Composable Causality in Semantic Robot Programming

May 2021

Emily Sheetz

Advised by Odest Chadwicke Jenkins

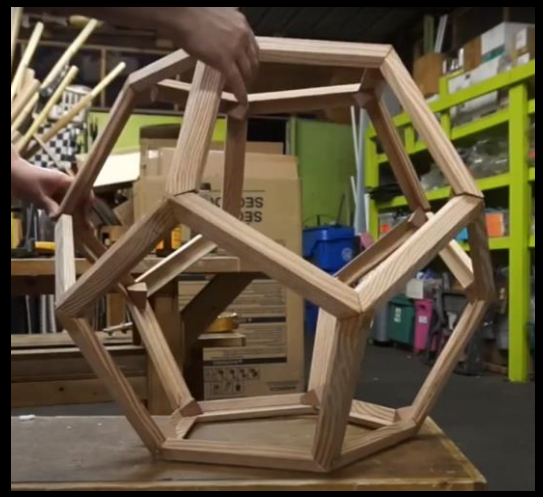
Challenges of Assembly Tasks

Barb Makes Things. “Dodecahedrum Frame – Fully Assembled!” YouTube.

Goal-Directed Manipulation Tasks

Initial Scene

Goal Scene



Semantic Robot Programming (SRP)

Understand goal state through perception

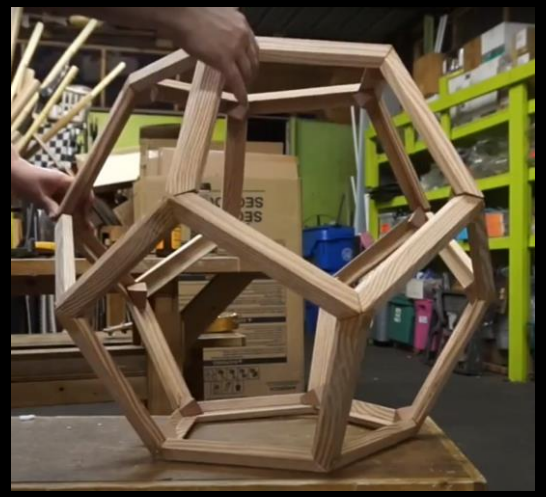
Move beyond atomic actions and motion planning

[2] Z. Zeng, Z. Zhou, Z. Sui, and O. C. Jenkins. "Semantic Robot Programming for Goal-Directed Manipulation in Cluttered Scenes." *IEEE ICRA*, 2018.

Goal-Directed Manipulation Tasks

Initial Scene

Goal Scene

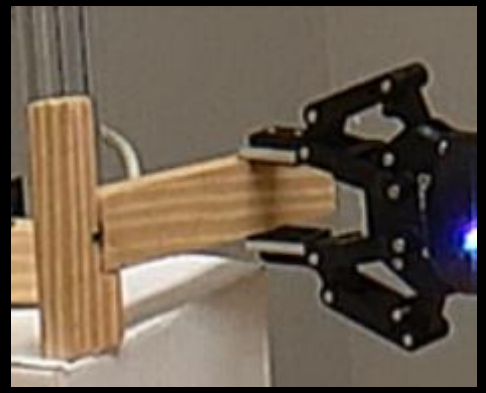


Extend SRP to allow robots to reason over and execute multi-objective object affordances in long-horizon tasks

[2] Z. Zeng, Z. Zhou, Z. Sui, and O. C. Jenkins. “Semantic Robot Programming for Goal-Directed Manipulation in Cluttered Scenes.” *IEEE ICRA*, 2018.

Manipulation Actions in Assembly Tasks

Scoop



Pound

Lift

Move beyond atomic actions to
long-horizon tasks

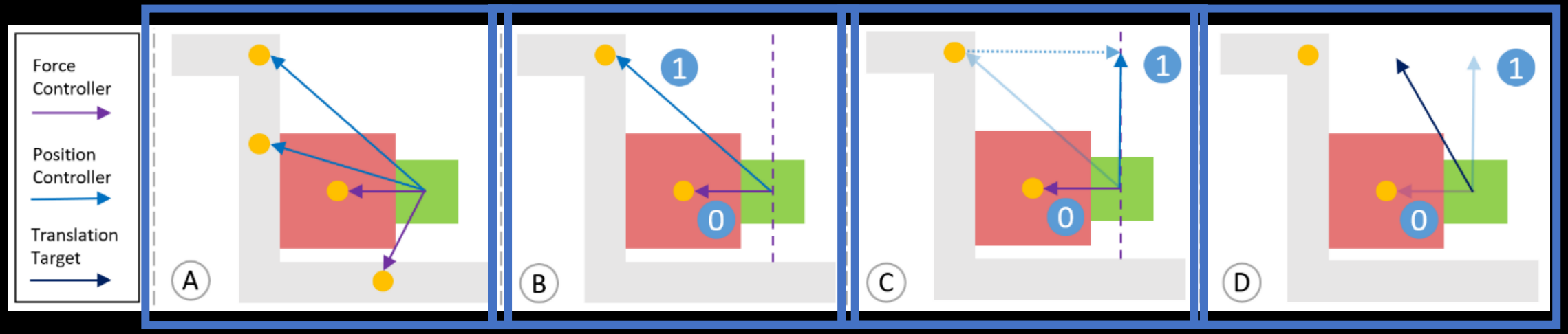
[1] L. Nair, J. Balloch, and S. Chernova. “Tool Macgyvering: Tool Construction Using Geometric Reasoning.” *IEEE ICRA*, 2019.

Executing Multi-Objective Actions

Composable
controllers

[3] R. Platt, A. Fagg, and R. Grupen. “Manipulation Gaits: Sequences of Grasp Control Tasks.” *IEEE ICRA*, 2004.

Learning Controller Compositions

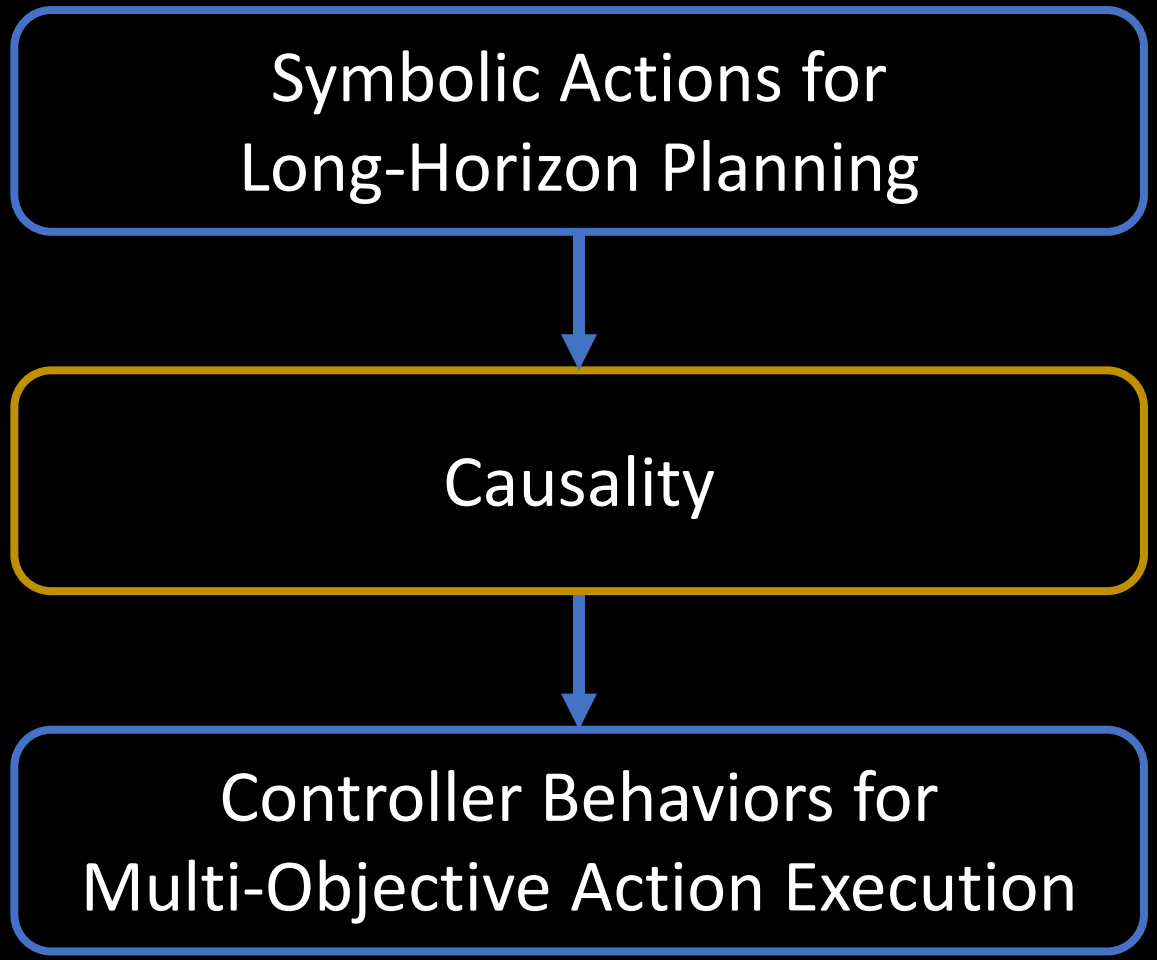


Nullspace composition

Priority of behaviors

[4] M. Sharma, J. Liang, J. Zhao, A. LaGrassa, and O. Kroemer. “Learning to Compose Hierarchical Object-Centric Controllers for Robot Manipulation.” *CoRL*, 2020.

Bridging the Gap

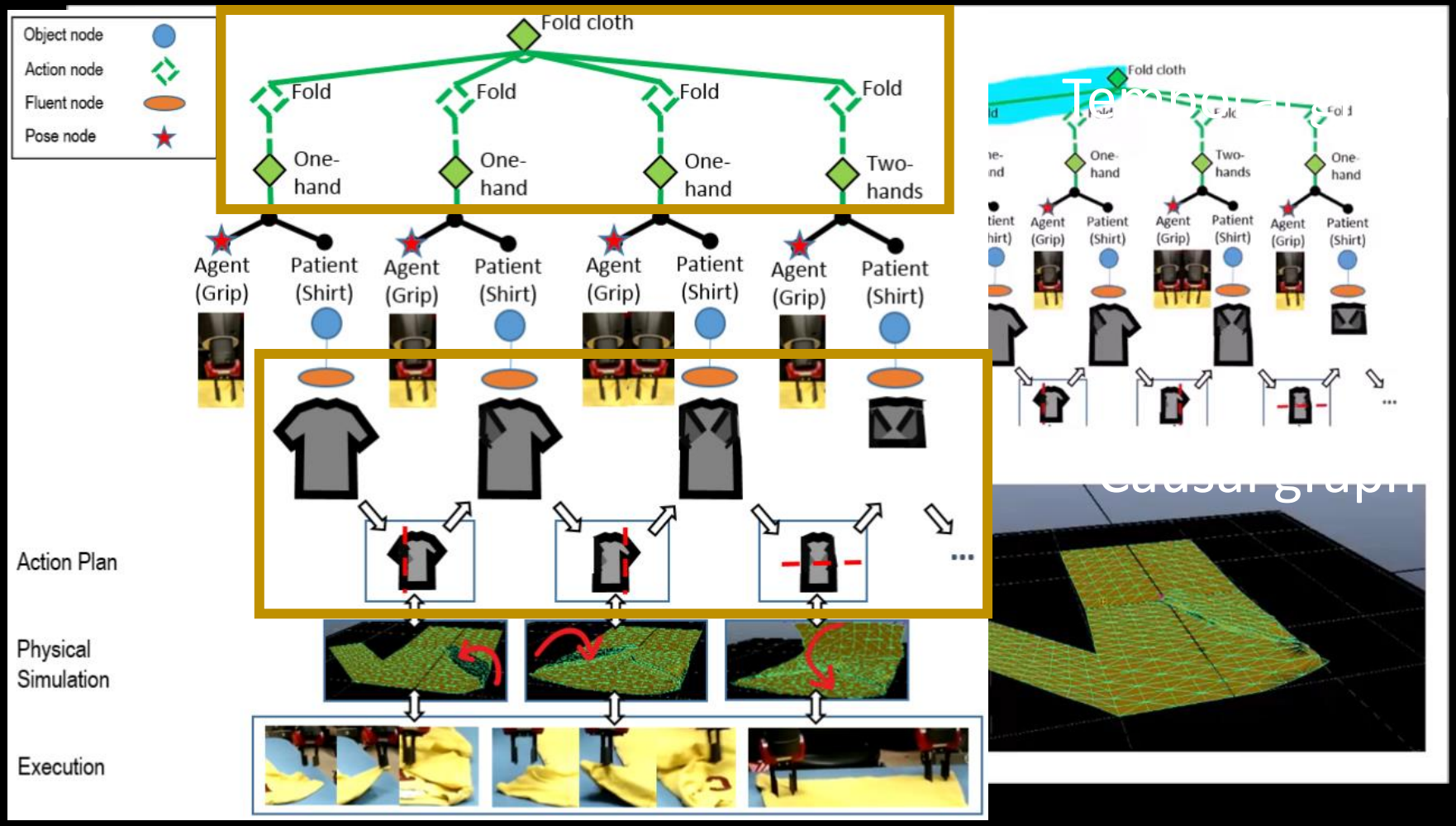


Contribution: Composable Causality

Autonomously compose controllers for multi-objective affordances without pre-defined priorities

Causal control basis to predict composed effects of multi-objective controllers

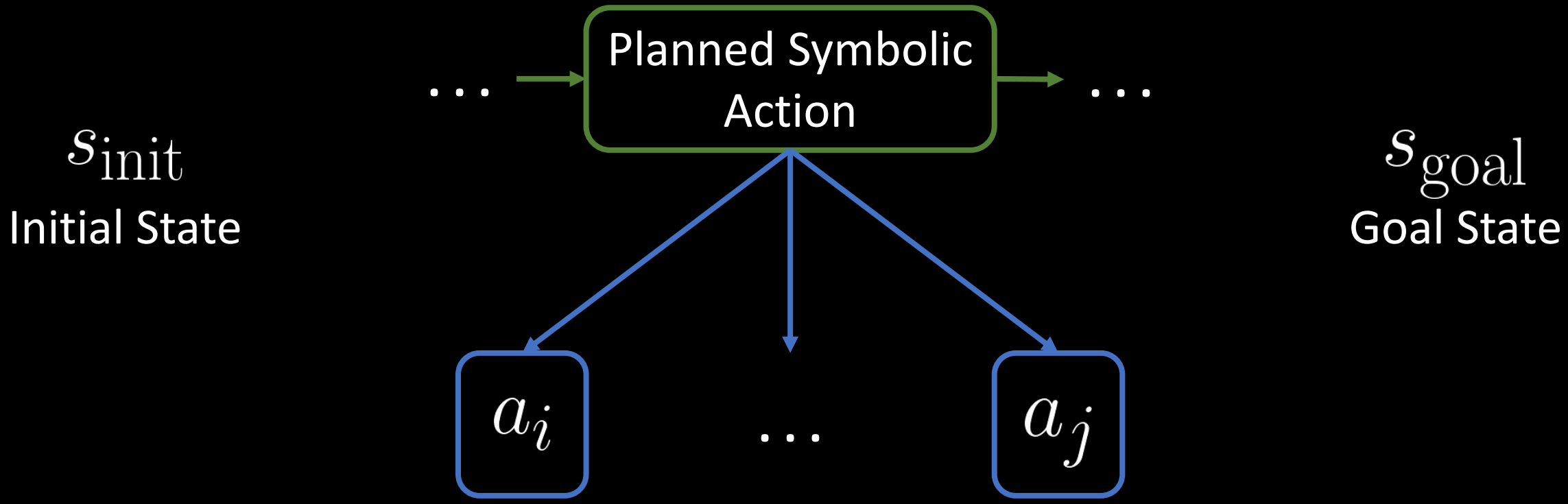
Causality



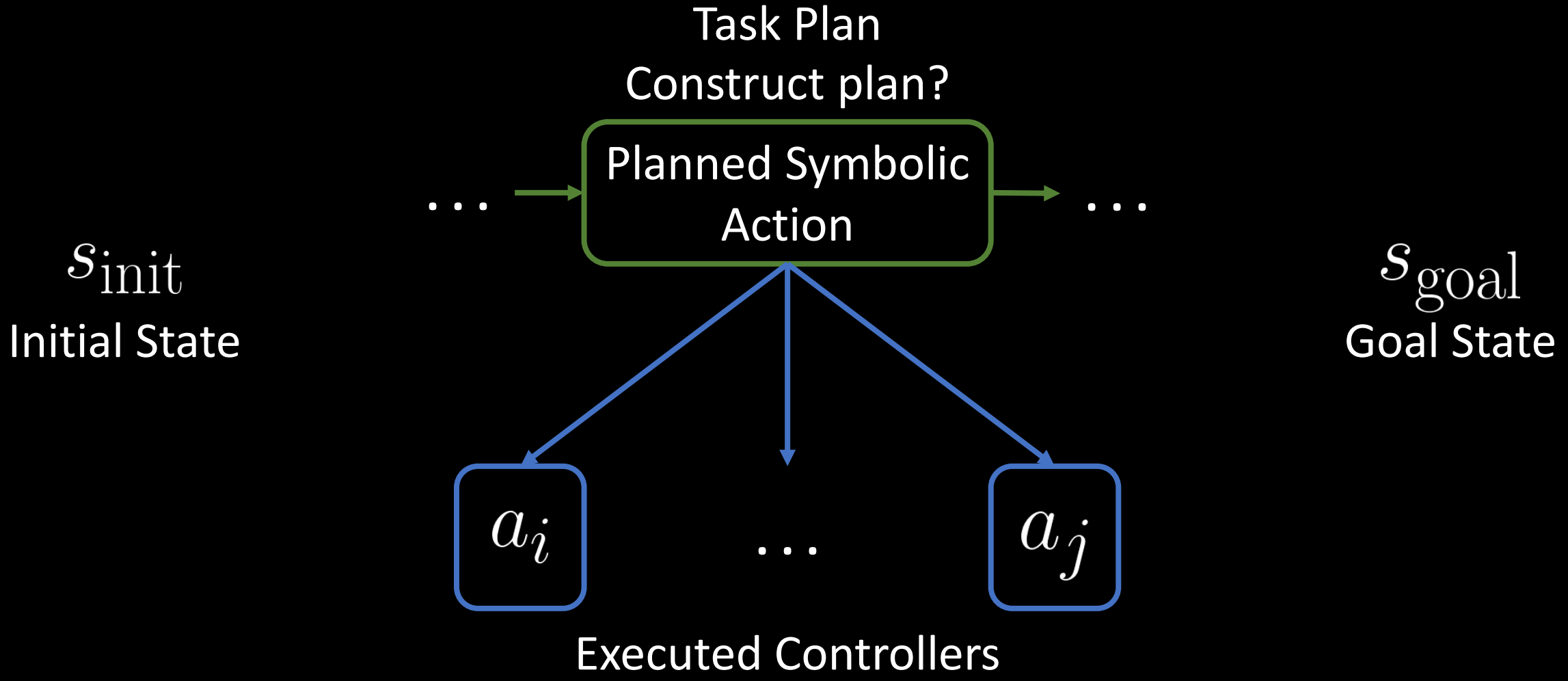
[5] C. Xiong, N. Shukla, W. Xiong, and S.-C. Zhu, "Robot Learning with a Spatial, Temporal, and Causal And-Or Graph." *IEEE ICRA*, 2016.

Problem Formulation

Task Plan



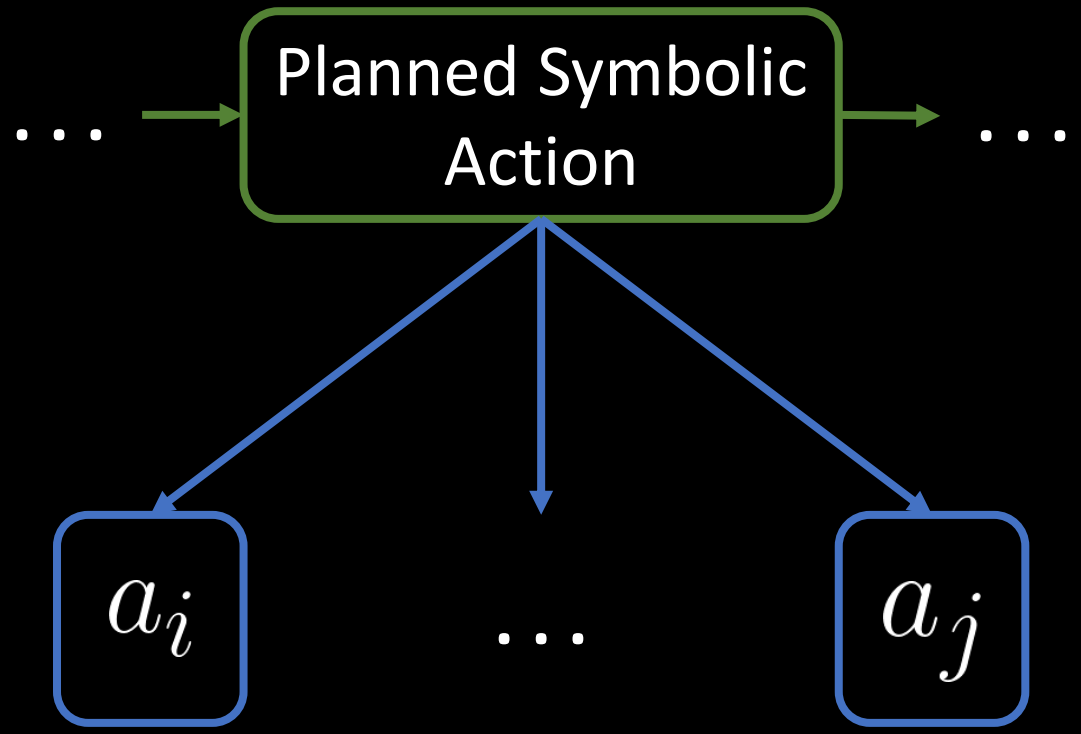
Problem Formulation



Problem Formulation

Task Plan

Off-The-Shelf Task Planner



s_{init}

Initial State

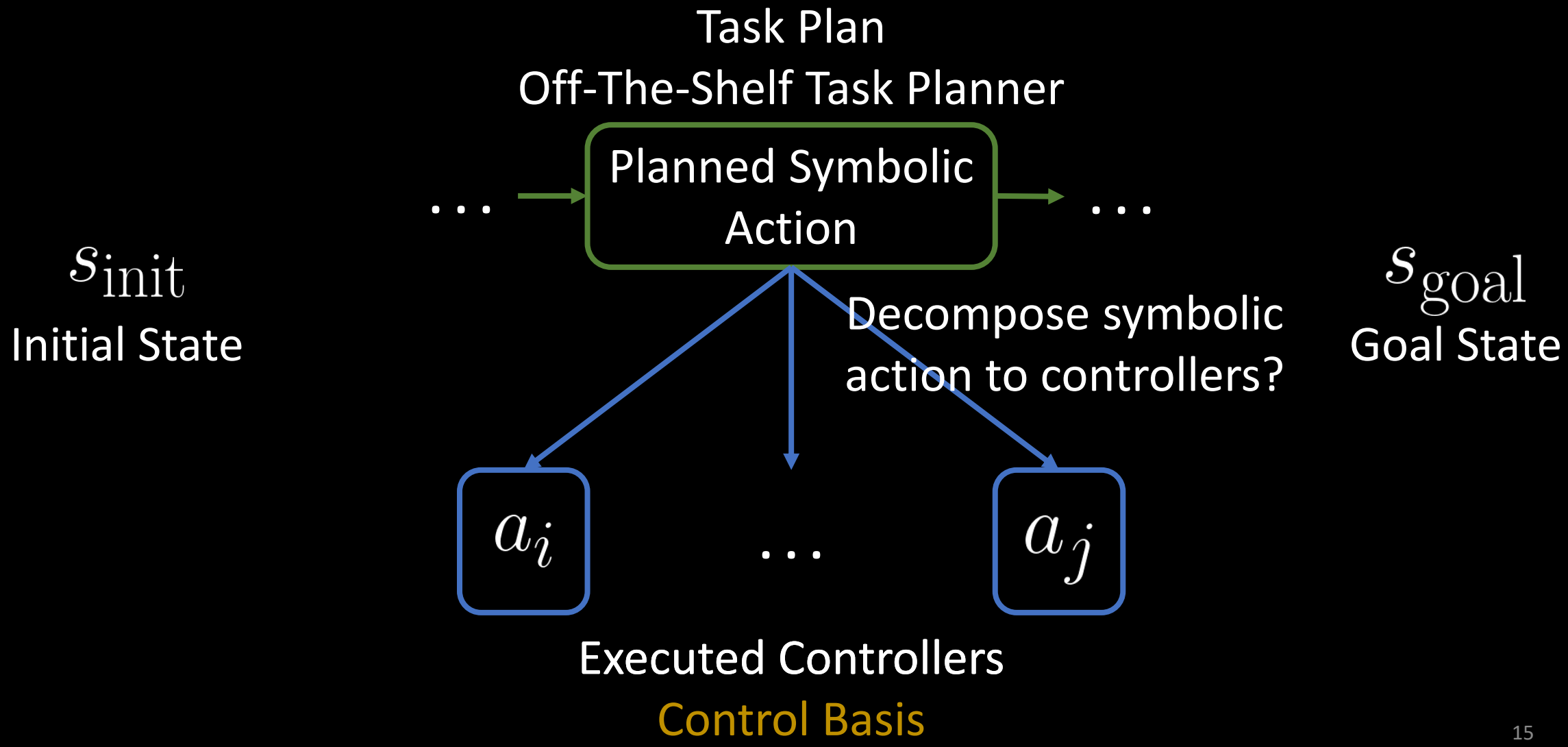
s_{goal}

Goal State

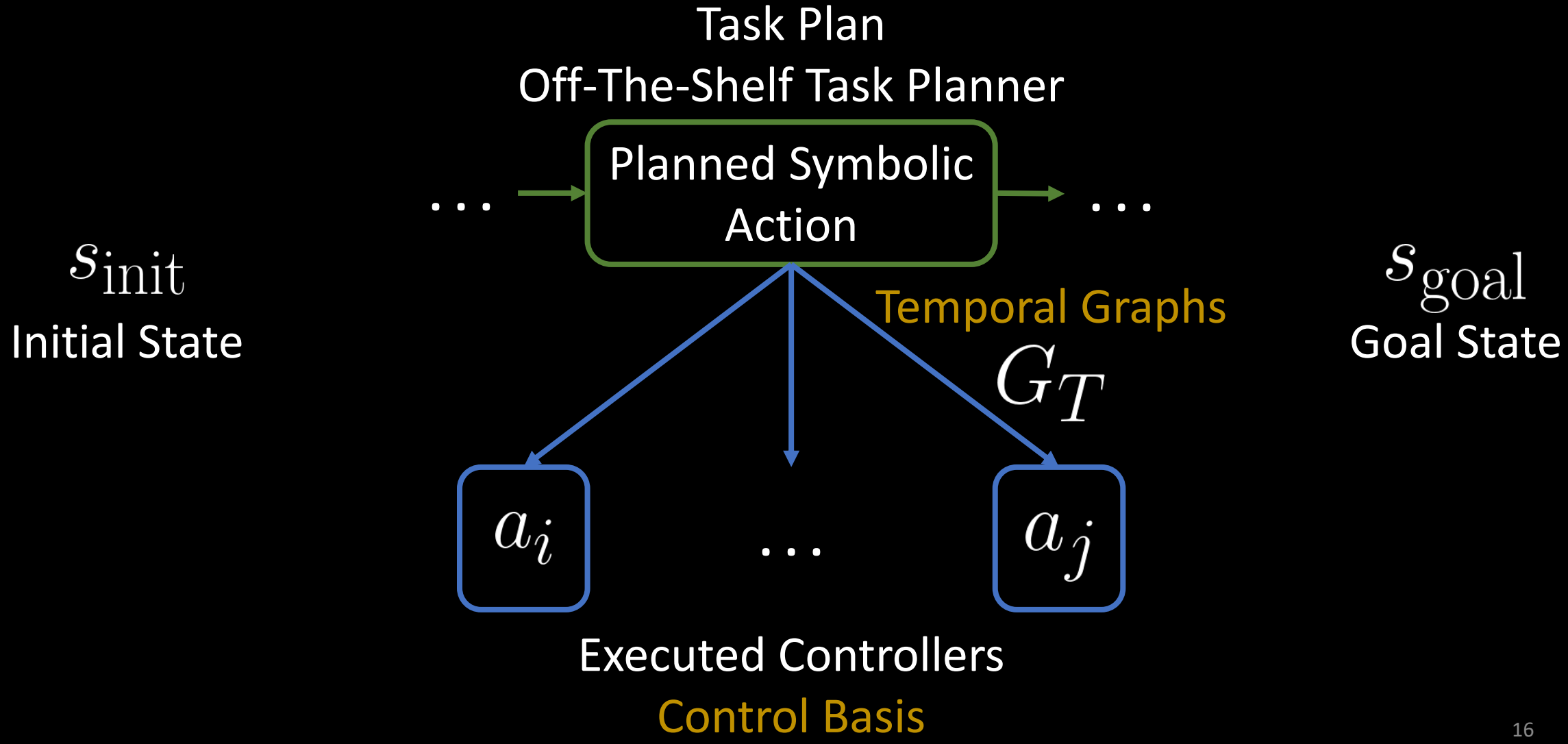
Executed Controllers

Behaviors to execute?

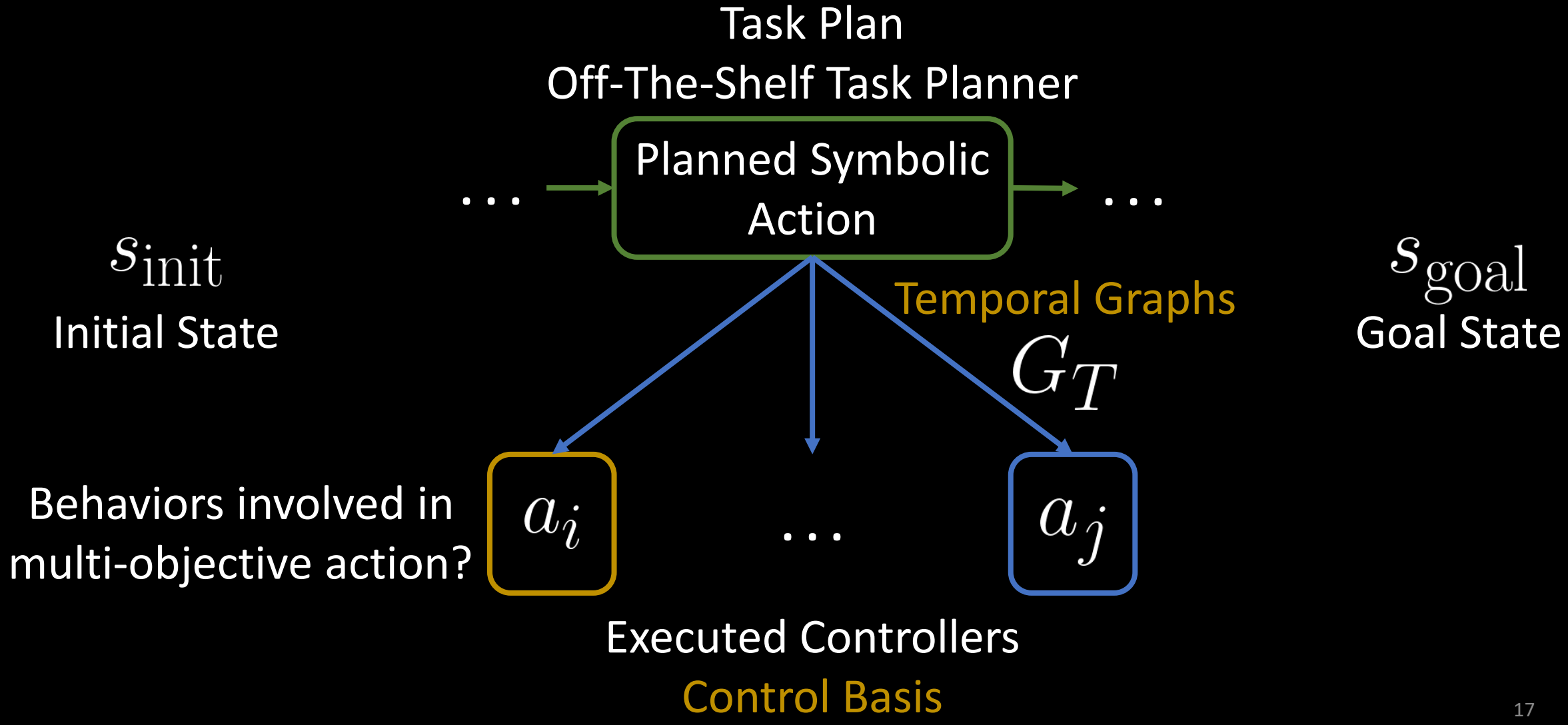
Problem Formulation



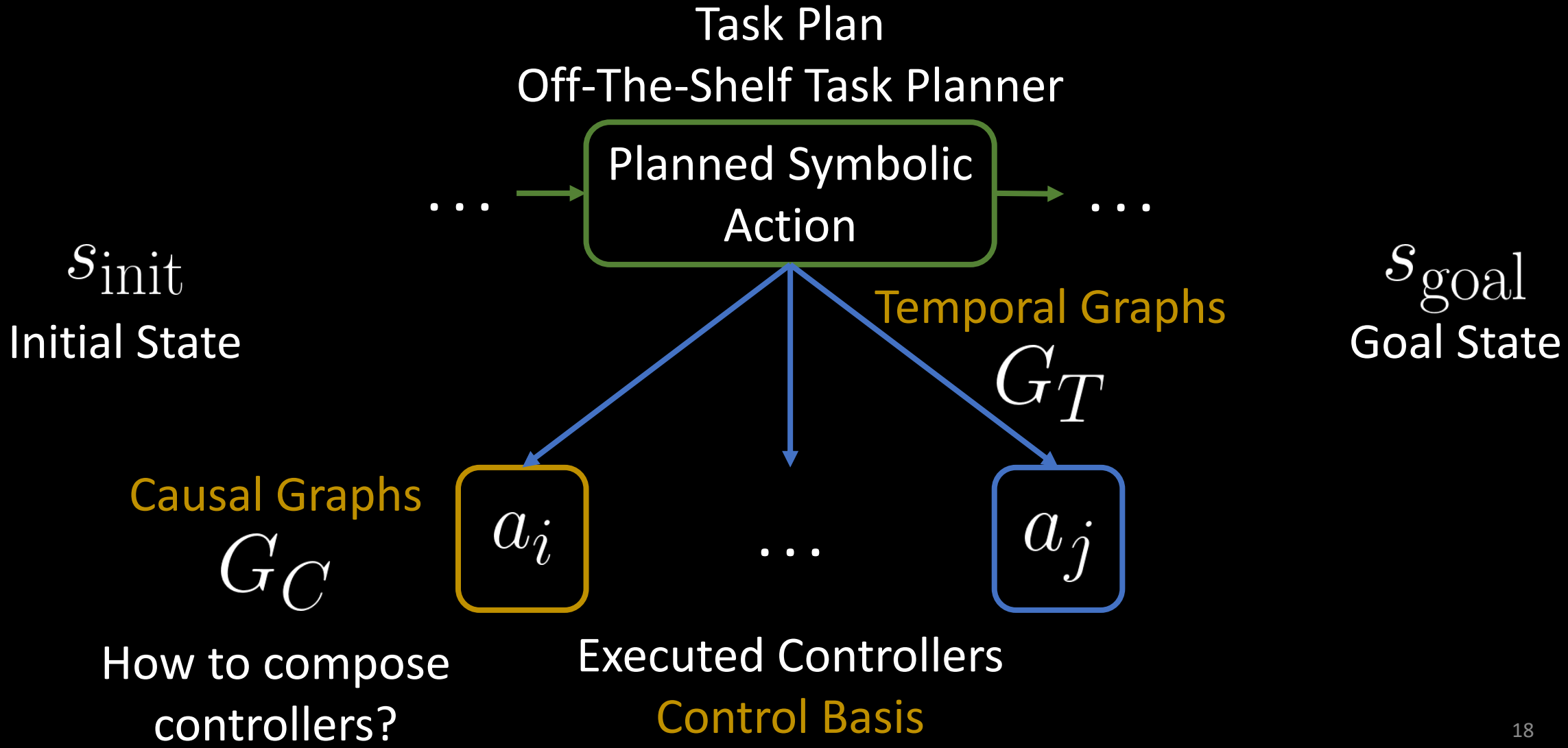
Problem Formulation



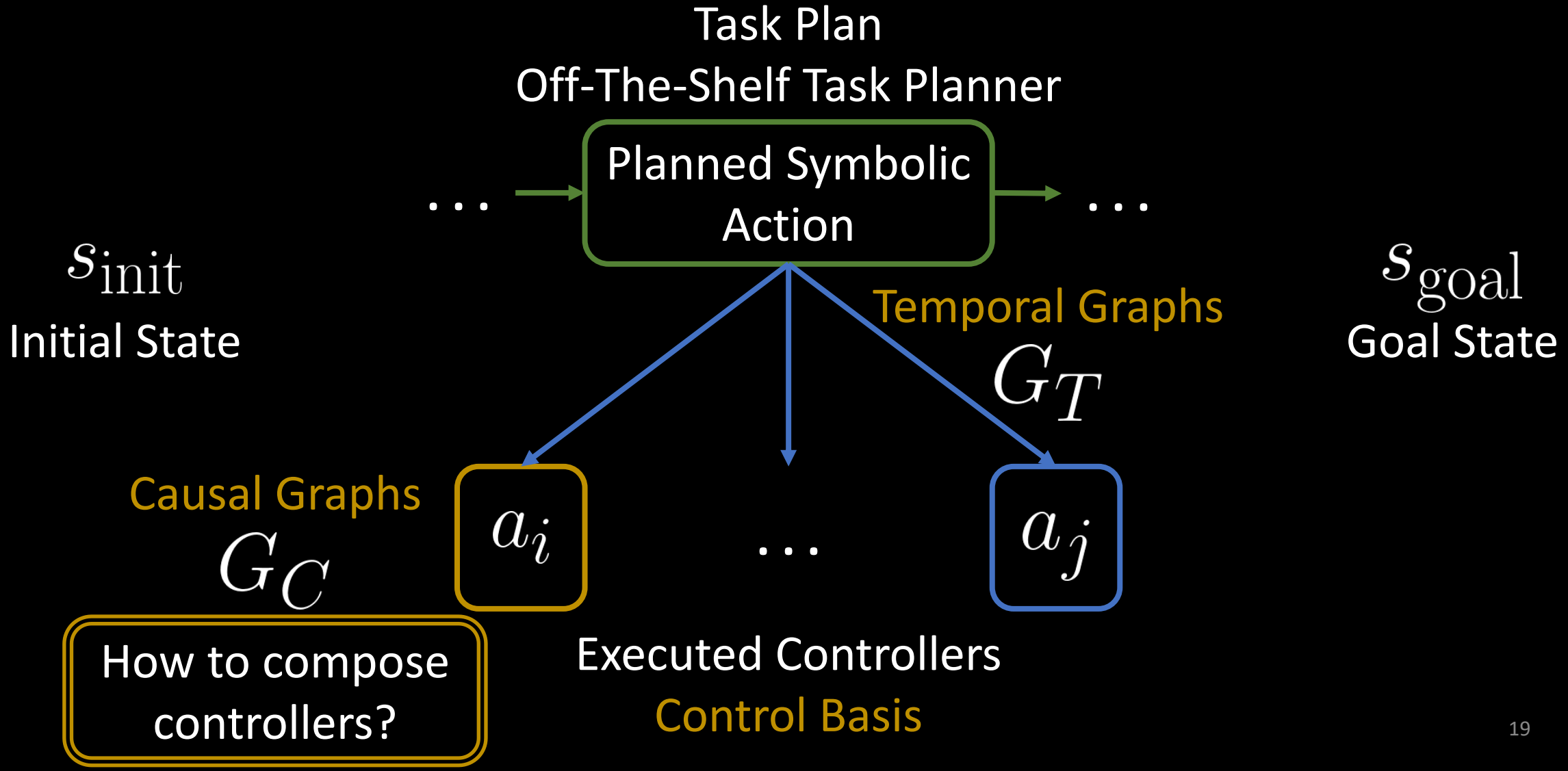
Problem Formulation



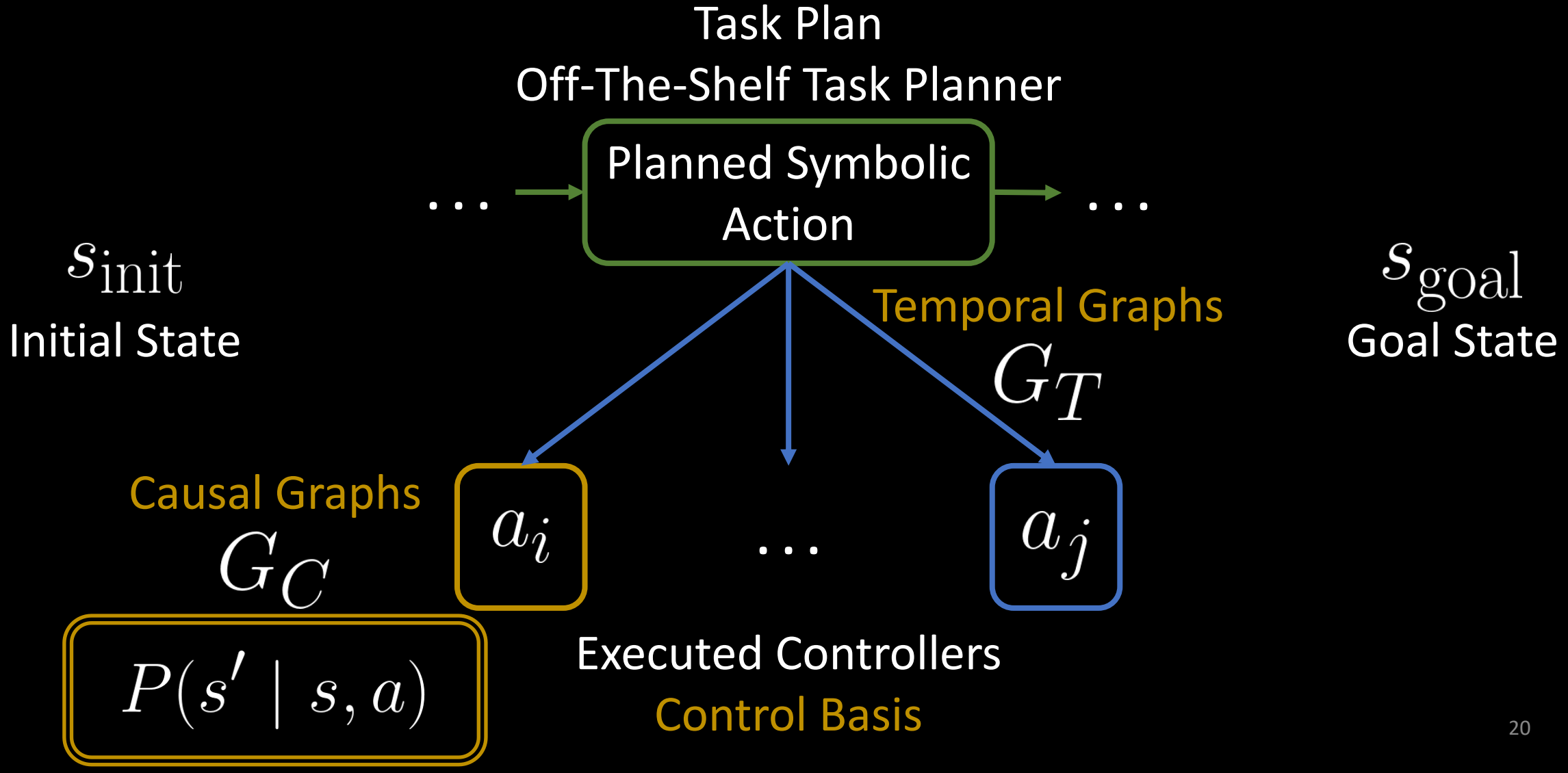
Problem Formulation



Problem Formulation



Problem Formulation



Causal Control Basis

- Control basis: behaviors to execute

$$\Phi$$

- Temporal graphs: decompose symbolic action to controllers

$$G_T$$

- Causal graphs: behaviors involved in multi-objective action

$$G_C$$

- Causal control basis:

$$\mathbf{\Phi} = (\Phi, G_T, G_C)$$

Causal Control Basis: Controllers

- 6D pose controller

  ϕ_{6Dpose}
- 3D position controller

  ϕ_{pos}
- Rotation controller

  ϕ_{rot}
- Screw controller

  ϕ_{screw}

Causal Control Basis

- Control basis:

$$\Phi$$

- Temporal graphs:

$$G_T$$

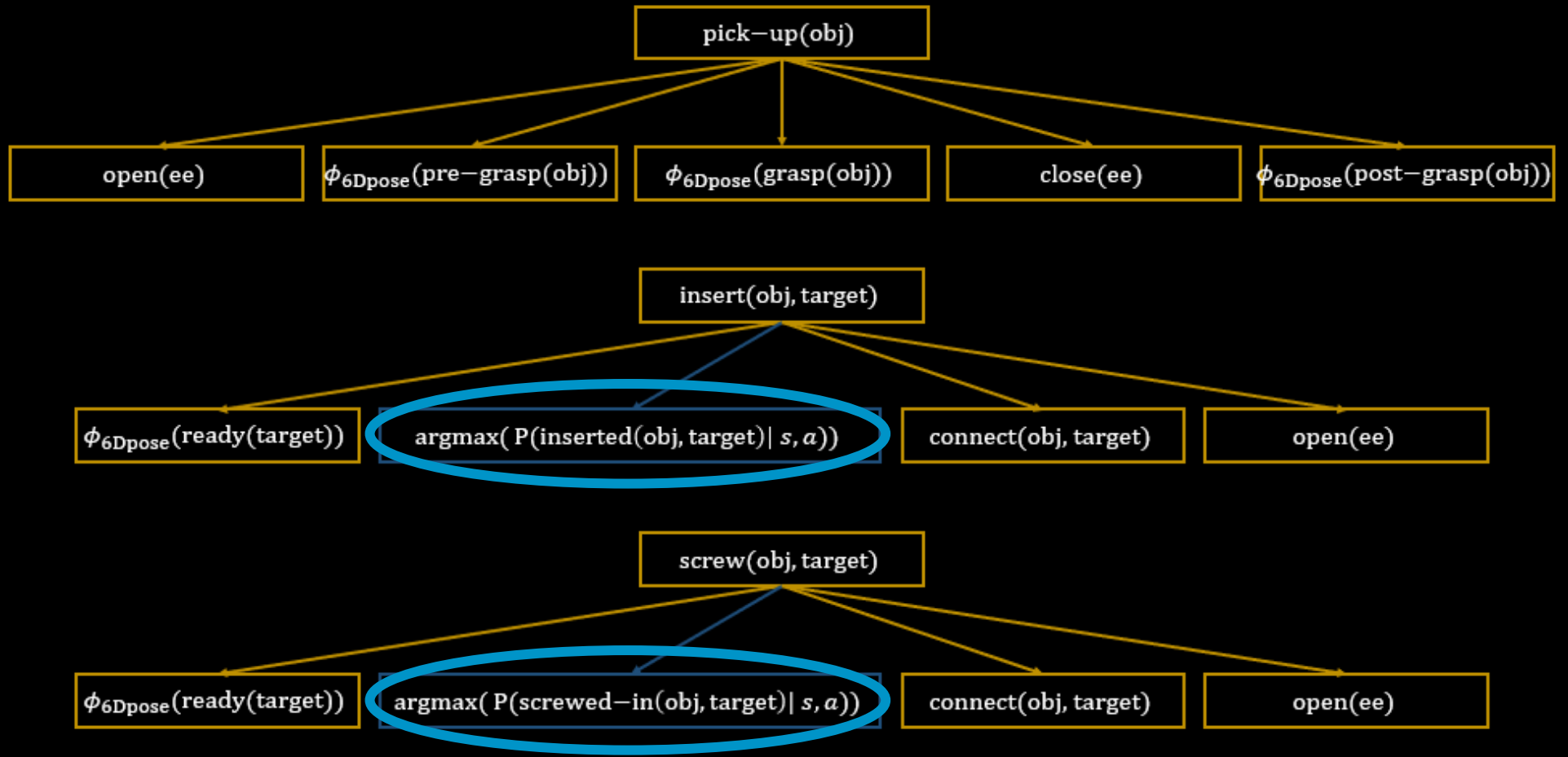
- Causal graphs:

$$G_C$$

- Causal control basis:

$$\mathbf{\Phi} = (\Phi, G_T, G_C)$$

Causal Control Basis: Temporal Graphs



Causal Control Basis

- Control basis:

$$\Phi$$

- Temporal graphs:

$$G_T$$

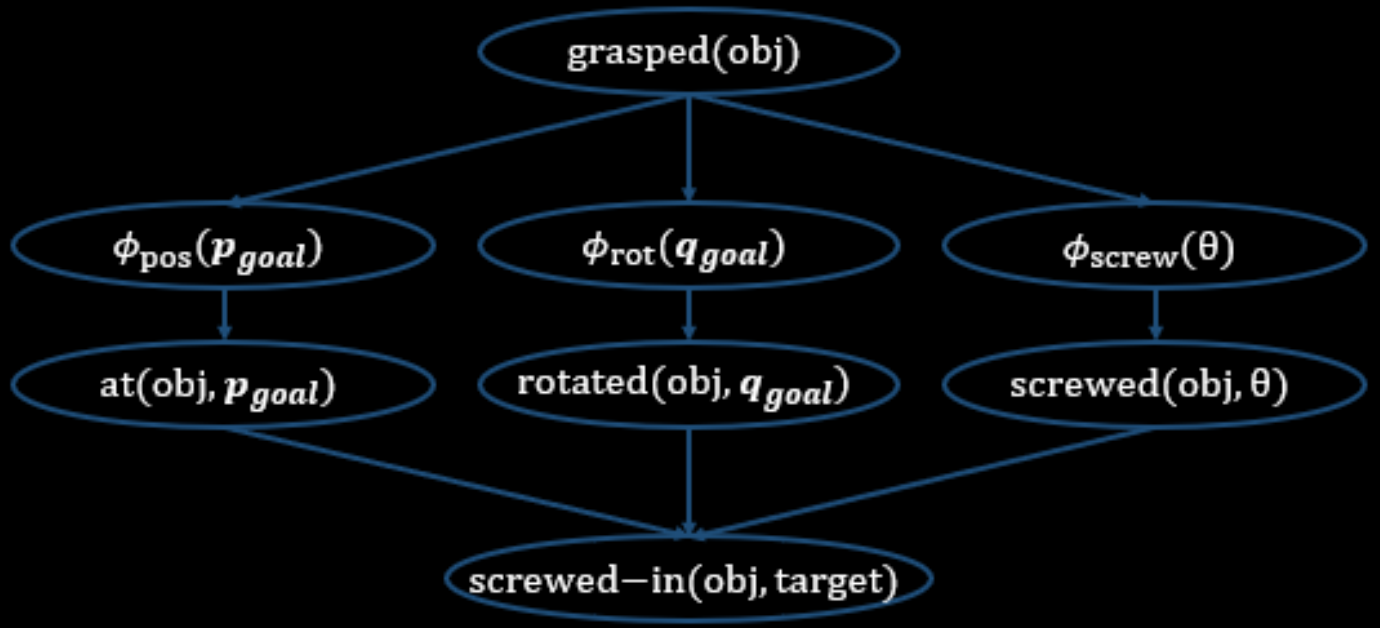
- Causal graphs:

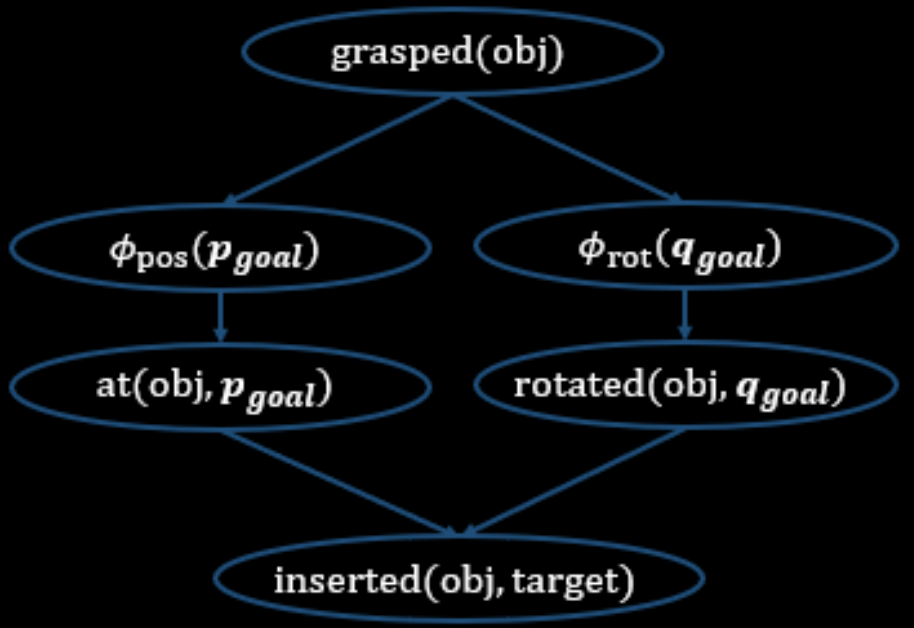
$$G_C$$

- Causal control basis:

$$\mathbf{\Phi} = (\Phi, G_T, G_C)$$

Causal Control Basis: Causal Graphs





Causal Control Basis

- Control basis:

$$\Phi$$

- Temporal graphs:

$$G_T$$

- Causal graphs:

$$G_C$$

- Causal control basis:

$$\mathbf{\Phi} = (\Phi, G_T, G_C)$$

- Use causal control basis to estimate the transition function:

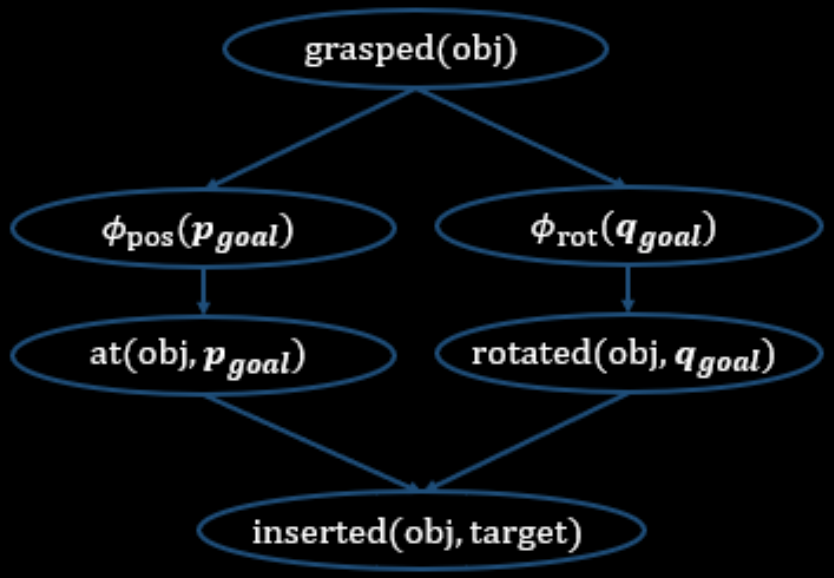
$$P(s' \mid s, a)$$

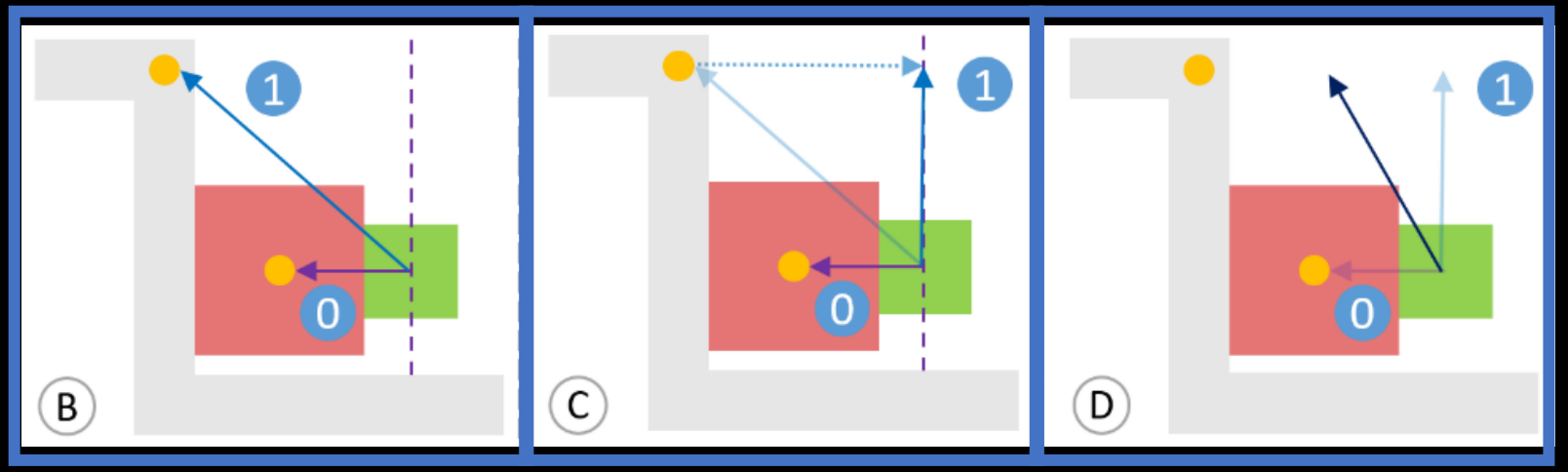
$$s' \in \{s^* \in S \mid \phi_a(s^*) = 0\}$$

- Execute composition most likely to achieve composed effects:

$$\underset{a}{\operatorname{argmax}}\ P(s' \mid s, a)$$

Causal Control Basis: Transition Probability Predictions





$$a = \phi_{\text{pos}} \lhd \phi_{\text{rot}}$$

$$a = \phi_{\text{rot}} \lhd \phi_{\text{pos}}$$

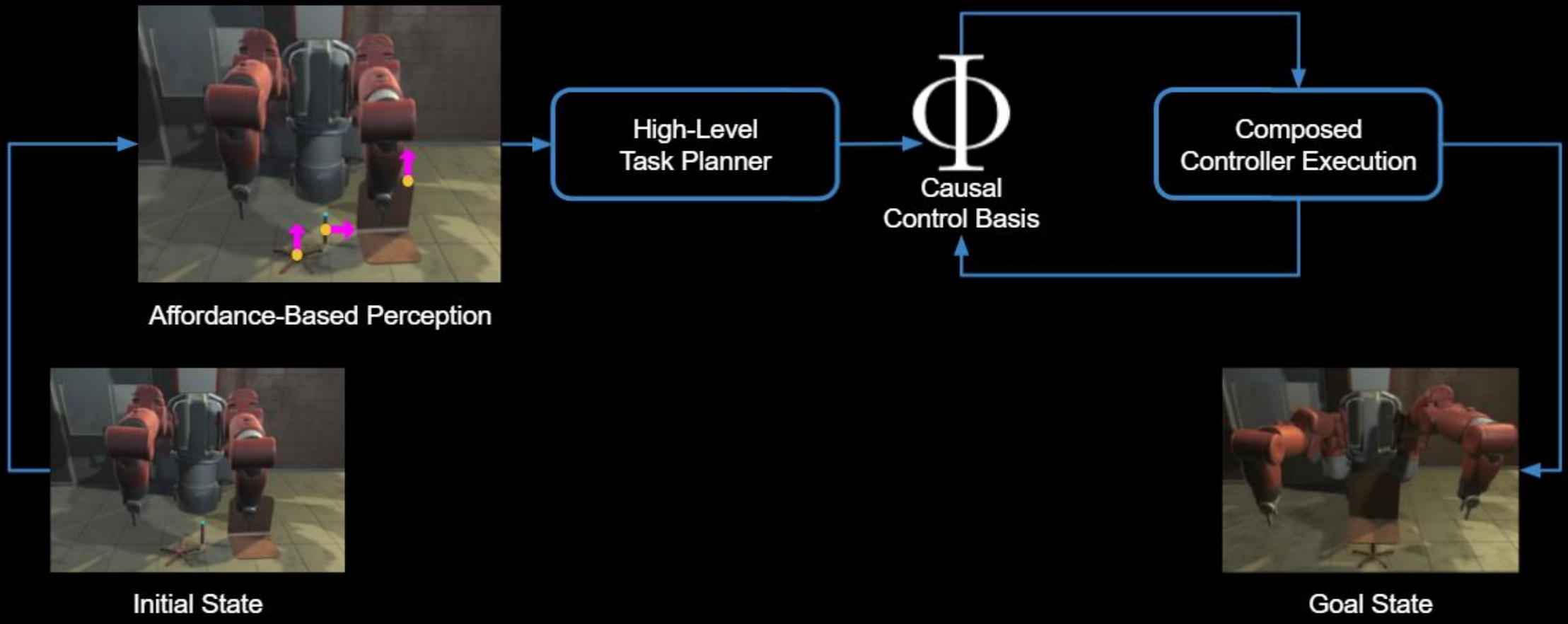
Causal Control Basis: Transition Probability Predictions

- Offline walkouts

$$a = \phi_k \lhd \phi_j \lhd \phi_i$$

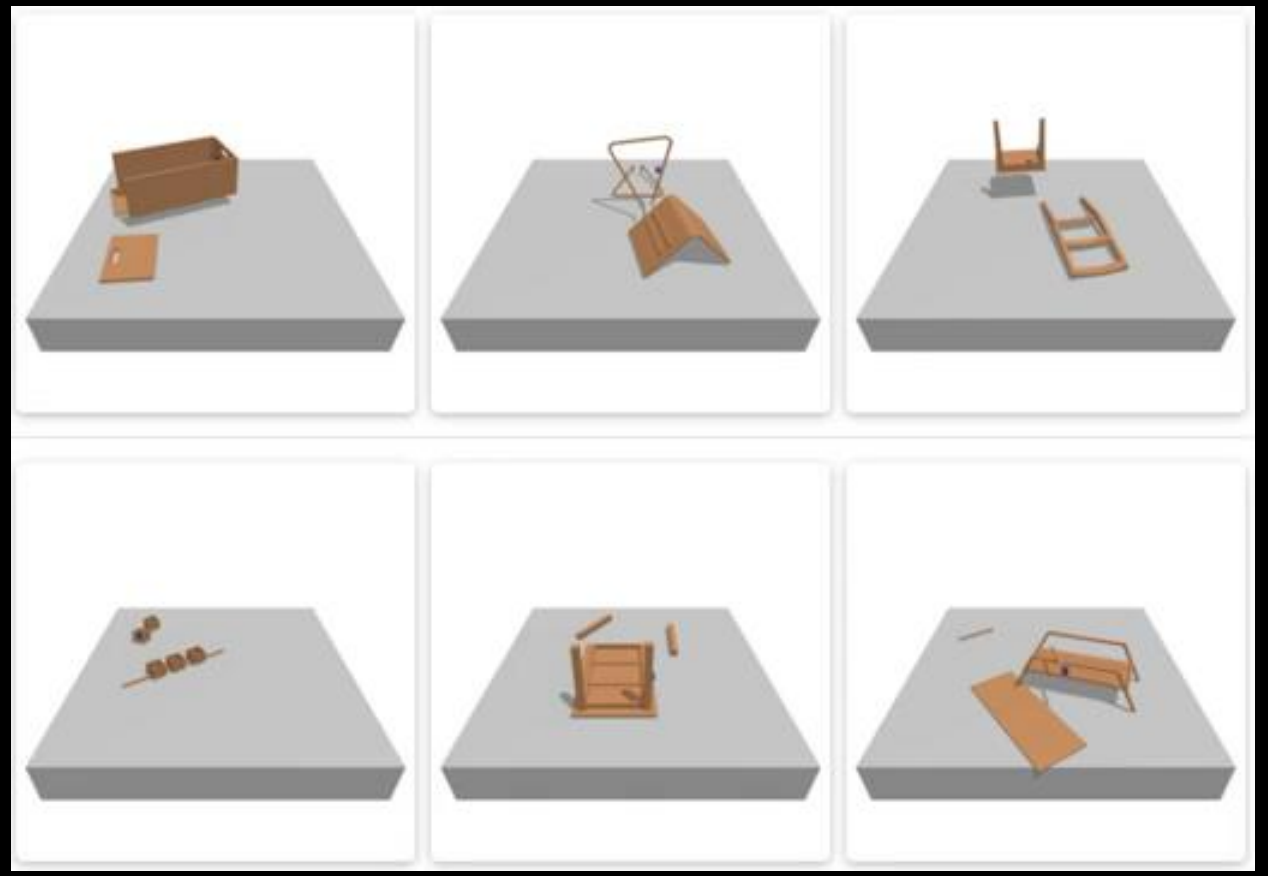
$$\hat{P}(s' \mid s, a) = \begin{cases} 1 & \text{objectives met} \\ 0 & \text{bad progress} \\ \frac{\phi_a(s) - \phi_a(s_T)}{\phi_a(s)} & \text{otherwise} \end{cases}$$

Composable Causality Pipeline



[6] X. Chen, K. Zheng, Z. Zeng, S. Basu, J. Cooney, J. Pavlasek, and O. C. Jenkins, “Manipulation-Oriented Object Perception in Clutter through Affordance Coordinate Frames.” *arXiv preprint arXiv:2101.08202*. 2020.
[7] Pyperplan STRIPS Planning Library. https://github.com/aibasel/pyperplan

IKEA Furniture Assembly Environment



[8] Y. Lee, E. Hu, Z. Yang, A. Yin, and J. Lim. “IKEA Furniture Assembly Environment for Long-Horizon Complex Manipulation Tasks.” *arXiv preprint arXiv:1911.07246*, 2019.
[9] IKEA Furniture Assembly Environment. https://clvrai.github.io/furniture/

Composed Causality Predictions

- Chair and table assembly tasks
- Insert and screw multi-objective connection actions
- 500 walkouts per composition (4000 total walkouts across actions)
- Threshold *T*=300 controller updates

Composed Causality Predictions: Insert Action

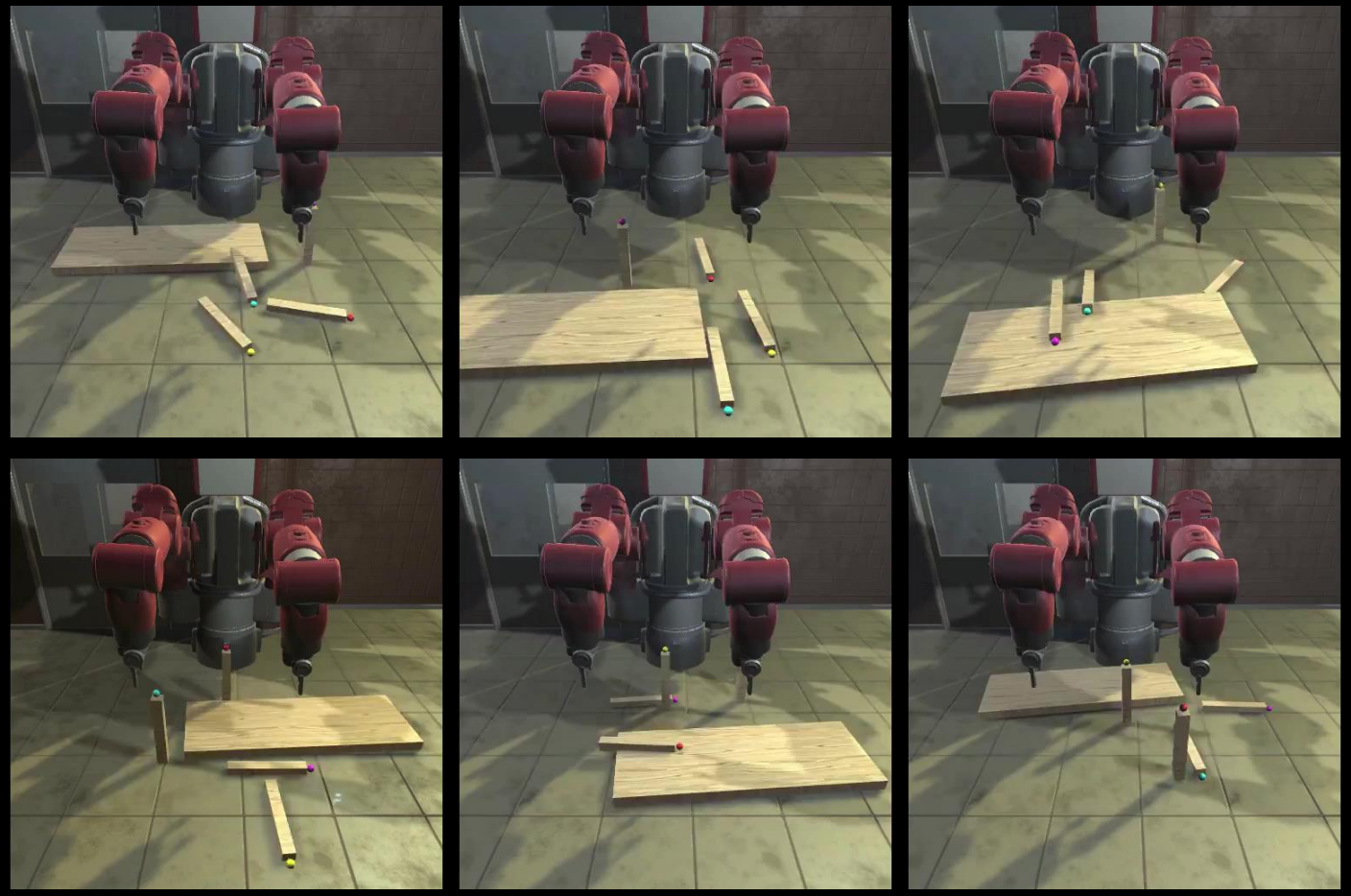
Composition a	Predicted Transition Probability $\hat{P}(s' \mid s, a)$
$\phi_{\text{pos}} \lhd \phi_{\text{rot}}$	**0.723**
$\phi_{\text{rot}} \lhd \phi_{\text{pos}}$	0.711

Composed Causality Predictions: Screw Action

Composition a	Predicted Transition Probability $\hat{P}(s' \mid s, a)$
$\phi_{\text{rot}} \lhd \phi_{\text{screw}} \lhd \phi_{\text{pos}}$	**0.937**
$\phi_{\text{pos}} \lhd \phi_{\text{screw}} \lhd \phi_{\text{rot}}$	0.936
$\phi_{\text{screw}} \lhd \phi_{\text{pos}} \lhd \phi_{\text{rot}}$	0.929
$\phi_{\text{pos}} \lhd \phi_{\text{rot}} \lhd \phi_{\text{screw}}$	0.925
$\phi_{\text{screw}} \lhd \phi_{\text{rot}} \lhd \phi_{\text{pos}}$	0.923
$\phi_{\text{rot}} \lhd \phi_{\text{pos}} \lhd \phi_{\text{screw}}$	0.904

Furniture Assembly Tasks: Insert Action

Furniture Assembly Tasks: Screw Action



Furniture Assembly Tasks

`Insert` Action Success Rate	0.714
Swivel Chair Assembly Task Success Rate	1
Average High-Level Task Planning Time (s)	0.028
Average Controller Selection/Instantiation Time (s)	0.205
Average Execution Time (s)	266.241

`Screw` Action Success Rate	0.923
Table Assembly Task Success Rate	1
Average High-Level Task Planning Time (s)	0.048
Average Controller Selection/Instantiation Time (s)	0.074
Average Execution Time (s)	492.072

Future Work

- Avoid joint limits and local minima
- Obstacle avoidance behaviors
- Bimanual manipulation

Conclusion

- Causal control basis
- Accurate transition probability predictions
- Successful execution of controller compositions
- Composable Causality for assembly tasks

Acknowledgements

Co-Authors:
Xiaotong Chen, Zhen Zeng, Kaizhi Zheng, and Qiuyu Shi

Project Support:
Iris Bahar, Steven Sloman, Jasmine Liu, and Semir Tatlidil
Jorge Vilchis and Matthew Shannon

This work was supported by a
NASA Space Technology Graduate Research Opportunity.