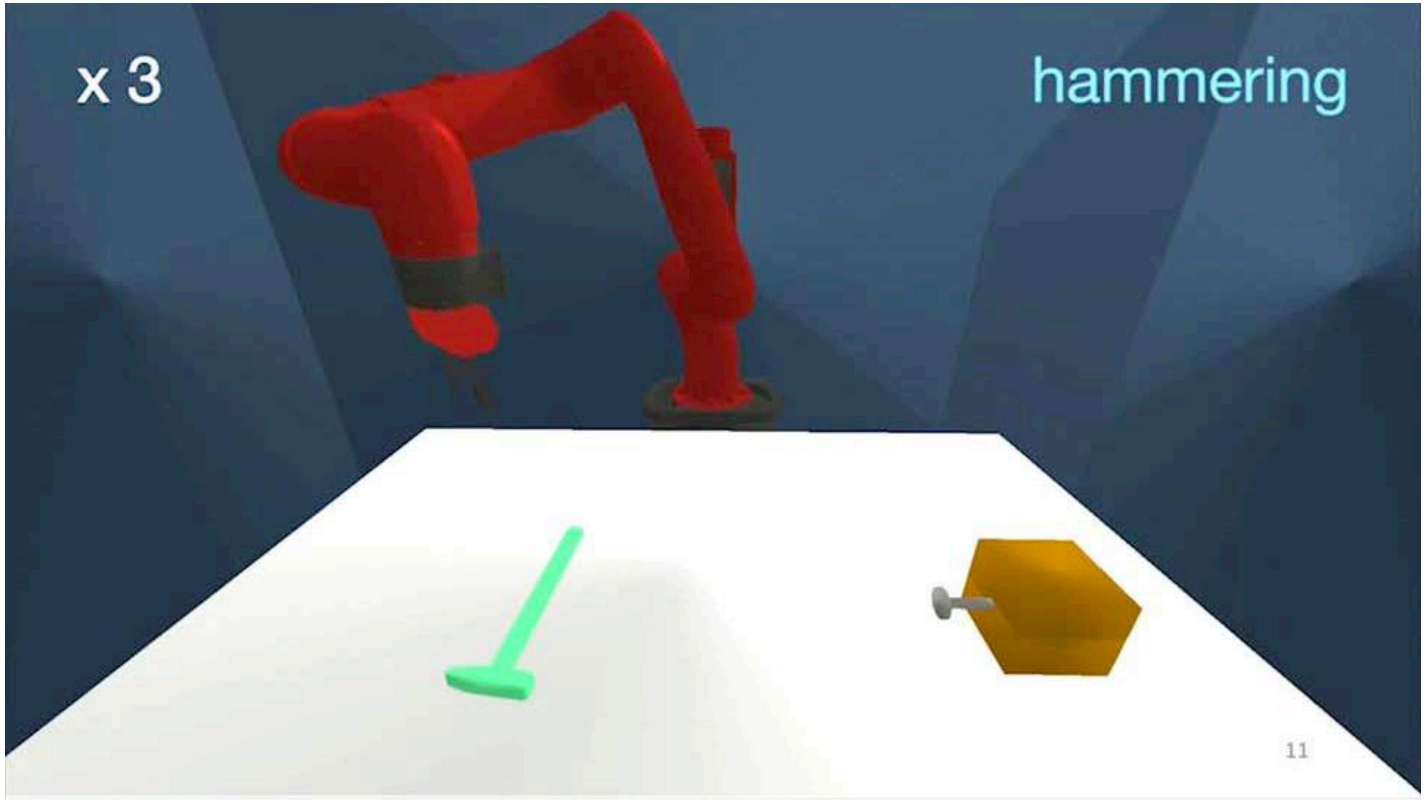
RSS 2018, IJRR 2019

Visuo-Motor Skills: Task-Oriented Grasping

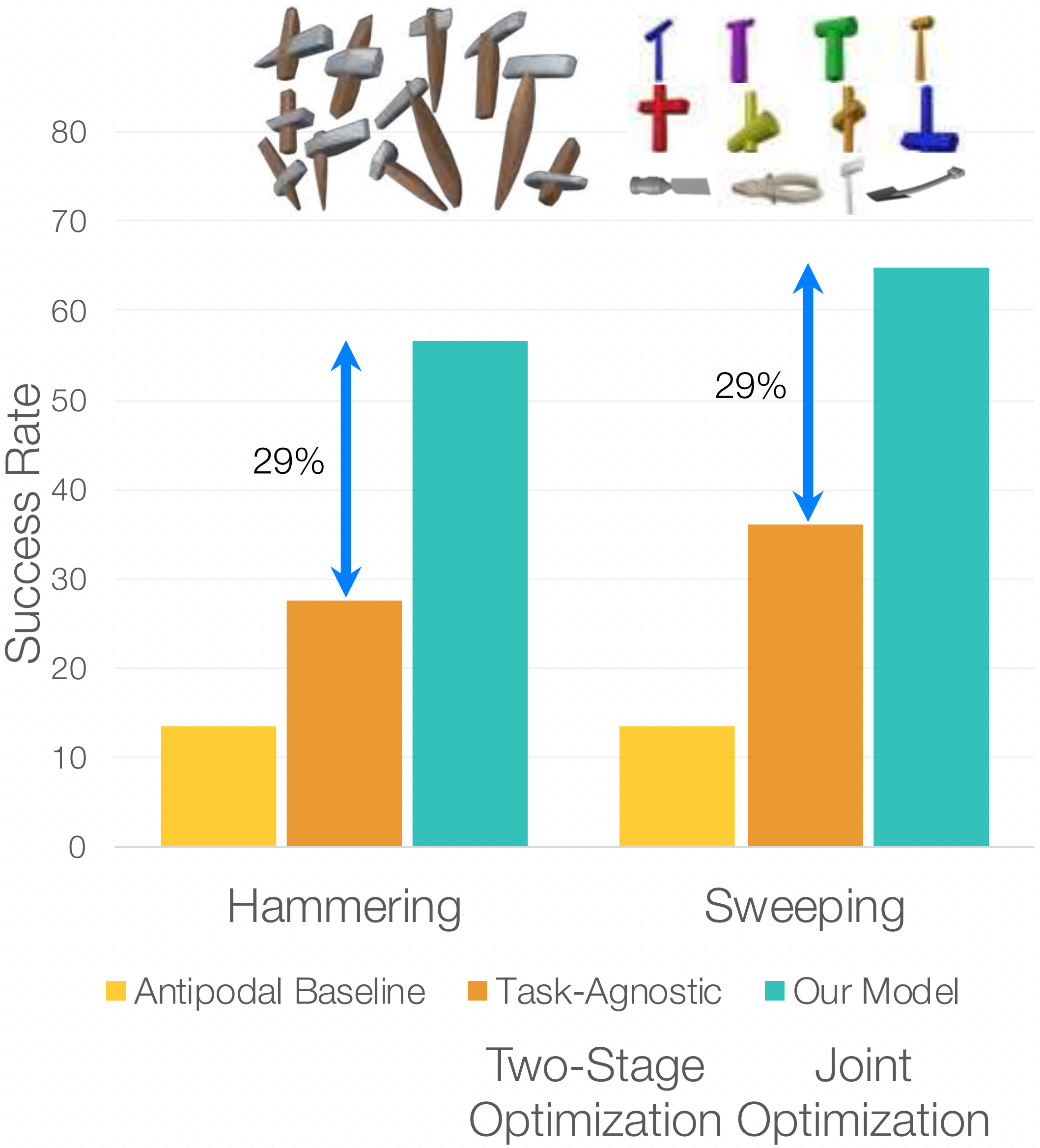


RSS 2018, IJRR 2019

Sequential Skills: Task-Oriented Grasping

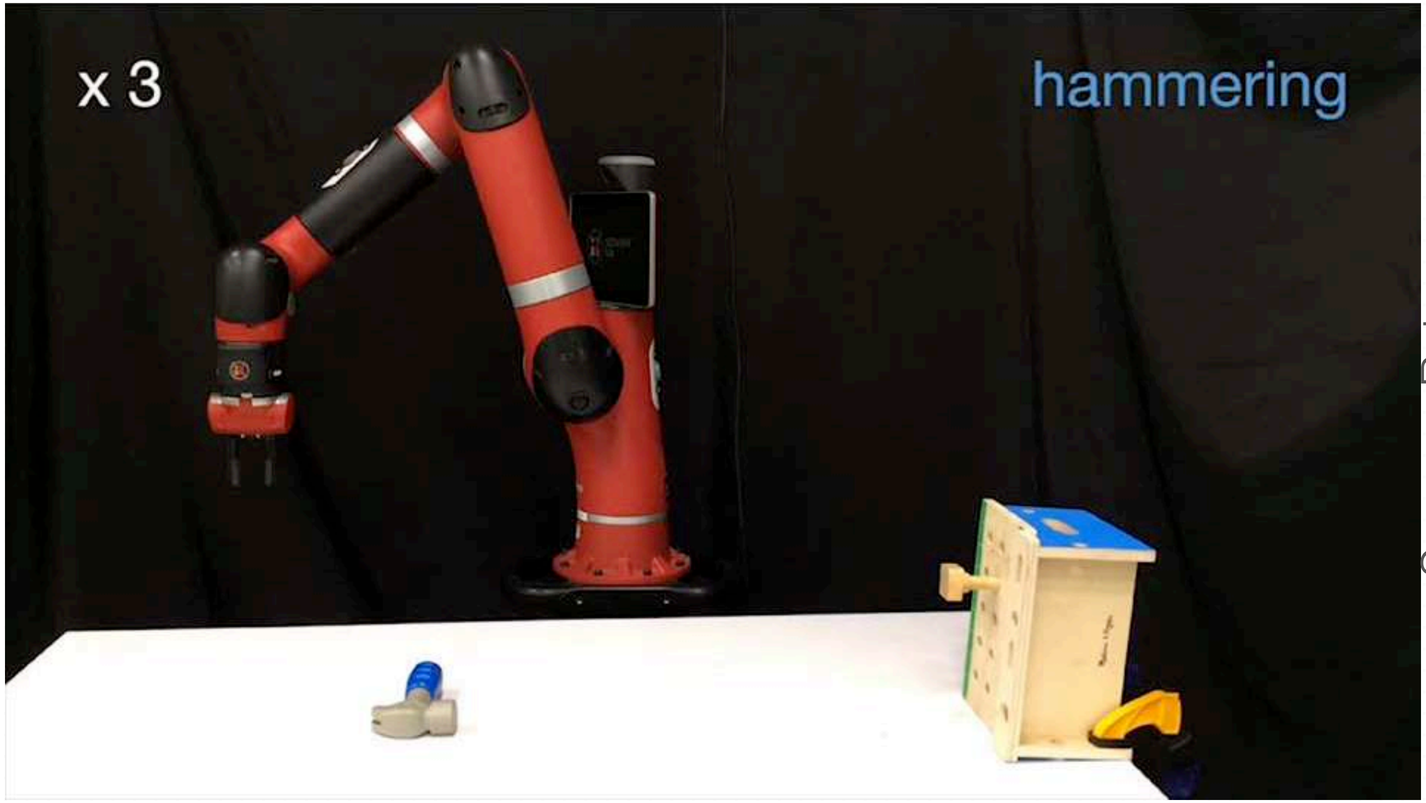


Trained Policy Rollout (Ours)
Unseen Test Objects

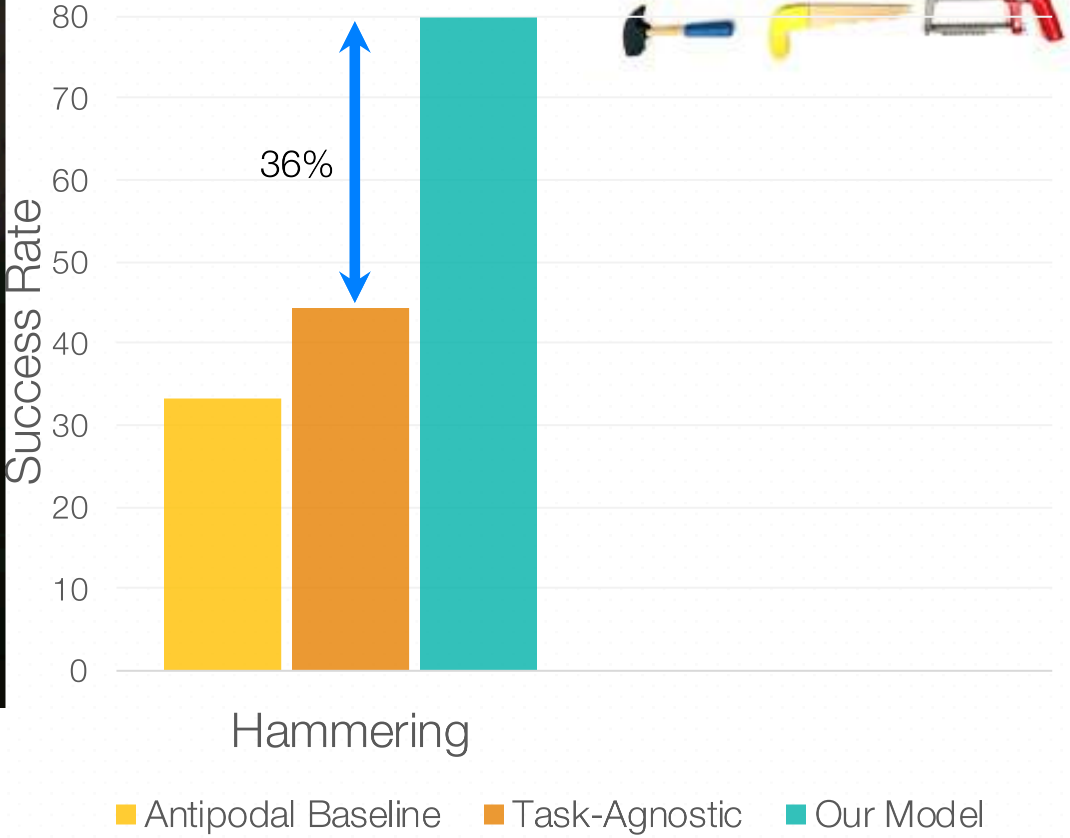


RSS 2018, IJRR 2019

Sequential Skills: Task-Oriented Grasping



Trained Policy Rollout (Ours)
Unseen Test Objects

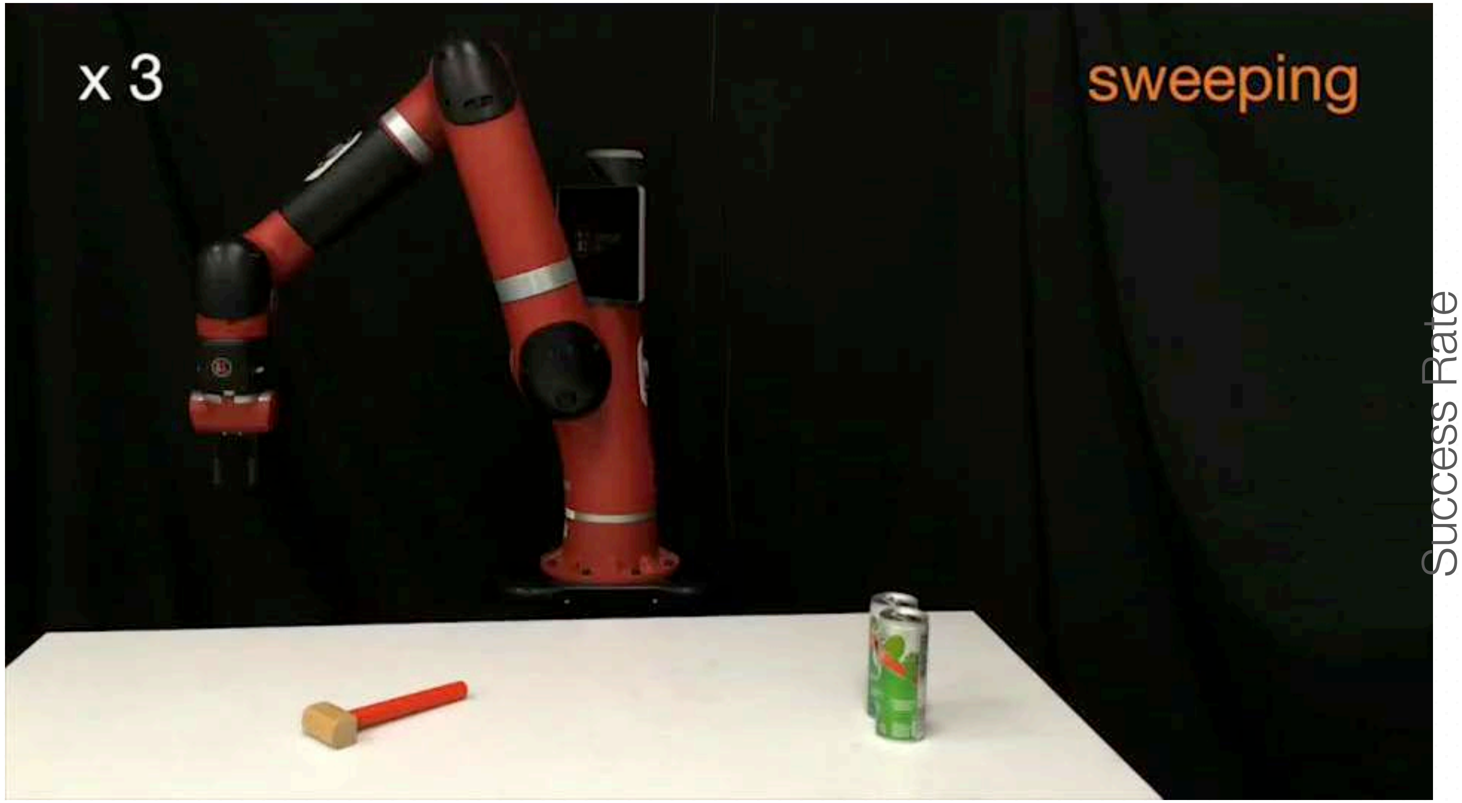


Two-Stage Optimization

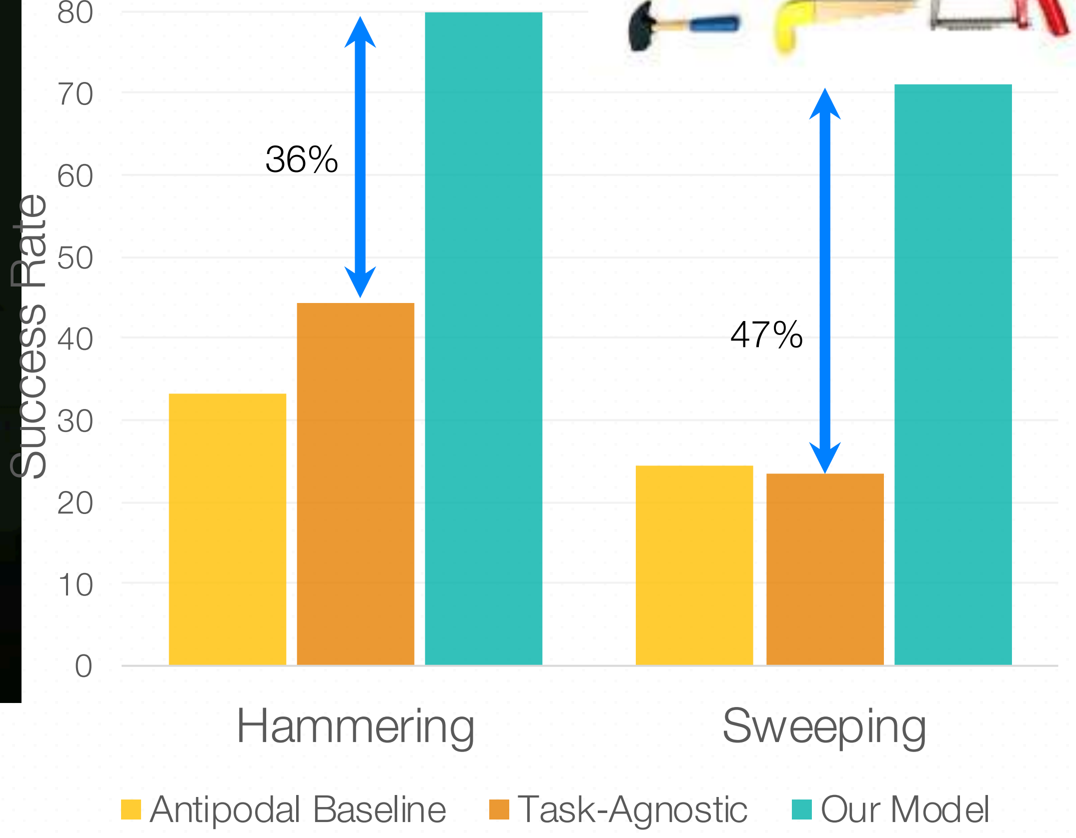
Joint Optimization

RSS 2018, IJRR 2019

Sequential Skills: Task-Oriented Grasping



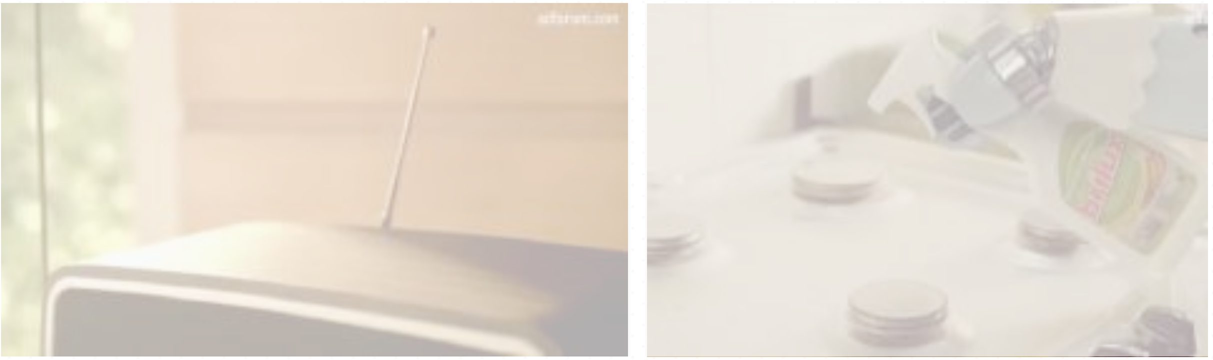
Trained Policy Rollout (Ours)
Unseen Test Objects



Two-Stage Optimization | Joint Optimization

RSS 2018, IJRR 2019

Sequential Skills



Skills: Surface Wiping

Skills: Tool Use

Primitive Skills

Grasping

Pushing

Picking

Wiping

Open door

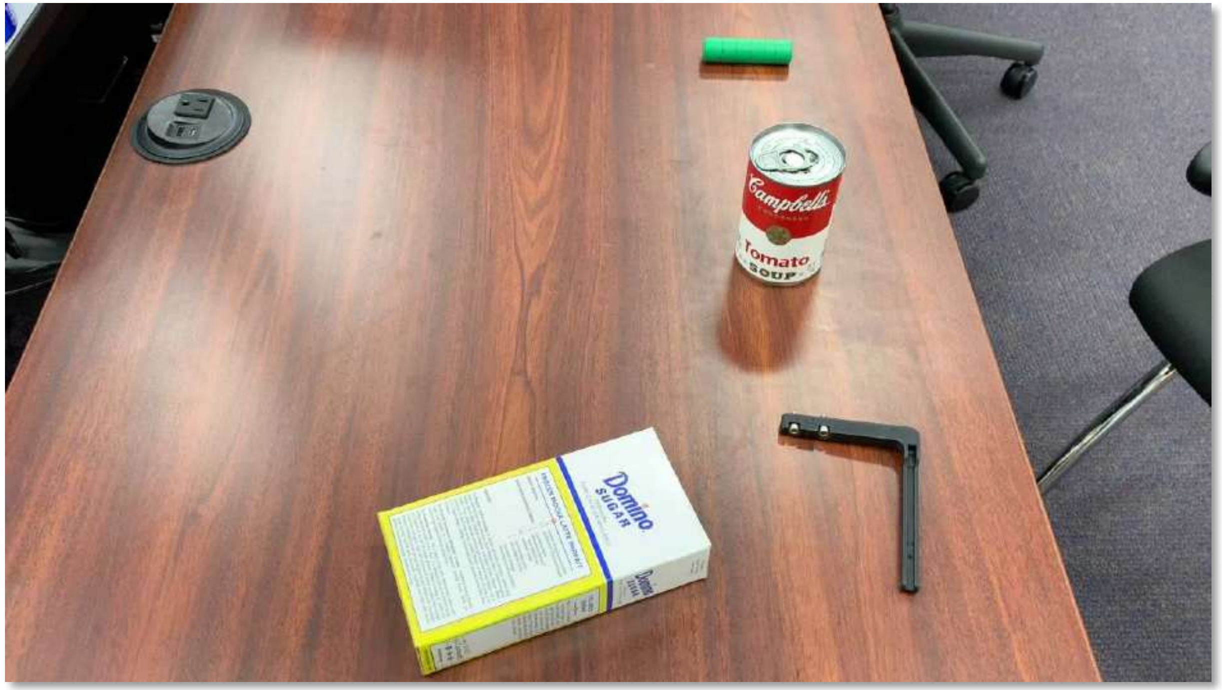
Sequential Skills

Hammering (with unknown objects)

Cutting (with new knife)

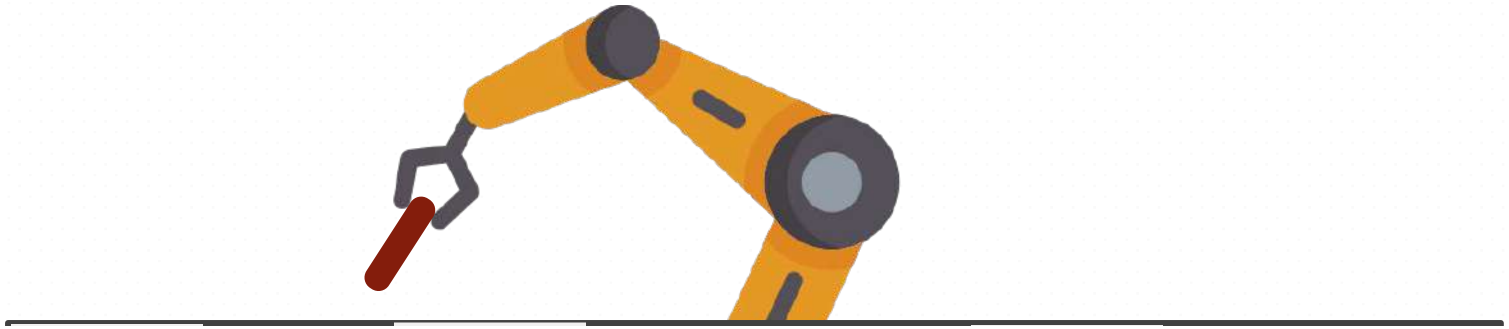
Sweeping (with new broom)

Sequential Skills: Multi-Step Reasoning

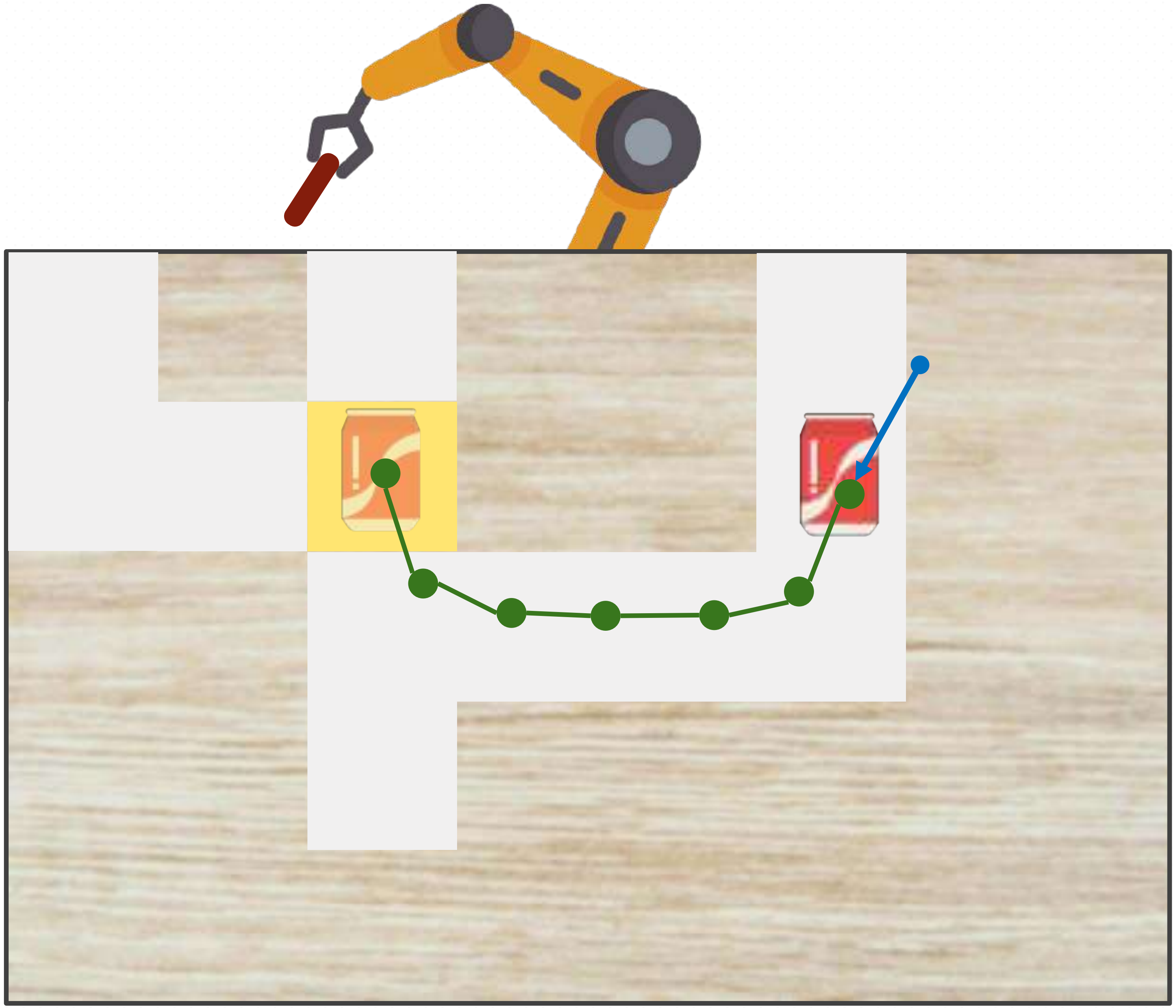


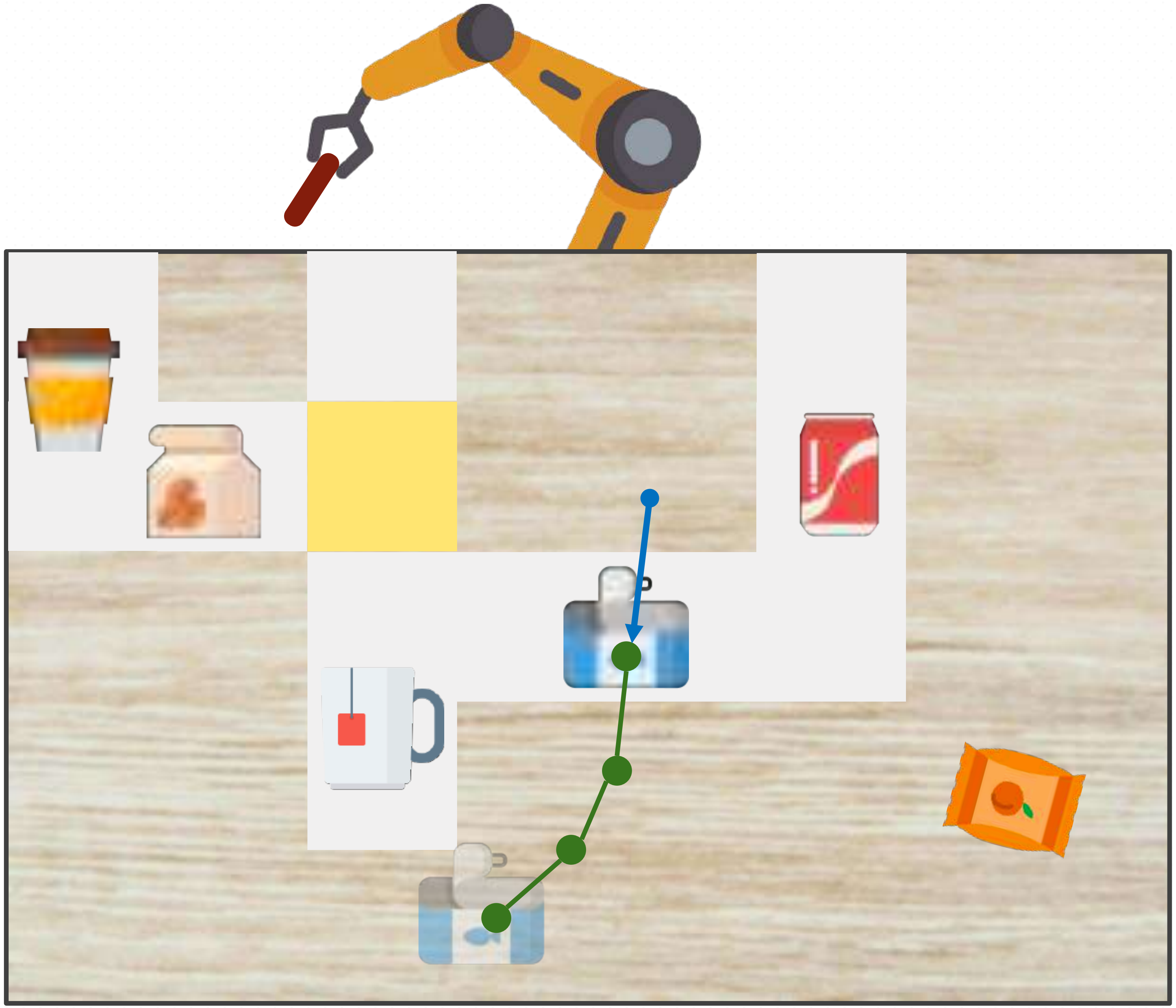
Skills: Multi-Step Reasoning

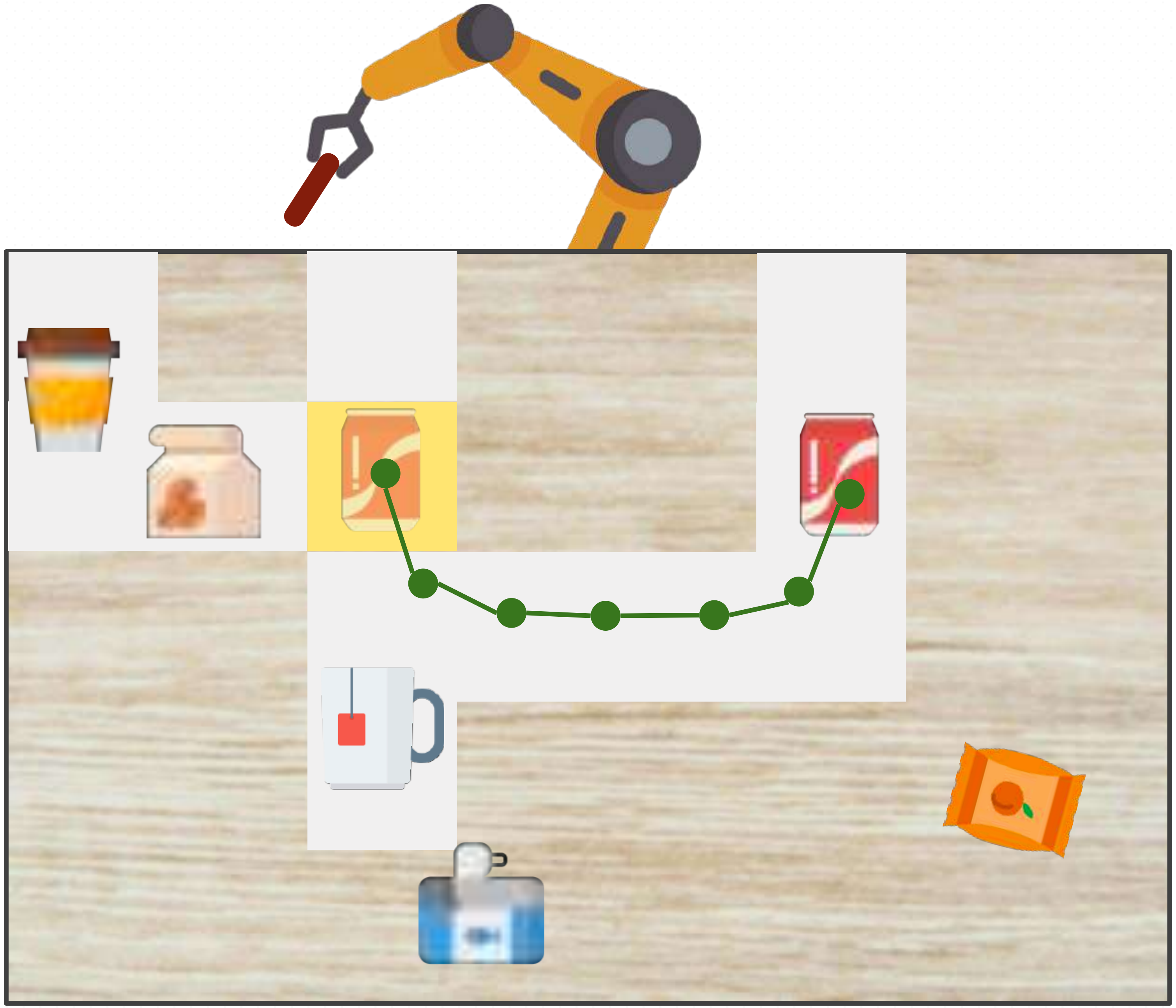
Generalization



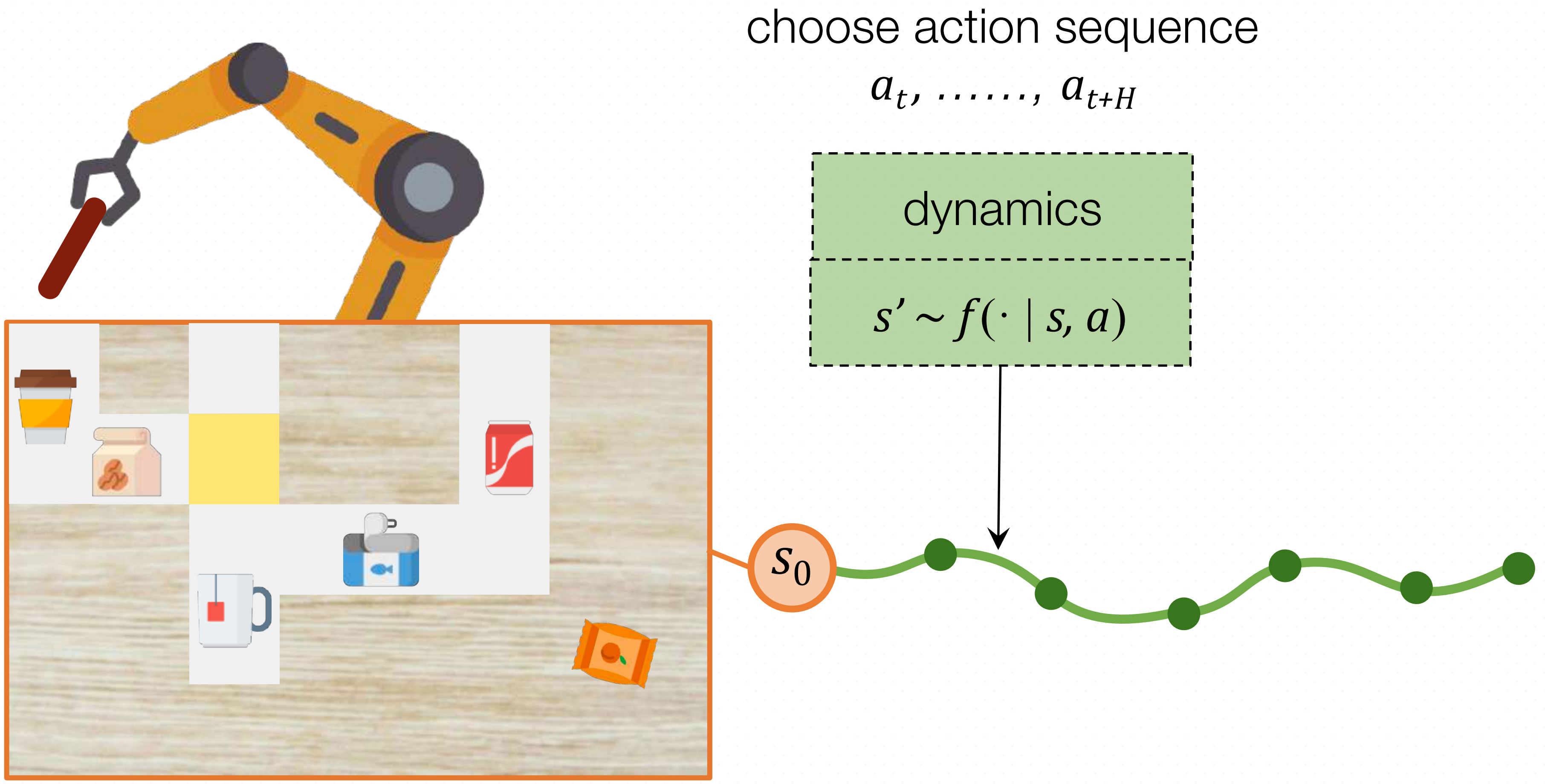
Can we learn multi-step reasoning in robotics under physical and semantic constraints







Model-based learning



[Deisenroth et al, RSS'07], [Guo et al, NeurIPS'14], [Watter et al, NeurIPS'15], [Finn et al, ICRA'17], ……

Model-based learning

?

data ↑
learning ↑

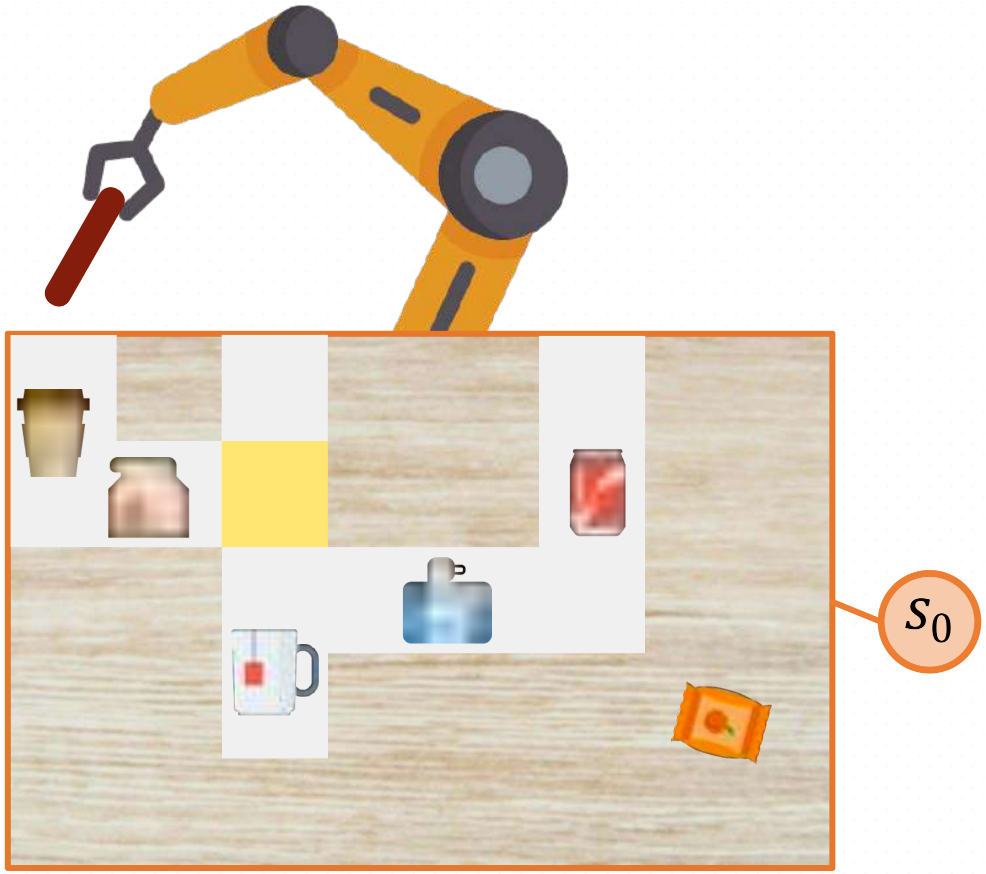
[Deisenroth et al. RSS'07]

[Agrawal et al. ICRA'16]

[Ebert et al. CoRL'17]

[Janer et al. ICRA'19]

CAVIN: Hierarchical planning in learned latent spaces



CAVIN Planner

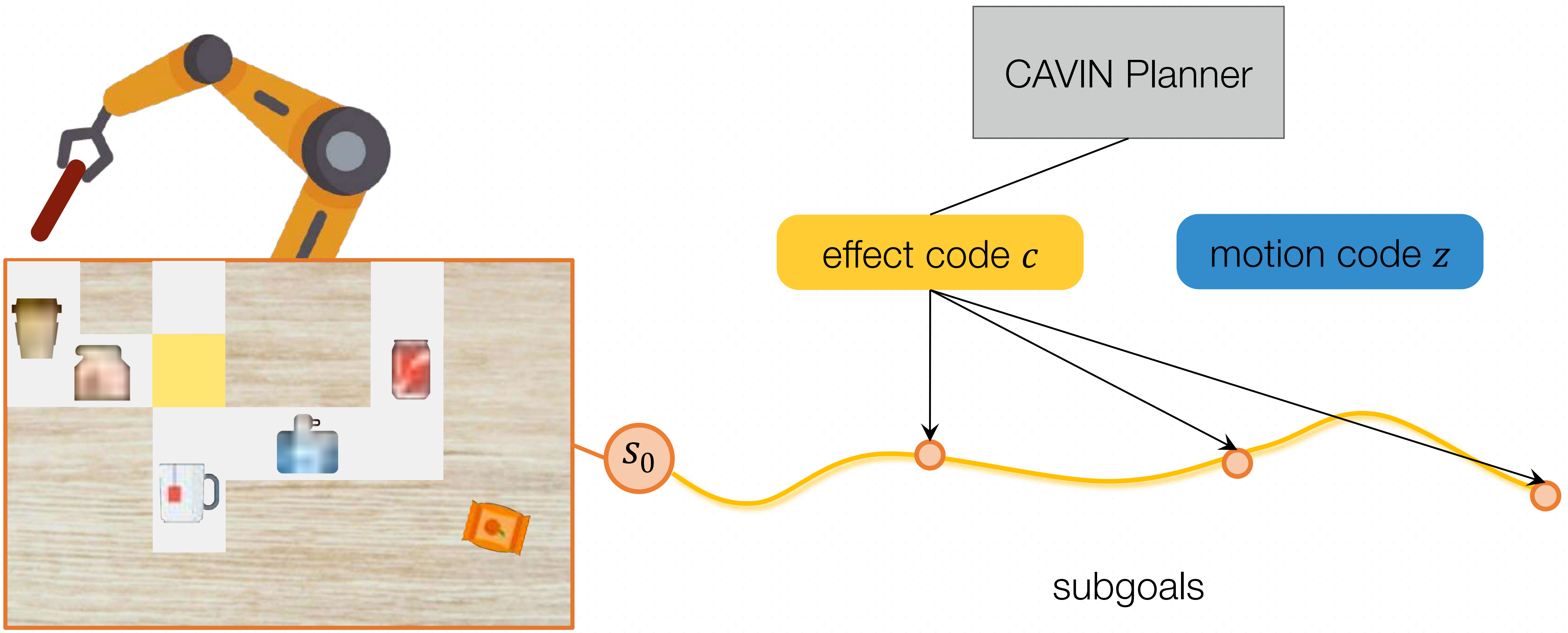
effect code c

motion code z

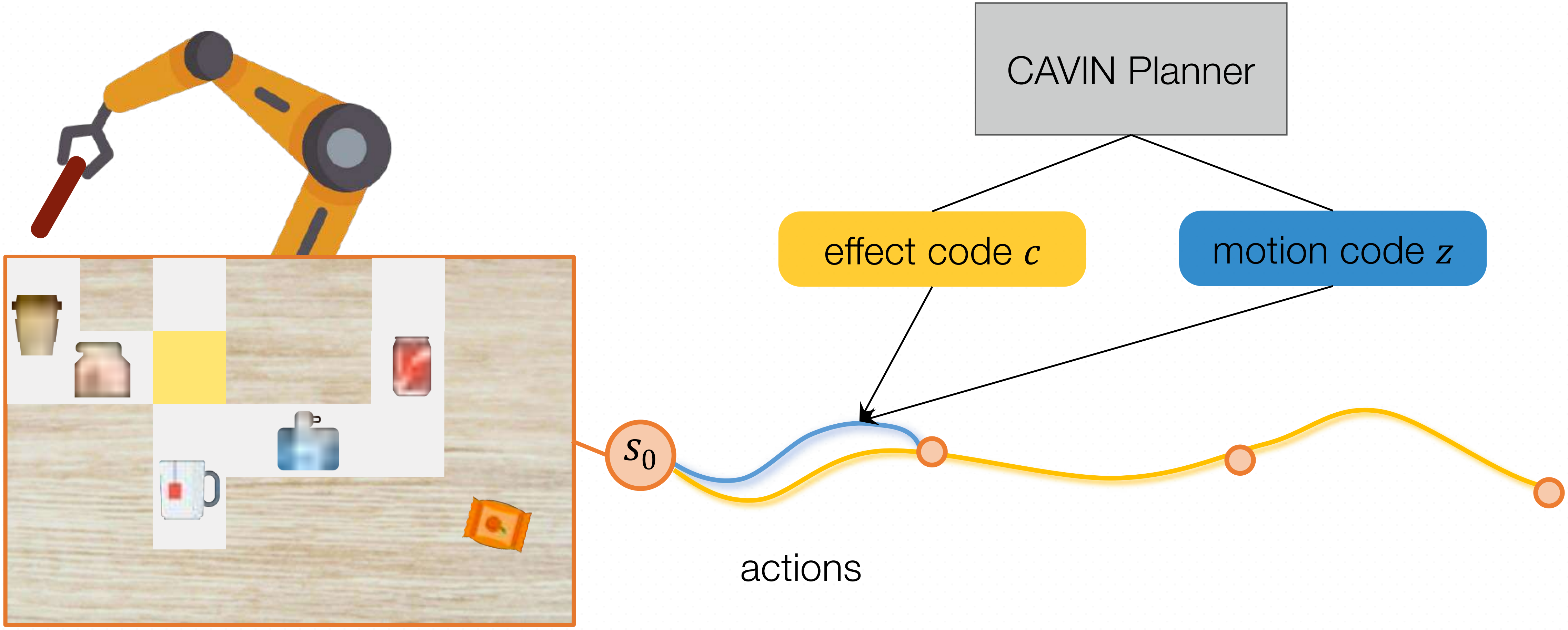
Leverage Hierarchical Abstraction in Action Space

Without Hierarchical Supervision

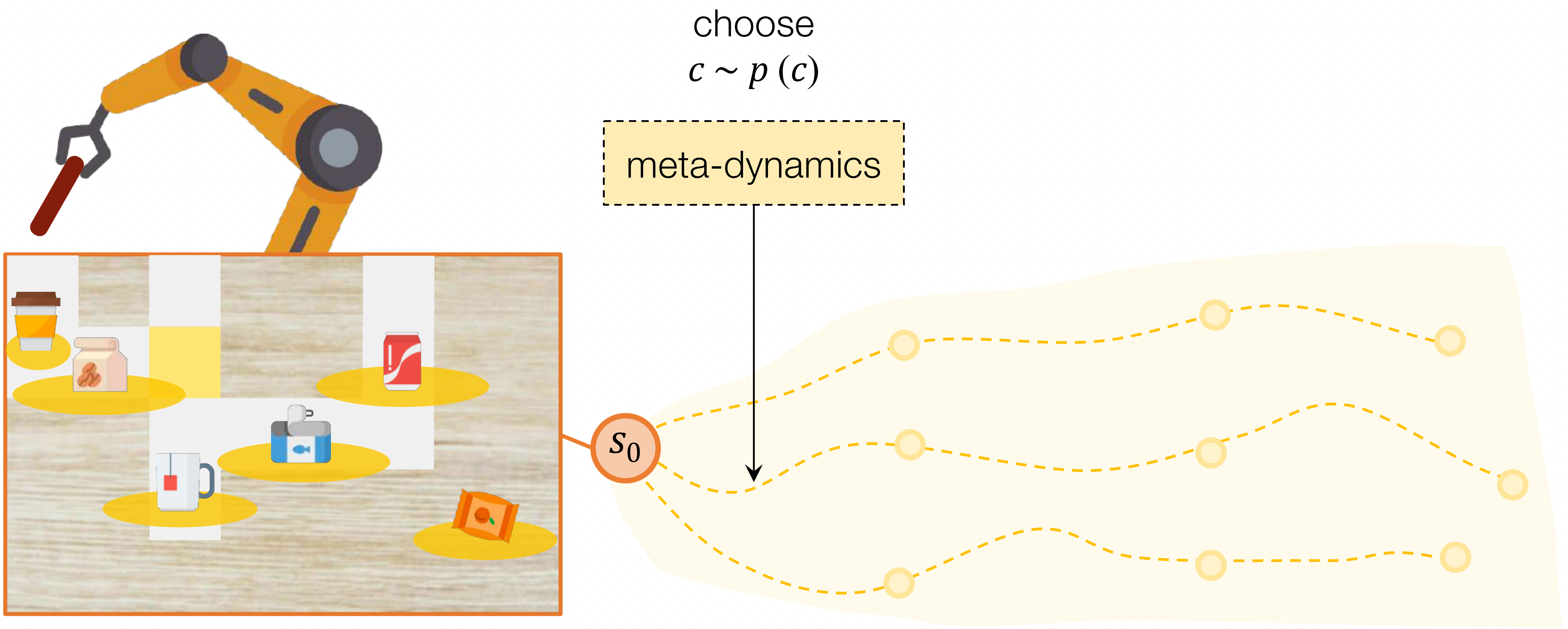
CAVIN: Hierarchical planning in learned latent spaces



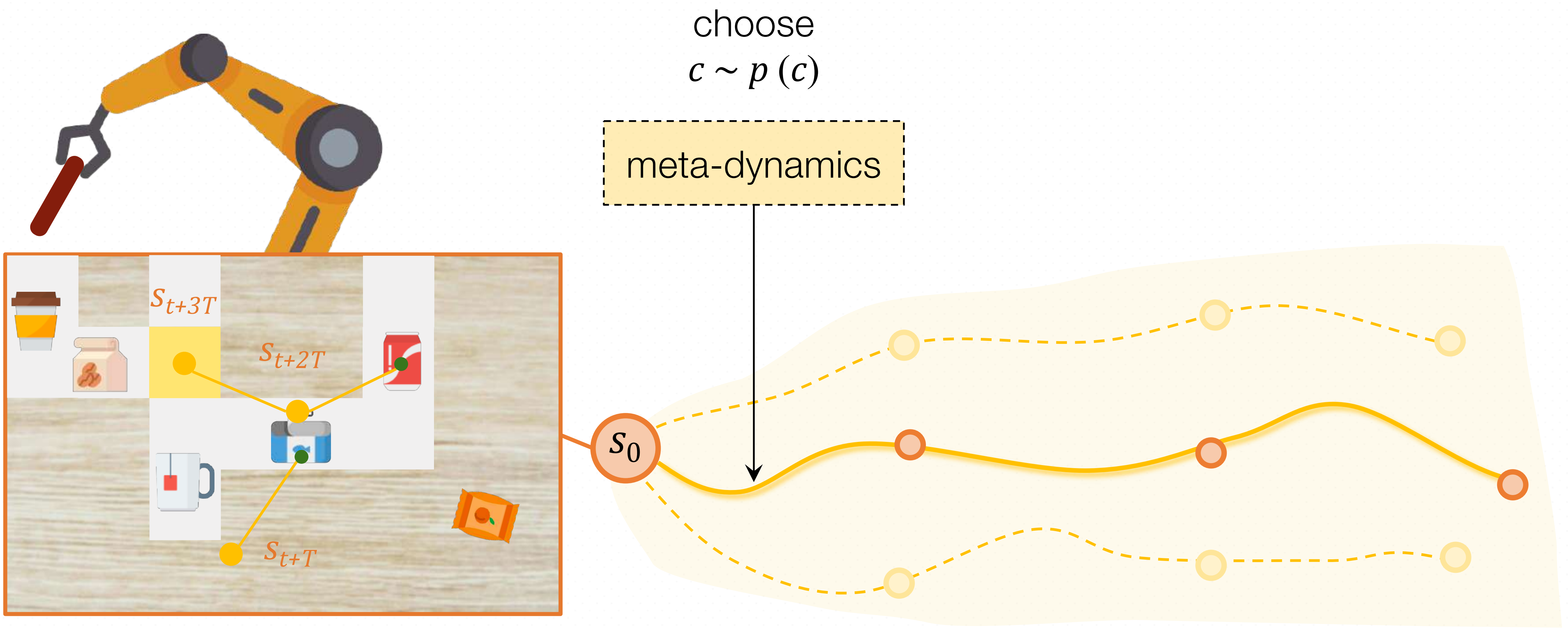
CAVIN: Hierarchical planning in learned latent spaces



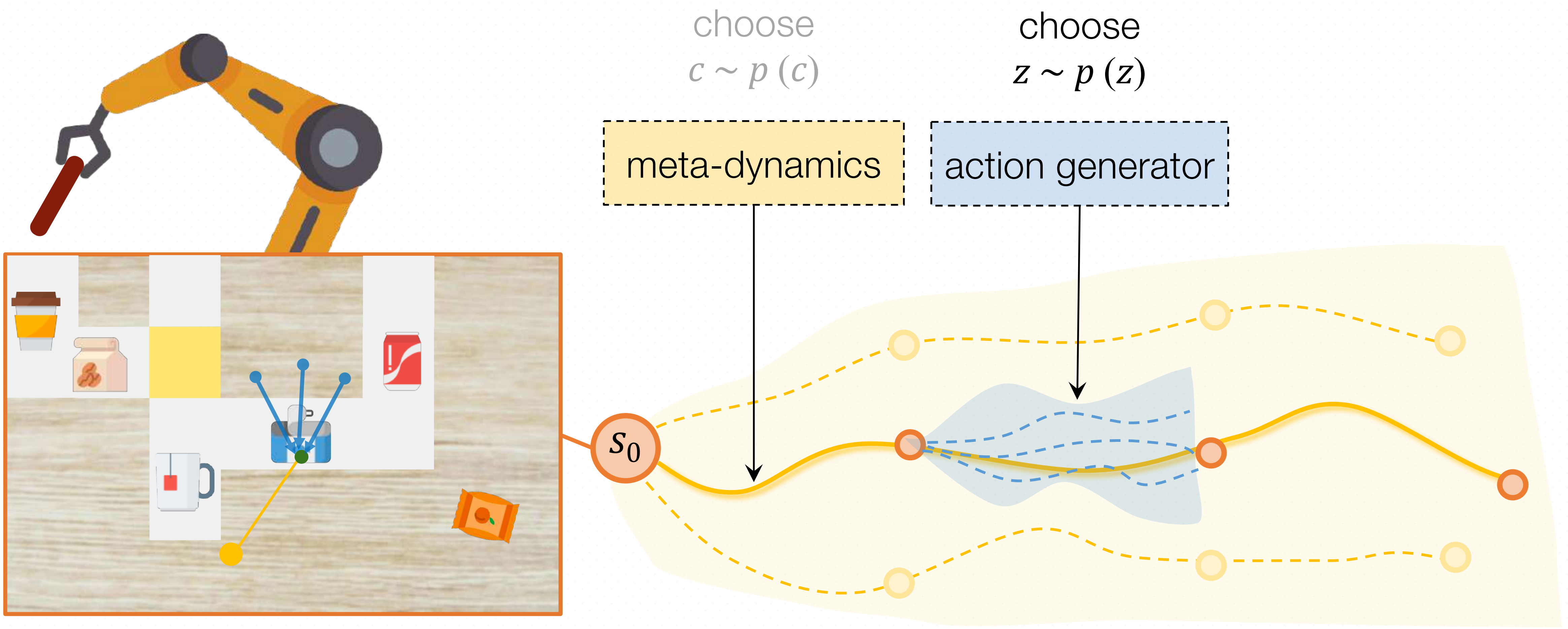
CAVIN: Hierarchical planning in learned latent spaces



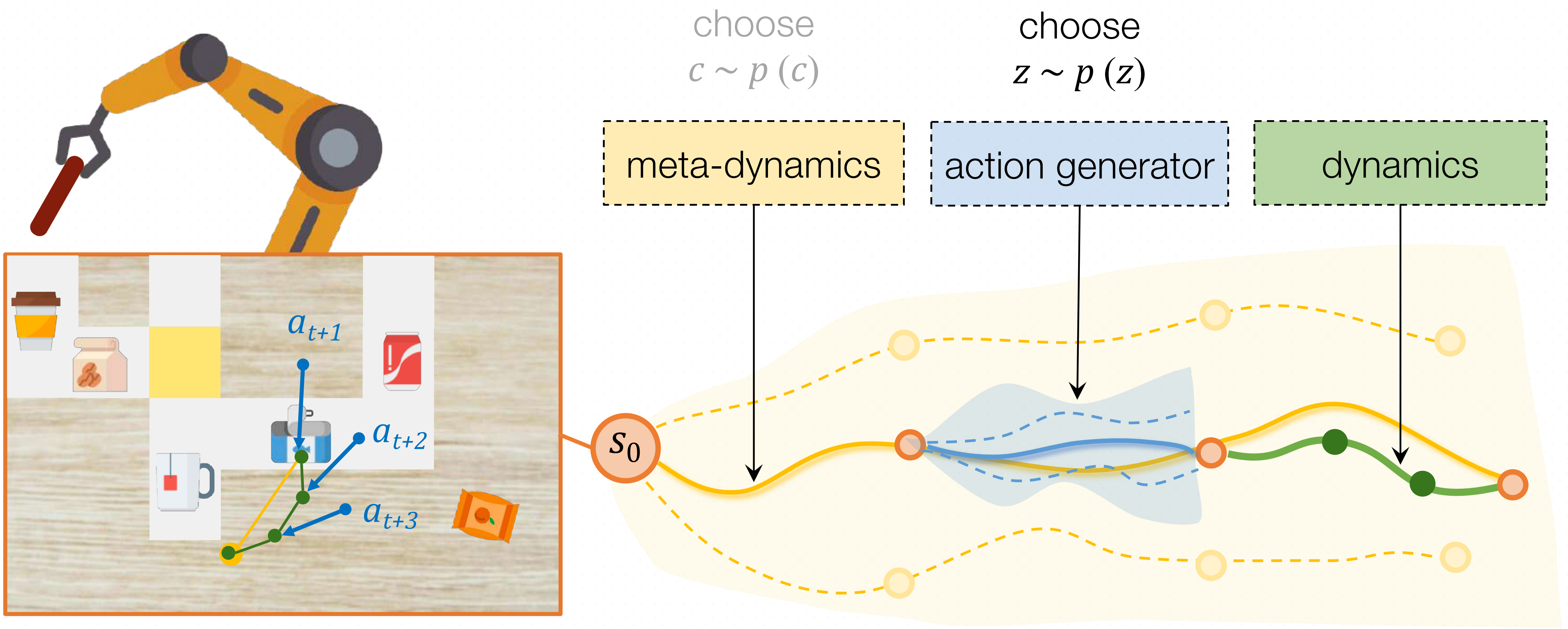
CAVIN: Hierarchical planning in learned latent spaces



Hierarchical planning in learned latent spaces

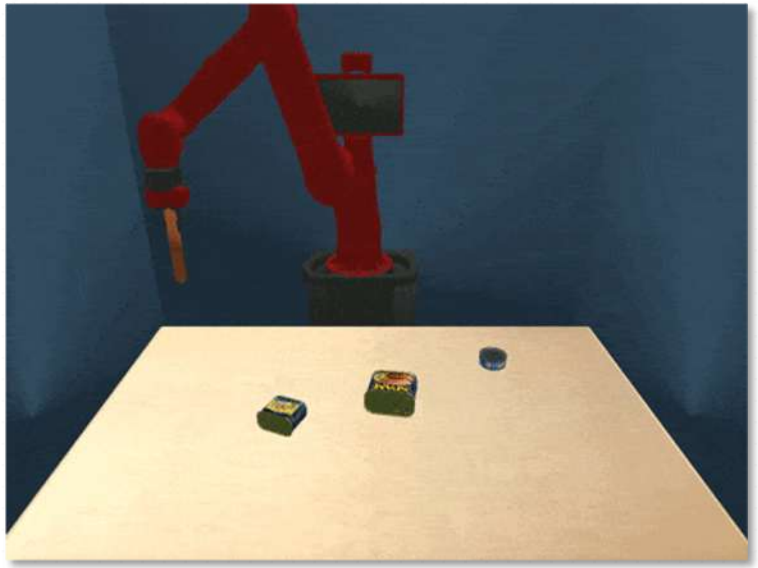


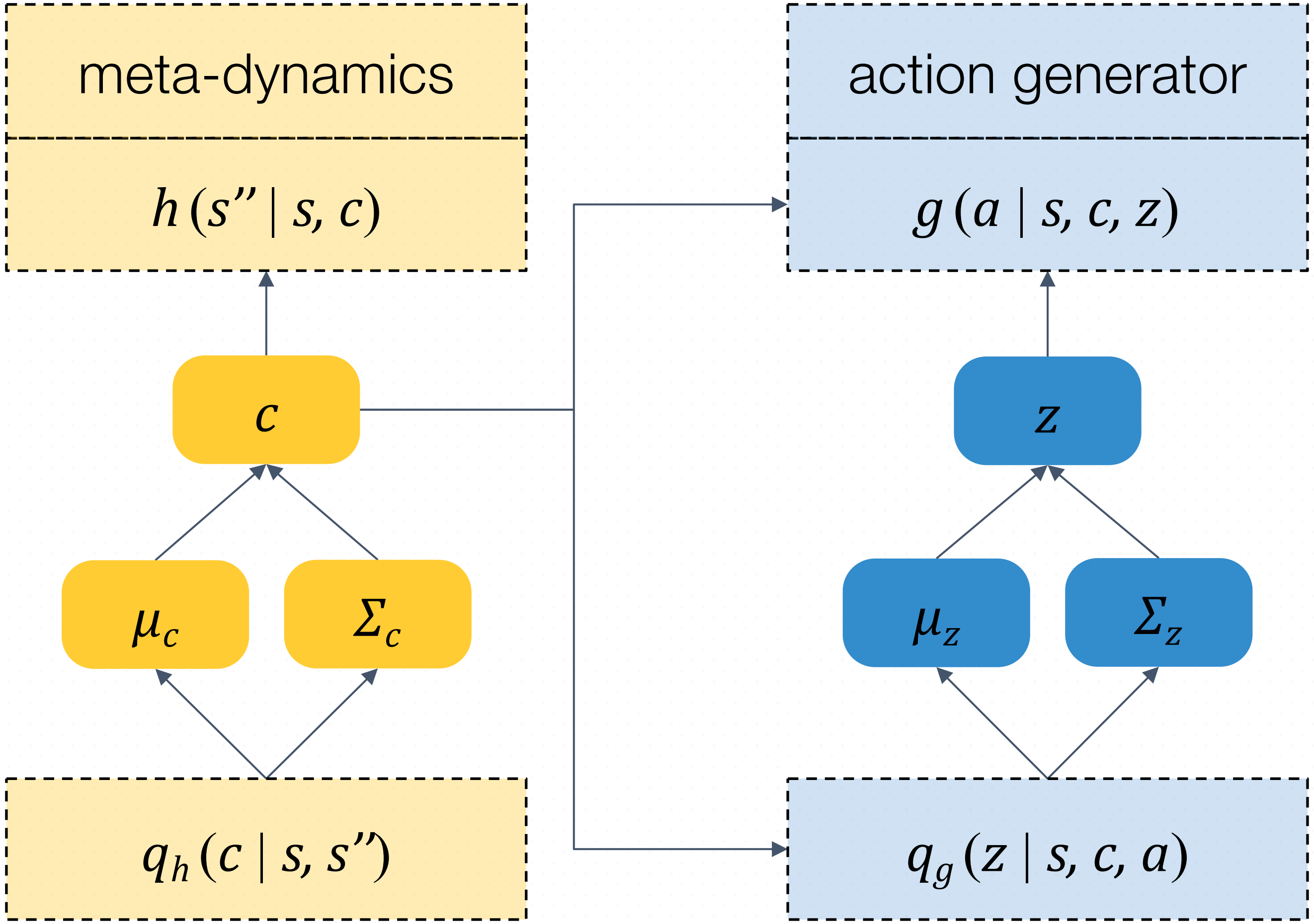
CAVIN: Hierarchical planning in learned latent spaces

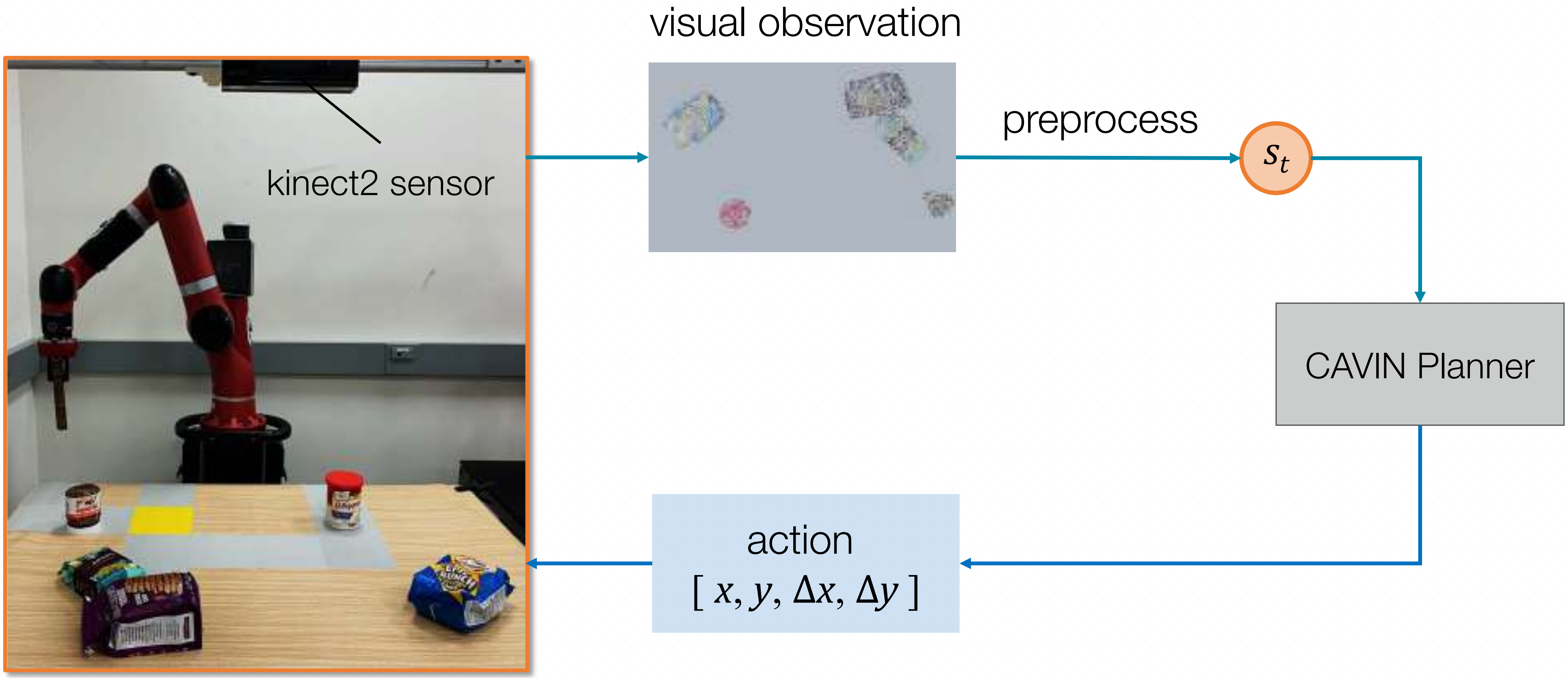


Learning with cascaded variational inference

task-agnostic interaction





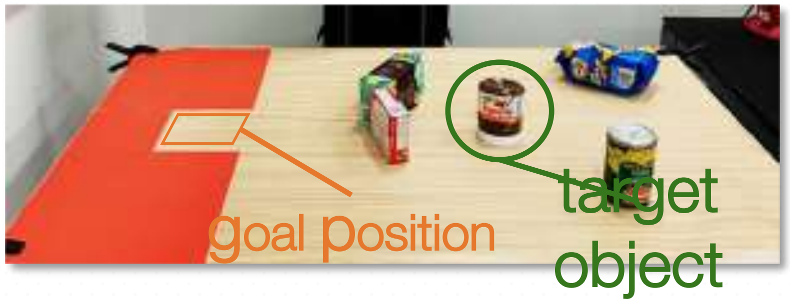

visual observation
kinect2 sensor
preprocess
s_t
CAVIN Planner
action
$[\ x, y, \Delta x, \Delta y\ ]$

Tasks

clearing

Clear all objects within the area of blue tiles.

insertion



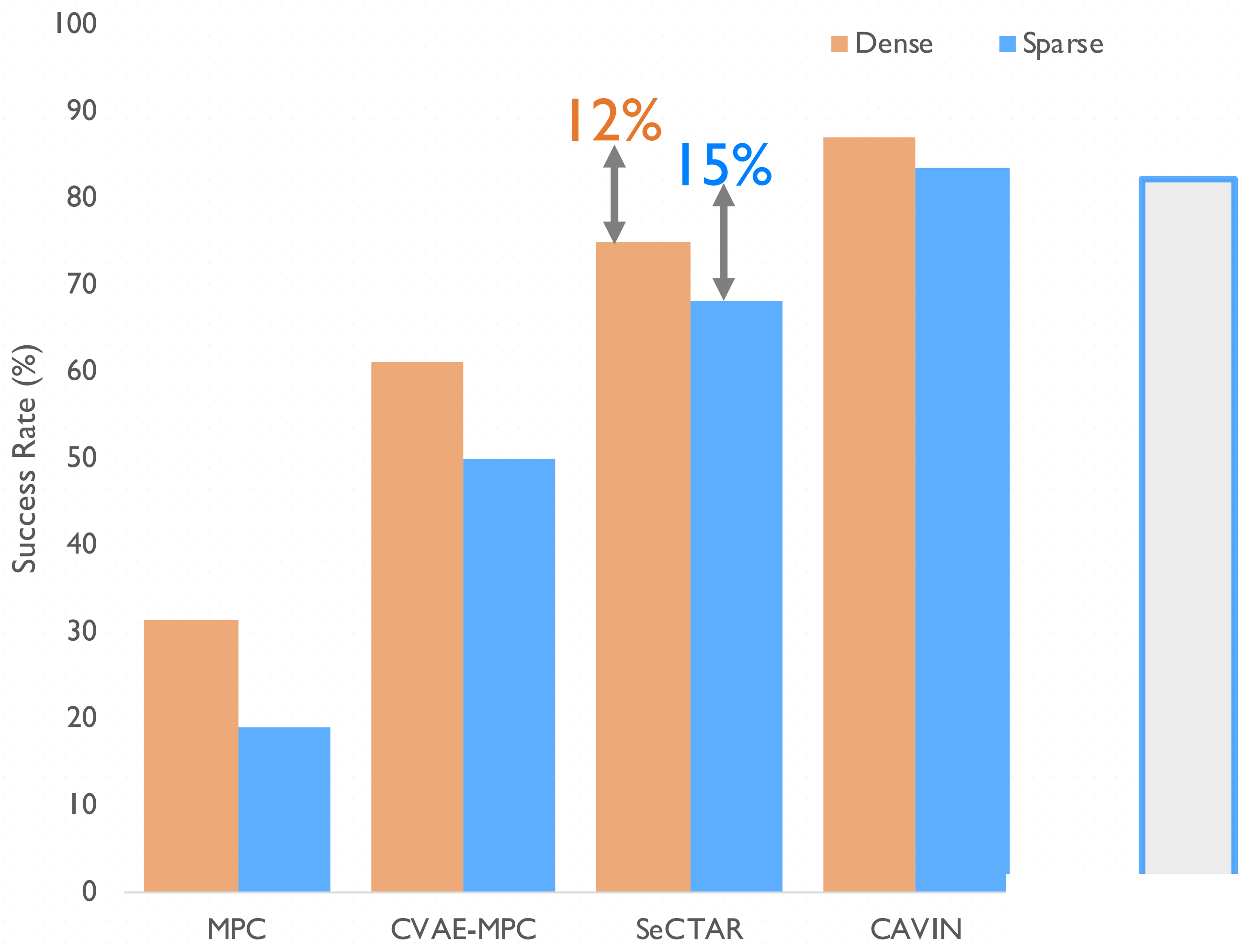
Move the target to the goal without traversing red tiles.

crossing

Move the target to the goal across grey tiles


Real
Simulated

Quantitative Evaluation



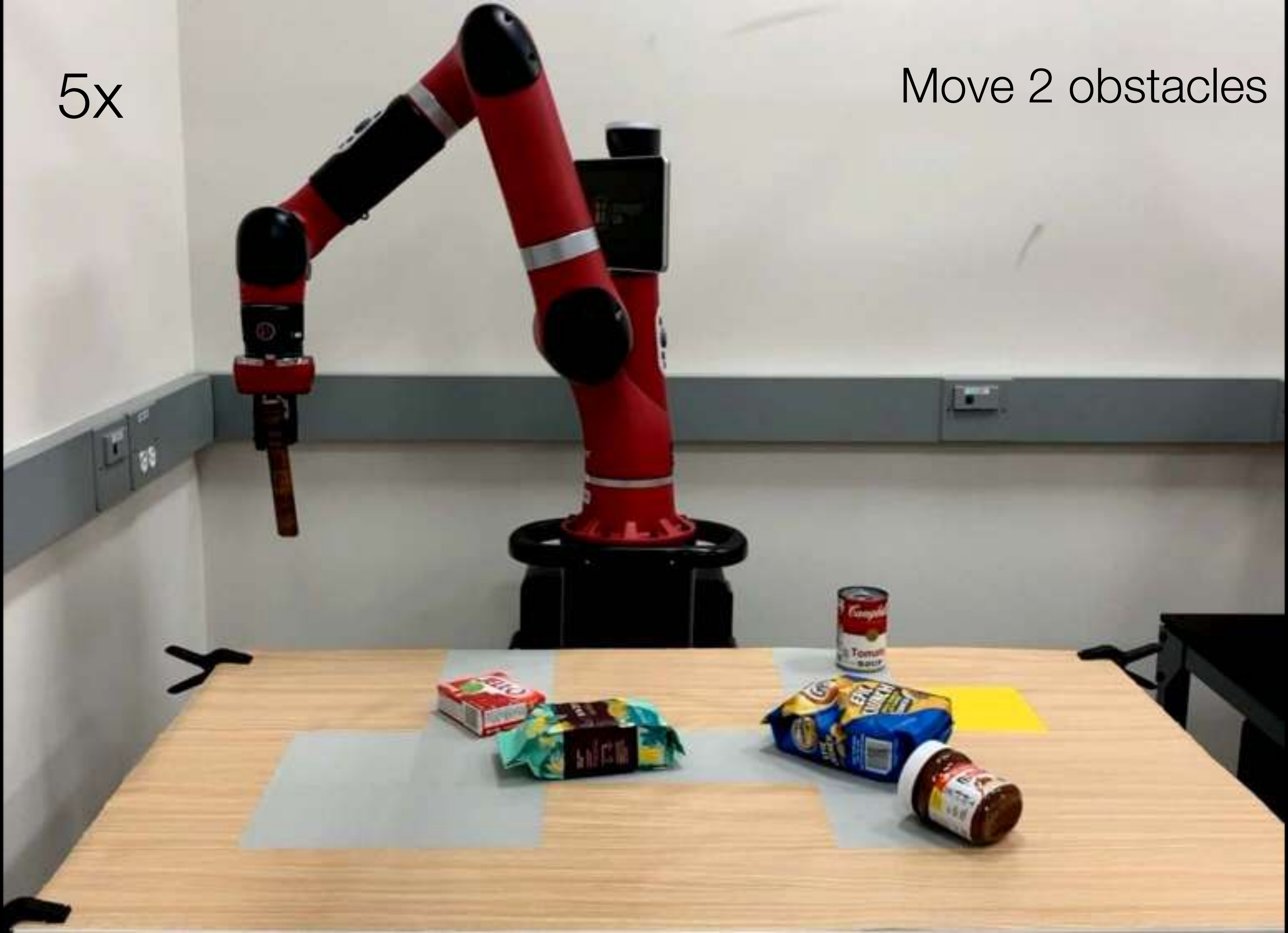
Hierarchical Latent space dyn.

↓

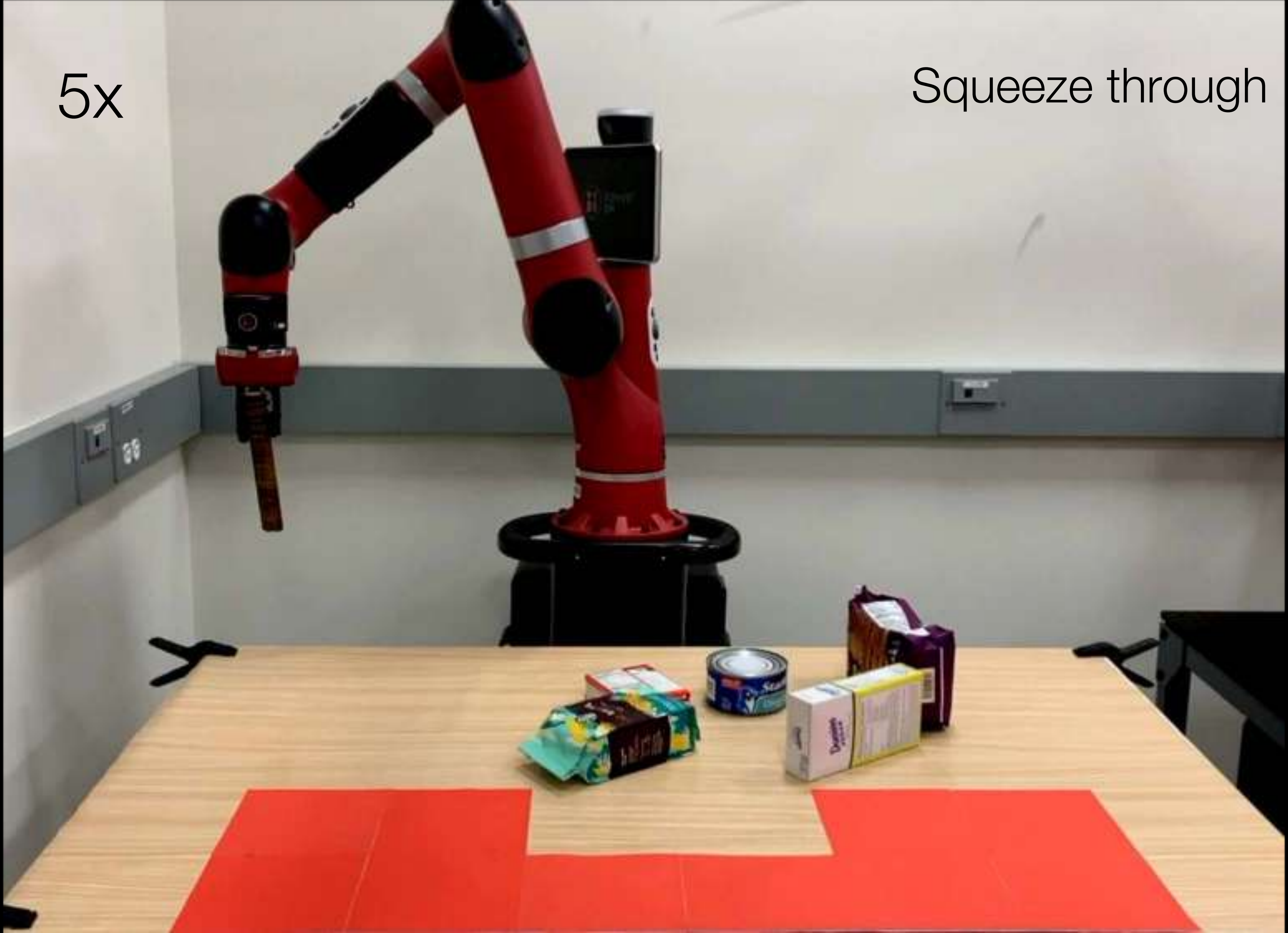
Better performance with sparse reward signal

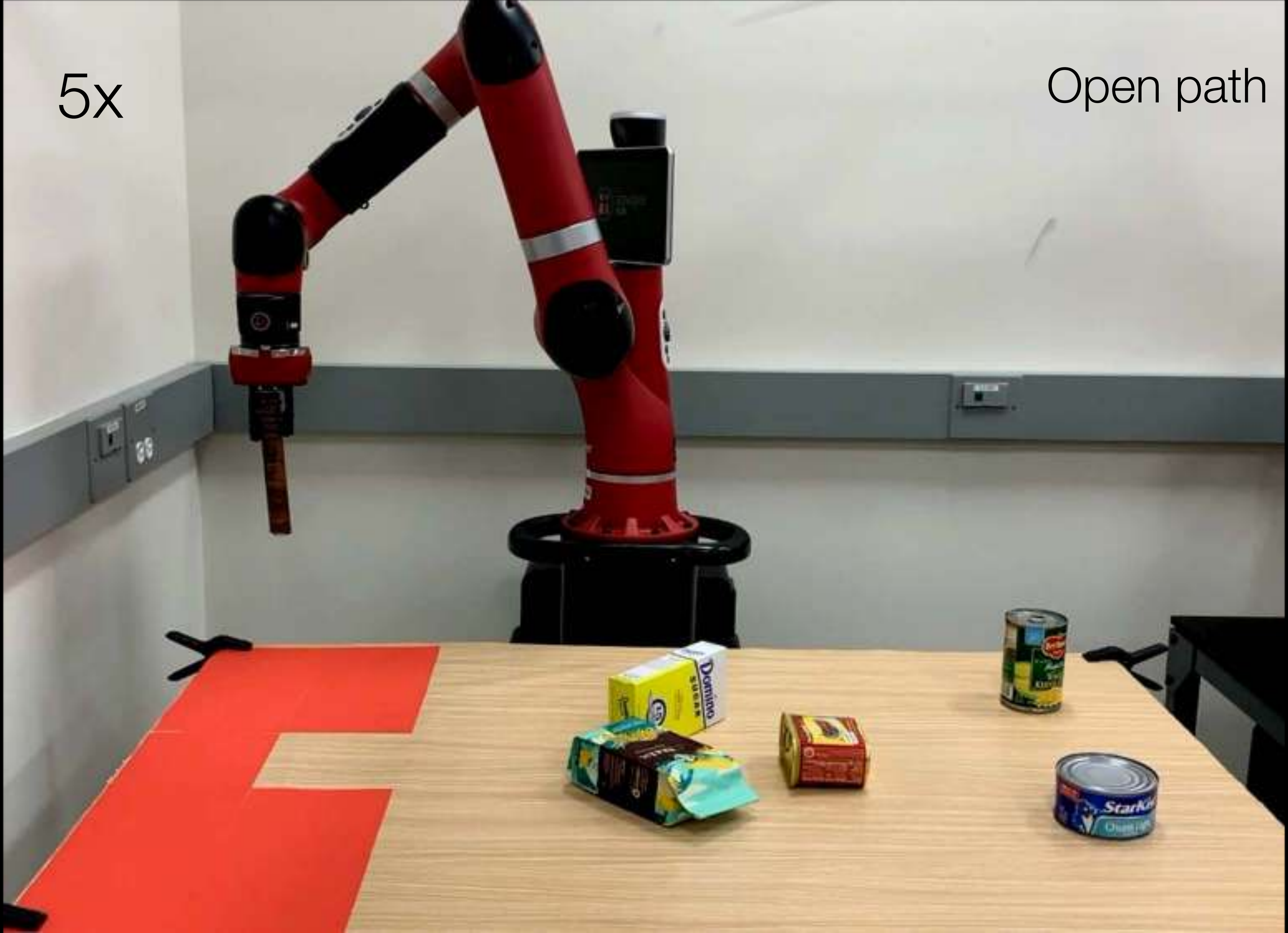
Averaged over 3 Tasks
with 1000 test instances each

MPC (Guo et al. '14, Agrawal et al. '16, Finn et al. 17); CVAE-MPC (Ichter et al. 18), SeCTAR (Co-Reyes et al '18)

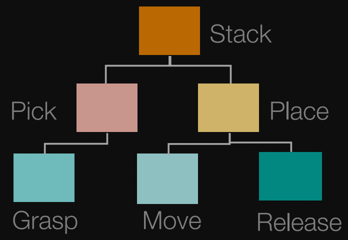

5x
Move 2 obstacles


5x
Get around
nutella


5x
Squeeze through

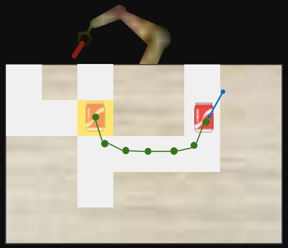

5x
Open path
Domino
SUGAR

Compositional Planning



Object Arrangement

RSS 2018,
IJRR 2019

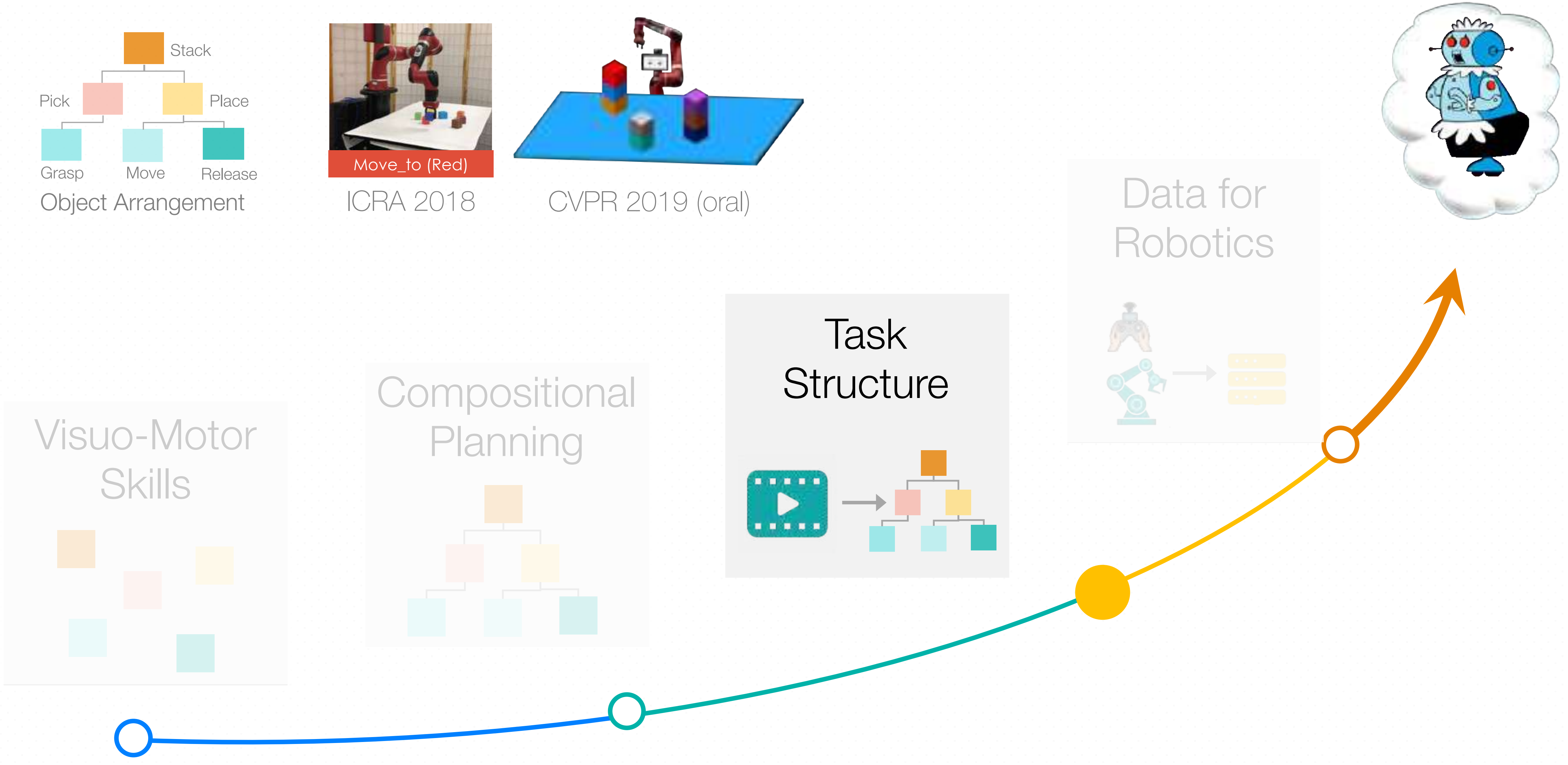


CoRL 2019 (oral)

Self-Supervision and Structured Latent Variable Models

lead to good representations that generalize

Generalizable Autonomy in Robot Manipulation



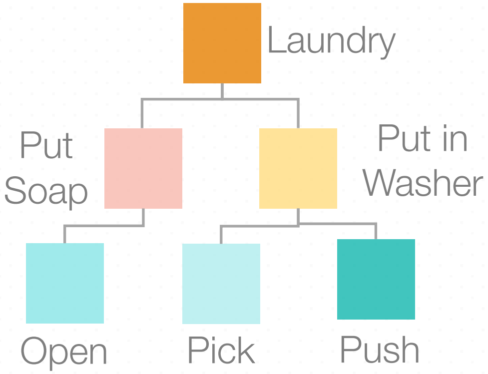
Complex Task Structure

Visuo-Motor Skills

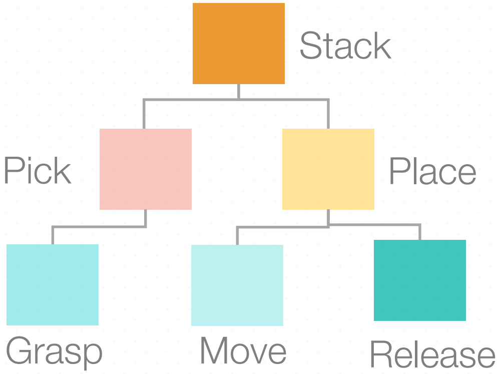
Complex Task Structure

Visuo-Motor Skills

Complex Task Structure

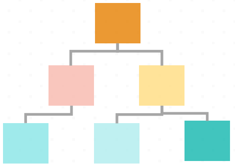


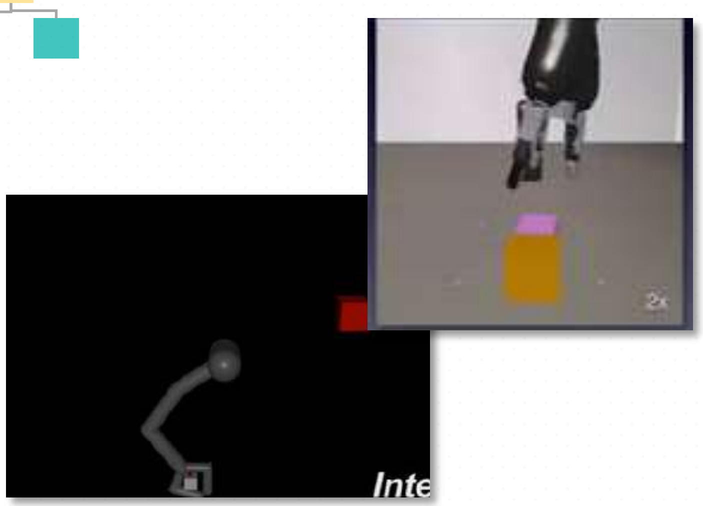
Do Laundry



Object Arrangement

Compositional Planning: Current Paradigm





Reinforcement Learning

- Sample Inefficient
- Multi-step Structured Tasks
- Needs non-trivial Reward Shaping

Imitation Learning

- Task Segmentation is non-trivial
- Multi-modality of Search Space
- Fixed Permutation of Primitives

Desired

Train ≠ Test

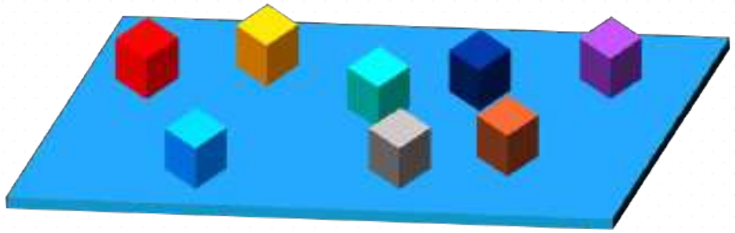
Meta Imitation Learning

- New Task Structures
- Few-Shot performance
- Input State as Video

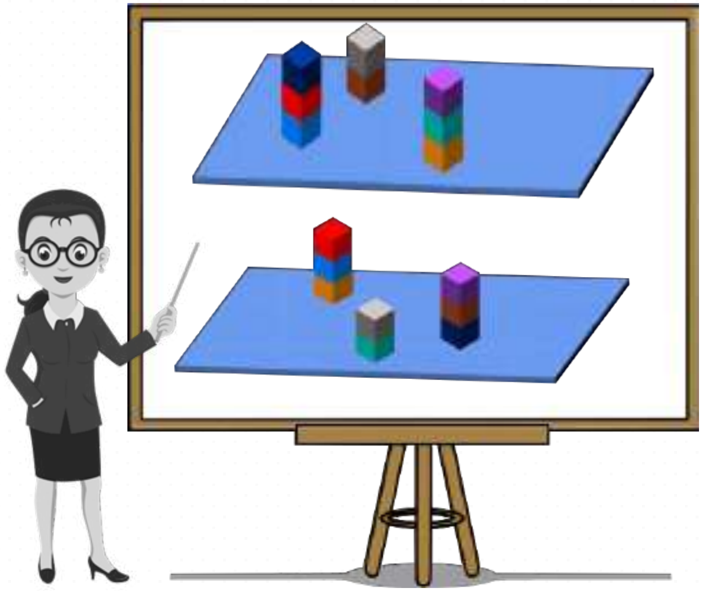
RL: [Schaal 1997], [Chebotar et al., '17], [Yahya et al., '16], [James et al., '17], [Popov et al., '17], [Zhu et al. 18], [Hausman et al. 18]
Imitation: [Calinon et al 2008], [Argall et al 2009], [Kober, Peters, et al. 09], [Pastor et al, 09], [Schulman et al. 2013], [Kroemer et al, 15], [Garg et al 2017]

Compositional Planning: Challenge

Task Domain

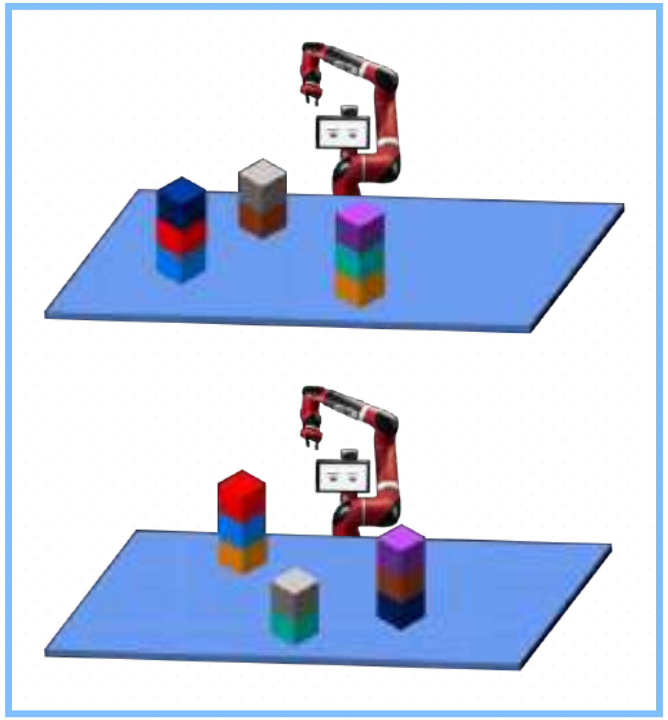


Instructional Demos



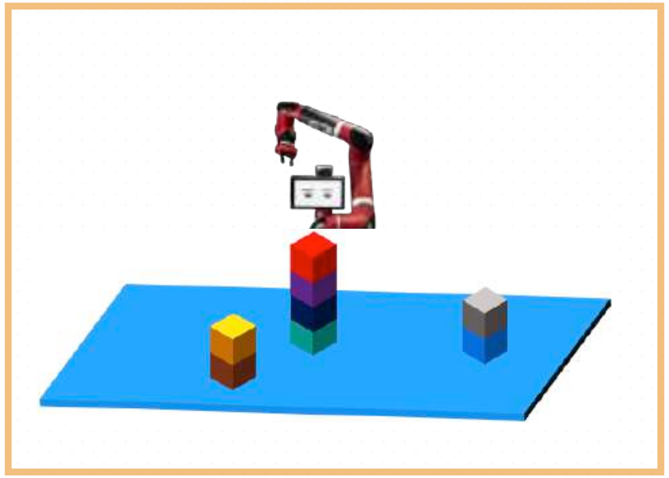
I. Learn Multiple Tasks in the Same Domain

Training Tasks

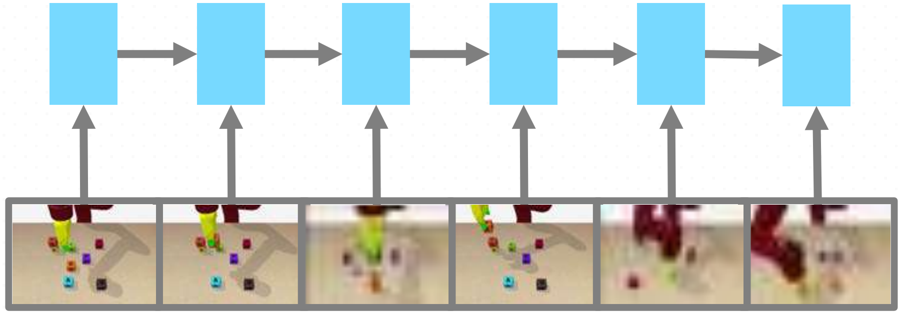


II. Generalize to New Tasks with a Single Demo

Test Task

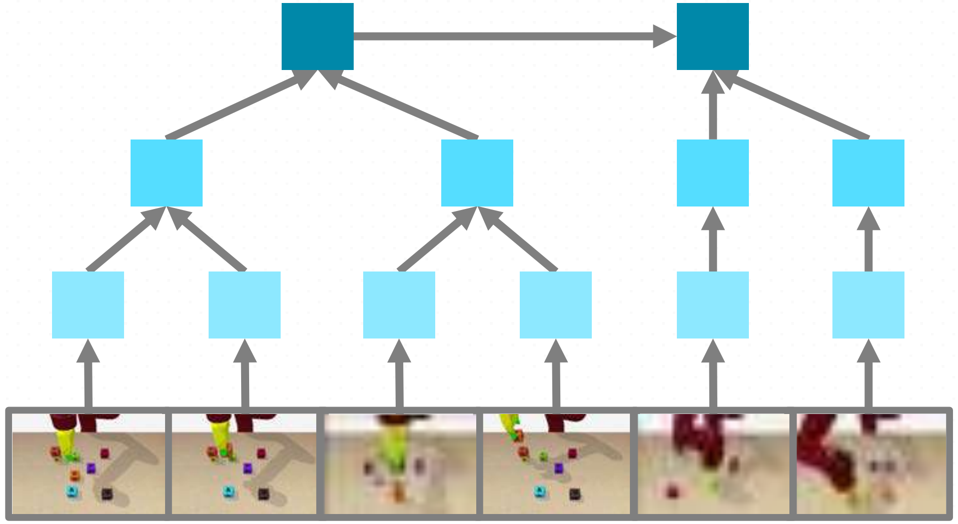


Compositional Planning



[Duan et al. 17; Finn et al. 2017;
Wang et al. 2017; Yu et al. 2018]

Models input demonstration
as a flat sequence



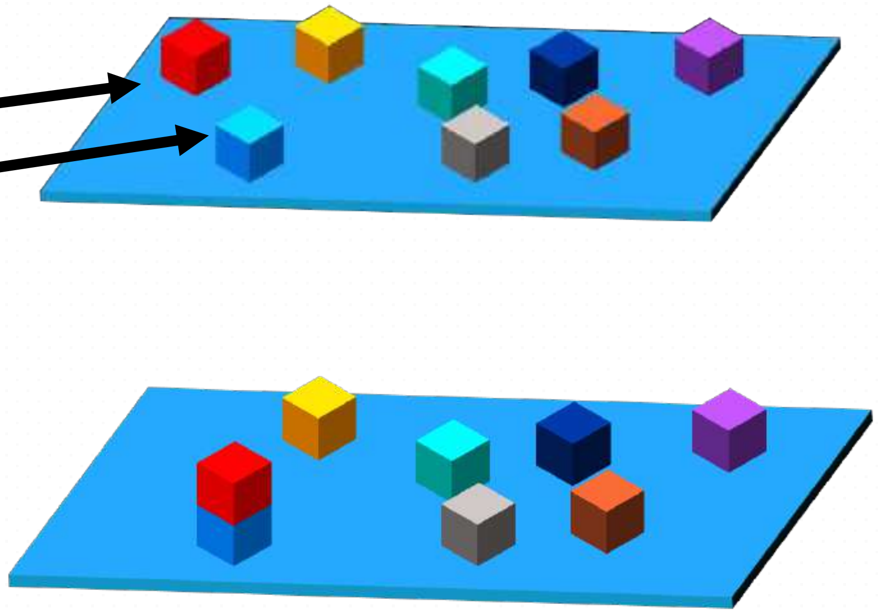
Our Method
[ICRA'18], [CVPR'19], [IROS'19]

Models input demonstration
as a Compositional Hierarchy

One Shot Imitation Learning from Videos

Compositional Planning: Task Programming

```
Block Stacking (...):
  while (done):
    pick_and_place (RED, BLUE):
      pick (RED):
        move_to (RED)
        Grasp (RED)
      <end> Pop
      place(BLUE):
        move_to (BLUE)
        Release (RED)
      <end> Pop
    <end> Pop
```



Task 1
Sub-task 1
Move Red-block on top of Blue

[ICRA'18, CVPR '19]

Compositional Planning: Task Programming

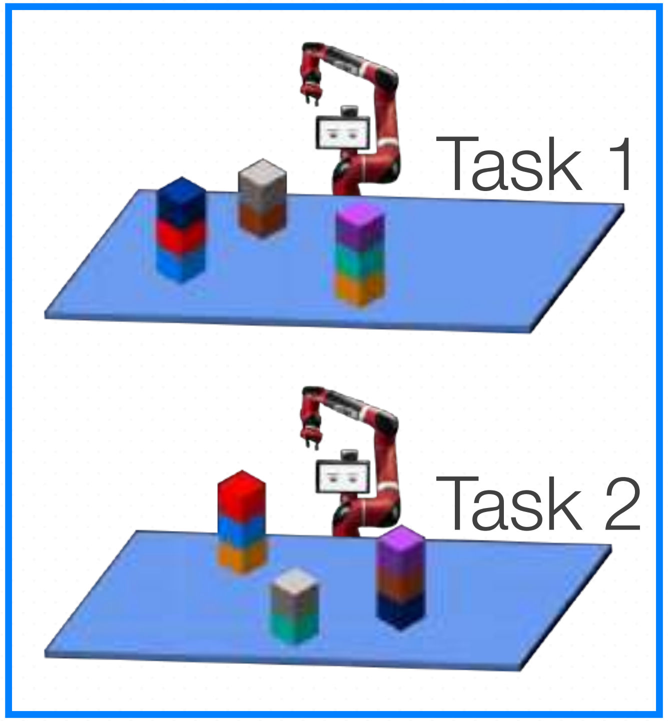
Program 1

```
Block Stacking (...):
```

Program 2

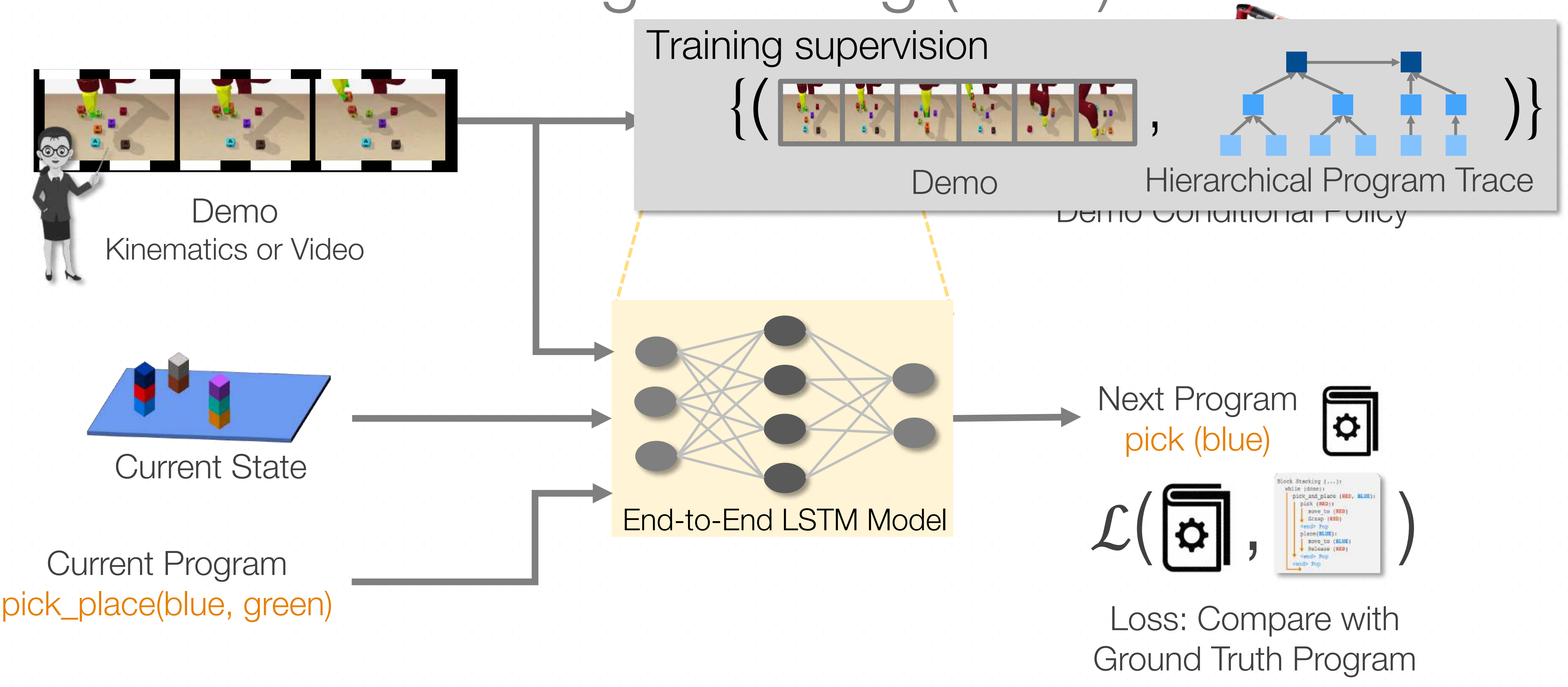
```
Block Stacking (...):
  while (done):
    pick_and_place (RED, BLUE):
      pick (RED):
        move_to (RED)
        Grasp (RED)
      <end> Pop
      place(BLUE):
        move_to (BLUE)
        Release (RED)
      <end> Pop
    <end> Pop
```

Training Task Structures



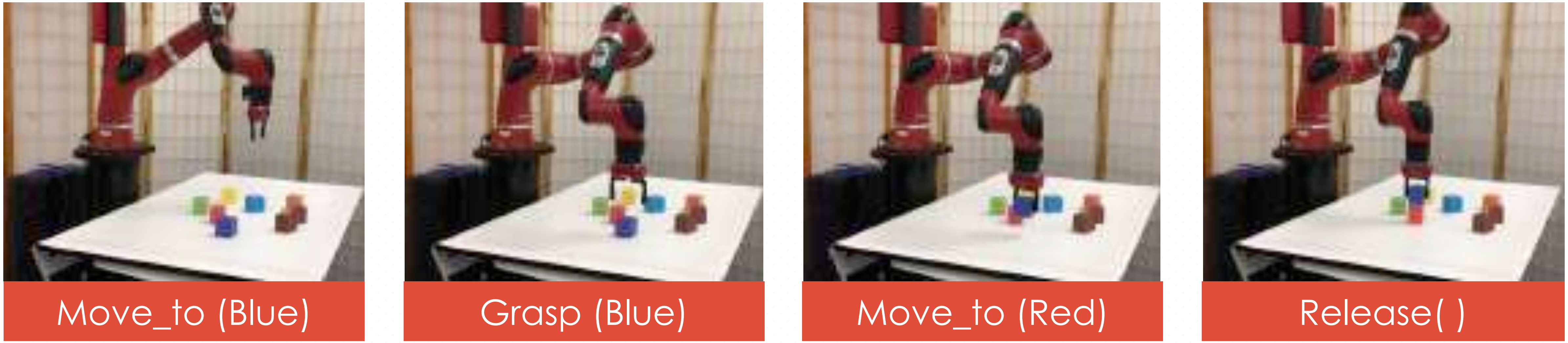
[ICRA'18, CVPR '19]

Neural Task Programming (NTP)

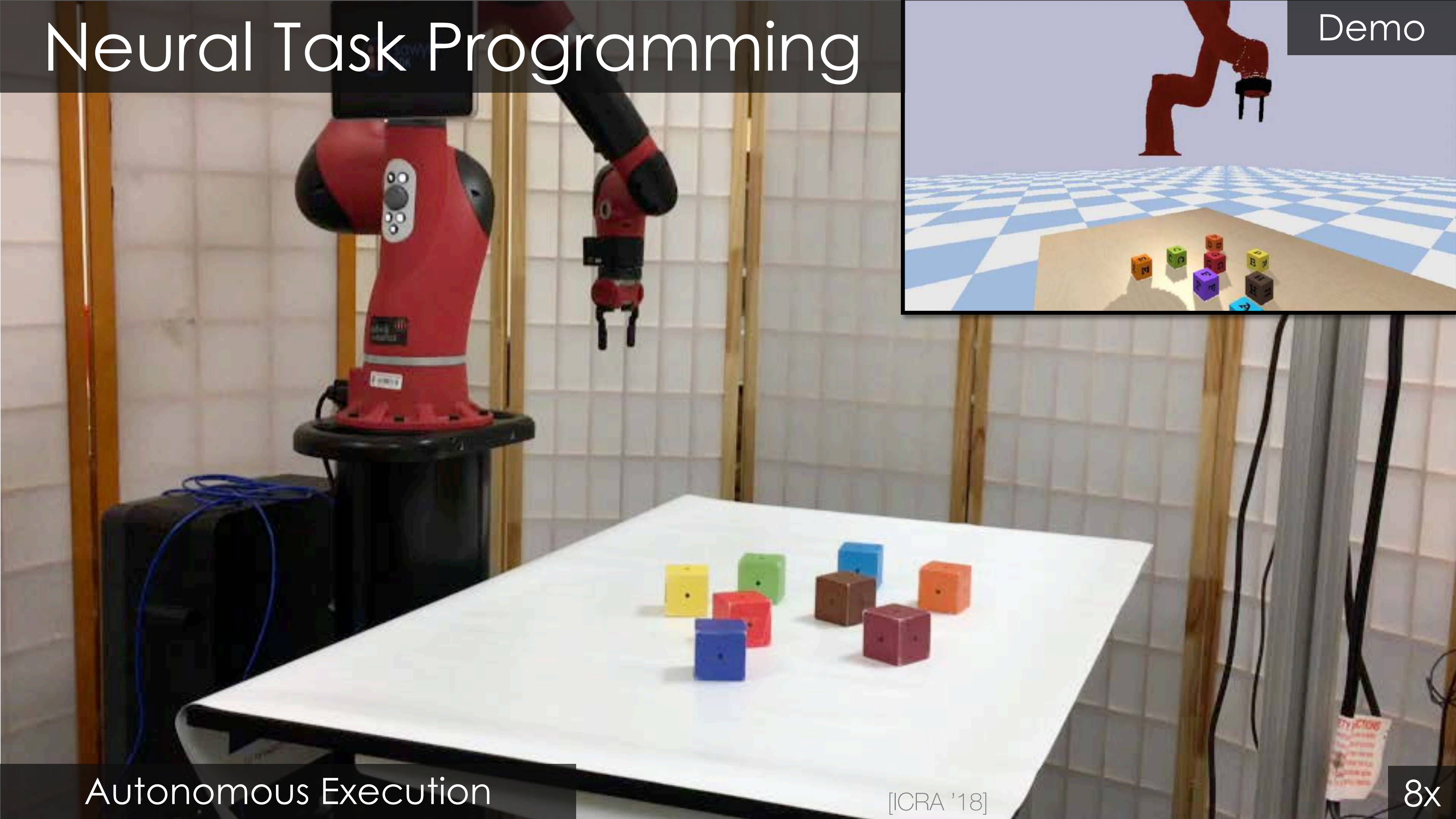


Hierarchical Policy Learning as Program Induction

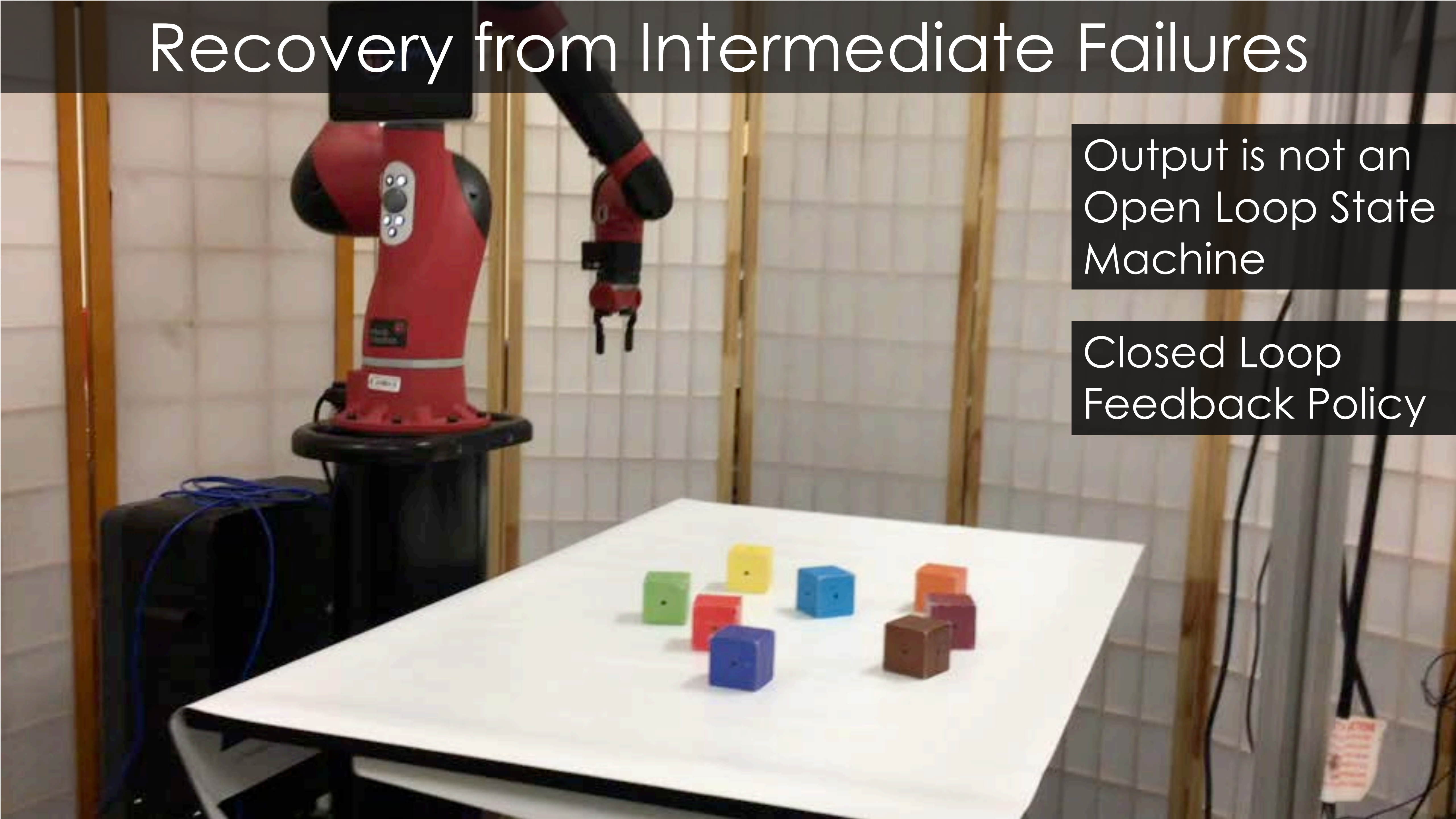
[ICRA'18, CVPR '19]


Move_to (Blue)
Grasp (Blue)
Move_to (Red)
Release( )

Neural Task Programming



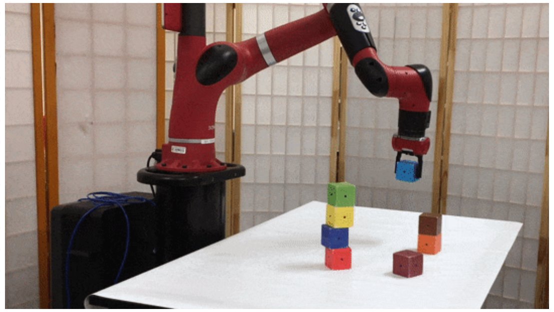
Recovery from Intermediate Failures

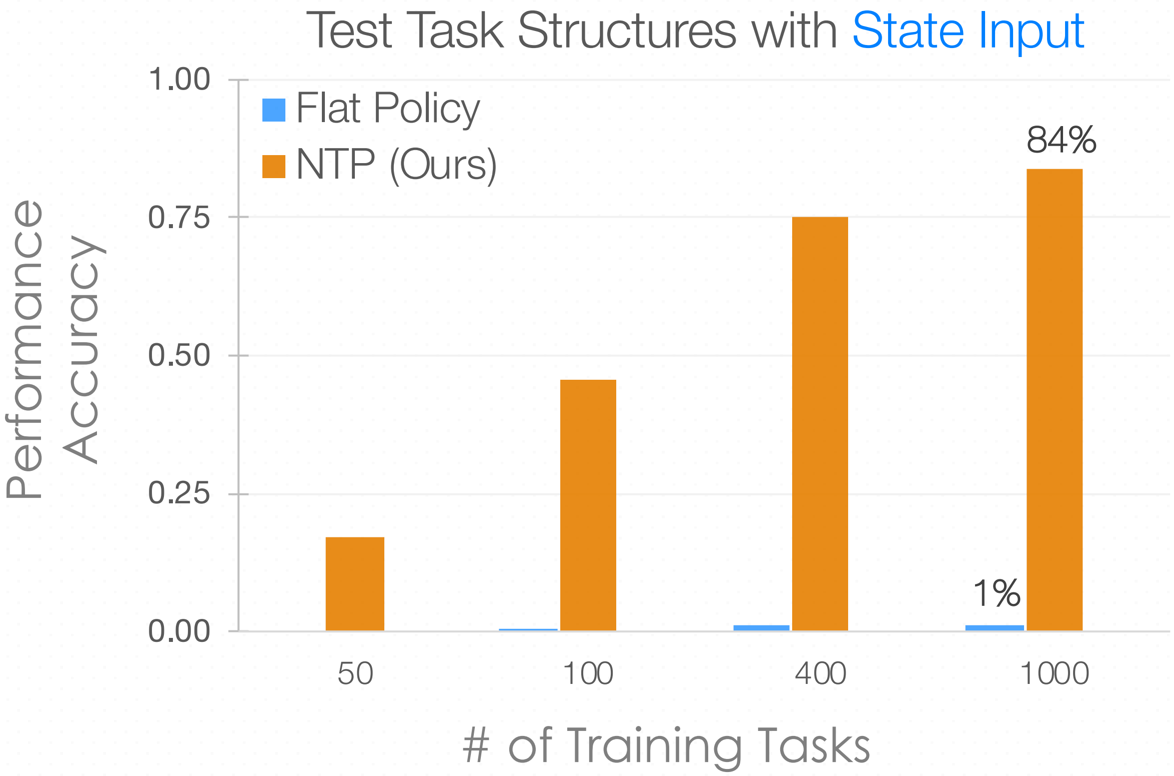


Output is not an Open Loop State Machine

Closed Loop Feedback Policy

Neural Task Programming
Results





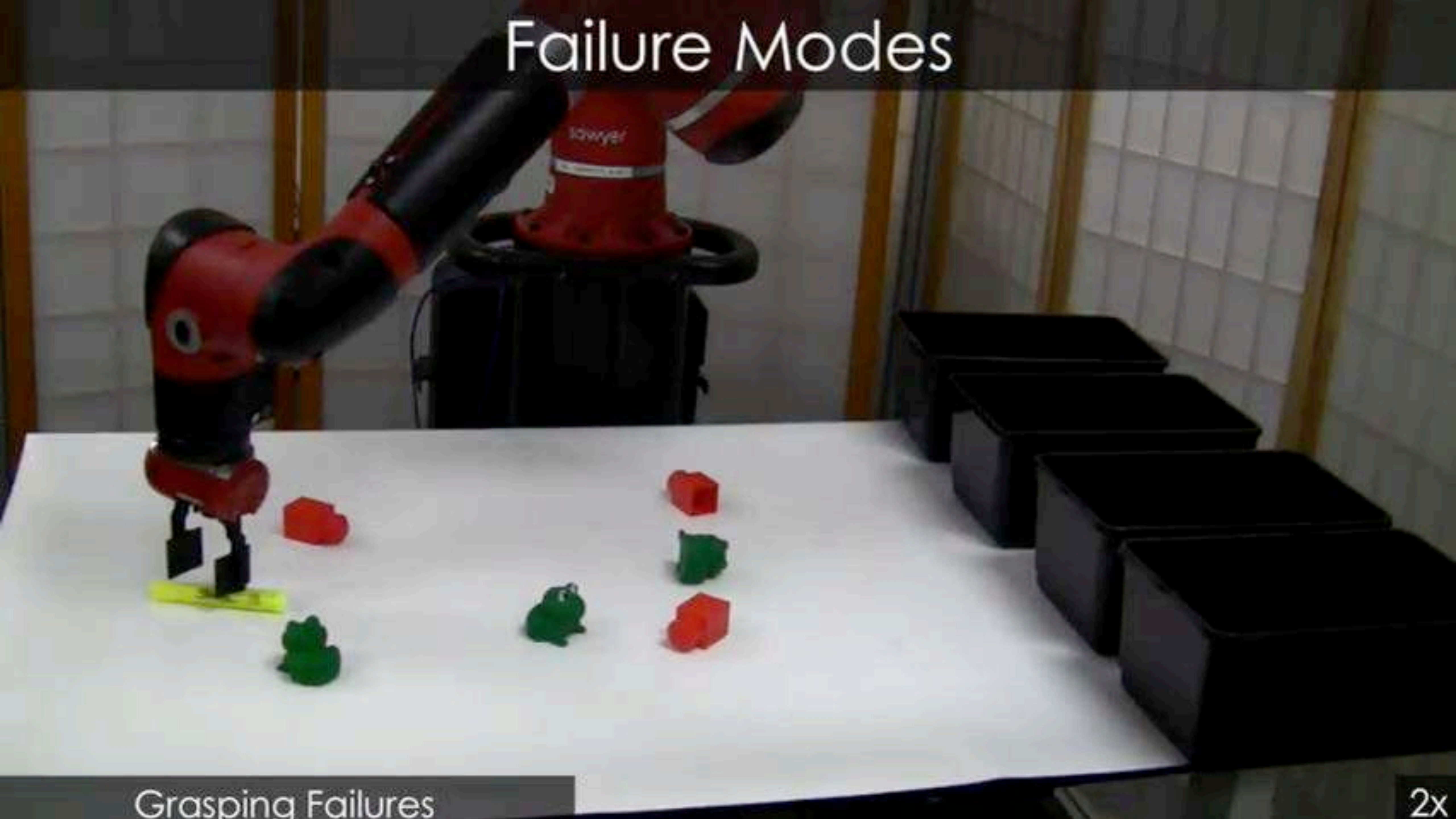
Pose Est. + Plan

E2E Plan

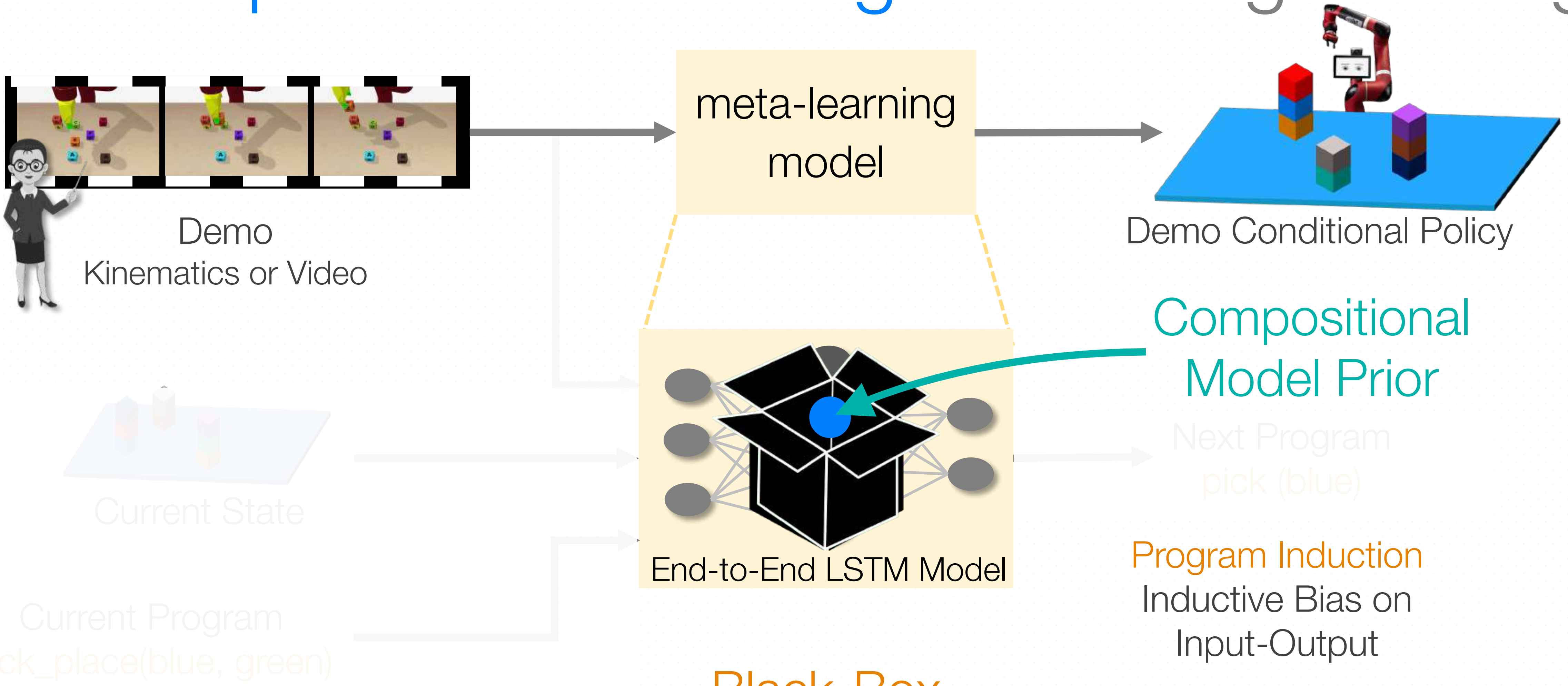
Better Generalization than Flat Policy + Works with Vision

[ICRA'18, CVPR '19]

Failure Modes



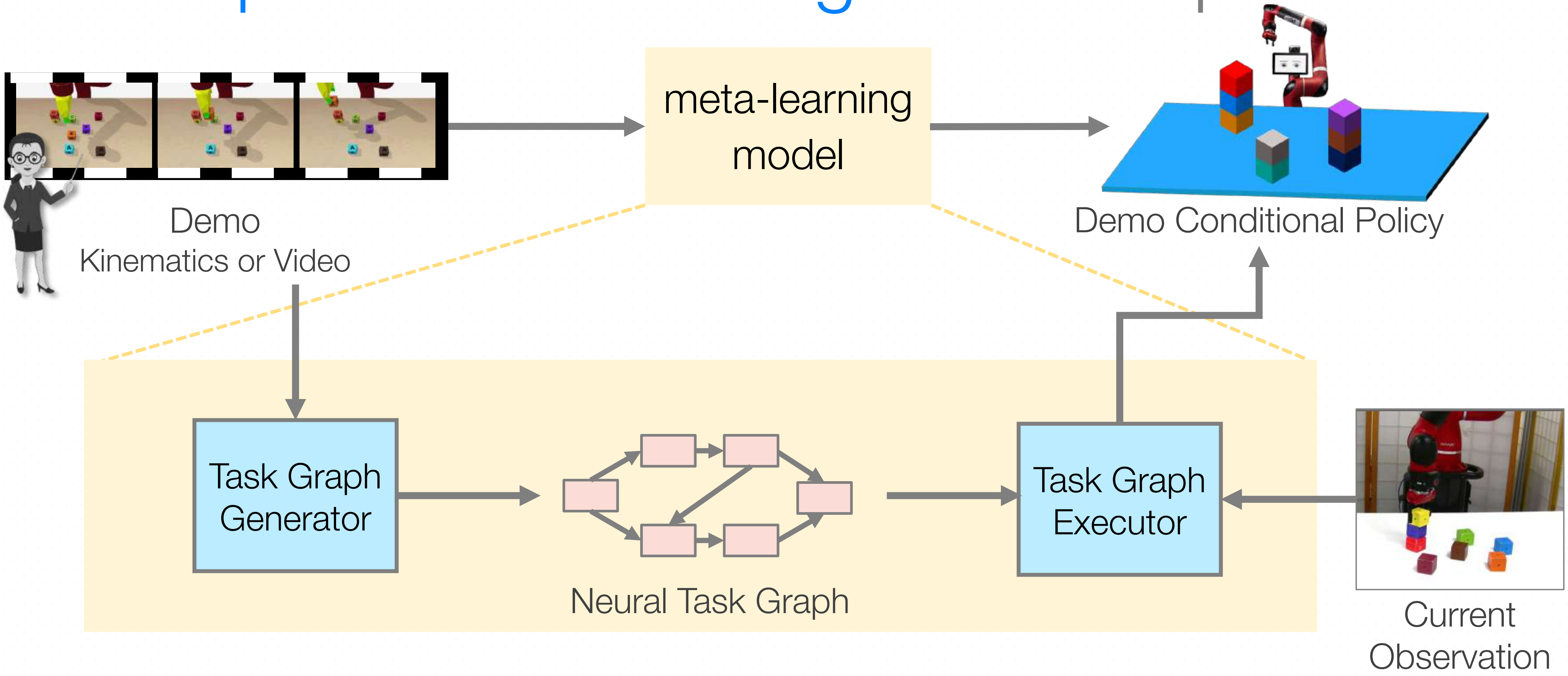
Compositional Planning: Task Programming



Black-Box
Model

[ICRA'18, CVPR '19]

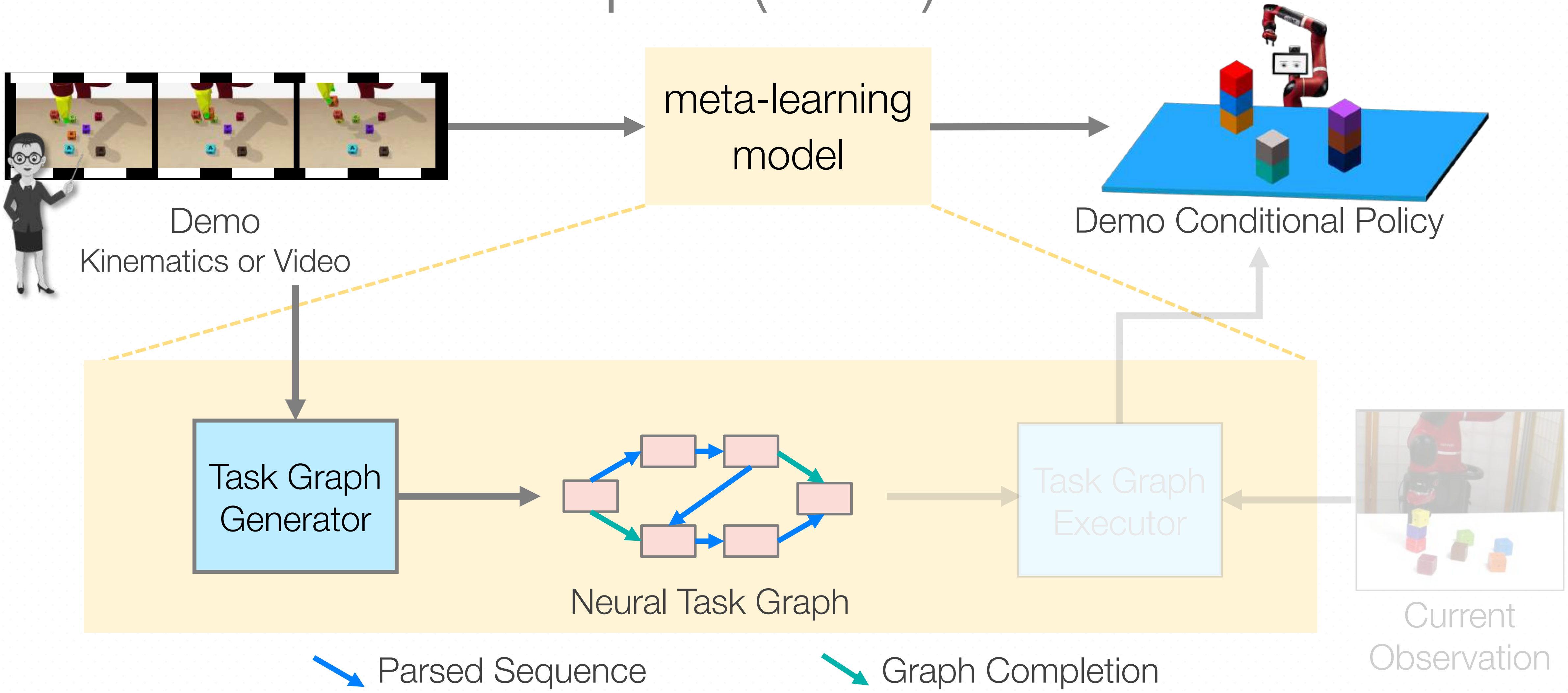
Compositional Planning: Task Graphs



Hierarchical Policy Learning as Graph Induction

[ICRA'18, CVPR '19]

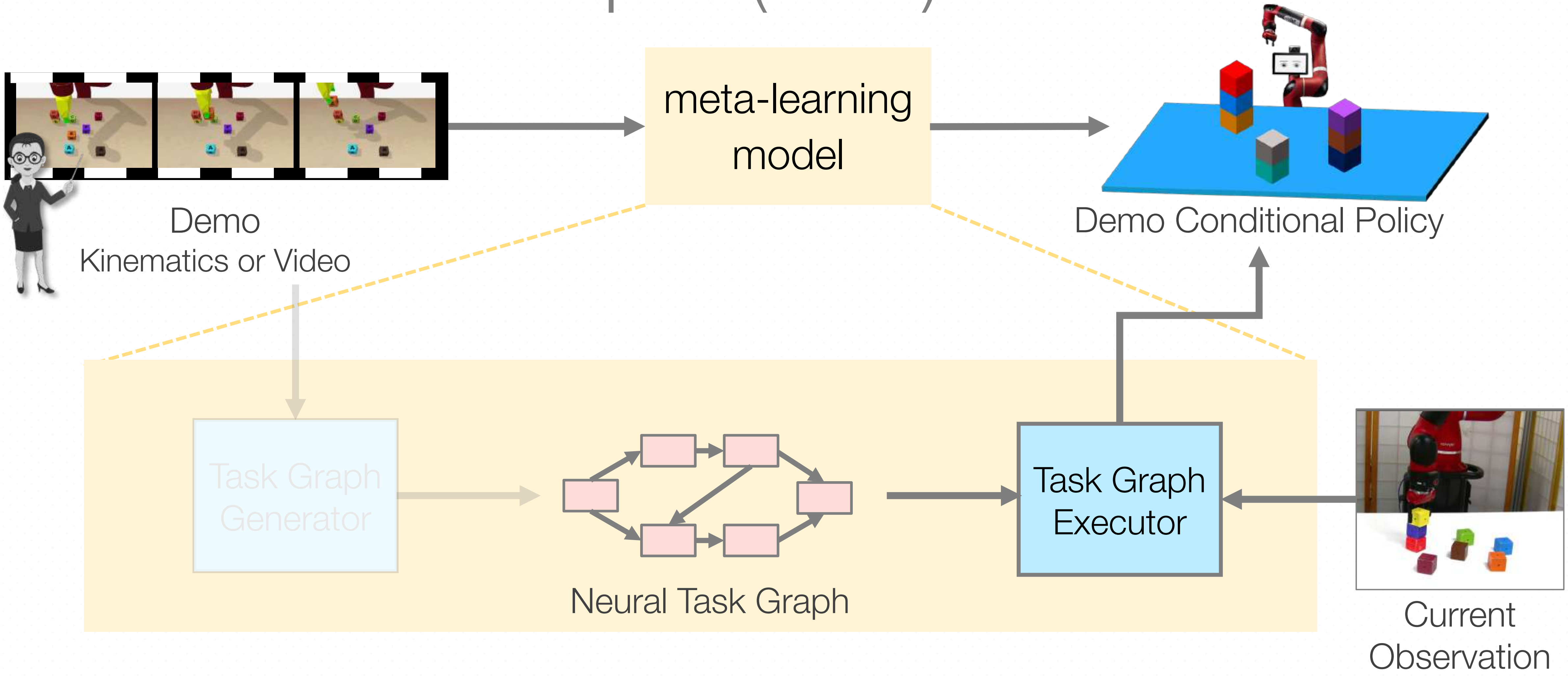
Neural Task Graphs (NTG)



Hierarchical Policy Learning as Graph Induction

[ICRA'18, CVPR '19]

Neural Task Graphs (NTG)

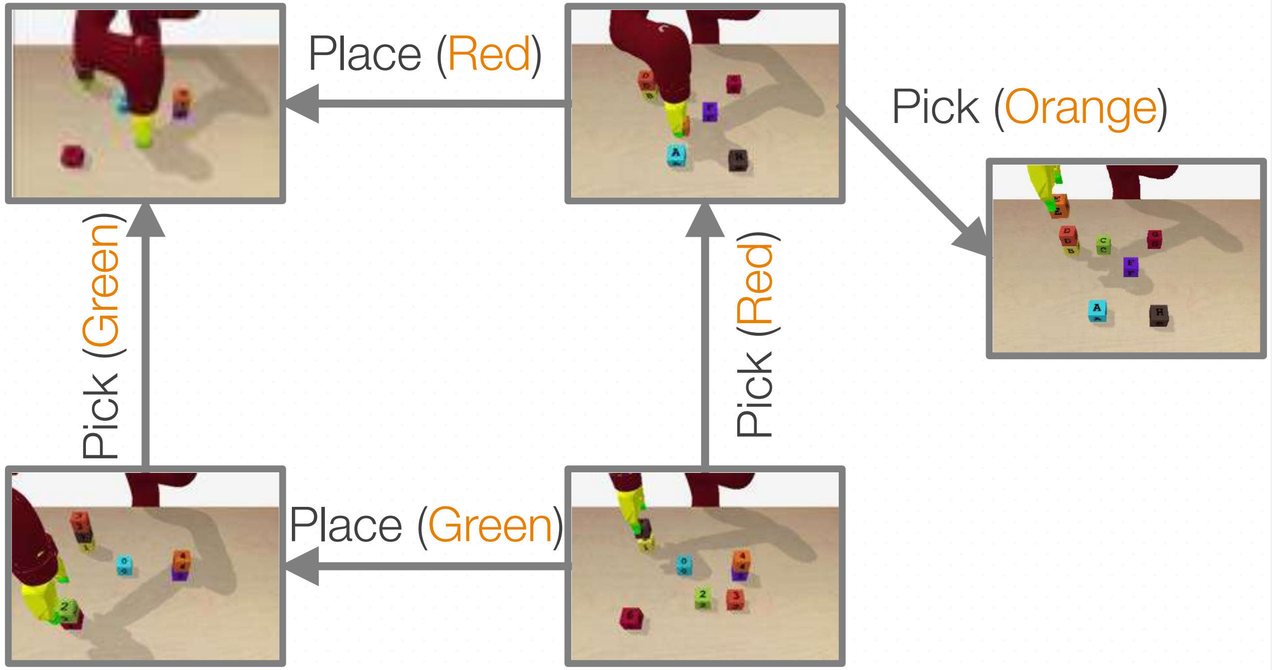


Hierarchical Policy Learning as Graph Induction

[ICRA'18, CVPR '19]

Neural Task Graphs (NTG): Representation

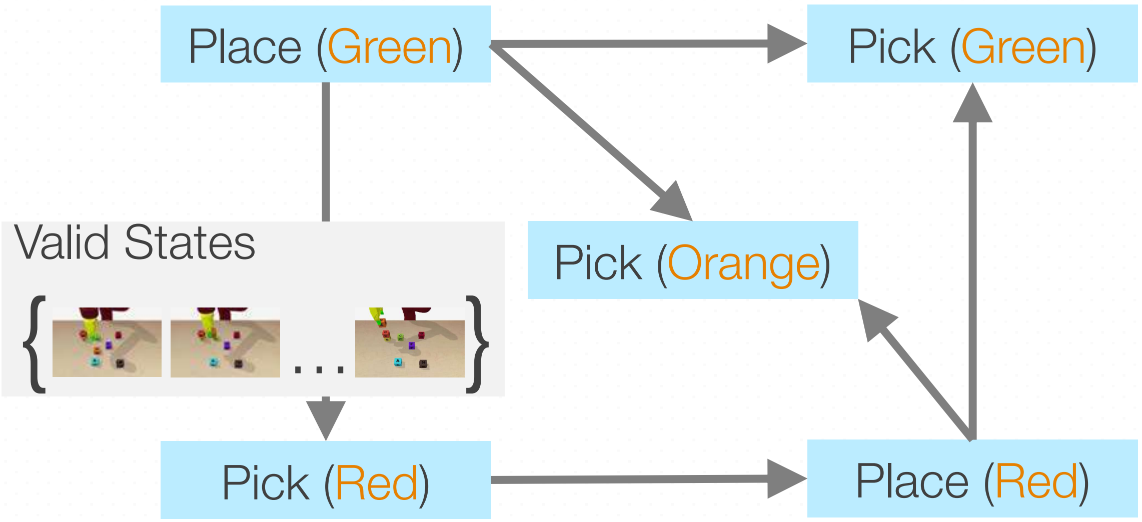
Task Graph



Nodes: States **Combinatorial**

Edges: Action

Conjugate Task Graph

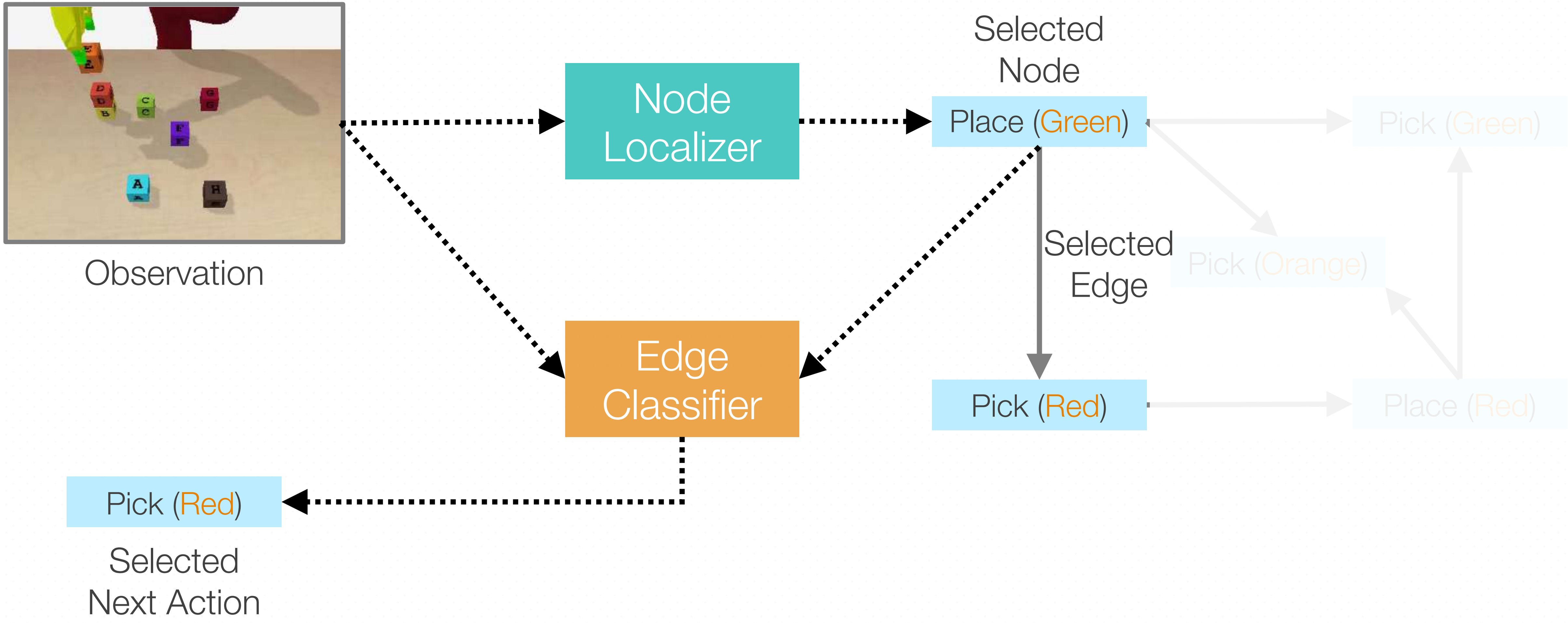


Nodes: Actions **Finite**

Edges: States (Preconditions)

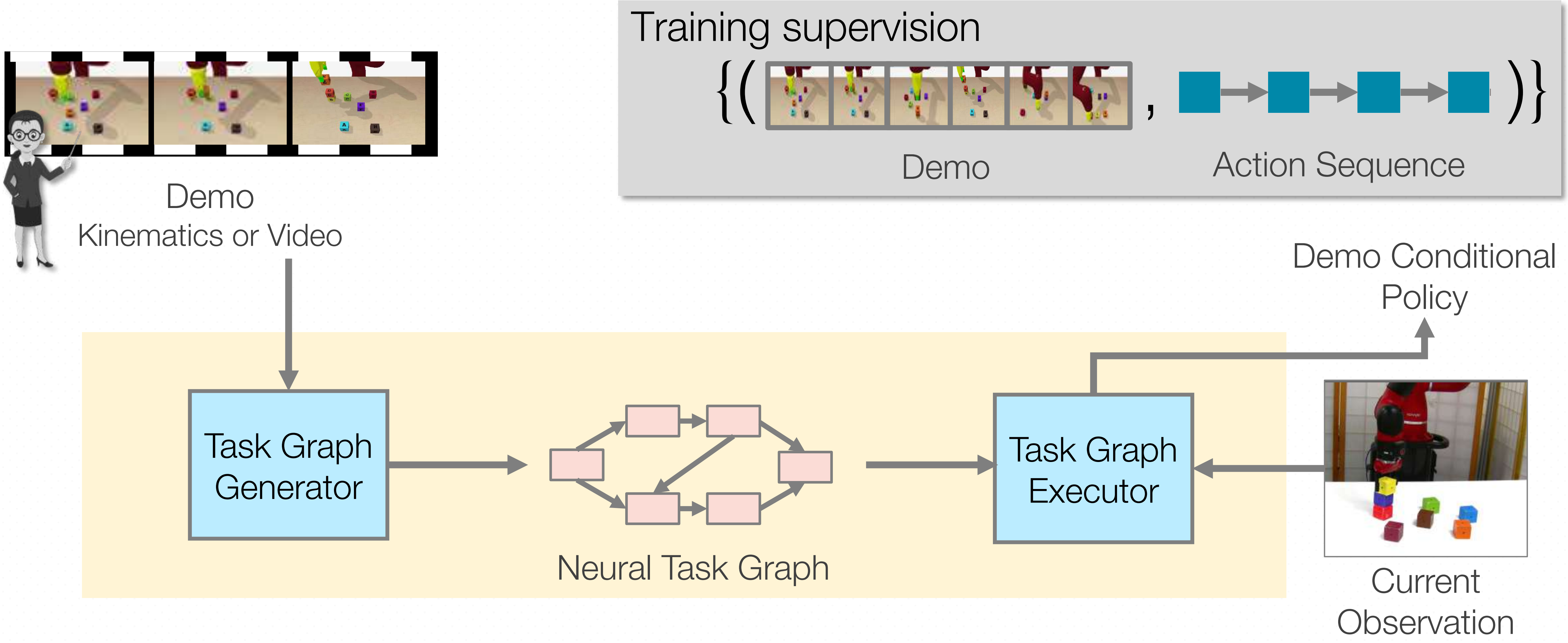
[ICRA'18, CVPR '19]

Neural Task Graphs (NTG): Execution



[ICRA'18, CVPR '19]

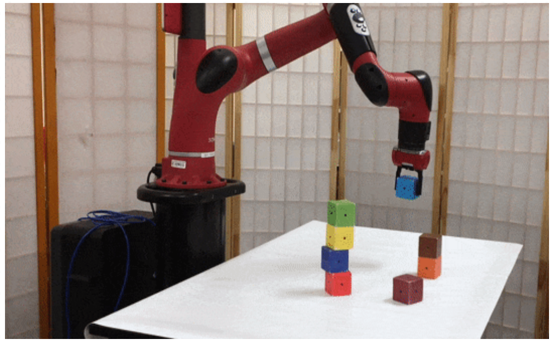
Neural Task Graphs (NTG)

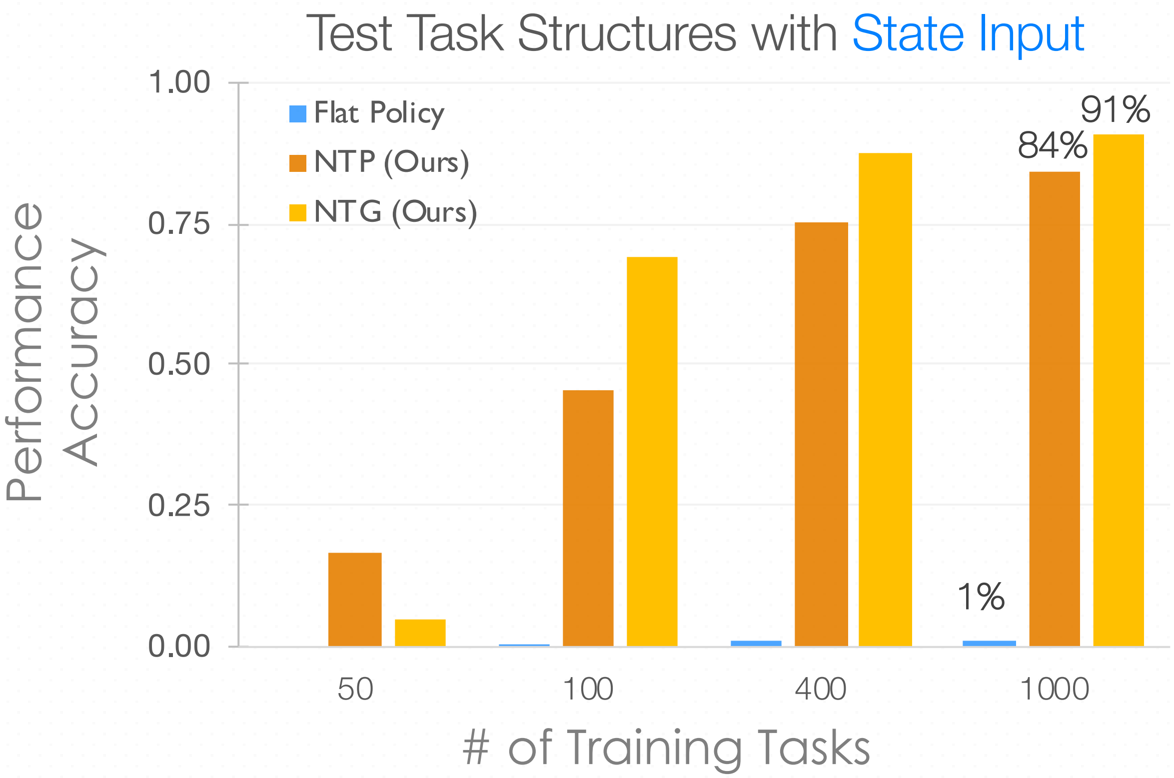


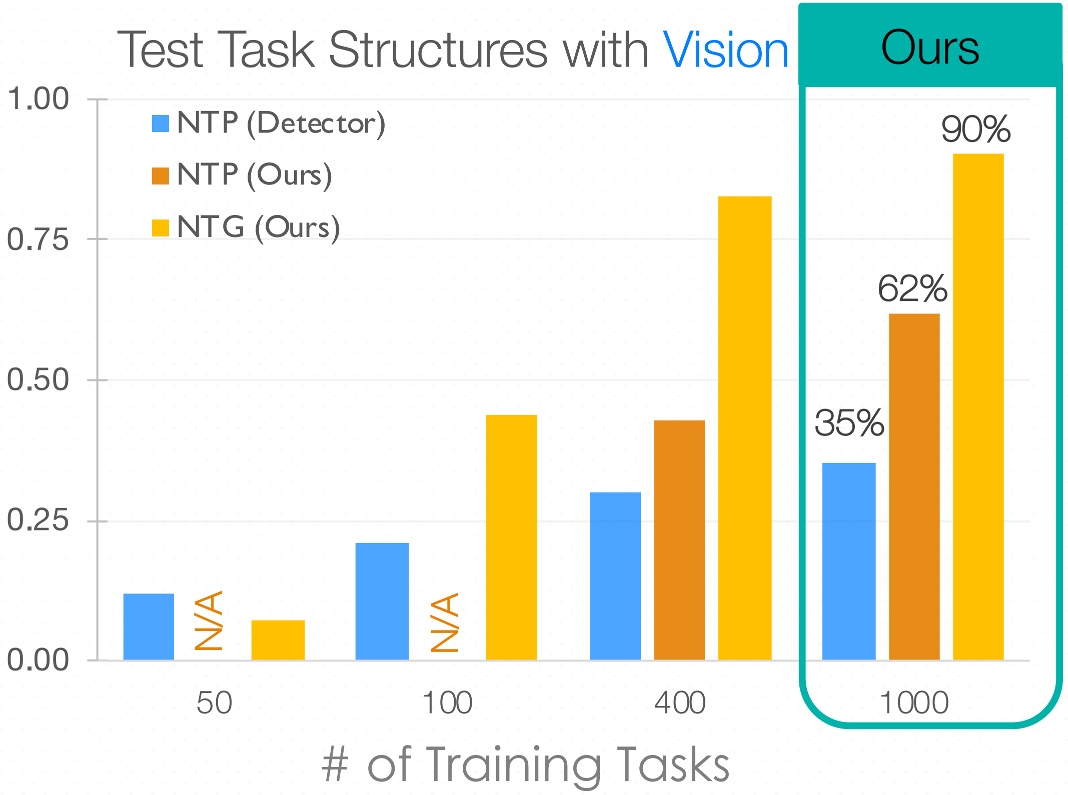
Hierarchical Policy Learning as Graph Induction

[ICRA'18, CVPR '19]

Neural Task Graph
Results



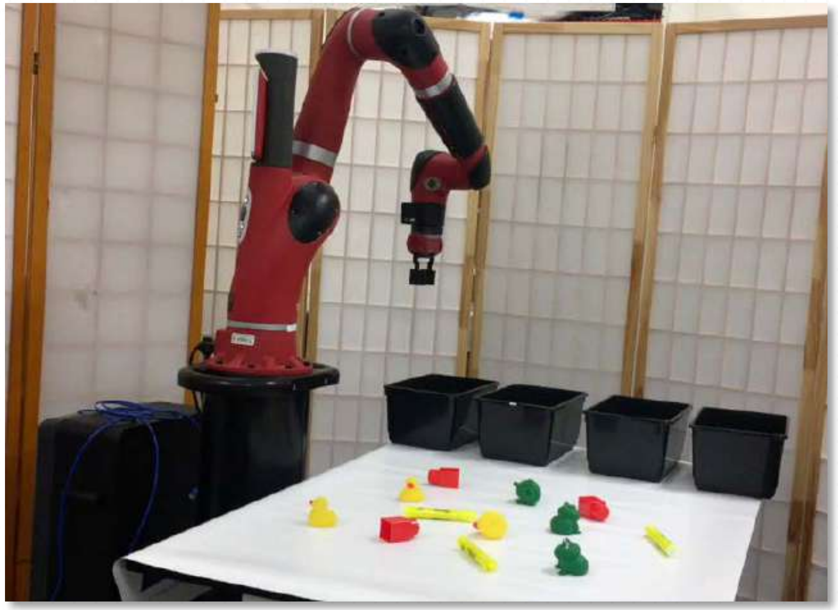




Weaker Supervision and Better Generalization

[ICRA'18, CVPR '19]

Compositional Planning: NTP and NTG



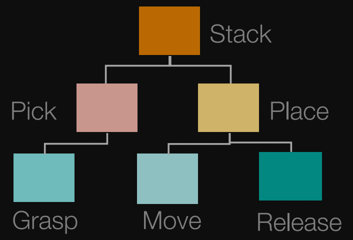
Object Sorting
(NTP)

Table Clean Up
(NTP)

Sequential Search and Prediction
AI2 Thor with NTG

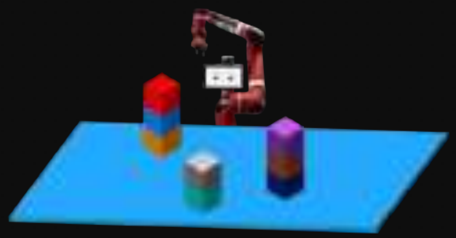
[ICRA'18, CVPR '19]

Task Structure Learning



Object Arrangement

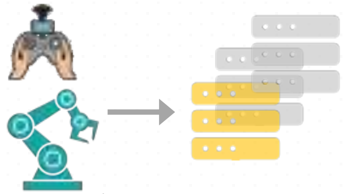
ICRA 2018



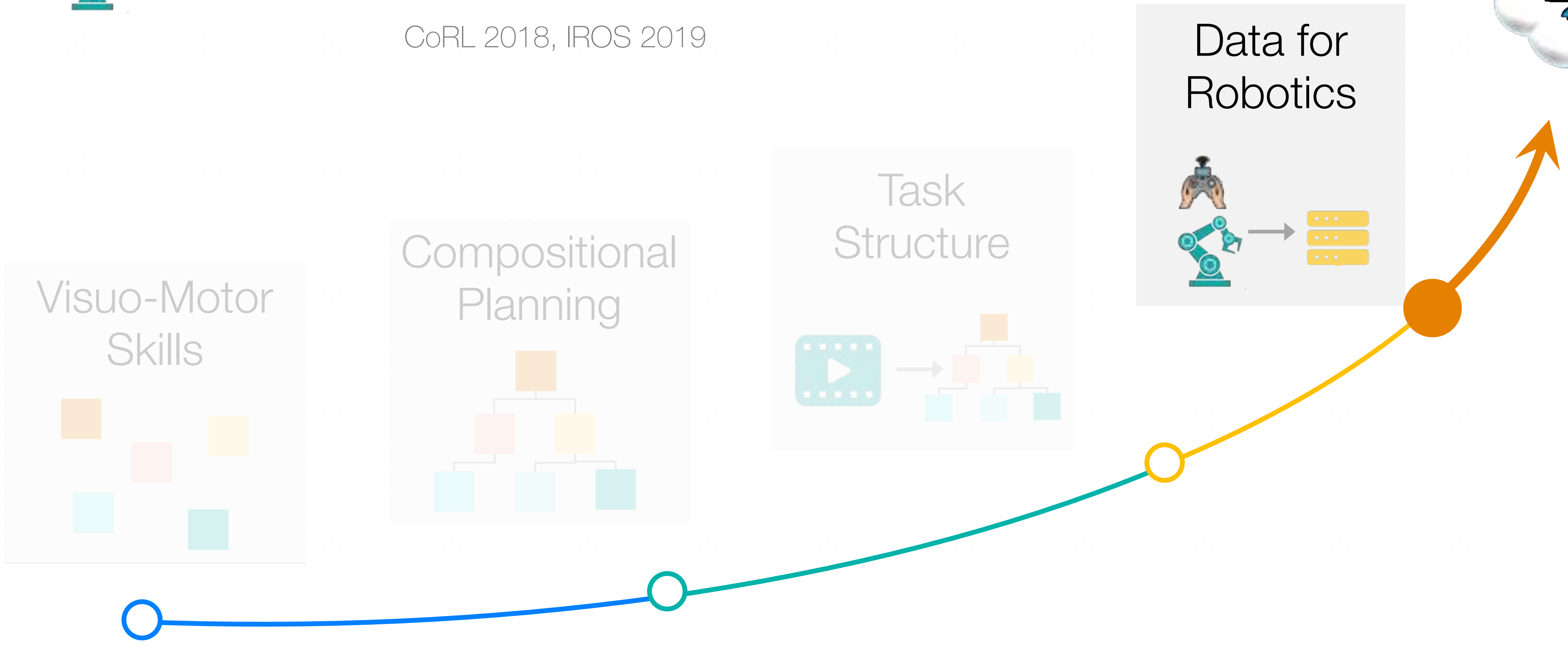
CVPR 2019 (oral)

Compositional priors with modular structure enable generalizable learning in hierarchical domains

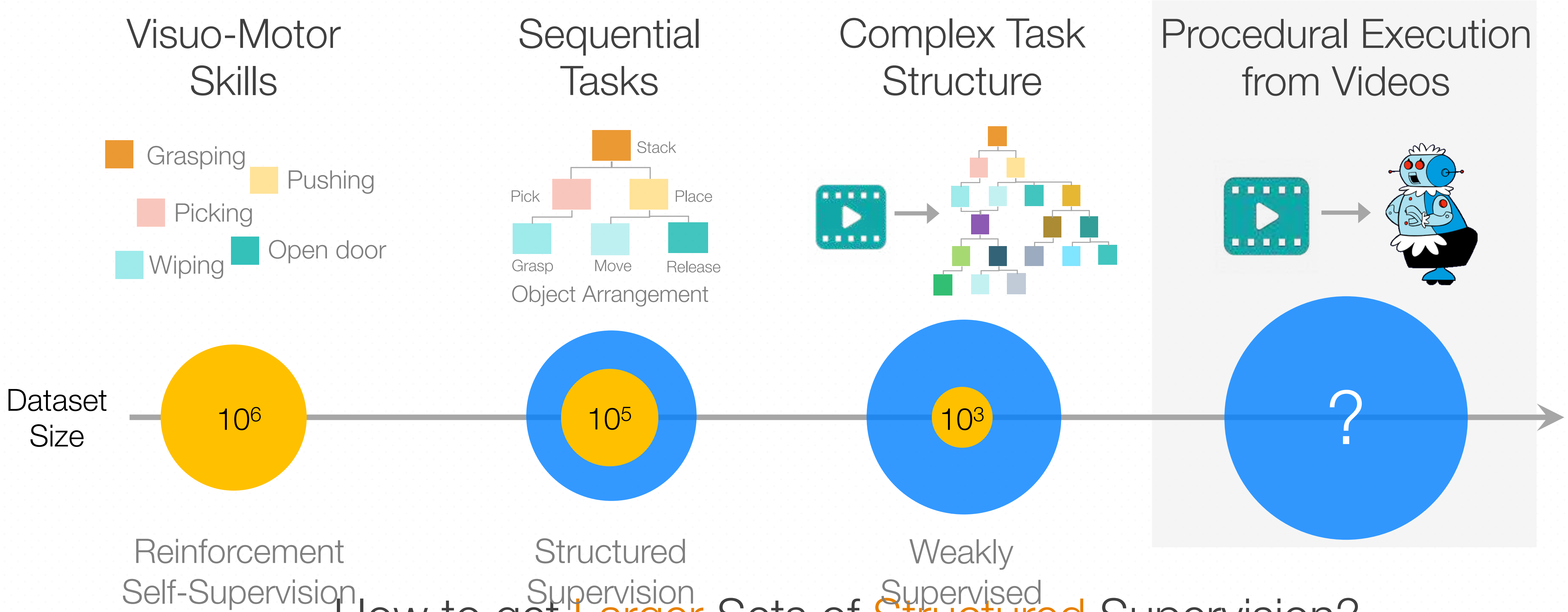
Generalizable Autonomy in Robot Manipulation



CoRL 2018, IROS 2019

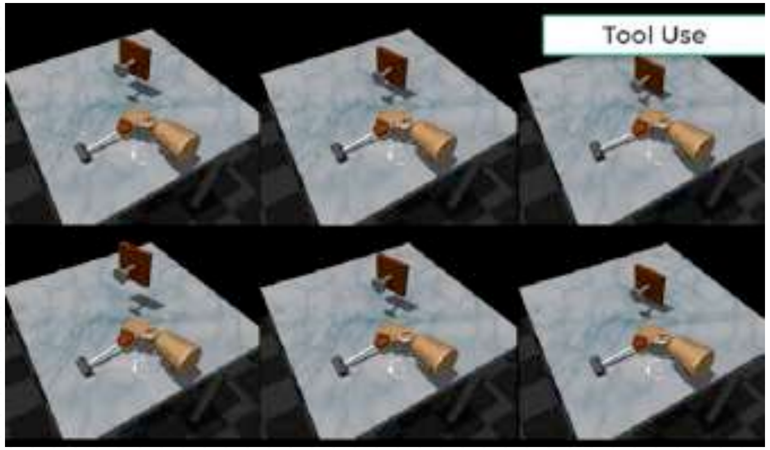


Data for Robotics



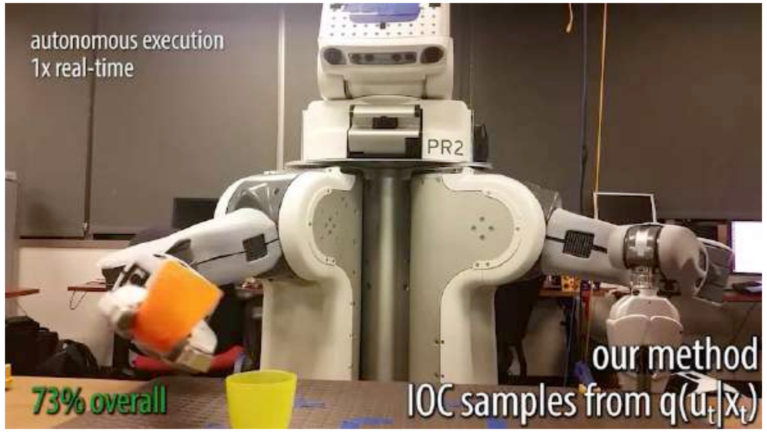
How to get Larger Sets of Structured Supervision?

Data for Robotics: Imitation + RL



Rajeswaran et al. (2018)

25 demonstrations
~ 10 Minutes



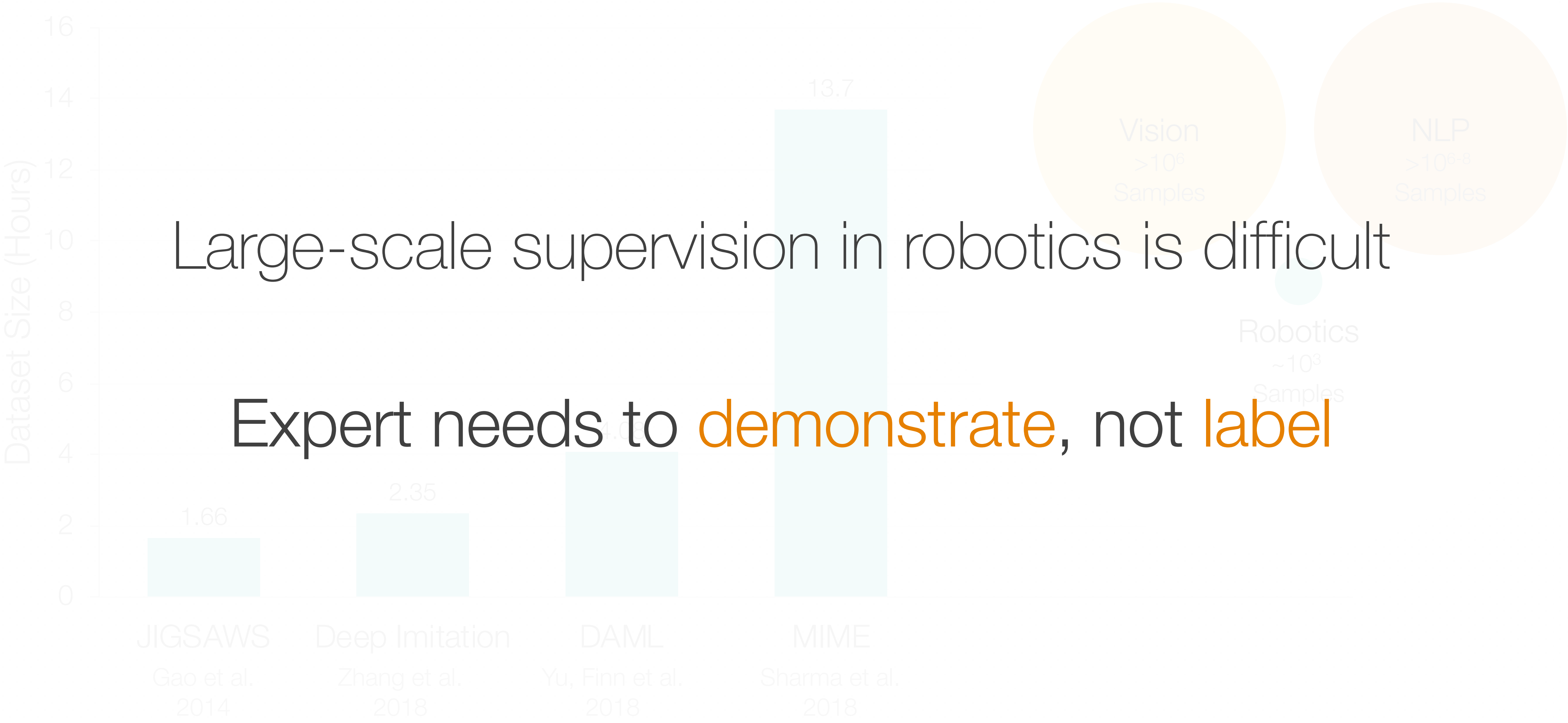
Finn et al. (2017)

30 demonstrations
~ 10 Minutes

Vecerik et al. (2017)

100 demonstrations
~ 30 Minutes

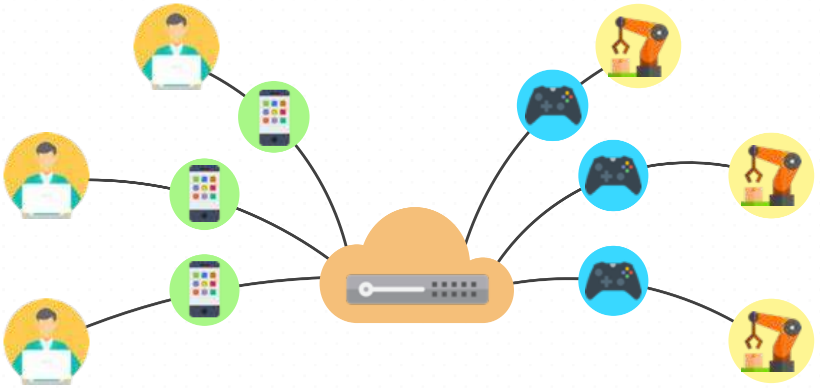
Data for Robotics

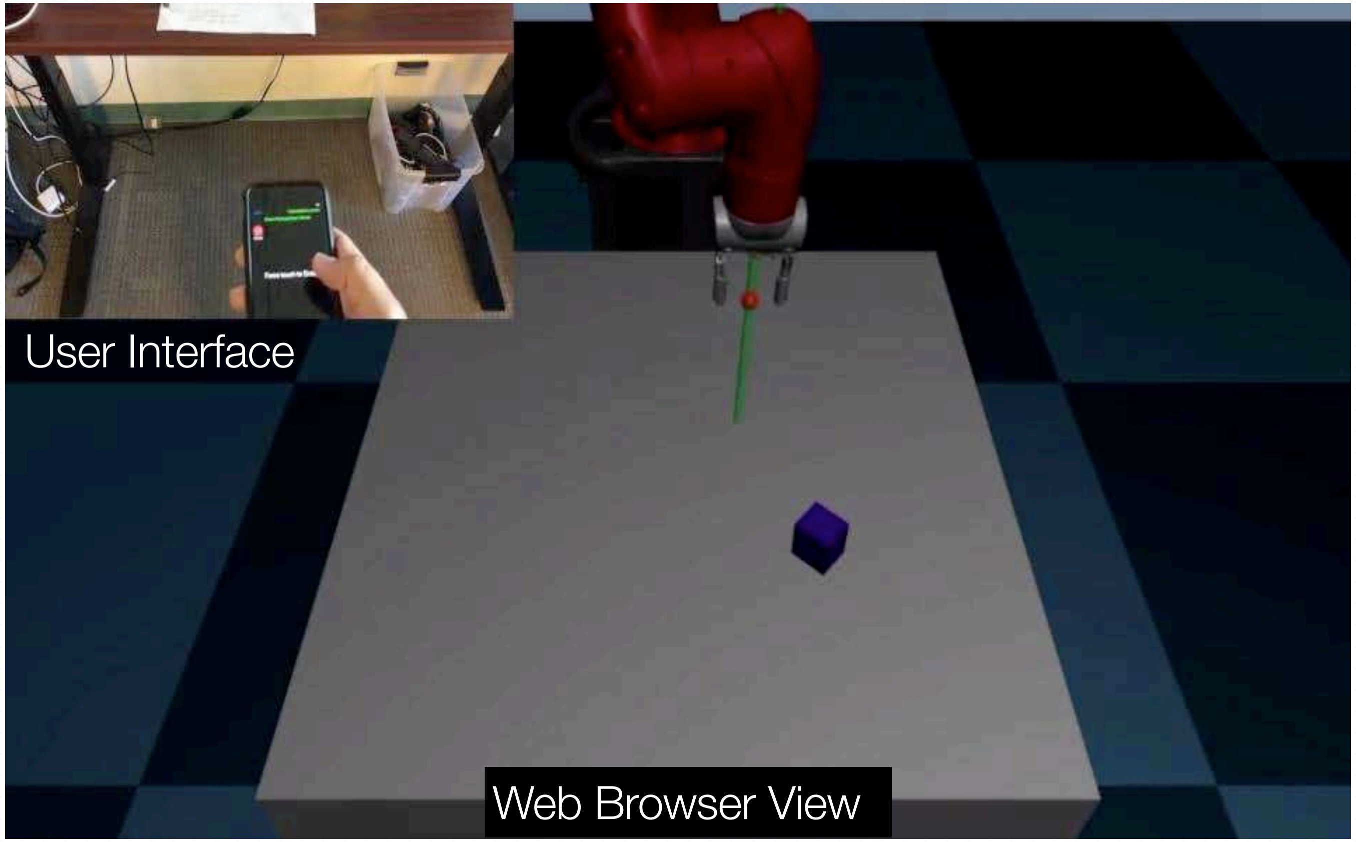


Large-scale supervision in robotics is difficult

Expert needs to demonstrate, not label

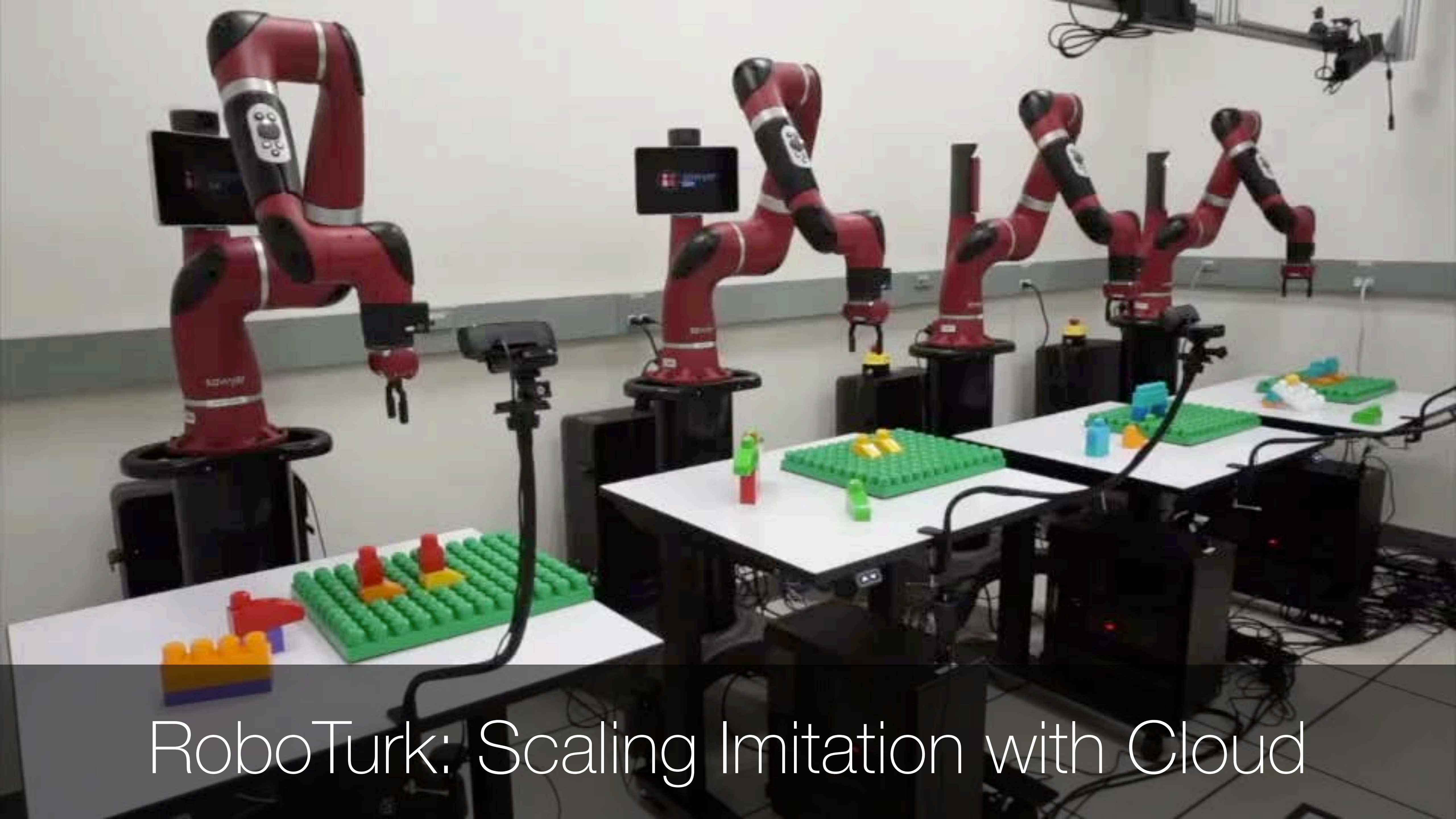
Data for Robotics: RoboTurk



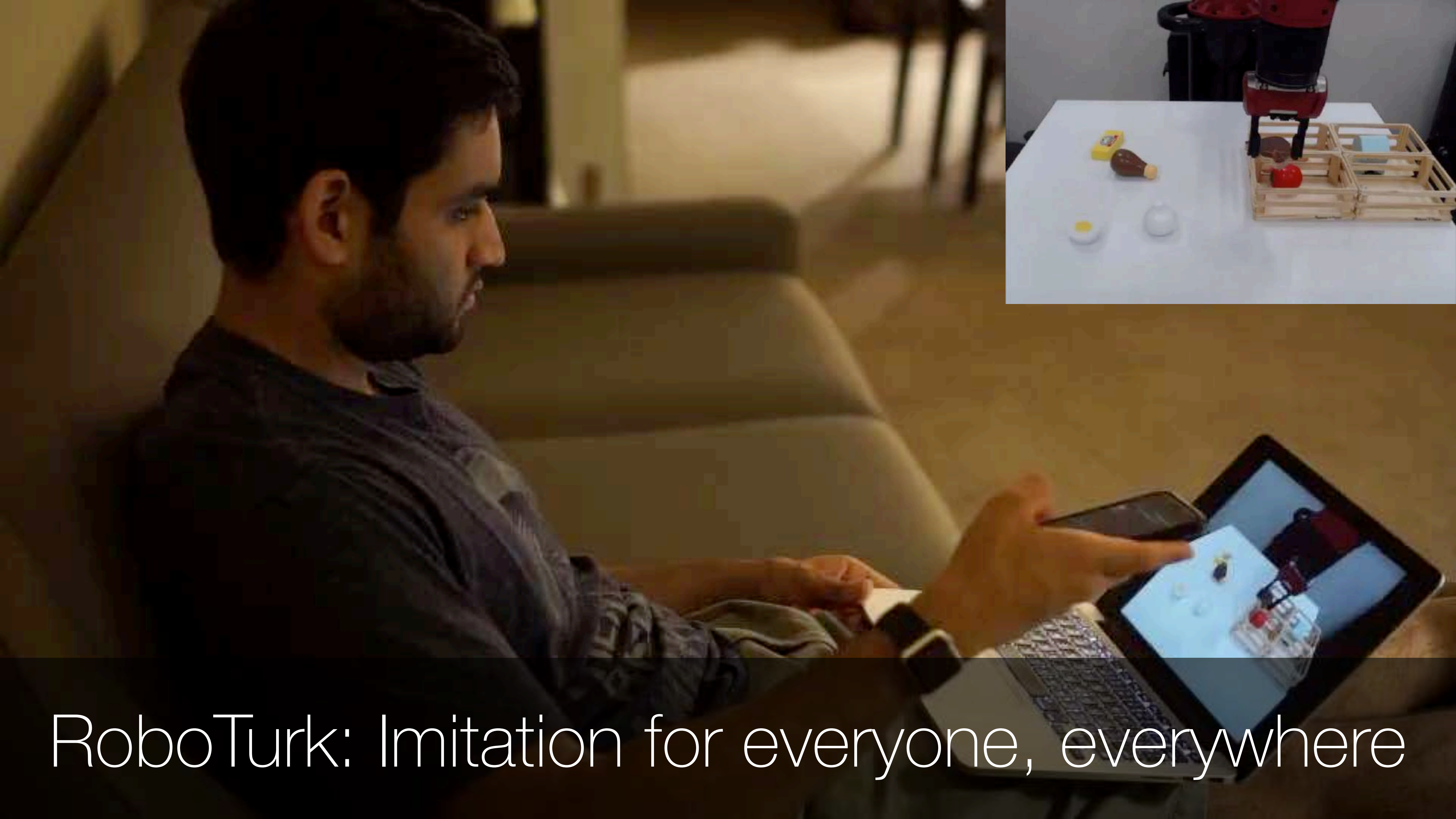


+ Scales easily with commodity hardware
+ Natural 6-DoF Free Space Control

[CoRL '18, IROS 2019]



RoboTurk: Scaling Imitation with Cloud



RoboTurk: Imitation for everyone, everywhere

RoboTurk **Pilot Datasets**

Simulated Data

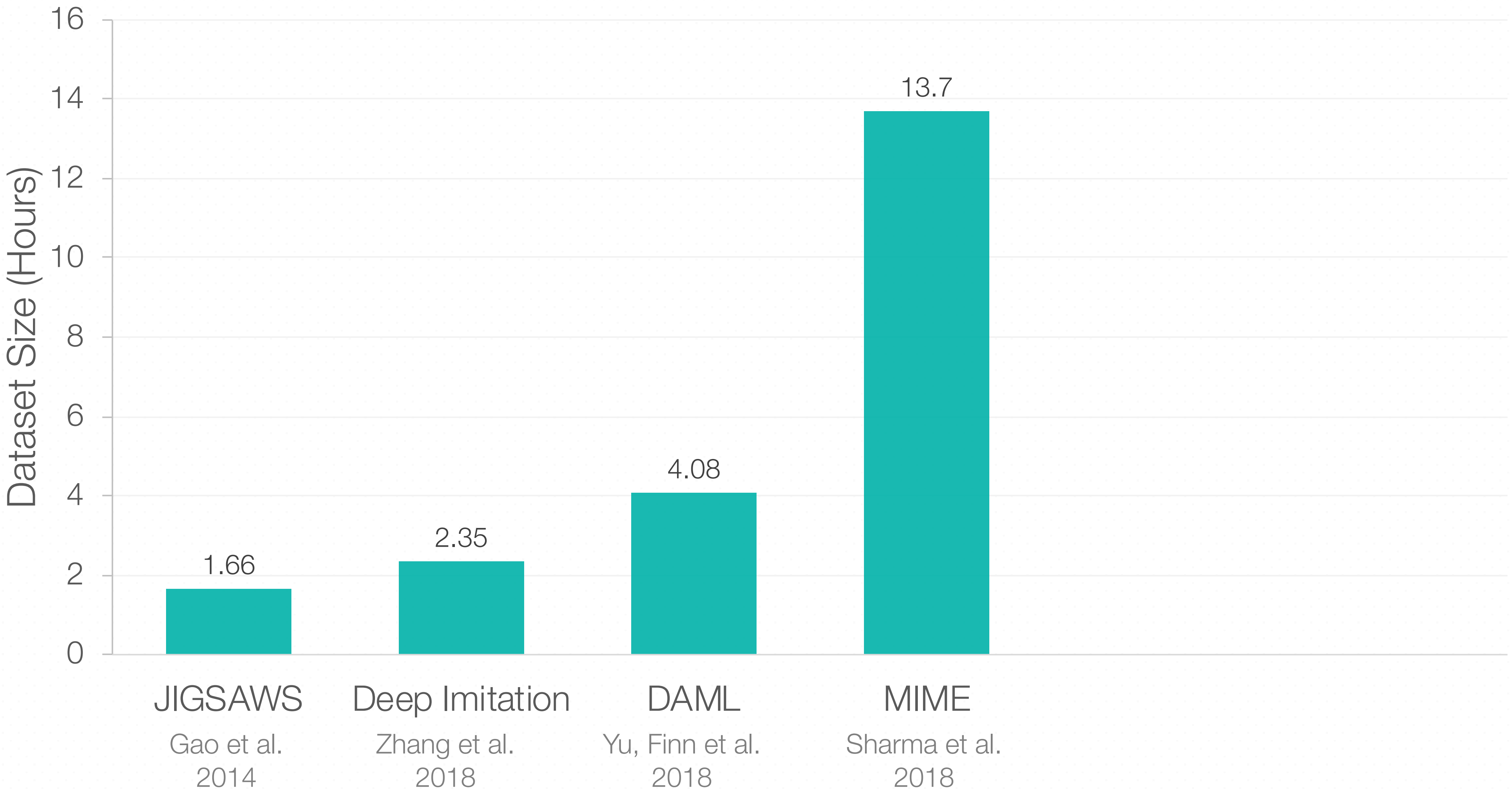
- 137.5 hours of demonstrations
- 22 hours of total platform usage
- 3 dexterous manipulation tasks
- 3224 total attempted demos
- 15 novice, remote users

Real Robot Data

- 111 hours of robot demos
- 1 week of data collection
- 3 dexterous manipulation tasks
- 2144 total demonstrations
- 54 non-expert users

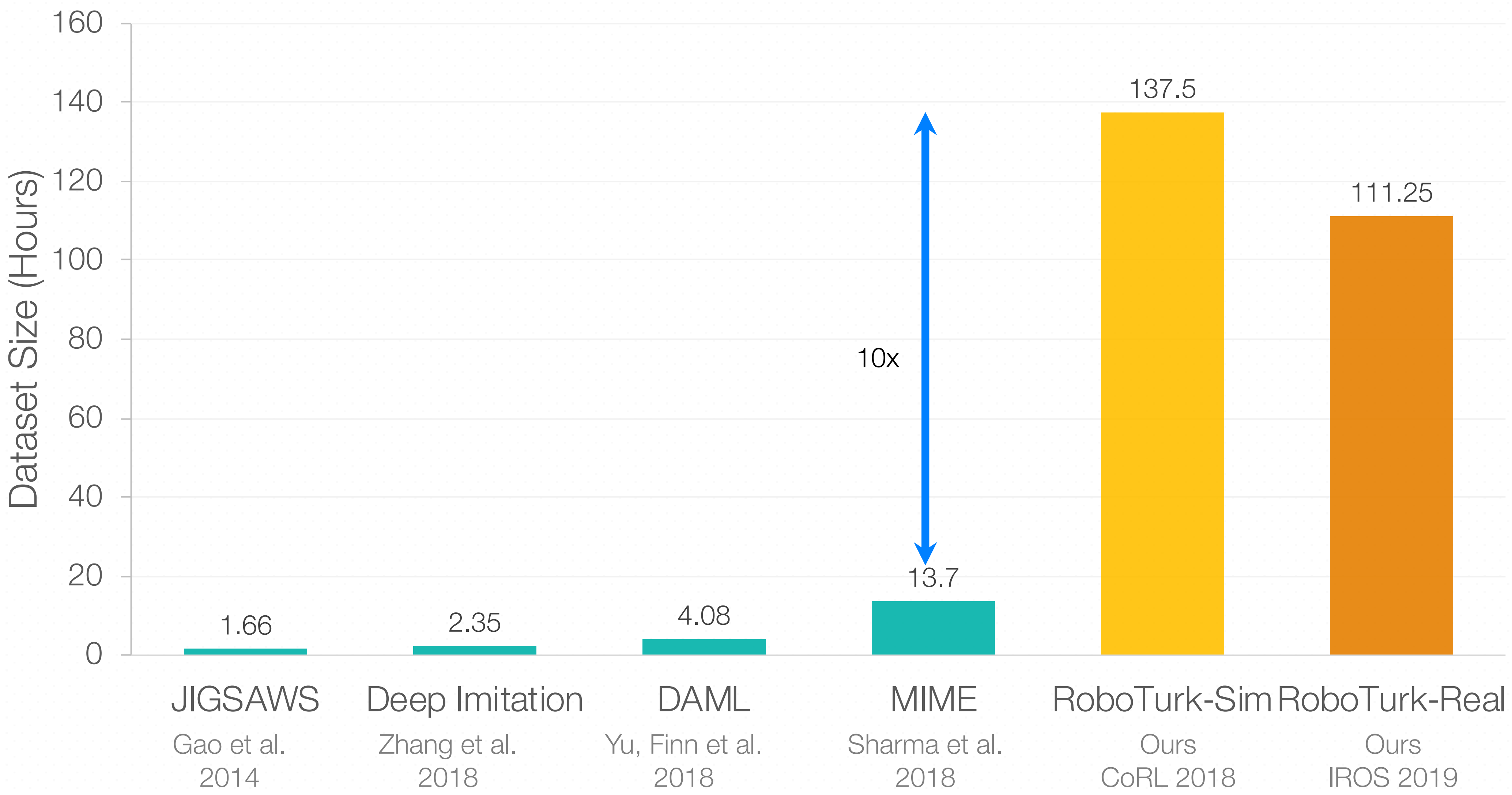
[CoRL '18, IROS 2019]

Data for Robotics: RoboTurk



[CoRL '18, IROS 2019]

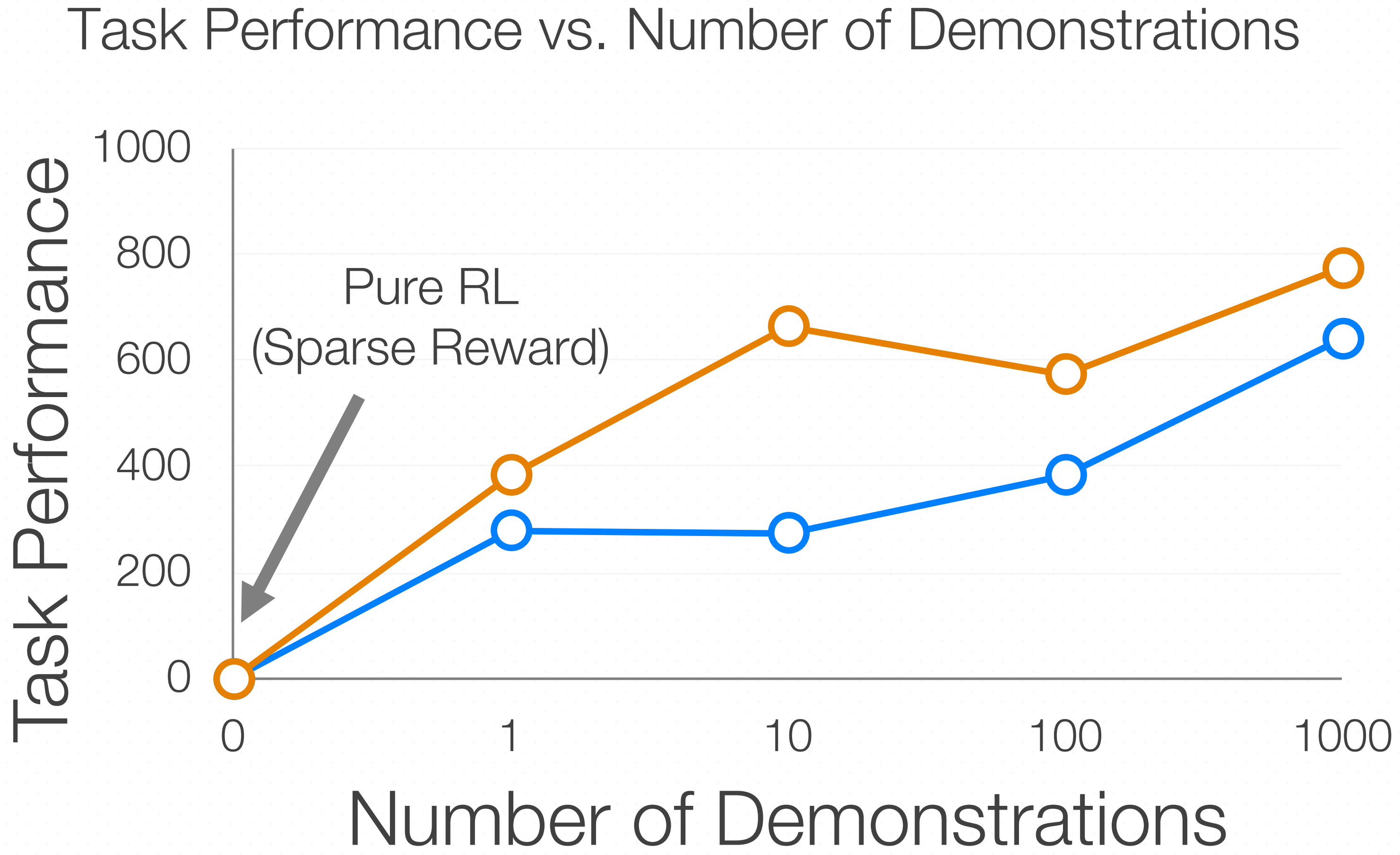
Data for Robotics: RoboTurk



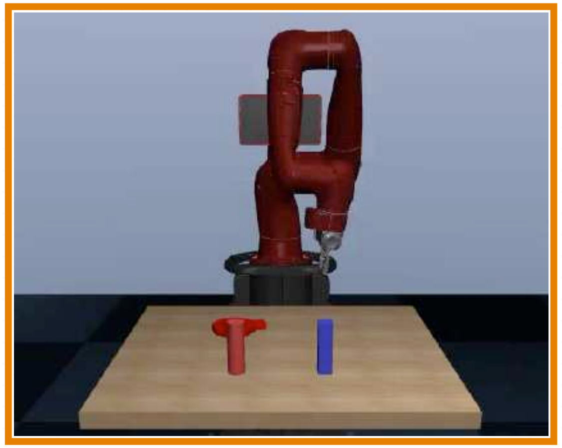
[CoRL '18, IROS 2019]

Data for Robotics: RoboTurk

Imitation + RL



Trained Policy Rollout



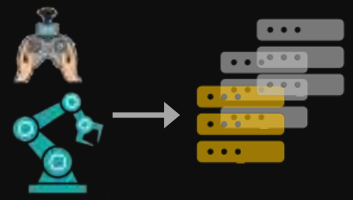
Nut Assembly

Bin Picking

Distributed PPO with curriculum: 32 workers, 24/48 hours

[CoRL '18, IROS 2019]

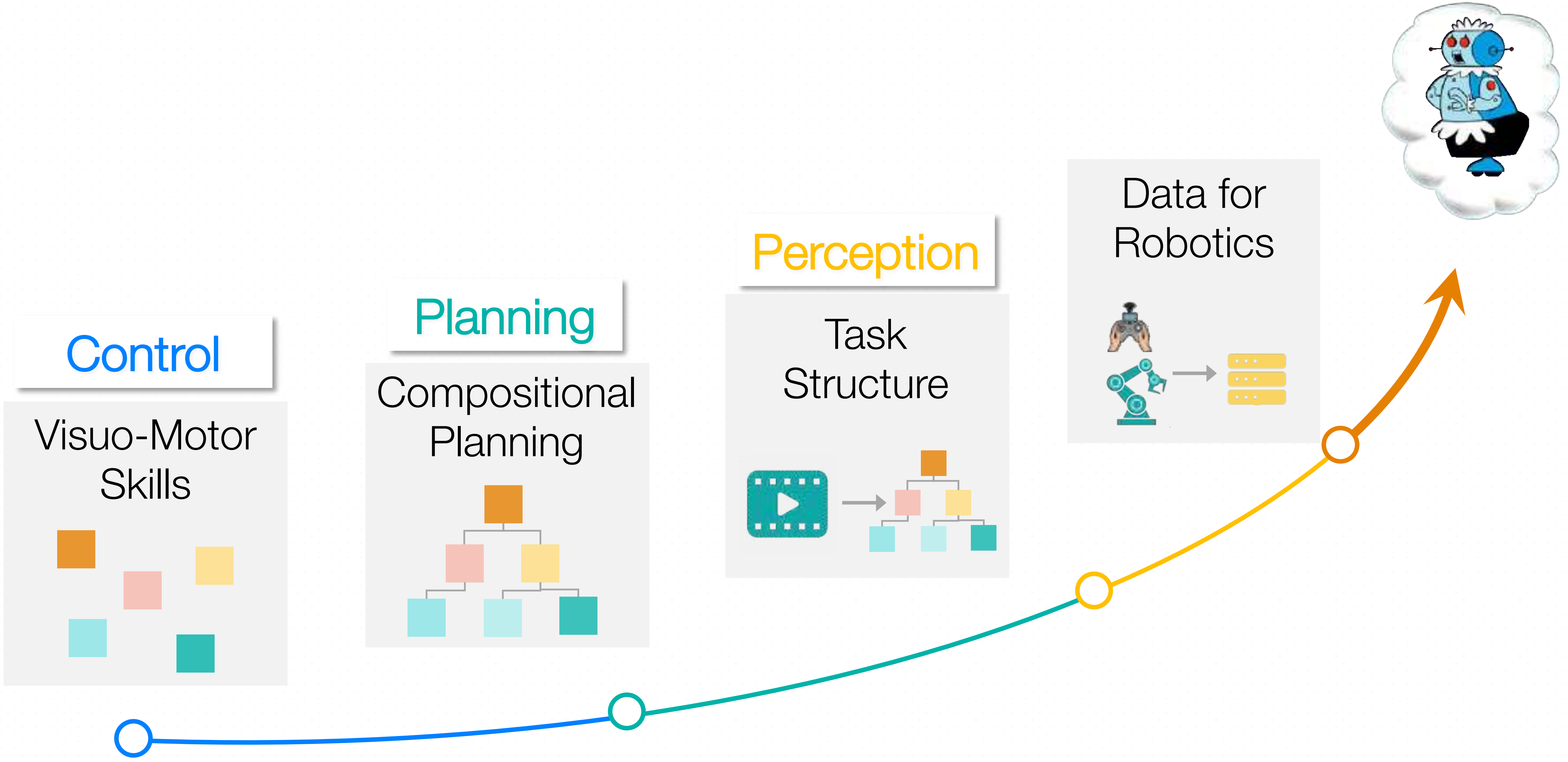
Data for Robotics: RoboTurk



CoRL 2018, IROS 2019

Structured supervision for Robotics through scalable crowdsourcing can empower robot learning in complex tasks.

Generalizable Autonomy in Robot Manipulation



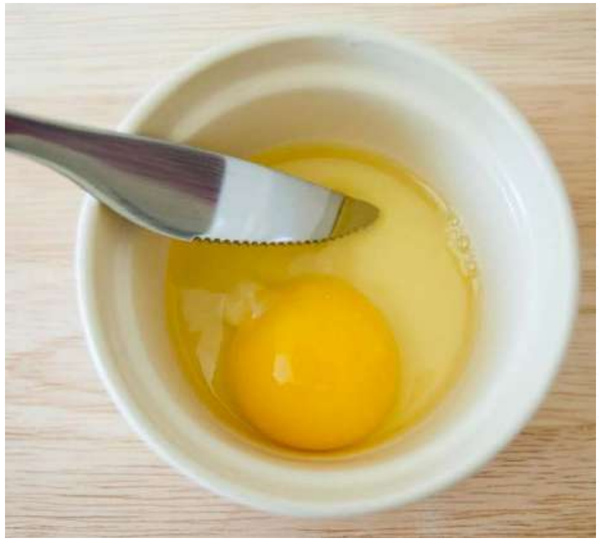
Opportunity: Personal Robotics

Instructional Youtube Video
How to make Meatball Pasta?

Where / How should Rosie start?
What is the recipe?
How to execute the plan?
How to plan?

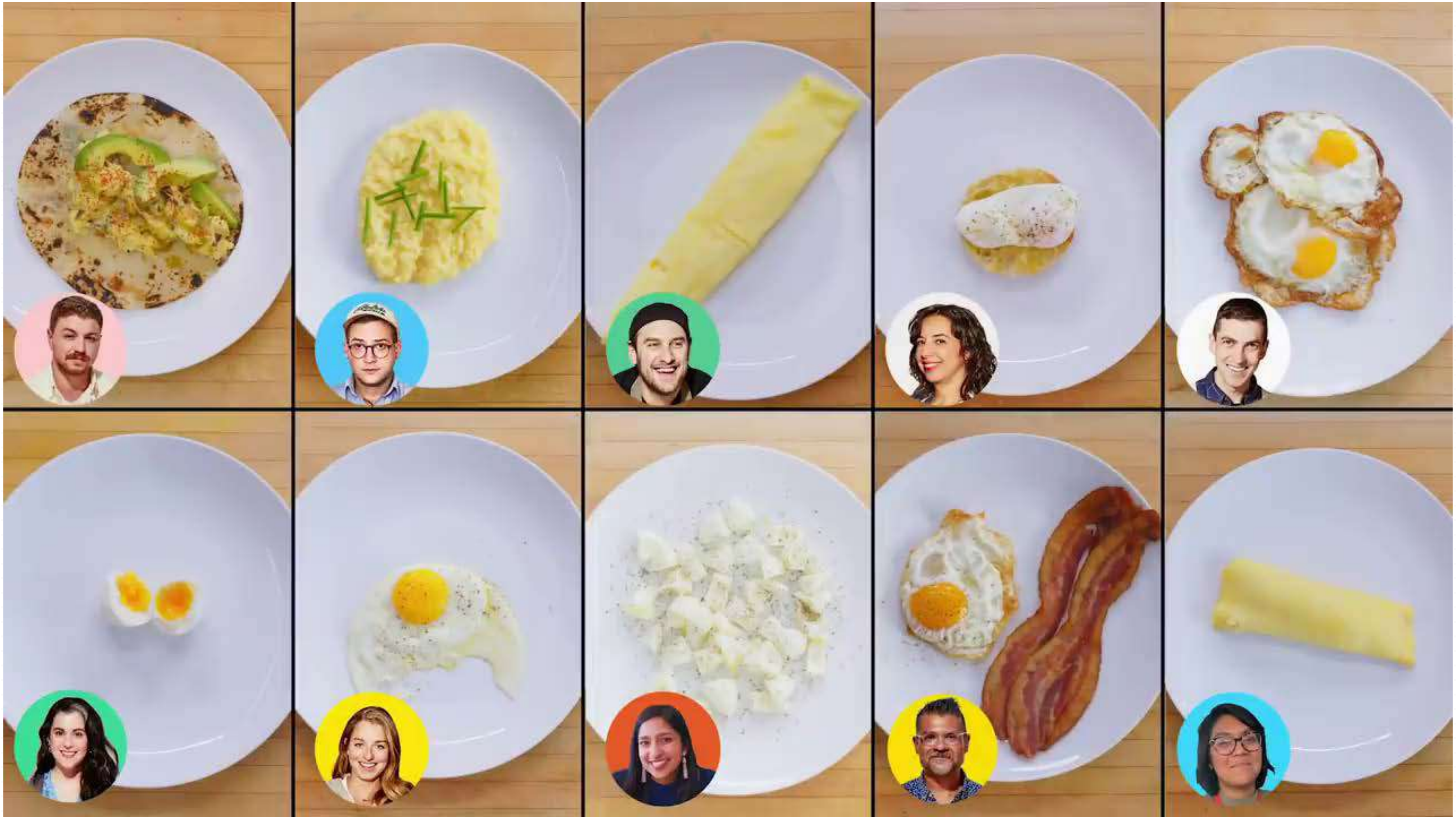
Reasoning for Physical Interaction
Understanding Purpose

Ideal Tool
During Training

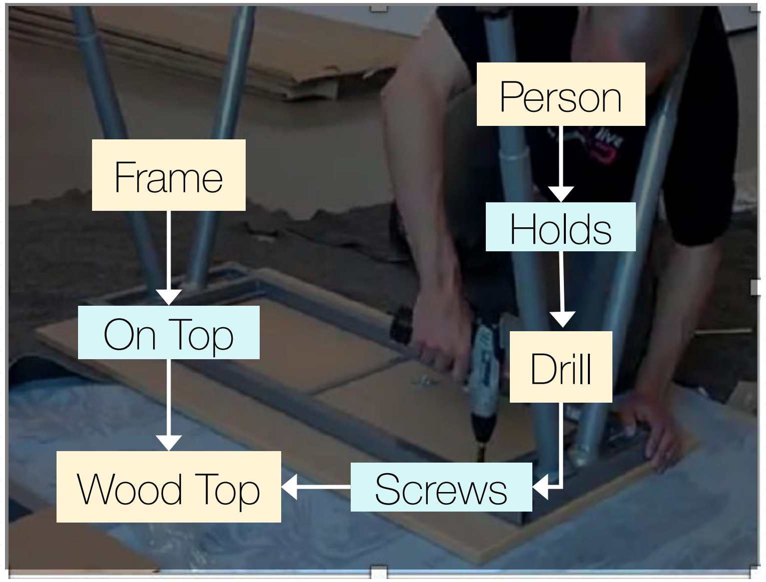



Task-Based Tool Adaptation
During Execution

Grounding: So many ways to "make eggs"



Generalizable Autonomy in Robot Manipulation



Higher-Order Semantics

What makes an object a hammer?

Failure

Success

State Change: Breaking Eggs

- Perception for Physical Interaction
- Reasoning through Learned Dynamics
- Transfer Learning with Formal Guarantees
- Continual Skill Adaptation & Accumulation

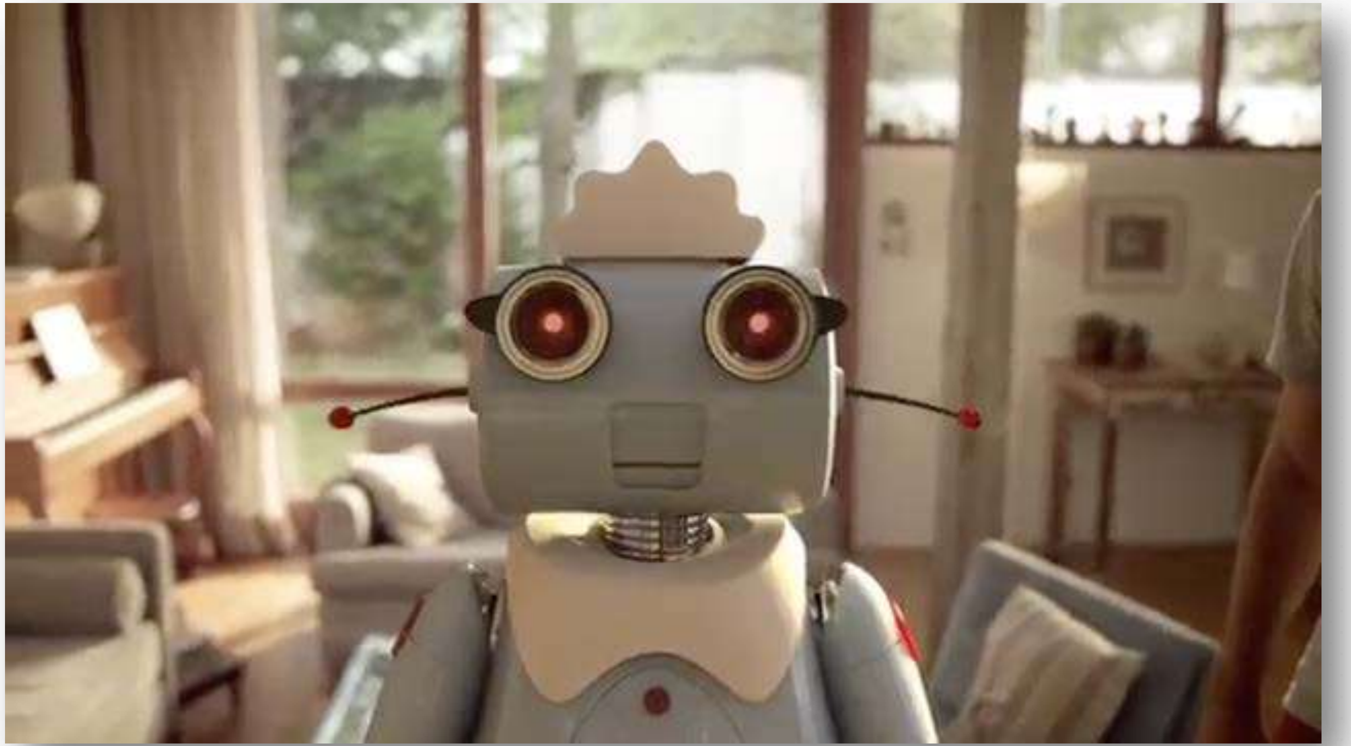
Generalizable Autonomy in Robot Manipulation

Learning with Structured Inductive Bias and Priors

- Efficiency and Generalization

- Combine: Domain Expertise + Data-Driven Methods

Generalizable Autonomy in Robot Manipulation



garg@cs.toronto.edu

@Animesh_Garg

Animesh Garg | UNIVERSITY OF TORONTO · VECTOR INSTITUTE · NVIDIA