

Symmetry in Decision Making

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GRAIL

Generalizable Robotics and
Artificial Intelligence Laboratory

Reinforcement learning is a promising framework for generalizable robotics.

Excitement



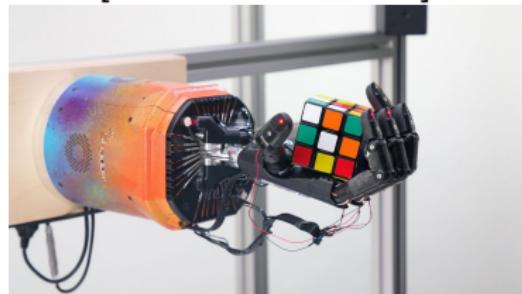
[Mnih et al. 2015]



[Silver et al. 2016]



[Levine et al. 2016]



[OpenAI 2019]

Excitement

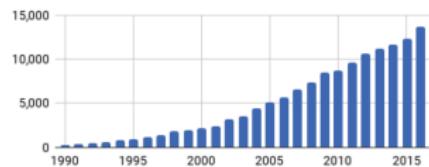


Figure 1: Growth of published reinforcement learning papers. Shown are the number of RL-related publications (y-axis) per year (x-axis) scraped from Google Scholar searches.

[Henderson et al. 2018]

Reinforcement Learning Papers Accepted to ICLR 2020

reinforcement-learning

Dec 24, 2019 • Seungjae Ryan Lee

| Rank | Average Rating | Title | Ratings | Variance | Decision |
|------|----------------|--|---------|----------|--------------------|
| 1 | 8.00 | Dynamics-aware Unsupervised Skill Discovery | 8 8 8 | 0.00 | Accept (Talk) |
| 1 | 8.00 | Contrastive Learning Of Structured World Models | 8 8 8 | 0.00 | Accept (Talk) |
| 1 | 8.00 | Implementation Matters In Deep RL: A Case Study On Ppo And Trpo | 8 8 8 | 0.00 | Accept (Talk) |
| 1 | 8.00 | Gendice: Generalized Offline Estimation Of Stationary Values | 8 8 8 | 0.00 | Accept (Talk) |
| 1 | 8.00 | Causal Discovery With Reinforcement Learning | 8 8 8 | 0.00 | Accept (Talk) |
| 2 | 7.33 | Is A Good Representation Sufficient For Sample Efficient Reinforcement Learning? | 8 8 6 | 0.89 | Accept (Spotlight) |
| 2 | 7.33 | Harnessing Structures For Value-based Planning And Reinforcement Learning | 6 8 8 | 0.89 | Accept (Talk) |
| 2 | 7.33 | Explain Your Move: Understanding Agent Actions Using Focused Feature Salency | 6 8 8 | 0.89 | Accept (Poster) |
| 2 | 7.33 | Meta-q-learning | 8 8 6 | 0.89 | Accept (Talk) |
| 2 | 7.33 | Discriminative Particle Filter Reinforcement Learning For Complex Partial Observations | 8 8 8 | 0.89 | Accept (Poster) |

Showing 1 to 10 of 106 entries

Previous 1 2 3 4 5 ... 11 Next

<https://www.endtoend.ai/blog/iclr2020-rl/>

Are we done?

Sorta Insightful

Reviews Projects Archive Research About 

In a world where everyone has opinions, one man...also has opinions

Deep Reinforcement Learning Doesn't Work Yet

Feb 14, 2018

June 24, 2018 note: If you want to cite an example from the post, please cite the paper which that example came from. If you want to cite the post as a whole, you can use the following BibTeX:

```
@misc{rlblogpost,
    title={Deep Reinforcement Learning Doesn't Work Yet},
    author={Irpan, Alex},
    howpublished={\url{https://www.alexirpan.com/2018/02/14/rl-hard.html}},
    year={2018}
}
```

This mostly cites papers from Berkeley, Google Brain, DeepMind, and OpenAI from the past few years, because that work is most visible to me. I'm almost certainly missing stuff from older literature and other institutions, and for that I apologize - I'm just one guy, after all.

Introduction

Once, on Facebook, I made the following claim.

Whenever someone asks me if reinforcement learning can solve their problem, I tell them it can't. I think this is right at least 70% of the time.

<https://www.alexirpan.com/2018/02/14/rl-hard.html>

Problem: Sample complexity / learning speed

Reinforcement Learning: works great for games and simulations.

► 57 Atari games: takes **83 hours equivalent real-time** (18 million frames) to reach a performance that humans reach in 15 minutes of play.
► [Hessel ArXiv:1710.02298]

► FAIR Elf OpenGo v2: 20 million self-play games. (2000 GPU for 14 days)
► [Tian arXiv:1902.04522]

► StarCraft: AlphaStar 200 years of equivalent real-time play
► [Vinyals blog post 2019]

► OpenAI

Please Use the Q&A Tool to Submit Your Questions

Relative normalized score

Millions of Frames

Y. LeCun

AlphaStar

StarCraft II

Relative Normalized Score

0% 100% 200%

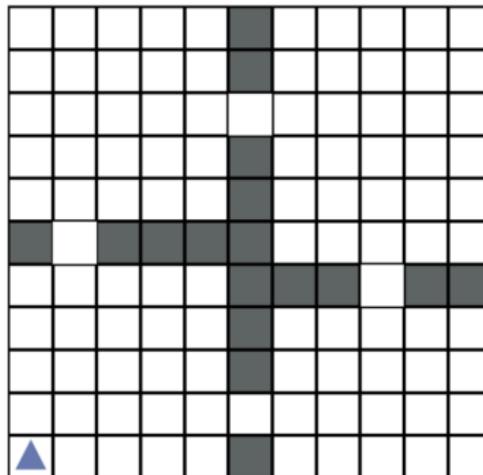
0 44 100 200 Millions of Frames

May 27, 2020

IEEE

[https://ieeetv.ieee.org/conference-highlights/
self-supervised-learning-world-models-icra-2020](https://ieeetv.ieee.org/conference-highlights/self-supervised-learning-world-models-icra-2020)
(See 11m00s in video)

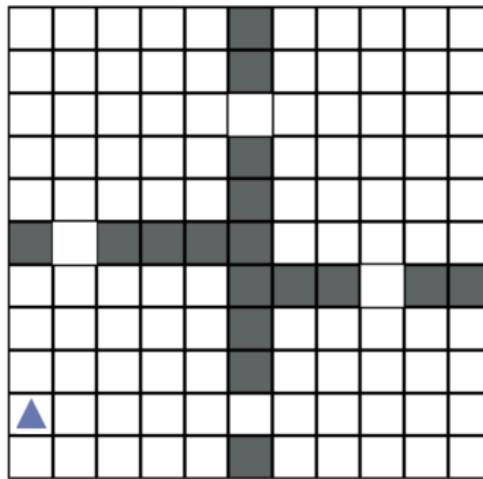
What is reinforcement learning?



(a) The Four Rooms Domain

State: $(0, 0)$

What is reinforcement learning?



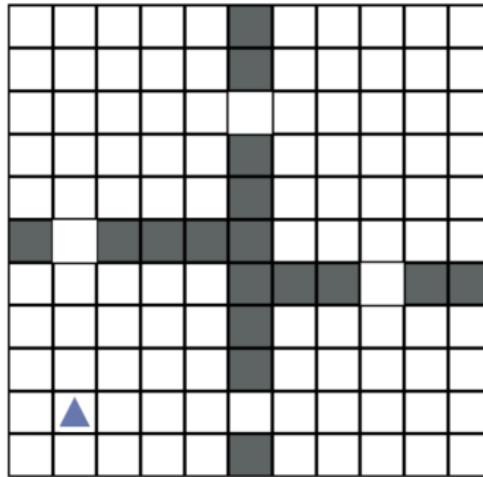
(a) The Four Rooms Domain

Action: up

State: $(0, 1)$

Reward: 0

What is reinforcement learning?



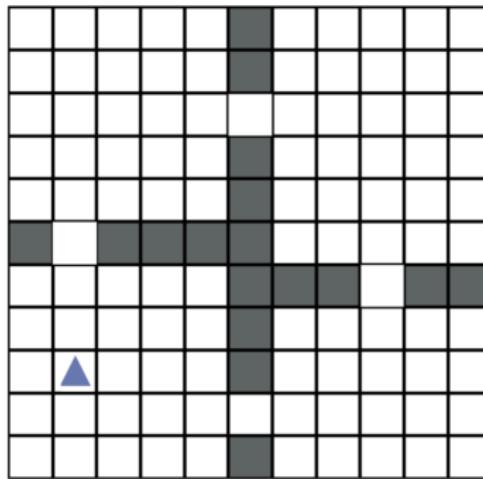
(a) The Four Rooms Domain

Action: up

State: (1, 1)

Reward: 0

What is reinforcement learning?



(a) The Four Rooms Domain

Action: up

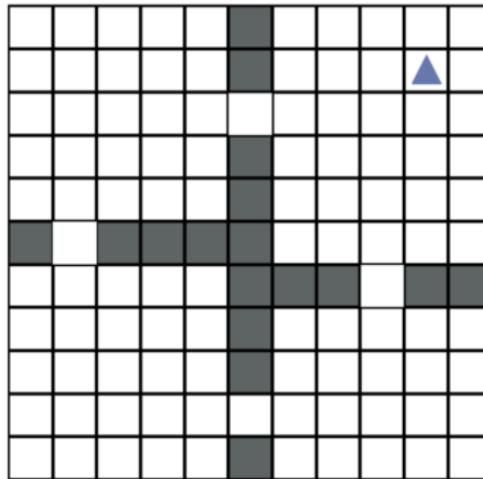
State: (1, 2)

Reward: 0

What is reinforcement learning?

(many time steps later ...)

What is reinforcement learning?



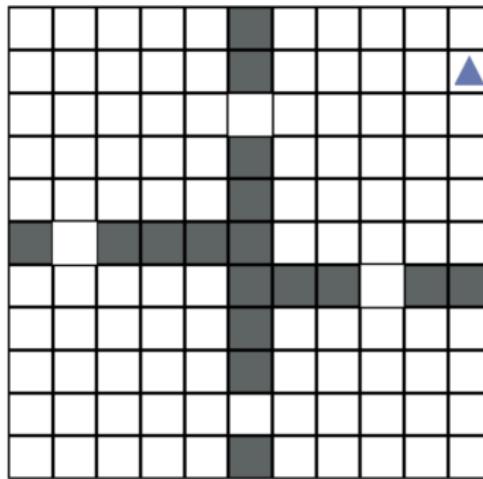
(a) The Four Rooms Domain

Action: right

State: (9, 9)

Reward: 0

What is reinforcement learning?



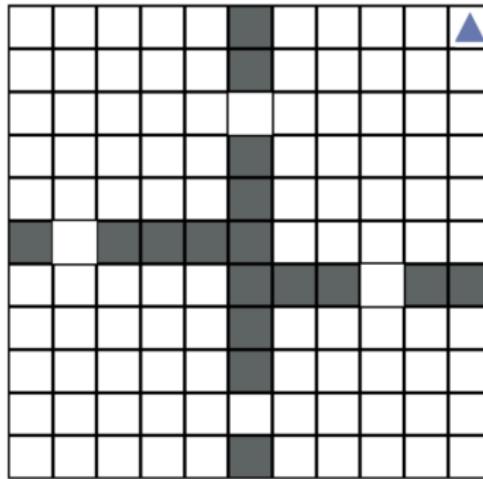
(a) The Four Rooms Domain

Action: right

State: (9, 10)

Reward: 0

What is reinforcement learning?



(a) The Four Rooms Domain

Action: up

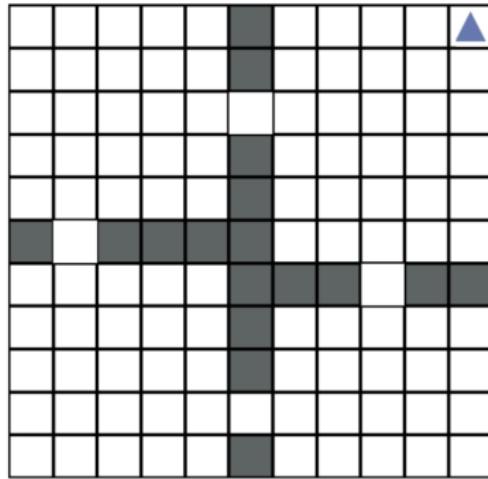
State: $(10, 10)$

Reward: +1

What is reinforcement learning?

(reset, try again)

What is reinforcement learning?



Objective: Find **policy**
(state-action mapping)

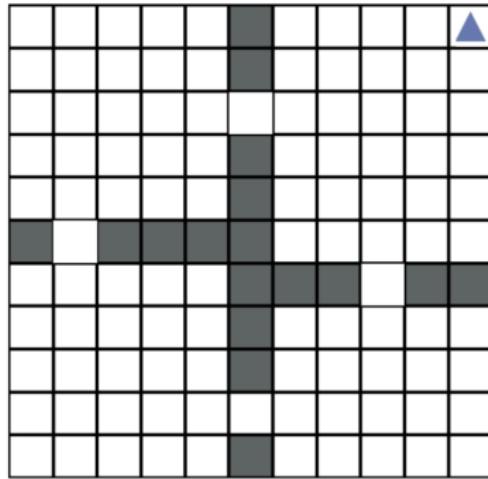
(a) The Four Rooms Domain

Action: up

State: $(10, 10)$

Reward: +1

What is reinforcement learning?



(a) The Four Rooms Domain

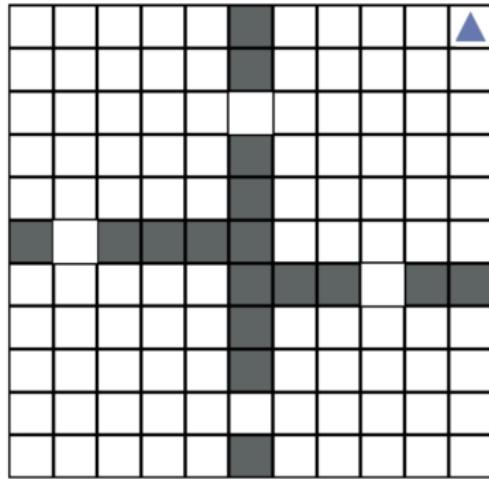
Action: up

State: $(10, 10)$

Reward: +1

Objective: Find **policy**
(state-action mapping)
that maximizes
expected sum of rewards

What is reinforcement learning?



(a) The Four Rooms Domain

Action: up

State: (10, 10)

Reward: +1

Objective: Find **policy**
(state-action mapping)
that maximizes
expected sum of rewards

Key issues:

- ▶ How good is +1?
- ▶ Credit assignment
- ▶ Sparse reward
- ▶ Exploration vs. exploitation

Thesis

Reinforcement learning is very general

Thesis

Reinforcement learning is very general ; but reinforcement learning algorithms are slow
because they are too general.

What additional guidance can we give RL agents so they are more specific but **useful**?

Symmetry in RL and decision making

- ▶ **Exploitation**

- Integrating symmetry into differentiable planning

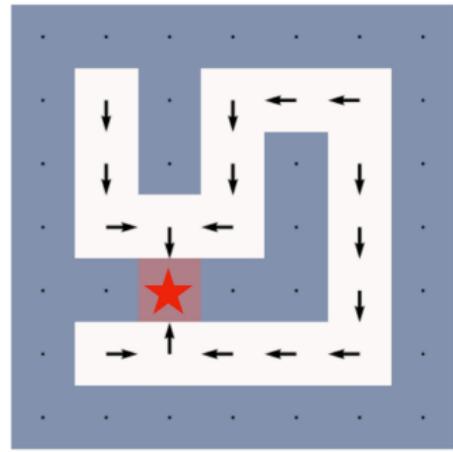
- ▶ **Opportunity**

- Robot navigation with coarse maps

- ▶ **Exploration**

- Speculative wish list

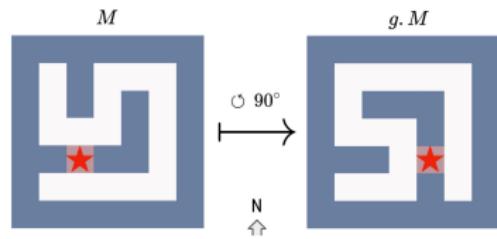
Symmetry in 2-D path-planning



Find shortest path / optimal actions to the goal location (red)

Symmetry in 2-D path-planning

What does the symmetry look like?



Linfeng Zhao *et al.* Integrating symmetry into differentiable planning with steerable convolutions.
ICLR 2023.



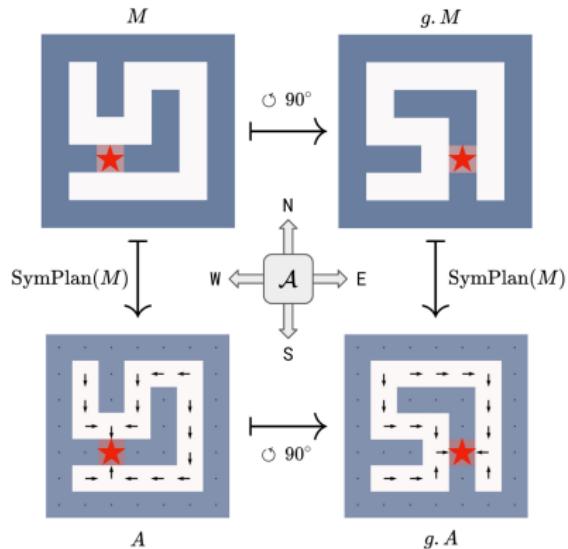
Symmetry in 2-D path-planning

What does the symmetry look like?

They can be described by

Equivariance

$$\circlearrowleft 90^\circ \circ (Plan(M)) = Plan(\circlearrowleft 90^\circ \circ M)$$



Linfeng Zhao *et al.* Integrating symmetry into differentiable planning with steerable convolutions.
ICLR 2023.



Symmetric planning: Background

- ▶ Classical planning:
Fox & Long, Pochter *et al.*, Domshlak
et al., Shleyfman *et al.*, Sievers *et al.*,
...
 - Perform orbit search

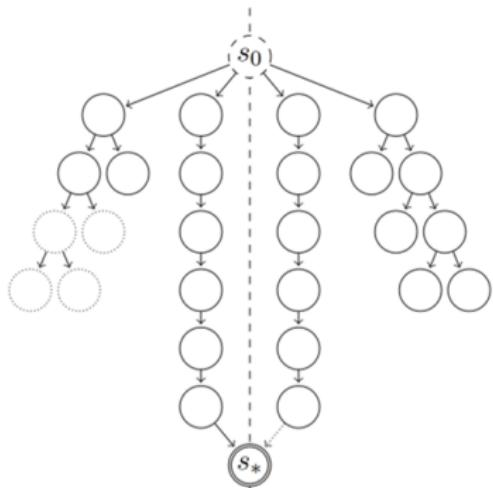


Figure from Shleyfman *et al.*

Symmetric planning: Background

- ▶ Classical planning:
Fox & Long, Pochter *et al.*, Domshlak
et al., Shleyfman *et al.*, Sievers *et al.*,
...
 - Perform orbit search
- ▶ Symmetries in MDPs:
Ravindran & Barto, Ravindran, Ferns
et al., Narayananurthy & Ravindran,
van der Pol *et al.*, ...
 - Construct “quotient MDP”

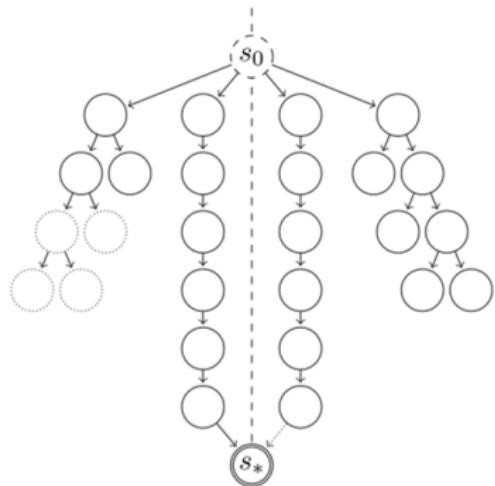


Figure from Shleyfman *et al.*

Symmetric planning: Background

Differentiable value iteration / planning algorithms:

Make planning algorithms fully differentiable

- ▶ Value iteration: Tamar *et al.*, Niu *et al.*, Lee *et al.*, Xu *et al.*, Chaplot *et al.*, Deac *et al.*, ...
- ▶ Differentiable planning: Oh *et al.*, Karkus *et al.*, Weber *et al.*, Srinivas *et al.*, Schrittwieser *et al.*, Amos & Yarats, Wang & Ba, Guez *et al.*, Hafner *et al.*, Pong *et al.*, Clavera *et al.*, Hansen *et al.*, ...

Bellman equation

$$Q(s, a) = R(s, a) + \gamma \sum_{s'} \mathbb{P}(s'|s, a') V(s')$$

$$V(s) = \max_a Q(s, a)$$

Learn R_a, P_a

$$Q_a = R_a + \text{Conv2D}(V, P_a)$$

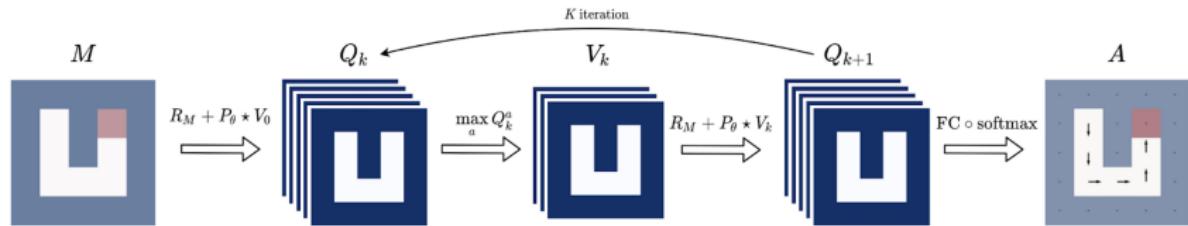
$$V = \max_a Q_a$$

Symmetric planning: Background

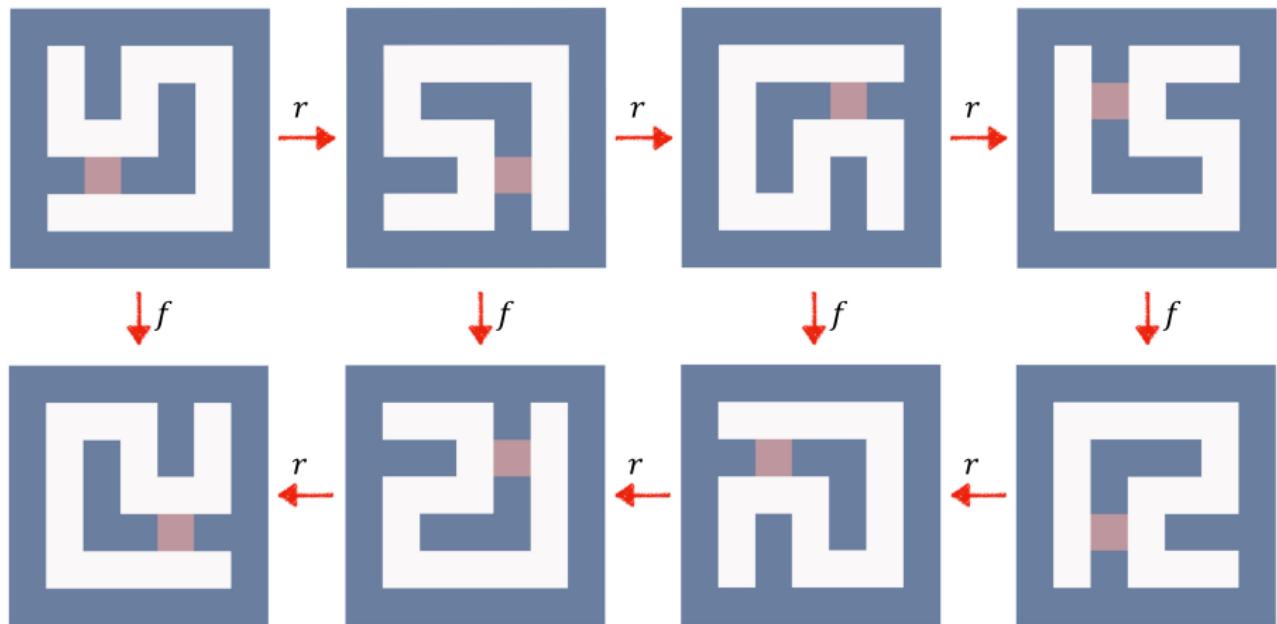
Differentiable value iteration / planning algorithms:

Make planning algorithms fully differentiable

- ▶ Value iteration: Tamar *et al.*, Niu *et al.*, Lee *et al.*, Xu *et al.*, Chaplot *et al.*, Deac *et al.*, ...
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Symmetry in 2-D path-planning: D_4



Exploiting symmetry in 2-D path-planning

Every update is equivariant
— Local Equivariance



Entire planning is equivariant
— Global Equivariance

$$\mathcal{G} 90^\circ \circ VI(M) \equiv \mathcal{G} 90^\circ \circ \mathcal{T}^\infty[V_0] = \mathcal{T}^\infty[\mathcal{G} 90^\circ \circ V_0] \equiv VI(\mathcal{G} 90^\circ \circ M)$$

- Use steerable convolution, equivariant to rotation and reflection:

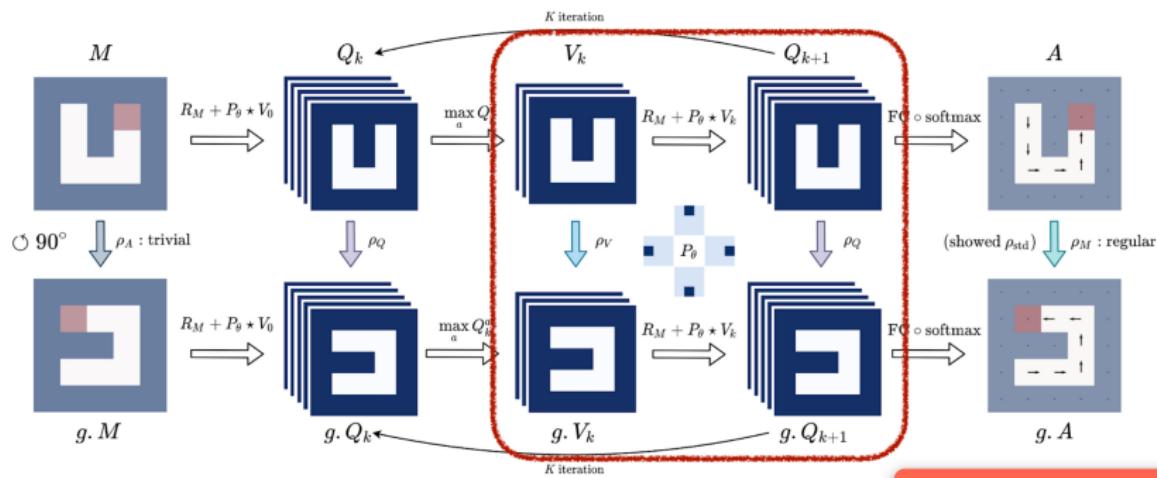
$$\bar{Q}^{(k)} = \bar{R}^a + Conv2D(\bar{V}^{(k-1)}; W_{\bar{a}}^V)$$



Replace

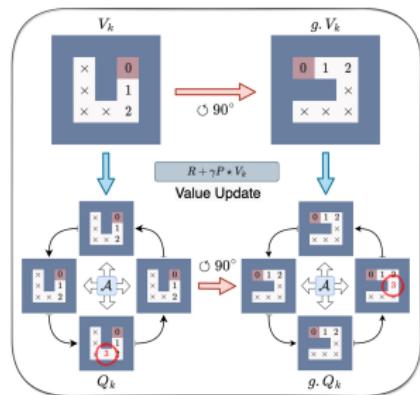
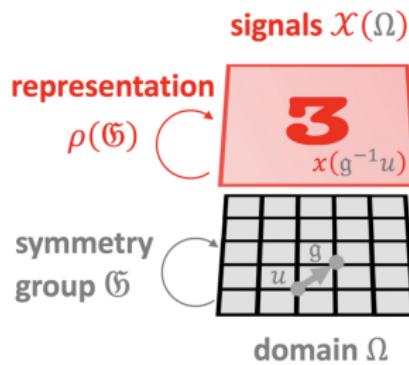
$$\bar{Q}_{\bar{a}}^{(k)} = \bar{R}_{\bar{a}} + SteerableConv(\bar{V}; W^V)$$

Symmetric planning: SymVIN



We use steerable convolutions to integrate symmetry in VINs.

Symmetric planning: Insights

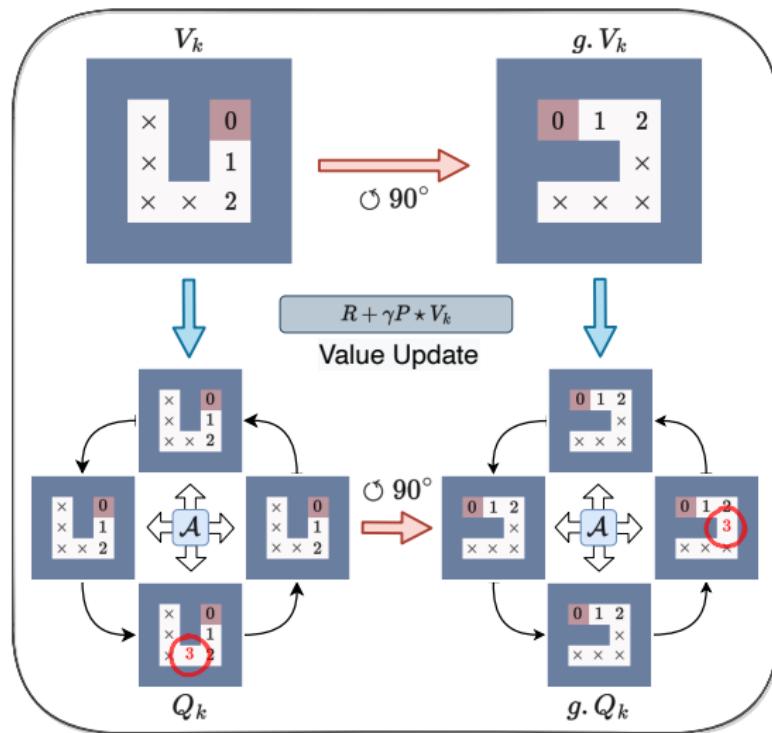


1: Represent (value) functions as “fields”

2: Value iteration as convolution (network)

Bronstein et al. (2021): Geometric Deep Learning: Grids, Groups, Graphs, Geodesics, and Gauges. arXiv.

Symmetric planning: Bellman back-up



Symmetric planning: Theory

Theorem 1 (informal): **Value iteration for path planning*** is equivariant to translation, rotation, and reflection

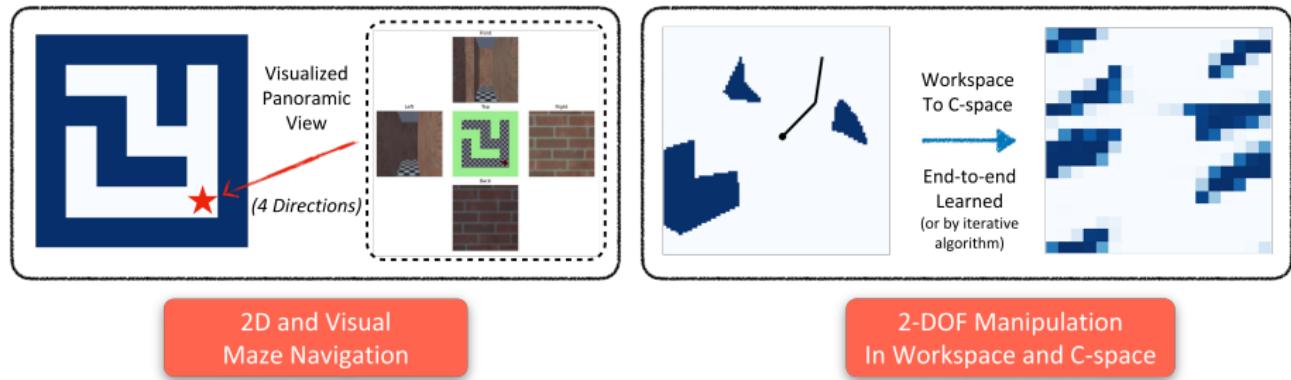
Theorem 2 (informal): **Value iteration for path planning*** is a form of **steerable convolution network****

*: Path planning on 2D grid, an example of homogeneous spaces

**: Steerable CNN over grids, equivariant under induced representations

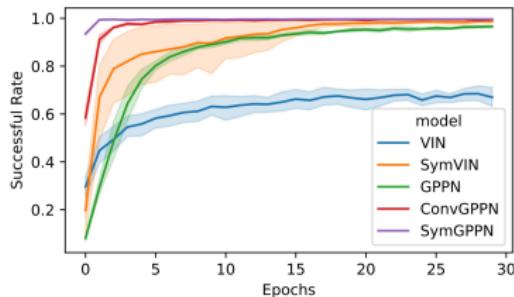
Cohen et al. (2017): Steerable CNNs, ICLR 2017

Symmetric planning: Domains

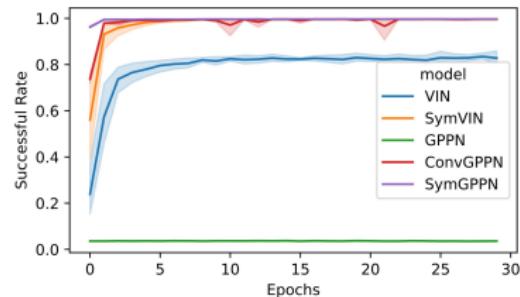


Symmetric planning: Efficient training

2D Maze Navigation



2-DOF Manipulation



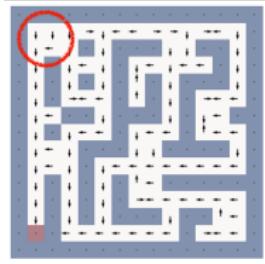
- Training curves on 15x15 maps
- All networks use 3x3 filters, fixed 30 iterations (shared convolution layers)
- SymGPPN — recurrent version of VIN with steerable convolution

Symmetric planning: Higher success rates

| Method (10K Data) | Navigation | | | | Manipulation | | |
|----------------------|--------------|--------------|--------------|--------------|---------------|--------------|--------------|
| | 15 × 15 | 28 × 28 | 50 × 50 | Visual | 18 × 18 | 36 × 36 | Workspace |
| VIN | 66.97 | 67.57 | 57.92 | 50.83 | 77.82 | 84.32 | 80.44 |
| SymVIN | 98.99 | 98.14 | 86.20 | 95.50 | 99.98 | 99.36 | 91.10 |
| GPPN | 96.36 | 95.77 | 91.84 | 93.13 | 2.62 | 1.68 | 3.67 |
| ConvGPPN | 99.75 | 99.09 | 97.21 | 98.55 | 99.98 | 99.95 | 89.88 |
| SymGPPN | 99.98 | 99.86 | 99.49 | 99.78 | 100.00 | 99.99 | 90.50 |

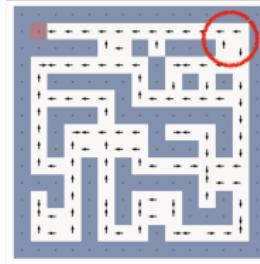
Symmetric planning: Equivariance

Feed in M and $\mathcal{O} 90^\circ \circ M$

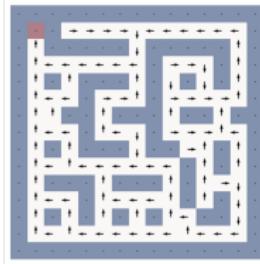
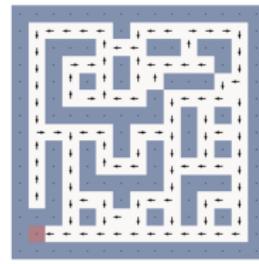


VIN output doesn't satisfy equivariance

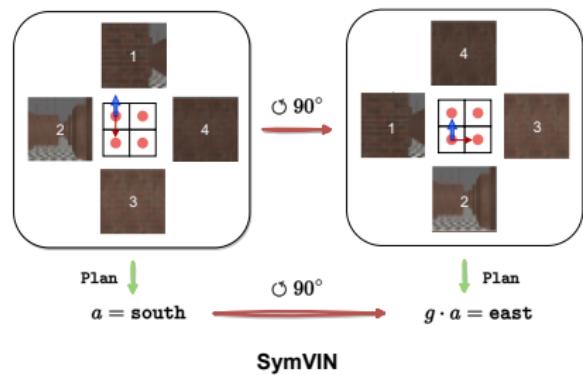
Feed in M and $\mathcal{O} 90^\circ \circ M$



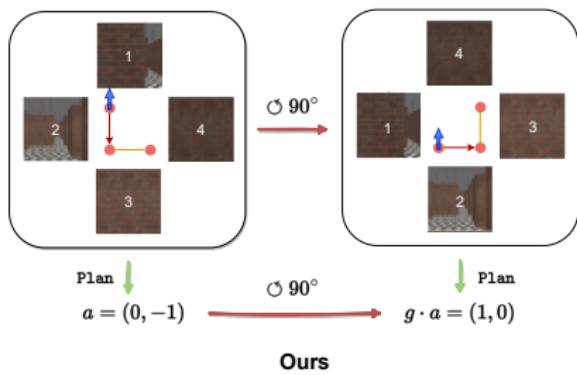
SymVIN guarantees output is equivariant



Extension: Symmetric planning on graphs



SymVIN

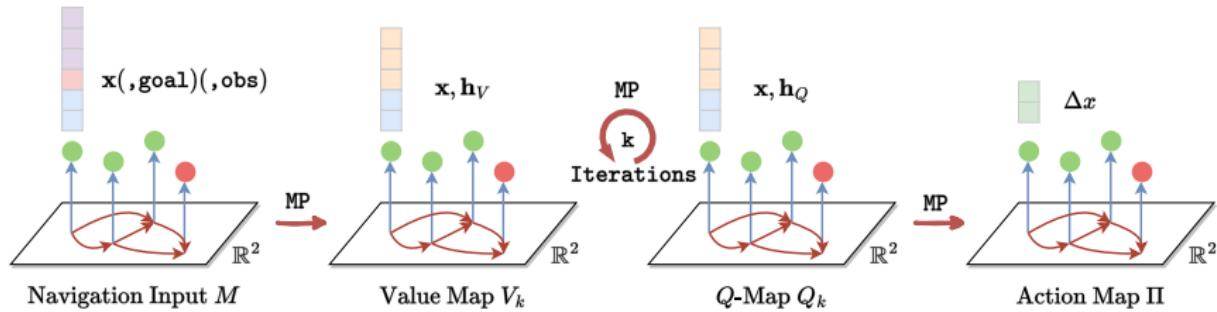


Ours

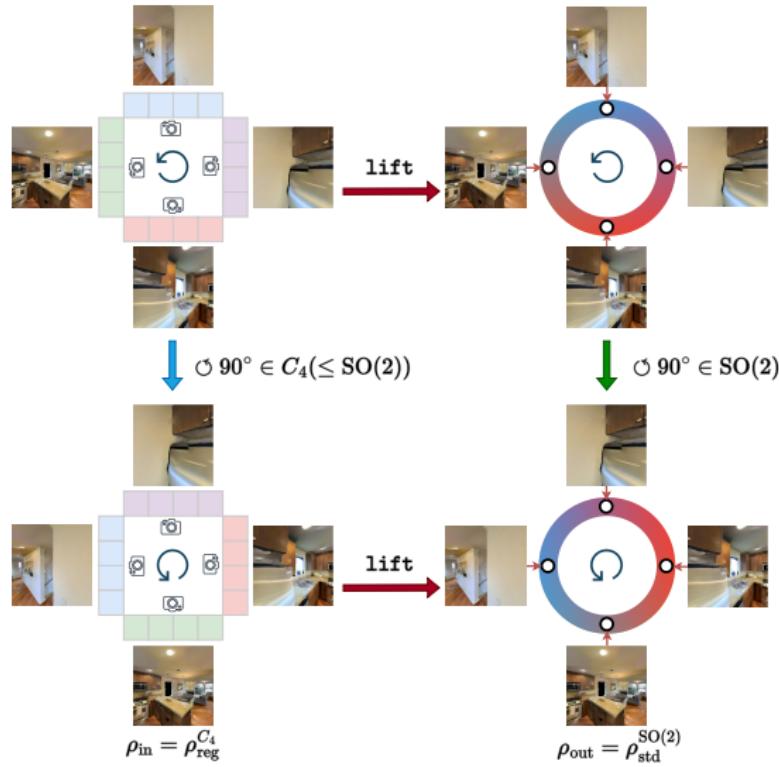
Linfeng Zhao*, Hongyu Li* et al. $E(2)$ -equivariant graph planning for navigation. In submission.



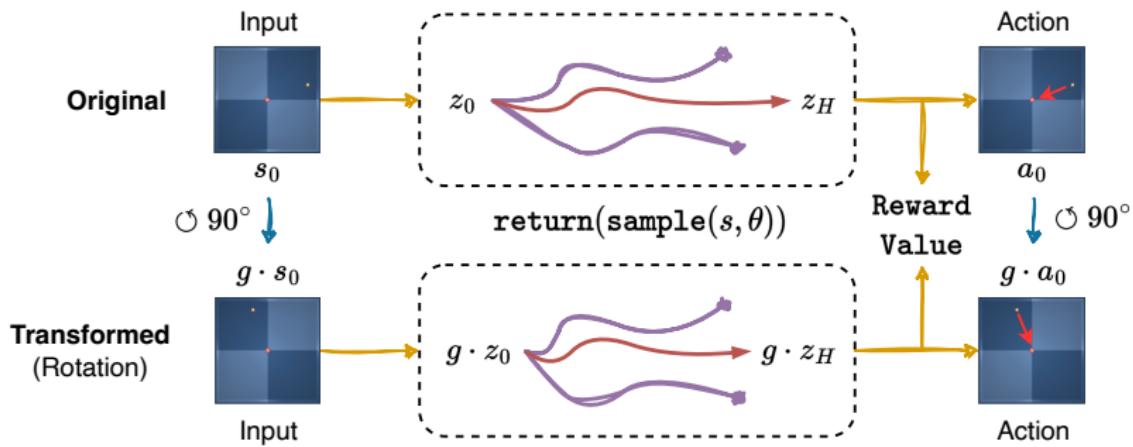
Extension: Symmetric planning on graphs



Extension: Symmetric planning on graphs



Extension: Sampling-based symmetric planning



Linfeng Zhao et al. Can Euclidean symmetry help in reinforcement learning and planning? In submission.

See Linfeng's poster!



Symmetry in RL and decision making

- ▶ **Exploitation**

Integrating symmetry into differentiable planning

- ▶ **Opportunity**

Robot navigation with coarse maps

- ▶ **Exploration**

Speculative wish list

Navigation

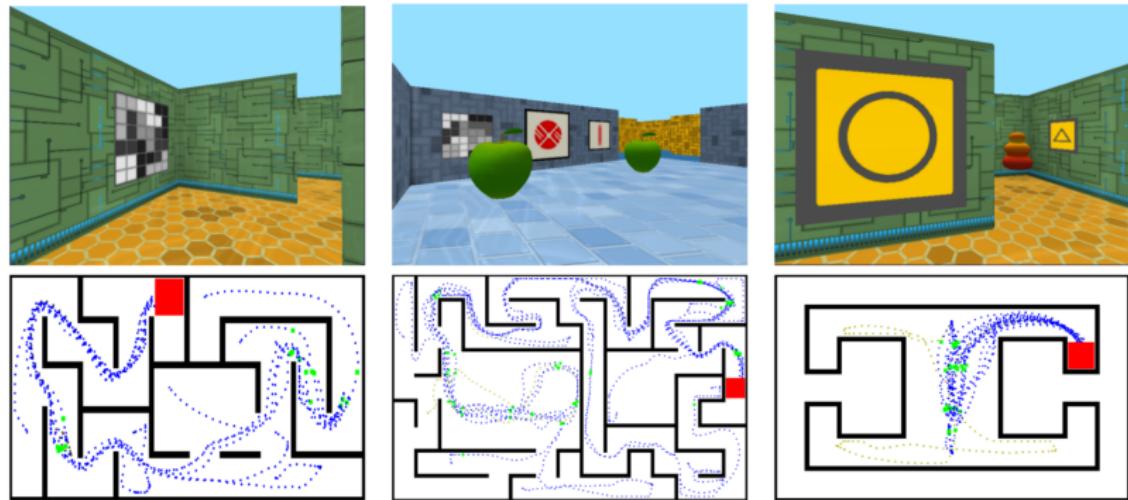


Figure 1: Views from a small 5×10 maze, a large 9×15 maze and an I-maze, with corresponding maze layouts and sample agent trajectories. The mazes, which will be made public, have different textures and visual cues as well as exploration rewards and goals (shown right).

Learning to navigate in complex environments [Mirowski et al. 2017]

Navigation

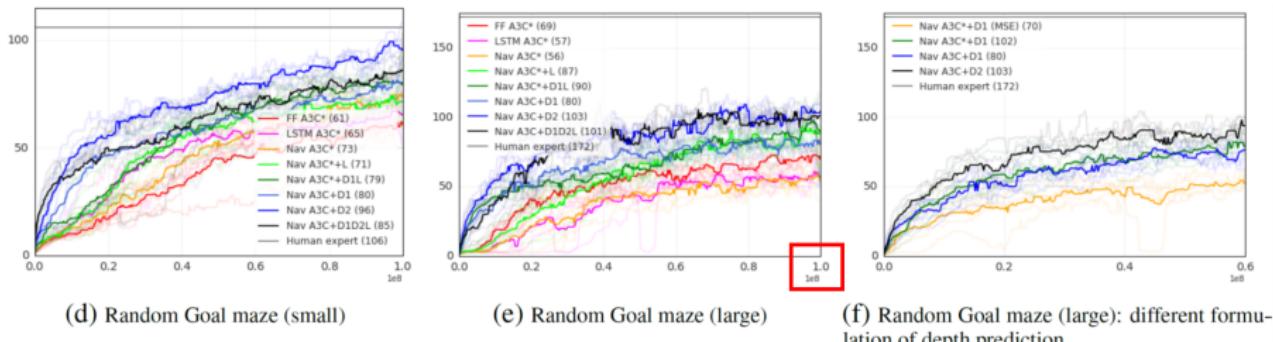
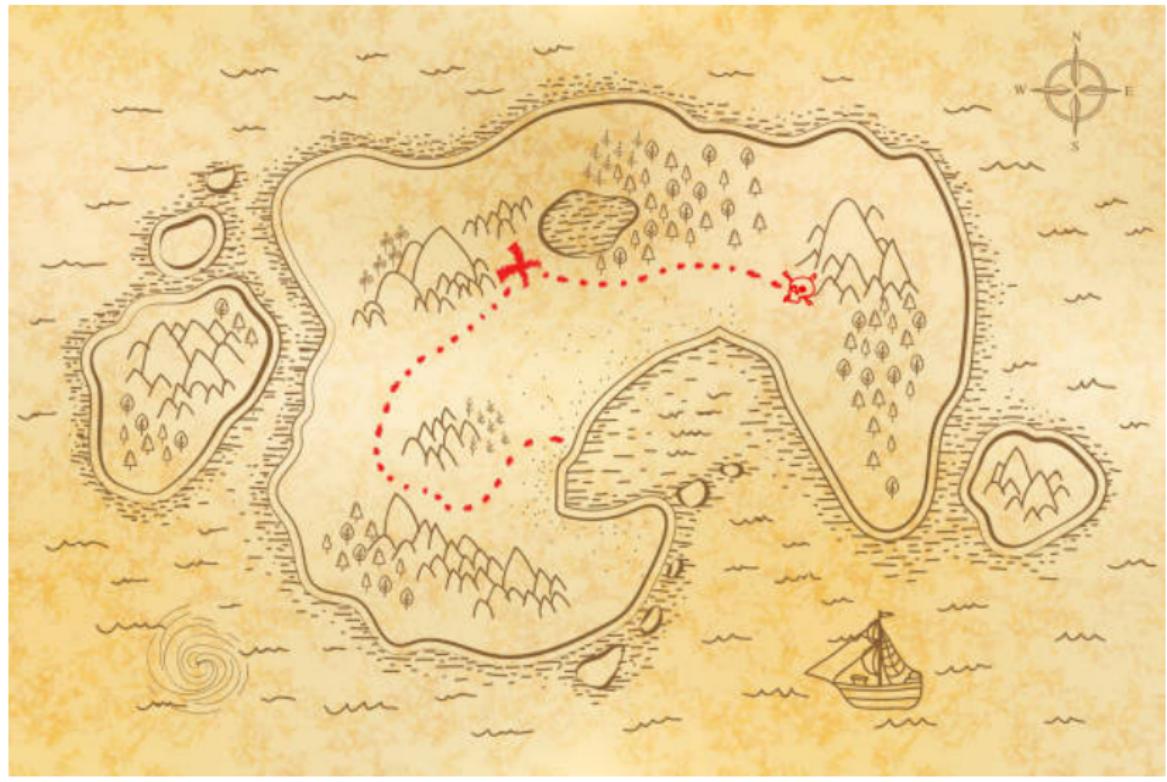


Figure 3: Rewards achieved by the agents on 5 different tasks: two static mazes (small and large) with fixed goals, two static mazes with comparable layout but with dynamic goals and the I-maze. Results are averaged over the top 5 random hyperparameters for each agent-task configuration. Star in the label indicates the use of reward clipping. Please see text for more details.

Learning to navigate in complex environments [Mirowski et al. 2017]

Navigation with a map



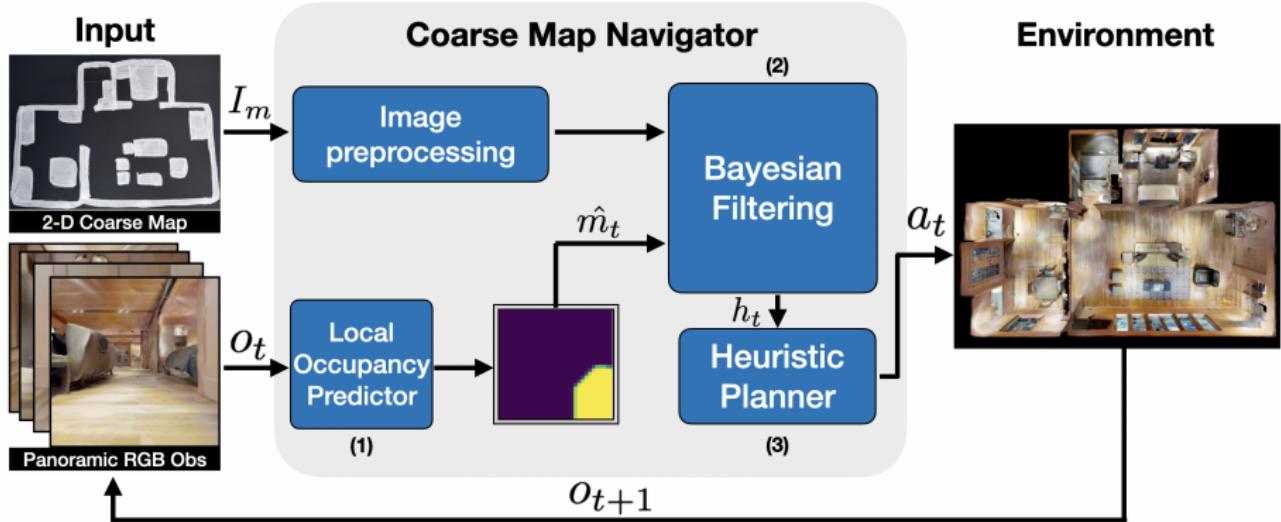
Navigation with a map



Academic and Service Buildings

- 12 1st Thr. Fensore (104)
- 22 177 Huntington (127)
- 23 256 Massachusetts Ave (216)
- 24 258 Huntington (224)
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Coarse map navigator



Chengguang Xu *et al.* Hierarchical robot navigation in novel environments using rough 2-D maps. CoRL 2020.

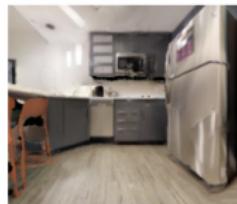
Chengguang Xu *et al.* Robot navigation in unseen environments using coarse maps. In submission.



Coarse map navigator

Panoramic RGB view

F



L



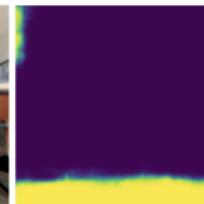
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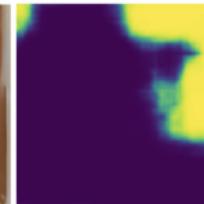
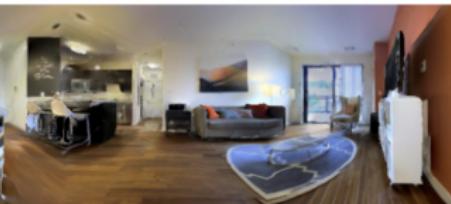
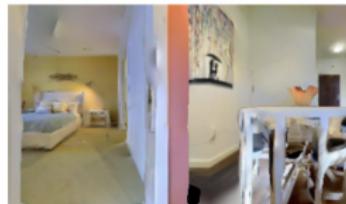


Prediction

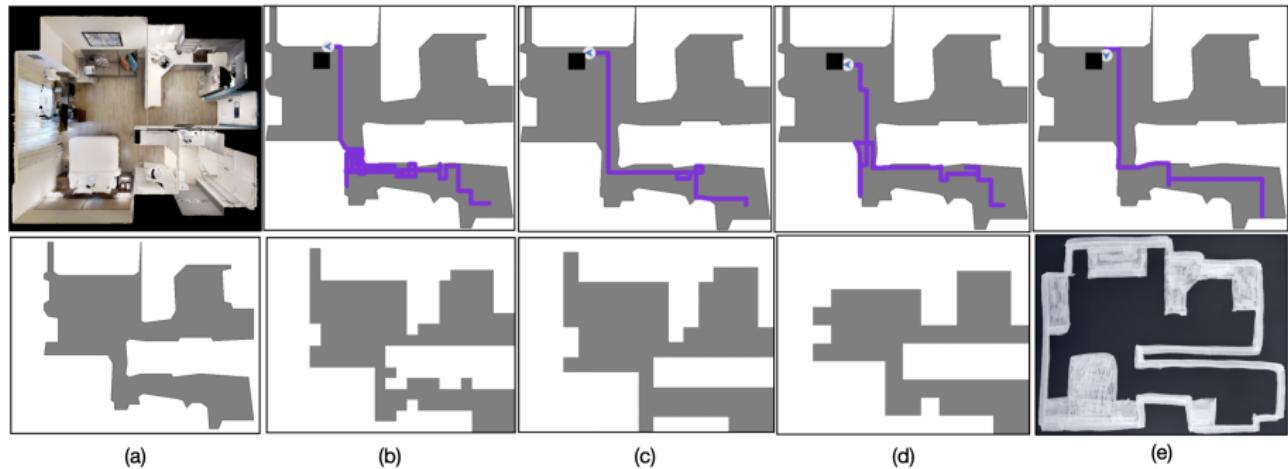


Local occupancy

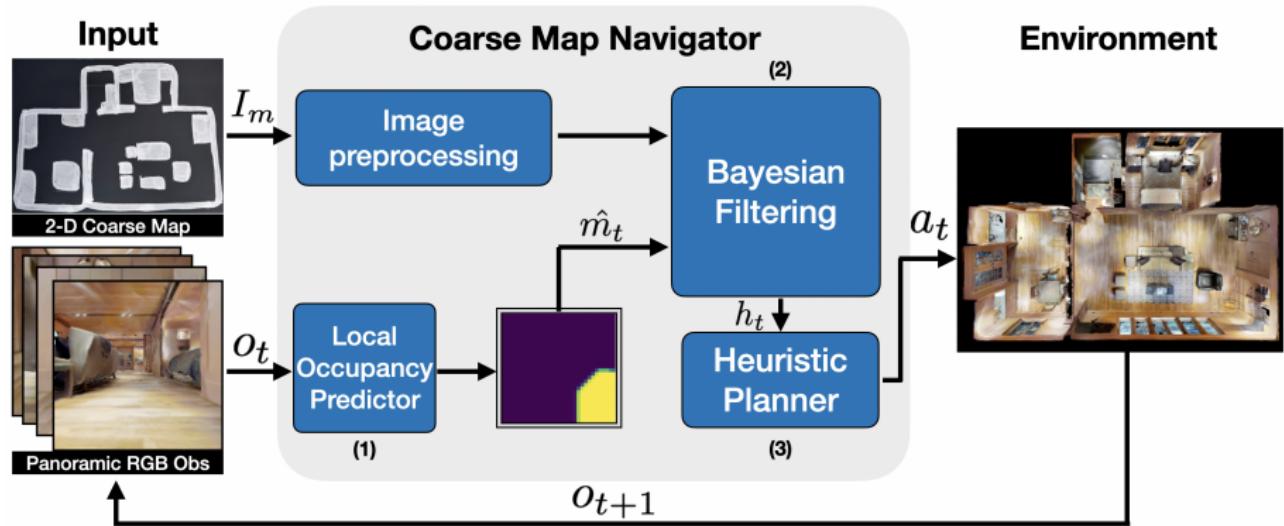
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Coarse map navigator



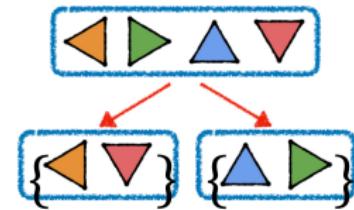
Opportunities for leveraging symmetry



Opportunities for leveraging symmetry

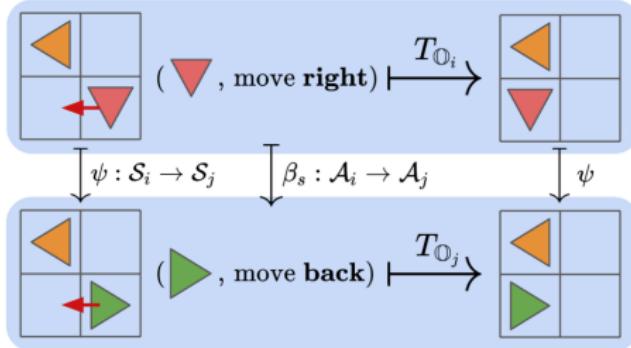


Why does CMN work? Compositional generalization



Object Interchangeability

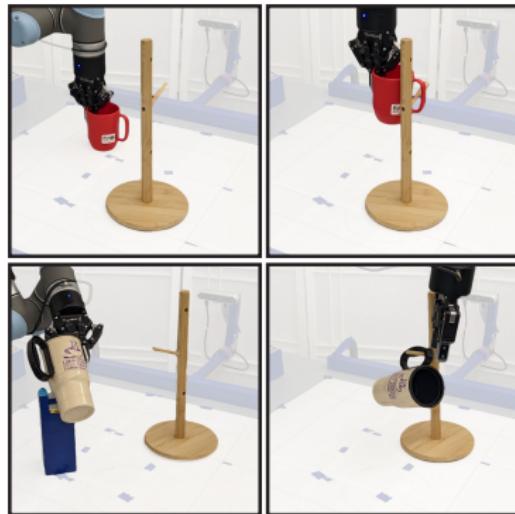
Permutation Symmetry S_N



Linfeng Zhao *et al.* Toward compositional generalization in object-oriented world modeling. ICML 2022.



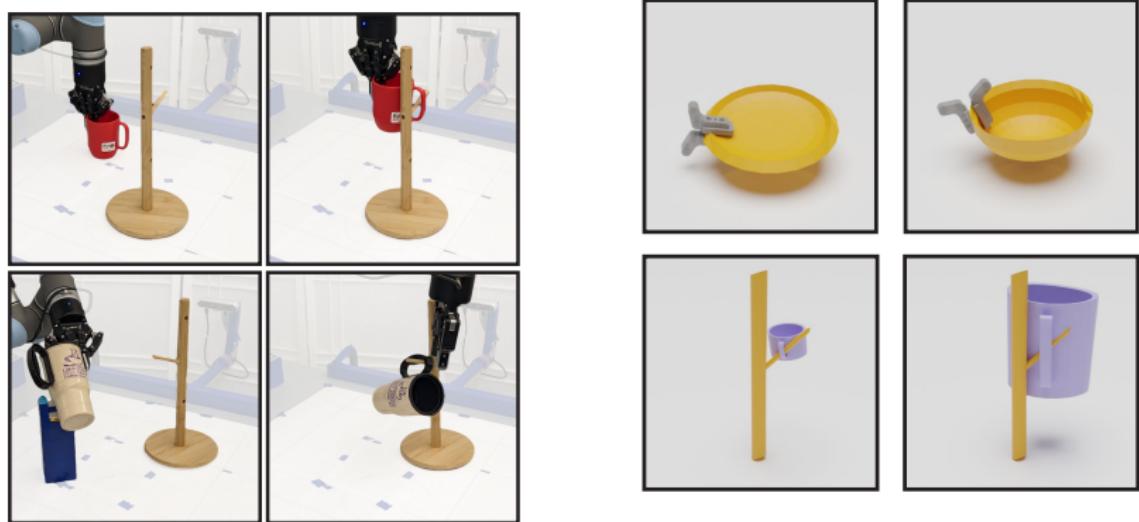
Following one high-level trajectory



Ondrej Biza *et al.* One-shot imitation learning via interaction warping. CoRL 2023.



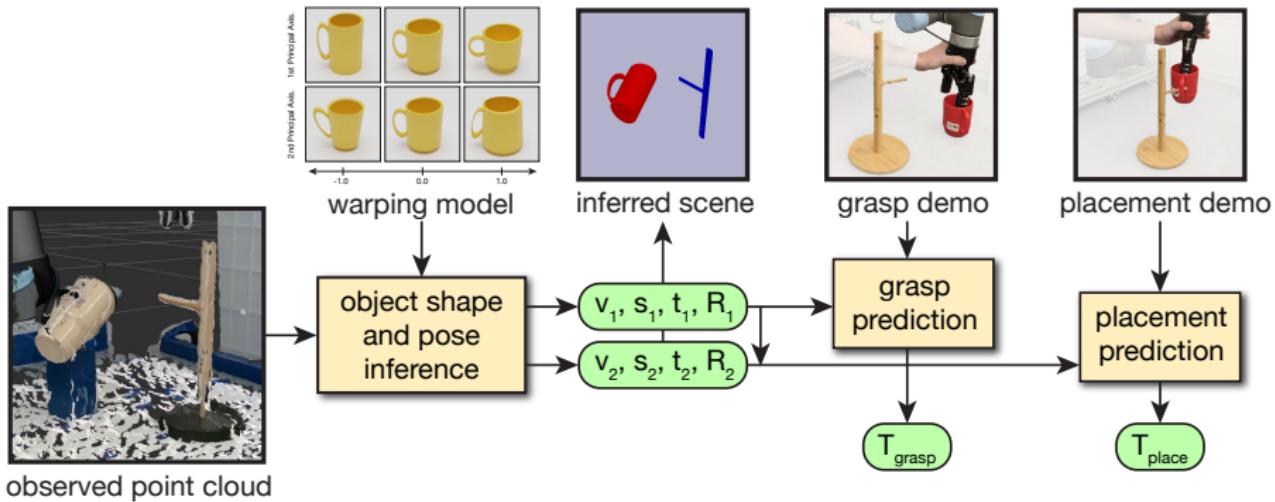
Following one high-level trajectory



Ondrej Biza *et al.* One-shot imitation learning via interaction warping. CoRL 2023.



Following one high-level trajectory



Symmetry in RL and decision making

- ▶ **Exploitation**

Integrating symmetry into differentiable planning

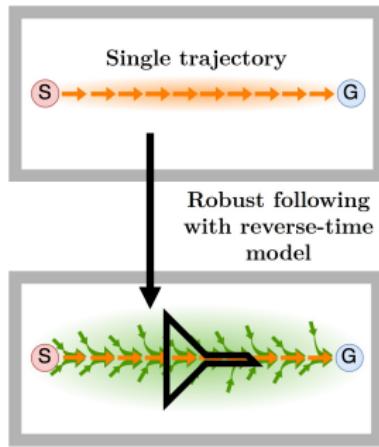
- ▶ **Opportunity**

Robot navigation with coarse maps

- ▶ **Exploration**

Speculative wish list

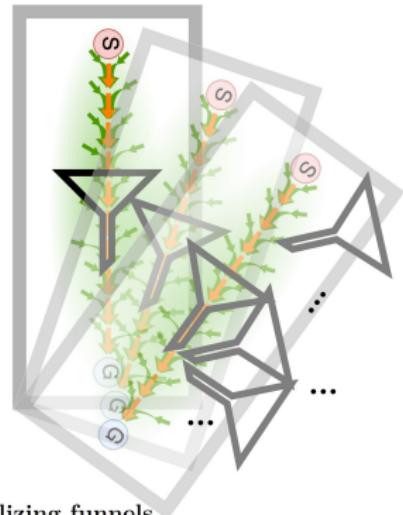
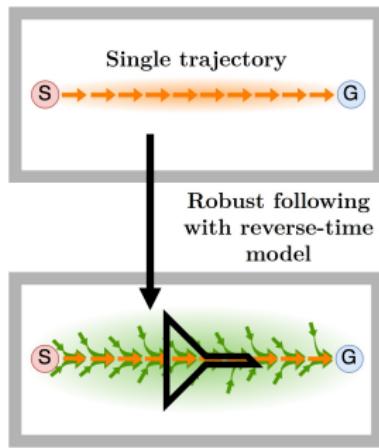
Demonstration \times symmetry



Jung Yeon Park & Wong. Robust imitation of a few demonstrations with a backwards model. NeurIPS 2022.
See John's poster! (on a different subject)



Demonstration \times symmetry



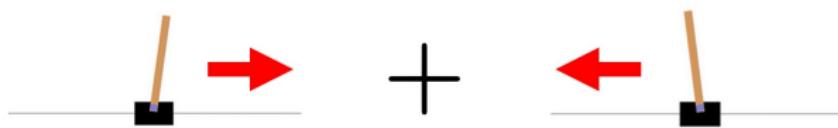
Generalizing funnels
with symmetry

Jung Yeon Park & Wong. Robust imitation of a few demonstrations with a backwards model. NeurIPS 2022.
See John's poster! (on a different subject)

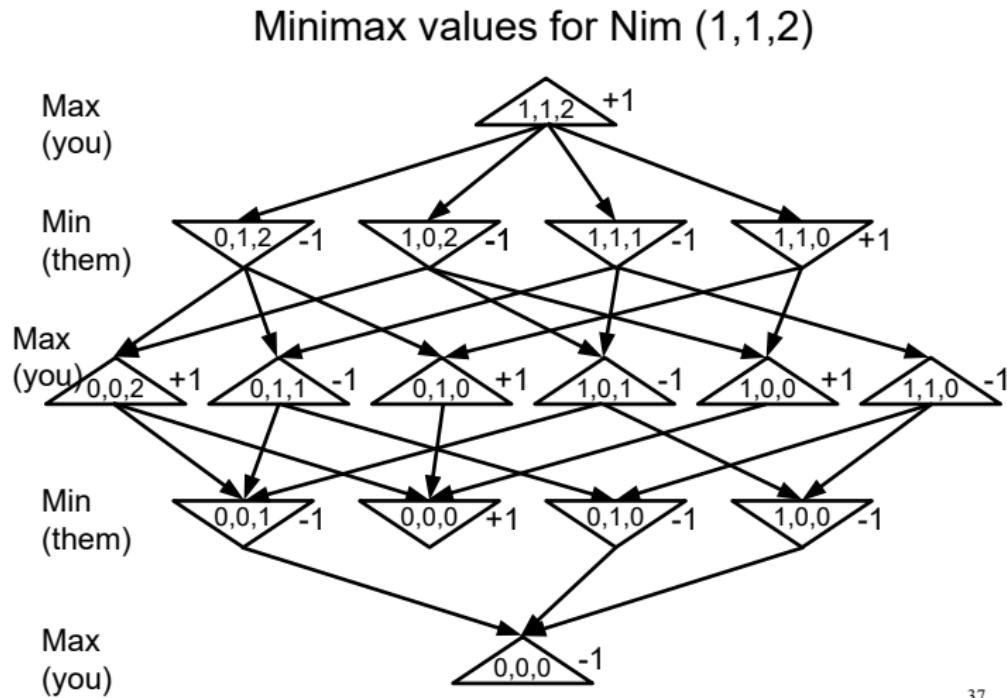


Symmetry discovery by demonstration

Discovering symmetry by demonstration:
Inferring reflection symmetry in cart-pole



The symmetry of (repeated) computation

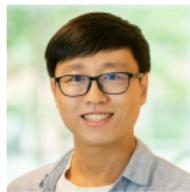


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Acknowledgments and references



Linfeng Zhao



Chengguang Xu



Ondřej Bíža



Jung Yeon Park



Robin Walters



Christopher Amato



Robert Platt



Xupeng Zhu, Lingzhi Kong, Hongyu Li, Owen Howell, Dian Wang

Kevin Robb, Skye Thompson, Kishore Reddy Pagidi, Abhinav Kumar, Neel Sortur

Taşkın Padır, Huaizu Jiang

Elise van der Pol, Thomas Kipf, Jan-Willem van de Meent

Acknowledgments and references



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Ondřej Bíža



Jung Yeon Park



Robin Walters



Christopher Amato



Robert Platt



National
Science
Foundation

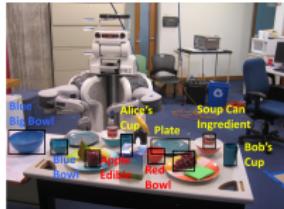
Integrating symmetry into differentiable planning with steerable convolutions. ICLR 2023

$E(2)$ -equivariant graph planning for navigation. In submission.

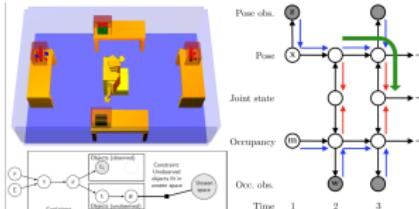
Can Euclidean symmetry be leveraged in RL and planning? In submission.

Hierarchical robot navigation in novel environments using rough 2-D maps. CoRL 2020.

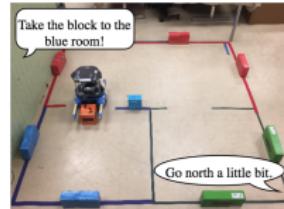
Robot navigation in unseen environments using coarse maps. In submission.



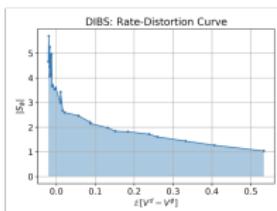
Object-based world modeling



Efficient state estimation

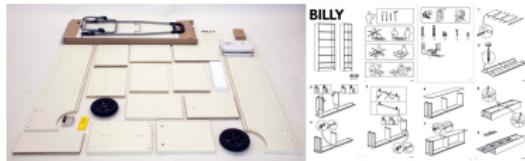


Grounding natural language



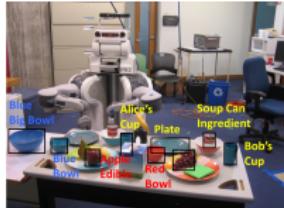
Fundamental limits of abstraction

Learning Task-relevant State representations

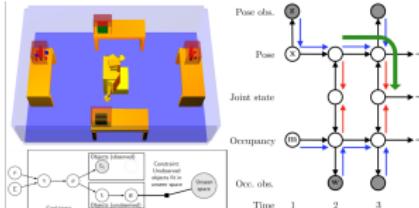


Learning to use existing abstractions

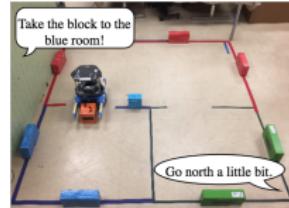
Let's chat! lsw@ccs.neu.edu



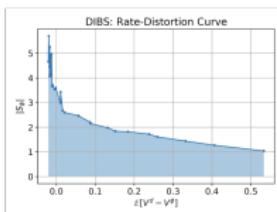
Object-based world modeling



Efficient state estimation



Grounding natural language



Fundamental limits of abstraction

Learning
Task-relevant
State representations



Learning to use existing abstractions

My research agenda

Identify and learn **intermediate state representations** that enable effective robot learning and planning, and therefore enable **robot generalization**.

Let's chat! lsw@ccs.neu.edu