

TASKOGRAPHY: Evaluating robot task planning over large 3D scene graphs

Project page: <https://taskography.github.io>

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Abstract: 3D scene graphs (3DSGs) are an emerging description; unifying symbolic, topological, and metric scene representations. However, typical 3DSGs contain hundreds of objects and symbols even for small environments; rendering task planning on the *full* graph impractical. We construct **TASKOGRAPHY**, the first large-scale robotic task planning benchmark over 3DSGs. While most benchmarking efforts in this area focus on *vision-based planning*, we systematically study *symbolic* planning, to decouple planning performance from visual representation learning. We observe that, among existing methods, neither classical nor learning-based planners are capable of real-time planning over *full* 3DSGs. Enabling real-time planning demands progress on *both* (a) sparsifying 3DSGs for tractable planning and (b) designing planners that better exploit 3DSG hierarchies. Towards the former goal, we propose SCRUB, a task-conditioned 3DSG sparsification method; enabling classical planners to match and in some cases surpass state-of-the-art learning-based planners. Towards the latter goal, we propose SEEK, a procedure enabling learning-based planners to exploit 3DSG structure, reducing the number of replanning queries required by current best approaches by an order of magnitude. We will open-source all code and baselines to spur further research along the intersections of robot task planning, learning and 3DSGs.

Keywords: Robot task planning, 3D scene graphs, learning to plan, benchmarks

1 Introduction

Real-world robotic task planning problems in large environments require reasoning over tens of thousands of object-action pairs. Faced with long-horizon tasks and an abundance of choices, state-of-the-art task planners struggle with an efficiency-reliability trade-off in grounding actions towards the goal. Hence, designing actionable scene abstractions suitable for a range of robotic tasks has drawn long-standing attention from the robotics and computer vision communities [1, 2, 3, 4, 5, 6].

A promising approach for building symbolic abstractions from raw perception data are 3D scene graphs (3DSGs, see Fig. 1) [7, 8, 9] – hierarchical representations of a scene that capture metric, semantic, and relational information, such as affordances, properties, and relationships among scene entities. While 3DSGs have to date been applied to simpler planning problems like goal-directed navigation [6, 10], active object search [11], and node classification [12], their amenability to more complex robotic task planning problems has yet to be thoroughly evaluated.

To investigate the joint application of 3DSGs and modern task planners to complex robotics tasks we propose **TASKOGRAPHY**: the first large-scale benchmark comprising a number of challenging task planning domains designed for 3DSGs. Analyzing planning times and costs on a diversity of domains in **TASKOGRAPHY** reveals that neither classical nor learning-based planners are capable of real-time planning over full 3DSGs, however, that they become so only when 3DSGs are sparsified.

Many real-world problems only require reasoning over a small subset of scene objects. E.g., the task “*fetch a mug from the kitchen*” primarily involves reasoning about scene elements associated with mugs or kitchens, rendering a vast majority of the remaining environment contextually irrelevant. Most planners aren’t able to exploit such implicitly defined task contexts, instead spending most of their computation time reasoning about extraneous scene attributes and actions [13] (see Fig. 5).

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We argue that performant task planning over 3DSGs demands progress on two fronts: (a) sparsifying 3DSGs to make planning problems tractable, and (b) designing task planners that exploit the spatial hierarchies encapsulated in 3DSGs. To address (a), we present **SCRUB**—a planner-agnostic strategy guaranteed to produce a minimal *sufficient* object set for grounded planning problems. That is, planning on this reduced subset of scene entities suffices to solve the planning problem defined over the full 3DSG. Classical planning over state spaces (3DSGs) augmented by SCRUB outperforms state-of-the-art learning-based planners on the majority of tasks on our benchmark, without requiring any prior learning, establishing a strong baseline for future work in robotic task planning. To address (b), we present **SEEK**: a procedure tailored to 3DSGs, which supplements learning-based incremental planners by imposing 3DSG structure, ensuring all objects in the *sufficient* set are reachable from the start state. In our experiments, augmenting state-of-the-art planners with SEEK results in computational savings and an order of magnitude fewer replanning iterations.

In summary, we make the following contributions:

- **TASKOGRAPHY**: a large-scale benchmark to evaluate robotic task planning over 3DSGs,
- **SCRUB**: a planner-agnostic strategy to adapt 3DSGs for performant planning,
- **SEEK**: a procedure that enables learning-based planners to better exploit 3DSGs

We will open-source all code and baselines in **TASKOGRAPHY-API**, enabling the construction of new task planning domains, and benchmarking the performance of newer learning-based planners.

2 Related work

Early research in **symbolic planning** was centered around *optimal* planning [14, 15, 16, 17, 18]; planners producing solutions that preserve cost or plan length optimality. These methods are computationally expensive and thereby untenable to even moderately sized problems. This spurred work on *satisficing* planners that forgo optimal solutions for cheaper, feasible plans. Notable paradigms include regression planning [19], tree search [20], and heuristic search [21, 22, 23, 24, 25]. Whilst the many successes of heuristic planners [26, 27], computing low-cost informative heuristics is deterred by many extraneous objects [28, 13]; an inauspicious characteristic of large 3DSGs.

Robot task planning techniques have focused on constructing more effective representations to plan upon [29, 30, 31]. There are also approaches that integrate task and motion planning [32, 33, 34]—further demonstrated in hierarchical task space [35]—but which fall outside the scope of our work. Several approaches exploit task hierarchies for robot task planning [36] and control [37, 38, 39]. Different from these, our work focuses on exploiting abstractions in *spatial structure* encapsulated in 3DSGs, not to be conflated with hierarchical planners that exploit *task structure* [40].

State-of-the-art **learning-based** planners have demonstrated promising performance in small-to-moderate problem sizes. However, techniques such as relational policy learning [41], relational heuristic learning [42], action grounding [43], program guided symbolic planning [44, 45, 46, 47, 48], and regression planning networks [49] fail in large problem instances with branching factors and operators of the order considered (see Fig. 2) in the **TASKOGRAPHY** benchmark. Moreover, several planners that learn to search [50, 51, 52, 53] depend on hard-to-obtain dense rewards or do not scale with domain complexity [54, 55, 56].

The simplification of planning problems via **pruning strategies** to enable efficient search has been explored in both propositional [57, 58, 43] and numeric [59] planning contexts. Among these, PLOI [13] is a particularly performant learning-based approach that leverages object-centric relational reasoning [60, 61, 62, 63] to score and prune *extraneous objects* to the task. While PLOI outperforms existing classical planners on the **TASKOGRAPHY** benchmark, it incurs a large number of replanning steps owing to inaccurate neural network predictions; and inability to exploit 3DSG hierarchies. Our proposed SEEK procedure decreases replanning steps by two orders of magnitude.

Planning benchmarks in the symbolic planning communities have featured a variety of tasks with time complexities ranging from polynomial (e.g., shortest-path) to NP-hard problems (e.g., traveling salesman). There also exists a handful of environments [64, 65, 66, 67, 68] for benchmarking learned action policies from language directives and ego-centric visual observations, task and motion planning [69], or the modelling of physical interactions [70, 71]. Another recent benchmark [72] only supports navigation and block-stacking tasks. However, there isn't currently a large-scale benchmark tailored to robotic task planning in 3DSGs with several hundreds of objects.

3 Background

Task planning. A task planning problem Π is a tuple $\langle \mathcal{O}, \mathcal{P}, \mathcal{A}, \mathcal{T}, \mathcal{C}, \mathcal{I}, \mathcal{G} \rangle$. As a running example, consider the task **find an apple, slice it, and place it on the counter**. \mathcal{O} is the set of all ground objects (instances) in the problem. \mathcal{P} is a set of properties, each defined over one or more objects; $\text{weight(apple)} = 70 \text{ grams}$. **Predicates** are subclasses of properties in that they are boolean-valued; $\text{canPlace(apple, refrigerator)} = \text{True}$. \mathcal{A} is a finite set of lifted actions operating over object tuples; slice(apple) , $\text{place(apple, counter)}$. \mathcal{T} is a transition model and \mathcal{C} denotes state transition costs. \mathcal{I} and \mathcal{G} are initial and goal states. A state is an assignment of values to all possible properties grounded over objects. For the running example, a goal state may be specified as **on(apple, counter)=True** and **sliced(apple)=True**. Planning problems may be grounded—*slice this apple*, or lifted—*slice an apple*.

3D scene graphs (3DSGs). A 3DSG [7, 8] is a hierarchical multigraph $G = (V, E)$ with $k \in \{1 \dots K\}$ levels, where $V^k \in V$ denotes the set of vertices at level k . Edges originating from a vertex $v \in V^k$ may only terminate in $V^{k-1} \cup V^k \cup V^{k+1}$ (i.e., edges connect nodes within one level of each other). Each 3DSG in our work comprises at least 5 levels with increasing spatial precision as we move down the hierarchy: the topmost level in the hierarchy is a root node representing a scene. This node branches out to indicate the various *floors* in the building, which in turn branches out to denote various *rooms* in a floor, and subsequently *places* within a room. A place is a collection of *objects*, which may themselves contain other *objects* (to allow for container types such as cabinets and refrigerators).² At each level, edges indicate various types of relations among nodes (e.g., at the room level, an edge indicates the existence of a traversable path between two rooms; at the object level, edges indicate multiple affordance relations). Each node also stores semantic attributes such as node type, functionality, affordances, etc., following [7].

4 TASKOGRAPHY

We propose **TASKOGRAPHY**: the first large scale benchmark to evaluate symbolic planning over 3DSGs. Currently, **TASKOGRAPHY** comprises 20 challenging robotic task planning domains totaling 3734 tasks. Different from current benchmarks for embodied AI that focus primarily on ego-centric *visual* reasoning [65, 73, 74, 64, 71, 67]; **TASKOGRAPHY** is designed to evaluate *symbolic* reasoning over 3DSGs. To emulate the complexity of real-world task planning problems, **TASKOGRAPHY** builds atop the Gibson [75] dataset comprising real-world scans of large building interiors (averaging 2-3 floors per building; 7 rooms per floor), and their corresponding 3DSGs [7].

Augmenting 3DSGs with plannable attributes. A prerequisite for planning over 3DSGs—absent in existing work [9, 7, 8]—is a database of *plannable attributes*: predicates, actions, and transition models. To support task planning, we augment each 3DSG in Gibson [75] (tiny and medium splits) with several layers of additional unary and binary predicates. For each 3DSG node, we obtain class labels, object dimensions and pose from [7]. We annotate object affordances by building a knowledge base of lifted object-action pairs and recursively applying it to every 3DSG node, while accounting for exceptions (objects that are concealed or contained within others). We also detect *door* objects in the 3DSG and use this to add additional edges describing room connectivity. We annotate objects with all possible properties in our planning domains (e.g., *“is this object typically a receptacle?”*). Our rich property set (*plannable attributes*) is chosen to support a wide range of realistic-robotic tasks geared towards large (building-scale) 3DSGs.

²The lowest level in [8] is a metric-semantic mesh. However since our focus is on symbolic planning, we only require scene graph levels that contain *objects*.

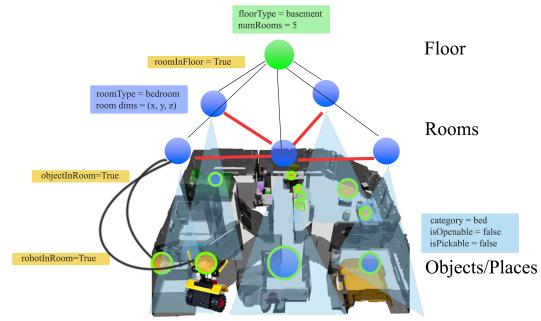


Figure 1: A *state* in a planning problem specified over a 3DSG. Nodes are scene entities and store unary predicates. Edges indicate binary predicates (relations). A goal is a conjunction of unary and binary literals. We only show a subset of relations for brevity. E.g., if the robot executes an action that moves it to another room, the `robotInRoom` relation shown in this figure will be set to `False` for the room on the lower left.

the existence of a traversable path between two rooms; at the object level, edges indicate multiple affordance relations). Each node also stores semantic attributes such as node type, functionality, affordances, etc., following [7].

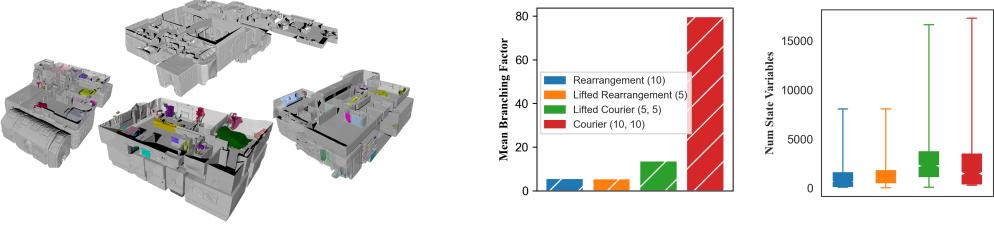


Figure 2: The **TASKOGRAPHY benchmark** comprises large-scale planning problems defined over buildings from the Gibson dataset [75]. (Left) Representative buildings from Gibson [75]. (Middle/Right) We feature a variety of problem classes ranging in scale and complexity as illustrated by the domain statistics.

Benchmark statistics. Each of the 20 TASKOGRAPHY domains specifies a class of planning problems that resemble real-world use cases (and theoretically complex extensions) that a robot would encounter in office, house, or building scale environments. These domains range from grounded planning domains to lifted planning domains, domains with no extraneous objects to domains where most objects are extraneous, and domains for which polynomial time solutions exist to NP-hard problems. The simplest domains in the benchmark have 1000 state variables and an average branching factor of 5; for hard domains, these are 4000 and 60 respectively (see Fig. 2).

TASKOGRAPHY-API. Our project page (<https://taskography.github.io>) will host code and data used in this work. In TASKOGRAPHY-API, an open-source python package, we provide access to 18 classical and learning-based symbolic planners, templates to implement novel domains, and methods to generate problem instances of varying complexities and train/evaluate learning-based planners.

Planners considered. TASKOGRAPHY supports a comprehensive set of planners to facilitate standardized evaluation on novel domains. The following planners are available at the time of writing.

- **Optimal planners:** Fast Downward (FD) with the `opt-lmcut` heuristic [23], SatPlan [16], Delfi [17], DecStar-optimal [25], and Monte Carlo tree search.
- **Satisficing planners:** Fast Forward (FF), FF with axioms (FF-X) [22], Fast Downward (FD) with the `lama-cut` heuristic [23], DecStar-satisficing [25], Cerberus [24], Best First Width Search (BFWS) [76], and regression planning.
- **Learning-based planners:** Relational policy learning [41], Planning with learned object importance (PLOI) [13] (and variants – see Sec. 6).

General assumptions. To facilitate evaluation of all of these classes of planners, the first edition of our benchmark only considers *fully observable* tasks and *discrete* state and action spaces. All goal states are specified as *conjunctions* of literals. While we make no distinction between deterministic or stochastic transitions, all current experiments assume a *closed world*, i.e., all possible lifted actions and effects are known apriori.

4.1 Robot planning domains: Case studies

The full TASKOGRAPHY benchmark comprises 20 domains. We discuss the four task categories from which all domains are constructed that we believe to be interesting to a broad robotics audience.

Domain 1. *Rearrangement(k): Based on the recently proposed rearrangement challenge [77], this task requires a robot randomly spawned to rearrange a set of k objects of interest into k corresponding receptacles. The robot often needs to execute multiple other actions along the way, such as opening/closing doors, navigating to goals, planning the sequence of objects to visit, etc.*

Domain 2. *Courier (n, k): A robot that couriers objects is equipped with a knapsack of maximum payload capacity of n units. The robot needs to locate and courier k objects (of varying weights $w \in \{1, 2, 3\}$ units) to k distinct delivery points. The knapsack can be used to stow and retrieve items in random-access fashion; effectively embedding a combinatorial optimization problem into the task. Stow and retrieve actions increase branching, necessitating far deeper searches.*

We also provide *lifted* variants of these tasks. Here, goals are specified over desired object-receptacle class relations (e.g., “put a cup on a table”) as opposed to over object instances (e.g., “put this cup on the table”). These tasks introduce ambiguity in both the search of classical task-planners and learning-based techniques, which must now distinguish object instances of relevant classes.

Table 1: **TASKOGRAPHY** benchmark results on select grounded and lifted *Rearrangement (Rearr)* and *Courier (Cour)* 3DSG domains. Planning times are reported in seconds and do not incorporate planner-specific domain translation times (factored into planning timeouts). A ‘-’ indicates planning timeouts or failures (10 minutes for optimal planners, 30 seconds for all others). Results are aggregated over 10 random seeds. Optimal task planning is infeasible in larger problem instances or for more complex domains, while most satisficing planners are unable to achieve real-time performance. PLOI [13], a recent learning-based planner consistently performs the best across all domains.

Planner	Rearr(1) Tiny			Rearr(2) Tiny			Rearr(10) Medium			Cour(7, 10) Medium			Lifted Rearr(5) Tiny			Lifted Cour(5, 5) Tiny			
	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	
optimal	FD-seq-opt-lmcut	15.77	24.81	0.04	25.80	104.47	0.55	-	-	1.00	-	-	1.00	-	-	-	-	1.00	
	SatPlan	14.77	10.35	0.45	26.67	3.27	0.67	-	-	1.00	-	-	1.00	-	-	1.00	-	1.00	
	Delfi	15.13	0.36	0.16	29.10	27.77	0.29	-	-	1.00	-	-	1.00	-	-	1.00	-	1.00	
	DecStar-opt-fb	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	1.00	
satisficing	MCTS	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	1.00	
	FF	16.71	0.19	0.00	34.44	0.55	0.00	159.04	5.30	0.09	128.41	6.62	0.24	62.86	3.40	0.47	57.74	4.03	0.44
	FF-X	16.71	0.25	0.00	34.44	0.58	0.00	159.80	5.02	0.08	128.19	6.72	0.24	67.88	3.48	0.89	61.19	7.56	0.77
	FD-lama-first	15.19	2.96	0.33	38.47	3.25	0.18	208.28	6.35	0.49	156.34	4.92	0.29	66.81	3.20	0.49	61.13	3.34	0.56
	Cerberus-sat	11.50	12.00	0.85	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	1.00	
	Cerberus-agl	14.77	5.13	0.45	33.00	7.30	0.49	176.60	8.91	0.72	125.73	12.99	0.83	60.50	7.62	0.60	59.19	7.05	0.77
	DecStar-agl-fb	14.72	2.62	0.55	34.96	2.58	0.58	211.16	7.20	0.82	132.60	4.50	0.58	66.30	3.02	0.71	58.75	4.46	0.71
	BFWS	15.56	0.90	0.22	32.16	0.37	0.18	151.17	0.41	0.23	152.71	1.13	0.21	56.90	0.94	0.41	61.92	2.30	0.43
	Regression-plan	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	1.00	
learn	Relational policy [41]	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00	-	1.00	
	PLOI [13]	16.45	0.00*	0.00	37.04	0.00*	0.00	213.43	0.17	0.00	161.90	0.34	0.00	78.68	0.22	0.24	71.71	0.26	0.26

Domain 3. Lifted Rearrangement (k): *A lifted version of the rearrangement domain where the goals are specified at an object category level, as opposed to an instance level.*

Domain 4. Lifted Courier (n, k): *A lifted version of the courier domain where the goals are specified at an object category level, as opposed to an instance level.*

To promote compatibility with a range of planning systems [27, 78], we represent all tasks in PDDL format [79, 80]. We also include mechanisms for translating tasks into alternative problem definition languages that are essential for some of our supported planners [16].

4.2 Benchmarking classical and learned planners on TASKOGRAPHY

We present the empirical results on the TASKOGRAPHY benchmark across several classes of task-planners in Table. 1. (Please consult supplementary material for a number of additional results).

Evaluation protocol. We treat the evaluation of optimal planners separately to the remaining methods. Optimal planners are not intended to be fast unlike satisficing and learning-based variants. Rather, they compute a solution of minimum length (not necessarily unique) to a given problem. Optimal planners are hence allotted 10 minutes to solve each problem, while satisficing and learning-based planners are allotted 30 seconds. For learning-based methods, we evaluate results over 10 random seeds for statistical significance. We report standard deviations in the supplementary material. All domains comprise 40 training problems. The domains tagged *Tiny* and *Medium* comprise 55 and 182 test problems respectively, unless otherwise specified.

Optimal planners work only on the simplest of domains. Despite the reasonable performance of optimal planners on the *Rearrangement(1)* domain, they are unable to efficiently scale with increasing task complexity and fail to solve a single task on the *Rearrangement (k)* and *Courier (n, k)* domains for $k > 2$. In particular, the *Rearrangement(1)* domain is a superset of the grounded hierarchical path planning (HPP) task as described by Rosinol et al. [6]. Because the HPP task does not consider state changes to the scene graph (i.e., directly equating the 3DSG to the planning graph for search), efficient shortest path planning is tractable. However, increasingly complex robot tasks requires more than the mere ability to path plan in 3DSGs.

Planning performance degrades with domain complexity, not scene complexity. We observe an increase in the number of planning failures and timeouts as satisficing planners are applied to larger *Rearrangement(k)* domains (Table 2). Interestingly, larger scenes do not appear to directly correlate with task complexity, as the performance metrics remain largely consistent between the tiny and medium splits of the same domain (Table. 2).

Table 2: Interestingly, task complexity does not correlate strongly with scene complexity. It is instead determined by the number of operators, and avg. branch factor.

Planner	Rearr(10) Tiny			Rearr(10) Medium		
	Len.	Time	Fail	Len.	Time	Fail
FF	162.61	7.04	0.07	159.04	5.30	0.09
FD (satisficing)	205.89	7.68	0.51	208.28	6.35	0.49
DecStar-agl-fb	193.00	6.78	0.85	211.16	7.20	0.82
BFWS	160.93	0.57	0.18	151.17	0.41	0.23

Satisficing planners fail in domains requiring long-horizon reasoning. In the $Courier(n, k)$ domains, satisficing planners tend to produce shorter length solutions by leveraging the knapsack’s capacity to stow objects on the way to various delivery points. However, the planners often display shortsighted behaviours by stowing objects early in the search, depleting knapsack slots that could potentially help further along the task. This yields dead-end configurations and excessive backtracking, and thus, an increase in timeouts is observed.

Planners that do not exploit forward heuristics fail due to large branching factors. Due to the large branching factor of our domains, common strategies such as Monte-Carlo Tree Search (MCTS) and MC Regression Planning are unable to solve any task within a reasonable time constraint. For instance, a *Rearrangement(10)* task has an average branching factor of 6.5 for MCTS. Since a reward is only obtained at the end (typical planners take 200 steps to get there), MCTS degenerates to a slow breadth-first search.

Learning based planners that prune the state space excel on all domains. We also evaluate two prevalent learning-to-plan methods based on generalized relational planning [41] and planning with learned abstractions [13]. While the relational policy struggles to generalize in our domains (long-horizon, sparse rewards), PLOI demonstrates an impressive ability to detect and prune contextually irrelevant parts of the 3DSGs. However, it also requires a significant number of replanning steps (see figure to the right) as it often retains objects within a graph without ensuring that all properties and ancestors required to access the object are also preserved.

Discussion. Our evaluation of existing performant planners on the TASKOGRAPHY benchmark consistently reveals two important trends across all domains.

- Pruning a 3DSG is essential for real-time performance, more so on challenging domains.
- While learning-based planners excel across all domains, they require a large number of replanning steps.

These imply that efficient utilization of 3DSGs in real-time robotic task planning requires *both* adapting 3DSGs to better suit existing planners, and enabling performant (learning-based) planners to better exploit 3DSG hierarchies. The remainder of our work addresses these issues.

5 SCRUB: Principled sparsification of 3DSGs for efficient planning

As discussed above, learning-based planners leverage a wealth of prior knowledge acquired during a training phase to significantly prune extraneous scene graph entities. We argue that, if equipped with the right sparsification machinery, classical planners can compete with, or outperform learning methods. We develop SCRUB, a principled 3DSG sparsification scheme that prunes a 3DSG G (w.r.t. planning problem $\Pi_G = \langle \mathcal{O}, \mathcal{P}, \mathcal{A}, \mathcal{T}, \mathcal{C}, \mathcal{I}, \mathcal{G} \rangle$) by removing vertices and edges extraneous to the task, resulting in a sparsified 3DSG \hat{G} (and planning problem $\hat{\Pi}_{\hat{G}} = \langle \hat{\mathcal{O}}, \hat{\mathcal{P}}, \hat{\mathcal{A}}, \hat{\mathcal{T}}, \hat{\mathcal{C}}, \hat{\mathcal{I}}, \mathcal{G} \rangle$)

Definition 1. A valid 3DSG sparsification of G for a planning problem Π_G to \hat{G} (and corresponding planning problem $\hat{\Pi}_{\hat{G}}$) is a computable function $SCRUB(\Pi_G) = \hat{\Pi}_{\hat{G}}$ such that, a plan p solves Π_G iff it solves $\hat{\Pi}_{\hat{G}}$.

A satisficing plan for Π_G may thus be obtained by simply solving the (much easier to solve) sparsified problem $\hat{\Pi}_{\hat{G}}$. Savings in planning time depend on the complexity of the sparsified subgraph \hat{G} . SCRUB presents a simple strategy which is guaranteed to be minimal for grounded planning problems and satisficing for lifted planning problems.

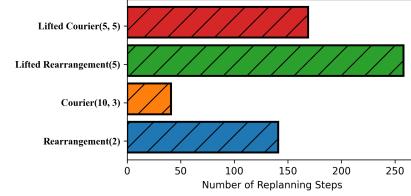


Figure 3: Learning-based planners like PLOI outperform all other planners on the benchmark, but still incur significant overhead (number of replanning steps).

Algorithm 1: SCRUB

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Input: 3DSG  $G$ , Planning problem
 $\Pi = \langle \mathcal{O}, \mathcal{P}, \mathcal{A}, \mathcal{T}, \mathcal{C}, \mathcal{I}, \mathcal{G} \rangle$ 
Result: Sparsified 3DSG  $\hat{G}$ 
 $\hat{\mathcal{O}} = \{\}$ ; /* Init. sufficient object set
*/
 $g = \text{OBJECTS}(\mathcal{G}.\text{literals}) \cup \{\text{robot}\}$ ; /* Init.
set of objects in the goal literal set
*/
while not empty  $g$  do
     $\hat{\mathcal{O}} \leftarrow \hat{\mathcal{O}} \cup g$ 
     $p \leftarrow \text{all binary predicates relating a newly added}$ 
     $\text{object (i.e. } o \in g - \hat{\mathcal{O}}\text{) to its ancestors in } G\text{}$ 
     $g \leftarrow \text{OBJECTS}(p)$ 
    if all objects  $\mathcal{O}$  visited then
        break
    end
end
 $\hat{G} \leftarrow G$ ; /* Initialize sparsified
scenegraph */
CONNECTROOMS; /* All-pairs shortest
paths */
Remove all nodes from  $\hat{G}$  that are not in  $\hat{\mathcal{O}}$ 
Prune literals that are no longer valid in the sparsified graph

```

For exposition, we consider grounded planning problems; see appendix for how SCRUB is adapted to lifted planning problems or stochastic transitions. SCRUB begins with an initially empty sufficient object set $\hat{\mathcal{O}}$. Satisfying the goal minimally requires all ground objects in the goal to be included in the sufficient object set $\hat{\mathcal{O}}$ (else goal objects are unreachable). In addition, the robot itself must be part of the sufficient set. Let p be the set of all binary predicates which include any of these objects. And let g be the set of all objects contained in p . In general, this will be a superset of the objects we started with. We iteratively repeat this process, each time adding the new objects in g to our sufficient set $\hat{\mathcal{O}}$.

The process terminates either when either the set g has no new objects (indicating convergence), or until all the objects in the scene graph are visited at least once (indicating the input graph already defines a minimal object set). We initialize the nodes of \hat{G} with objects in $\hat{\mathcal{O}}$, and copy over all edges $(u, v) \in G$ for which both $u, v \in \hat{\mathcal{O}}$. SCRUB terminates in time linear in the number of the predicates or nodes (whichever is larger).

Proposition 1. SCRUB is complete and results in a minimal scene subgraph for all grounded planning problems over the scenegraph domain. (Please refer to supp. material for proof)

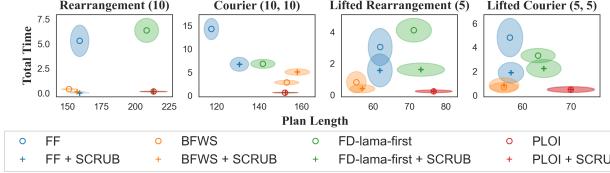


Figure 4: Best performing planners with and without SCRUB.

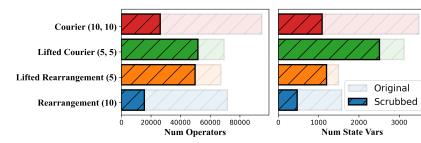


Figure 5: SCRUB greatly prunes operators and states of planning problems.

5.1 Impact of SCRUB on modern task planners

In this section, we investigate the effect that a 3DSG reduction scheme like SCRUB may have on the performance of modern task planners. We experiment with the four domains shown in Fig. 4 and evaluate the impact of scrub on planning performance and on domain structure.

SCRUB enables classical planners to obtain performance at least as good as state-of-the-art planners. In Fig. 4, we see that SCRUB drastically reduces planning time for FF, FD-lama-first, and BFWS to a few milliseconds on Rearrangement(10), and upper-bounds times at 5 seconds on Courier(10, 10). We see this enables BFWS, FD, and FF to outperform PLOI (lower plan lengths for similar plan times). The grounded domains each have 182 test problems, and the lifted domains each have 70 test problems.

SCRUB greatly reduces the number of operators and states. To asses the impact of SCRUB, we compute statistics (number of operators, number of state variables) in Fig. 5. We see that SCRUB prunes *more than two-thirds* of the operators and state variables for grounded planning problems, and about a third in the case of lifted planning problems.

SCRUB enables optimal planners to run on lifted domains. Table 3 reports results of running the satisficing and optimal variants of FD with and without SCRUB, on the *Lifted Rearrangement(5)* domain. While FD (optimal) did not converge even with a timeout of 24 hours, FD (optimal) + scrub solved about 72% of the tasks under a 30-second timeout, taking 2 seconds per task on average.

Table 3: Planner statistics evaluated over 70 test problems on *Lifted Rearrangement(5)*.

Planner	% Success	Length	Time
FD (satisficing)	51.43	66.81	3.20
FD (satisficing) + SCRUB	72.86	73.09	1.61
FD (optimal)	-	-	-
FD (optimal) + SCRUB	72.86	68.33	2.26

6 SEEK: A procedure for efficient learning-based planning

While SCRUB results in a 3DSG reduction that is guaranteed to find a satisficing plan—if one exists—its conservative approach hurts performance in challenging lifted planning problems as shown in Fig. 4. For such problems, learning-based graph-pruning strategies like PLOI [13] outperform classical planners over SCRUBBED 3DSGs. However, as can be seen in Sec. 4.2, even PLOI [13] incurs a significant number of replanning iterations.

Table 4: SEEK significantly reduces the number of replanning steps required by state-of-the-art learning-based planners. For each planner, we report average *wall time* (including translation time).

Planner	Rearrangement (2) - Medium				Courier (10, 3) - Medium				Lifted Rearrangement (5) - Medium				Lifted Courier (5, 5) - Medium			
	% Succ.	Len.	% Used	Time	#Replan	% Succ.	Len.	% Used	Time	#Replan	% Succ.	Len.	% Used	Time	#Replan	
Random	0.87	39.81	0.99	9.51	836	0.62	180	0.10	12.11	204	0.63	68.98	0.99	10.93	235	
Random + SEEK	0.86	39.82	0.98	8.55	543	0.60	183.49	0.99	12.33	162	0.59	69.22	0.97	9.52	155	
Hierarchical	1	35.76	0.28	0.45	150	1	191.75	0.48	1.16	40	0.80	76.75	0.59	2.60	269	
Hierarchical + SEEK	1	35.76	0.28	0.30	12	1	191.75	0.48	0.97	7	0.80	76.70	0.56	2.20	208	
PLOI[13]	1	35.76	0.28	0.44	141	1	191.75	0.48	1.13	41	0.79	78.16	0.59	2.49	258	
PLOI + SEEK	1	35.76	0.28	0.31	14	1	191.75	0.48	0.97	7	0.80	76.61	0.56	2.18	197	

We posit that several replanning iterations may be avoided by exploiting the 3DSG hierarchy. Pruning strategies like PLOI first score all objects, and retain a minimal set by thresholding. A simple threshold does little to ensure that all retained objects are reachable from the root of the scene graph. To alleviate this issue, we propose SEEK: a procedure that ensures we obtain a connected graph, with the objective of reducing the number of replanning steps needed.

SEEK requires as input the 3DSG, the planning problem Π , and an object scoring mechanism f_θ . This scoring mechanism is typically a graph neural network (akin to [13]) that, given the current state, scores each object with an *importance* value in $[0, 1]$. We first run the scorer and only retain objects above a threshold score t . We follow an identical approach to PLOI [13] and at each step geometrically decay the threshold by γ , such that at iteration i , the threshold is $t_i = \gamma t_{i-1}$, with $t_0, \gamma \in [0, 1)$. For each retained object o , we recursively traverse up the 3DSG, adding all ancestors of o to the sufficient object set. This procedure ensures that all objects are reachable from their respective room nodes. While SEEK, unlike SCRUB, is not guaranteed to be satisfying, it results in far fewer replanning steps without affecting computation time.

SEEK reduces replanning steps by an order of magnitude. To assess the impact of the SEEK procedure on planning performance, we evaluate performance with respect to other learning-based planners on TASKOGRAPHY in Table 4. As a baseline, we evaluate a *random* pruning strategy that uniformly randomly retains or prunes every object. Even for this naive strategy, SEEK offers significant performance improvement. We also evaluate *PLOI* [13] and our adaptation dubbed *hierarchical*, which trains multiple graph neural networks, one for each level of the 3DSG hierarchy. For each variant, SEEK offers a consistent performance improvement by decreasing the number of replanning steps required as seen in Fig. 6. SEEK is thus a conceptually simple strategy for use with learning-based planners.

SCRUB on grounded domains, SEEK on lifted domains: In general, we note that SCRUB is more performant on grounded domains (due to minimality properties) and SEEK is more performant on lifted domains (where SCRUB typically retains all instances of important object categories, but SEEK is more effective due to its opportunistic retention of instances (Fig. 7)).

7 Concluding remarks

Limitations. TASKOGRAPHY currently supports only a fraction of the diverse types of planning problems possible on 3DSGs. Geared towards identifying the most promising avenues in learning-based planning, the first release of this benchmark focuses exclusively on offline task planning in fully observable and deterministic domains. Furthermore, low-level motion planning is excluded from our benchmark. Robots operating in the real world will need to reason under partial observability, sensor noise, and resource constraints.

Outlook. TASKOGRAPHY, in conjunction with SCRUB and SEEK aid the robot learning community by (a) providing guidelines and implementations for practitioners choosing a task planner, (b) serving as a benchmark for upcoming learning-based planners, and (c) guiding the design of futuristic spatial representations for robotic task planning. We believe TASKOGRAPHY is a first step towards addressing several of the grand challenges along the road to developing general planning capabilities for autonomous intelligent robots.

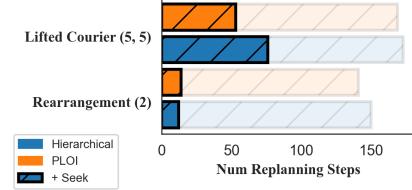


Figure 6: SEEK reduces replanning steps by an order of magnitude.

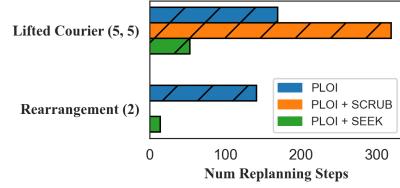


Figure 7: SCRUB on grounded domains, SEEK on lifted domains.

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References

- [1] B. Kuipers. The spatial semantic hierarchy. *Artificial intelligence*, 119(1-2):191–233, 2000.
- [2] E. Remolina and B. Kuipers. Towards a general theory of topological maps. *Artificial Intelligence*, 152(1):47–104, 2004.
- [3] C. Galindo, A. Saffiotti, S. Coradeschi, P. Buschka, J.-A. Fernandez-Madrigal, and J. González. Multi-hierarchical semantic maps for mobile robotics. In *2005 IEEE/RSJ international conference on intelligent robots and systems*, pages 2278–2283. IEEE, 2005.
- [4] H. Zender, O. M. Mozos, P. Jensfelt, G.-J. Kruijff, and W. Burgard. Conceptual spatial representations for indoor mobile robots. *Robotics and Autonomous Systems*, 56(6):493–502, 2008.
- [5] J.-R. Ruiz-Sarmiento, C. Galindo, and J. Gonzalez-Jimenez. Building multiversal semantic maps for mobile robot operation. *Knowledge-Based Systems*, 119:257–272, 2017.
- [6] A. Rosinol, A. Violette, M. Abate, N. Hughes, Y. Chang, J. Shi, A. Gupta, and L. Carlone. Kimera: from slam to spatial perception with 3d dynamic scene graphs. *arXiv preprint arXiv:2101.06894*, 2021.
- [7] I. Armeni, Z.-Y. He, J. Gwak, A. R. Zamir, M. Fischer, J. Malik, and S. Savarese. 3d scene graph: A structure for unified semantics, 3d space, and camera. In *Proceedings of Computer Vision and Pattern Recognition (CVPR)*, 2019.
- [8] A. Rosinol, A. Gupta, M. Abate, J. Shi, and L. Carlone. 3d dynamic scene graphs: Actionable spatial perception with places, objects, and humans. In *Robotics Science and Systems (R-SS)*, 2020.
- [9] U.-H. Kim, J.-M. Park, T.-J. Song, and J.-H. Kim. 3-d scene graph: A sparse and semantic representation of physical environments for intelligent agents. *IEEE transactions on cybernetics*, 50(12):4921–4933, 2019.
- [10] Z. Ravichandran, L. Peng, N. Hughes, J. D. Griffith, and L. Carlone. Hierarchical representations and explicit memory: Learning effective navigation policies on 3d scene graphs using graph neural networks. *arXiv preprint arXiv:2108.01176*, 2021.
- [11] A. Kurenkov, R. Martín-Martín, J. Ichnowski, K. Goldberg, and S. Savarese. Semantic and geometric modeling with neural message passing in 3d scene graphs for hierarchical mechanical search. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2020.
- [12] R. Talak, S. Hu, L. Peng, and L. Carlone. Neural trees for learning on graphs. *arXiv preprint arXiv:2105.07264*, 2021.
- [13] T. Silver, R. Chitnis, A. Curtis, J. Tenenbaum, T. Lozano-Perez, and L. P. Kaelbling. Planning with learned object importance in large problem instances using graph neural networks. *AAAI International conference on Artificial Intelligence*, 2020.
- [14] H. Kautz and B. Selman. Pushing the envelope: Planning, propositional logic, and stochastic search. In *Proceedings of the National Conference on Artificial Intelligence*, pages 1194–1201. Citeseer, 1996.
- [15] H. Kautz and B. Selman. Unifying sat-based and graph-based planning. In *IJCAI*, volume 99, pages 318–325, 1999.

- [16] H. Kautz, B. Selman, and J. Hoffmann. Satplan: Planning as satisfiability. In *5th international planning competition*, volume 20, page 156, 2006.
- [17] M. Katz, S. Sohrabi, H. Samulowitz, and S. Sievers. Delfi: Online planner selection for cost-optimal planning. *IPC-9 planner abstracts*, pages 57–64, 2018.
- [18] C. B. Browne, E. Powley, D. Whitehouse, S. M. Lucas, P. I. Cowling, P. Rohlfsagen, S. Tavener, D. Perez, S. Samothrakis, and S. Colton. A survey of monte carlo tree search methods. *IEEE Transactions on Computational Intelligence and AI in games*, 4(1):1–43, 2012.
- [19] B. Bonet and H. Geffner. Planning as heuristic search: New results. In *European Conference on Planning*, pages 360–372. Springer, 1999.
- [20] H. Kaindl. Tree searching algorithms. *Computers, Chess, and Cognition*, pages 133–158, 1990.
- [21] B. Bonet and H. Geffner. Planning as heuristic search. *Artificial Intelligence*, 129(1-2):5–33, 2001.
- [22] J. Hoffmann and B. Nebel. The ff planning system: Fast plan generation through heuristic search. *Journal of Artificial Intelligence Research*, 14:253–302, 2001.
- [23] M. Helmert. The fast downward planning system. *Journal of Artificial Intelligence Research*, 26:191–246, 2006.
- [24] M. Katz. Cerberus: Red-black heuristic for planning tasks with conditional effects meets novelty heuristic and enhanced mutex detection. *IPC-9 planner abstracts*, pages 47–51, 2018.
- [25] D. Gnad, A. Shleyfman, and J. Hoffmann. Decstar-star-topology decoupled search at its best. *IPC-9 planner abstracts*, pages 42–46, 2018.
- [26] D. Long and M. Fox. The 3rd international planning competition: Results and analysis. *Journal of Artificial Intelligence Research*, 20:1–59, 2003.
- [27] M. Vallati, L. Chrpa, M. Grześ, T. L. McCluskey, M. Roberts, S. Sanner, et al. The 2014 international planning competition: Progress and trends. *Ai Magazine*, 36(3):90–98, 2015.
- [28] R. Chitnis, T. Silver, B. Kim, L. P. Kaelbling, and T. Lozano-Perez. Camps: Learning context-specific abstractions for efficient planning in factored mdps. *arXiv preprint arXiv:2007.13202*, 2020.
- [29] C. Galindo, J.-A. Fernandez-Madrigal, and J. Gonzalez. Improving efficiency in mobile robot task planning through world abstraction. *IEEE Transactions on Robotics (T-RO)*, 20(4):677–690, 2004.
- [30] L. E. Kavraki, P. Svestka, J.-C. Latombe, and M. H. Overmars. Probabilistic roadmaps for path planning in high-dimensional configuration spaces. *IEEE transactions on Robotics and Automation*, 12(4):566–580, 1996.
- [31] C. Galindo, J.-A. Fernández-Madrigal, J. González, and A. Saffiotti. Robot task planning using semantic maps. *Robotics and Autonomous Systems*, 56(11):955–966, 2008. ISSN 0921-8890. doi:<https://doi.org/10.1016/j.robot.2008.08.007>.
- [32] L. P. Kaelbling and T. Lozano-Pérez. Integrated task and motion planning in belief space. *The International Journal of Robotics Research*, 32(9-10):1194–1227, 2013.
- [33] B. Kim, Z. Wang, L. P. Kaelbling, and T. Lozano-Pérez. Learning to guide task and motion planning using score-space representation. *The International Journal of Robotics Research*, 38(7):793–812, 2019.
- [34] C. R. Garrett, R. Chitnis, R. Holladay, B. Kim, T. Silver, L. P. Kaelbling, and T. Lozano-Pérez. Integrated task and motion planning. *Annual review of control, robotics, and autonomous systems*, 4:265–293, 2021.

- [35] L. P. Kaelbling and T. Lozano-Pérez. Hierarchical planning in the now. In *Workshops at the Twenty-Fourth AAAI Conference on Artificial Intelligence*, 2010.
- [36] S. Stock, M. Mansouri, F. Pecora, and J. Hertzberg. Online task merging with a hierarchical hybrid task planner for mobile service robots. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 6459–6464. IEEE, 2015.
- [37] J. C. González, J. C. Pulido, and F. Fernández. A three-layer planning architecture for the autonomous control of rehabilitation therapies based on social robots. *Cognitive Systems Research*, 43:232–249, 2017.
- [38] M. Beetz, D. Jain, L. Mosenlechner, M. Tenorth, L. Kunze, N. Blodow, and D. Pangercic. Cognition-enabled autonomous robot control for the realization of home chore task intelligence. *Proceedings of the IEEE*, 100(8):2454–2471, 2012.
- [39] G. Konidaris, S. Kuindersma, R. Grupen, and A. Barto. Robot learning from demonstration by constructing skill trees. *The International Journal of Robotics Research*, 31(3):360–375, 2012.
- [40] P. Bercher, R. Alford, and D. Höller. A survey on hierarchical planning—one abstract idea, many concrete realizations. In *IJCAI*, pages 6267–6275, 2019.
- [41] O. Rivlin, T. Hazan, and E. Karpas. Generalized planning with deep reinforcement learning. *arXiv preprint arXiv:2005.02305*, 2020.
- [42] R. Karia and S. Srivastava. Learning generalized relational heuristic networks for model-agnostic planning. *arXiv preprint arXiv:2007.06702*, 2020.
- [43] D. Gnad, A. Torralba, M. Domínguez, C. Areces, and F. Bustos. Learning how to ground a plan—partial grounding in classical planning. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 33, pages 7602–7609, 2019.
- [44] J. Oh, S. Singh, H. Lee, and P. Kohli. Zero-shot task generalization with multi-task deep reinforcement learning. In *International Conference on Machine Learning*, pages 2661–2670. PMLR, 2017.
- [45] J. Andreas, D. Klein, and S. Levine. Modular multitask reinforcement learning with policy sketches. In *International Conference on Machine Learning*, pages 166–175. PMLR, 2017.
- [46] M. Denil, S. G. Colmenarejo, S. Cabi, D. Saxton, and N. de Freitas. Programmable agents. *arXiv preprint arXiv:1706.06383*, 2017.
- [47] S.-H. Sun, T.-L. Wu, and J. J. Lim. Program guided agent. In *International Conference on Learning Representations*, 2019.
- [48] Y. Yang, J. P. Inala, O. Bastani, Y. Pu, A. Solar-Lezama, and M. Rinard. Program synthesis guided reinforcement learning. *arXiv preprint arXiv:2102.11137*, 2021.
- [49] D. Xu, R. Martín-Martín, D.-A. Huang, Y. Zhu, S. Savarese, and L. Fei-Fei. Regression planning networks. *arXiv preprint arXiv:1909.13072*, 2019.
- [50] A. Guez, T. Weber, I. Antonoglou, K. Simonyan, O. Vinyals, D. Wierstra, R. Munos, and D. Silver. Learning to search with mctsnets. In *International Conference on Machine Learning*, pages 1822–1831. PMLR, 2018.
- [51] P. Karkus, D. Hsu, and W. S. Lee. Qmdp-net: Deep learning for planning under partial observability. *arXiv preprint arXiv:1703.06692*, 2017.
- [52] P. Karkus, D. Hsu, and W. S. Lee. Integrating algorithmic planning and deep learning for partially observable navigation. *arXiv preprint arXiv:1807.06696*, 2018.
- [53] A. Guez, M. Mirza, K. Gregor, R. Kabra, S. Racanière, T. Weber, D. Raposo, A. Santoro, L. Orseau, T. Eccles, et al. An investigation of model-free planning. In *International Conference on Machine Learning*, pages 2464–2473. PMLR, 2019.

- [54] D.-A. Huang, S. Nair, D. Xu, Y. Zhu, A. Garg, L. Fei-Fei, S. Savarese, and J. C. Niebles. Neural task graphs: Generalizing to unseen tasks from a single video demonstration. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 8565–8574, 2019.
- [55] D. Xu, S. Nair, Y. Zhu, J. Gao, A. Garg, L. Fei-Fei, and S. Savarese. Neural task programming: Learning to generalize across hierarchical tasks. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*, pages 3795–3802. IEEE, 2018.
- [56] Y. Shen, J. Chen, P.-S. Huang, Y. Guo, and J. Gao. M-walk: Learning to walk over graphs using monte carlo tree search. *arXiv preprint arXiv:1802.04394*, 2018.
- [57] D. Fišer. Lifted fact-alternating mutex groups and pruned grounding of classical planning problems. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 34, pages 9835–9842, 2020.
- [58] D. Fišer, R. Horčík, and A. Komenda. Strengthening potential heuristics with mutexes and disambiguations. In *Proceedings of the International Conference on Automated Planning and Scheduling*, volume 30, pages 124–133, 2020.
- [59] N. Kumar, M. Fishman, N. Danas, M. L. Littman, S. Tellex, and G. Konidaris. Task scoping: Building goal-specific abstractions for planning in complex domains. *CoRR*, abs/2010.08869, 2020. URL <https://arxiv.org/abs/2010.08869>.
- [60] P. W. Battaglia, J. B. Hamrick, V. Bapst, A. Sanchez-Gonzalez, V. Zambaldi, M. Malinowski, A. Tacchetti, D. Raposo, A. Santoro, R. Faulkner, et al. Relational inductive biases, deep learning, and graph networks. *arXiv preprint arXiv:1806.01261*, 2018.
- [61] T. Kipf, E. Fetaya, K.-C. Wang, M. Welling, and R. Zemel. Neural relational inference for interacting systems. In *International Conference on Machine Learning*, pages 2688–2697. PMLR, 2018.
- [62] T. Kipf, E. van der Pol, and M. Welling. Contrastive learning of structured world models. *arXiv preprint arXiv:1911.12247*, 2019.
- [63] F. Locatello, D. Weissenborn, T. Unterthiner, A. Mahendran, G. Heigold, J. Uszkoreit, A. Dosovitskiy, and T. Kipf. Object-centric learning with slot attention. *arXiv preprint arXiv:2006.15055*, 2020.
- [64] E. Kolve, R. Mottaghi, W. Han, E. VanderBilt, L. Weihs, A. Herrasti, D. Gordon, Y. Zhu, A. Gupta, and A. Farhadi. Ai2-thor: An interactive 3d environment for visual ai. *arXiv preprint arXiv:1712.05474*, 2017.
- [65] M. Shridhar, J. Thomason, D. Gordon, Y. Bisk, W. Han, R. Mottaghi, L. Zettlemoyer, and D. Fox. Alfred: A benchmark for interpreting grounded instructions for everyday tasks. In *Proceedings of Computer Vision and Pattern Recognition (CVPR)*, 2020.
- [66] X. Puig, K. Ra, M. Boben, J. Li, T. Wang, S. Fidler, and A. Torralba. Virtualhome: Simulating household activities via programs. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 8494–8502, 2018.
- [67] M. Savva, A. Kadian, O. Maksymets, Y. Zhao, E. Wijmans, B. Jain, J. Straub, J. Liu, V. Koltun, J. Malik, et al. Habitat: A platform for embodied ai research. In *Proceedings of Computer Vision and Pattern Recognition (CVPR)*, 2019.
- [68] L. Weihs, M. Deitke, A. Kembhavi, and R. Mottaghi. Visual room rearrangement. *arXiv preprint arXiv:2103.16544*, 2021.
- [69] C. Gan, S. Zhou, J. Schwartz, S. Alter, A. Bhandwaldar, D. Gutfreund, D. L. Yamins, J. J. DiCarlo, J. McDermott, A. Torralba, et al. The threedworld transport challenge: A visually guided task-and-motion planning benchmark for physically realistic embodied ai. *arXiv preprint arXiv:2103.14025*, 2021.

- [70] B. Shen, F. Xia, C. Li, R. Martín-Martín, L. Fan, G. Wang, S. Buch, C. D’Arpino, S. Srivastava, L. P. Tchapmi, et al. igibson, a simulation environment for interactive tasks in large realistic scenes. *IEEE International Conference on Robotics and Automation (ICRA)*, 2020.
- [71] F. Xiang, Y. Qin, K. Mo, Y. Xia, H. Zhu, F. Liu, M. Liu, H. Jiang, Y. Yuan, H. Wang, et al. Sapien: A simulated part-based interactive environment. In *Proceedings of Computer Vision and Pattern Recognition (CVPR)*, 2020.
- [72] Y.-q. Jiang, S.-q. Zhang, P. Khandelwal, and P. Stone. Task planning in robotics: an empirical comparison of pddl- and asp-based systems. *Frontiers of Information Technology & Electronic Engineering*, 20(3):363–373, 2019.
- [73] M. Shridhar, X. Yuan, M.-A. Côté, Y. Bisk, A. Trischler, and M. Hausknecht. Alfworld: Aligning text and embodied environments for interactive learning. *arXiv preprint arXiv:2010.03768*, 2020.
- [74] C. Gan, J. Schwartz, S. Alter, M. Schrimpf, J. Traer, J. De Freitas, J. Kubilius, A. Bhandwadar, N. Haber, M. Sano, et al. Threedworld: A platform for interactive multi-modal physical simulation. *arXiv preprint arXiv:2007.04954*, 2020.
- [75] F. Xia, A. R. Zamir, Z. He, A. Sax, J. Malik, and S. Savarese. Gibson env: Real-world perception for embodied agents. In *Proceedings of Computer Vision and Pattern Recognition (CVPR)*, 2018.
- [76] N. Lipovetzky and H. Geffner. Best-first width search: Exploration and exploitation in classical planning. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 31, 2017.
- [77] D. Batra, A. X. Chang, S. Chernova, A. J. Davison, J. Deng, V. Koltun, S. Levine, J. Malik, I. Mordatch, R. Mottaghi, et al. Rearrangement: A challenge for embodied ai. *arXiv preprint arXiv:2011.01975*, 2020.
- [78] Planutils. <https://github.com/AI-Planning/planutils>. Accessed: June 18 2021.
- [79] D. McDermott, M. Ghallab, A. Howe, C. Knoblock, A. Ram, M. Veloso, D. Weld, and D. Wilkins. Pddl-the planning domain definition language. 1998.
- [80] T. Silver and R. Chitnis. Pddlgym: Gym environments from pddl problems. *arXiv preprint arXiv:2002.06432*, 2020.

Supplementary material: TASKOGRAPHY – Evaluating robot task planning over large 3D scene graphs

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Abstract: This supplementary material discusses additional details and design choices for the TASKOGRAPHY benchmark, including extended descriptions for all supported planning domains and their constituents - object types, relations (i.e., properties, predicates), and goal specifications. We provide results for these additional domains, and discuss SCRUB and its favourable properties in greater detail.

Please visit our [project page](#) for more details, including a [video abstract](#).

Keywords: Robot task planning, 3D scene graphs, learning to plan, benchmarks

1 Benchmark Details

The TASKOGRAPHY benchmark comprises 20 robot task planning domains over 3D scene graphs (3DSGs). In the main paper, we detailed the *Rearrangement(k)*, *Courier(n,k)*, *Lifted Rearrangement(k)*, and *Lifted Courier(n, k)* task definitions following the recently proposed Rearrangement challenge [1]. Table. 1 lists the set of *lifted* objects in each planning domain. In all problems, we have one instance of an *agent*, but several ground objects corresponding to the other categories.

1.1 TASKOGRAPHY domain construction: Parsing Gibson 3DSGs

We parse the 3DSGs created over Gibson [2, 3] mapping scene entities to objects and structural relations to predicates over objects. We retain key connectivity constraints that govern traversable paths between locations in the same place, places in the same room, and between rooms. Because room connectivity data is not provided in the original database, we estimate it by computing a minimal spanning tree over rooms in the 3DSGs with edge weights reflecting the Euclidean distance between room centroids. For larger scenes, we impose a single connection between rooms in different floors (e.g., one set of stairs). Several additional properties are used to express the state of agent and interactable objects, and to associate each of them to a particular location in the 3DSG.

Table 1: Evaluated 3DSG planning domains in TASKOGRAPHY and object types present in each. Domains are further partitioned into tiny and medium splits akin to the 3DSGs provided over Gibson [2, 3]. Scene entities are instantiated as a particular object type according to their semantic class.

	n	k	Agent	Room	Place	Location	Receptacle	Item	Bagslot	Receptacle Class	Item Class
Rearr(k)	-	{1, 2, 5, 10}	✓	✓	✓	✓	✓	✓	✗	✗	✗
Cour(n, k)	{3, 5, 7, 10}	{5, 10}	✓	✓	✓	✓	✓	✓	✓	✗	✗
Lifted Rearr(k)	-	{5}	✓	✓	✓	✓	✓	✓	✗	✓	✓
Lifted Cour(n, k)	{5}	{5}	✓	✓	✓	✓	✓	✓	✓	✓	✓

An assignment of values to all possible properties over objects defines a symbolic *state* in the planning problem; hence, actions taken by the robot in TASKOGRAPHY alter the symbolic state of the 3DSG. We observe a significant variation in the size of the state space between different types of domains as a result of the varying subsets of object and predicate types used to express their respective tasks (see Table. 2). For instance, the *Rearrangement(k)* task represents the lowest complexity domain on TASKOGRAPHY and is thereby defined by the smallest subset of object types, predicates, and actions available to the robot. In contrast, the *Lifted Courier(n, k)* extends the *Rearrangement(k)*

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task definition with bagslots enabling stow and retrieve operators, as well as receptacle classes and item classes to express lifted class relations in the 3DSG at particular state.

We leverage **task samplers** built into TASKOGRAPHY-API for generating large-scale and diverse datasets of planning problems over 3DSGs. In a two step process the task samplers automatically parse 3DSGs into plannable symbolic representations (i.e., embedding the agent forms the initial state \mathcal{I}) before composing goal literals over randomly sampled scene entities. For grounded problems, goals are conjunctions of `inReceptacle` literals expressed over randomly sampled item and receptacle target ground instances. For lifted problems, goal are conjunctions of `classRelation` literals expressed over randomly sampled item and receptacle target class relations.

Table 2: Structural relations of 3DSGs and the state of the robot and interactable objects (i.e., items and receptacles) are captured with an assignment of values to all possible predicates over objects. The most challenging *Lifted Courier(n, k)* is the only domain to incorporate all relations, while other domain types in TASKOGRAPHY require only a subset of the properties and relations.

Object (types)	Agent	Room	Place	Location	Receptacle	Item	Bagslot	Receptacle Class	Item Class
Agent	holdsAny	inRoom	inPlace	atLoc	-	holdsItem	-	-	-
Room	inRoom	connected	placeInRoom + roomCenter	placeInRoom + roomCenter	-	-	-	-	-
Place	inPlace	placeInRoom + roomCenter	-	locInPlace + placeCenter	-	-	-	-	-
Location	atLoc	-	locInPlace + placeCenter	-	recepAtLoc	itemAtLoc	-	-	-
Receptacle	-	-	-	recepAtLoc	recepOpened	inRecep	-	recepClass	-
Item	holdsItem	-	-	itemAtLoc	inRecep	small + medium + large	inSlot	-	itemClass
Bagslot	-	-	-	-	recepClass	isSlot	slotHoldsAny	-	-
Receptacle Class	-	-	-	-	itemClass	-	-	classRelation	-
Item Class	-	-	-	-	-	-	-	-	*

1.2 Domain specifications

To provide further clarity on the four task categories (*Rearrangement(k)*, *Courier(n,k)*, *Lifted Rearrangement(k)*, and *Lifted Courier(n, k)*) from which our 3DSG planning domains are constructed, we herein outline hypothetical problem instances involving but a fraction of the objects, attributes, and relations available in TASKOGRAPHY. Let the environment consist of v rooms connected by e undirected traversability constraints; e.g., `connected(roomA, roomB)`. The spatial hierarchy of 3DSGs [2, 4] is induced by the appropriate application of structural relations (see Table. 2) to a discrete set of places in each room, and locations in each place; e.g., `placeInRoom(placeD, roomC)`, `locInPlace(locF, placeD)`. The lowest level of the spatial hierarchy (locations) encodes all occupiable positions for the agent, items, and receptacles in the scene; e.g., `atLoc(agent, locationB)`, `itemAtLoc(mugA, locationD)`, `recepAtLoc(fridgeC, locationG)`. Such relations equate to logical predicates in [5] and can be altered by the agent should the required preconditions of an action be met in the current state; e.g., `~holdsAny(agent)` and `~(atLoc(agent, locX), itemAtLoc(mugA, locX))` are preconditions for `PICKUPITEM(mugA, agent)`.

As mentioned in Sec. 1.1, the goals in grounded planning problems are specified with `inReceptacle` literals. Concretely, a *Rearrangement(k)* task for $k = 1$ requires the agent to pick-and-place a ground item in a ground receptacle, where each object in the goal is uniquely identified; e.g., $G = \text{inReceptacle}(\text{mugA}, \text{fridgeC})$. By extension, a *Rearrangement(k)* task for $k = 2$ is solved iff the agent derives a state satisfying the conjunction of two `inReceptacle` goal literals; e.g., $G = \wedge(\text{inReceptacle}(\text{mugA}, \text{fridgeC}), \text{inReceptacle}(\text{plateD}, \text{shelfB}))$. The *Courier(n, k)* domains attribute weights ($w \in 1, 2, 3$ units) to items based on their volume, and equips the agent with a knapsack of fixed capacity n to stow and retrieve items as it traverses the scene. While the knapsack in *Courier(n, k)* enables planners to exploit stowing capacity to compute lower cost solutions (at the expense of task complexity) in comparison to *Rearrangement(k)*, goals are identically specified between the two task categories since they are both considered grounded.

In stark contrast, lifted planning problems are specified with `classRelation` literals expressed over item-receptacle class combinations. For instance, the following *Lifted Rearrangement(k)* or *Lifted Courier(n, k)* domain with $k = 2$, $G = \wedge(\text{classRelation}(\text{cup}, \text{cupboard}), \text{classRelation}(\text{plate}, \text{sink}))$, requires the agent to place **at least one** cup in a cupboard and plate in a sink for the task to be complete. This disambiguates the planner which is no longer able to exploit ground objects featured in the goal as heuristic landmarks, and reduces the effectiveness of deterministic graph sparsification techniques such as SCRUB. As in the grounded domain variants, the goal specifications for both the *Lifted Rearrangement(k)* and *Lifted Courier(n, k)* are identical.

1.3 Symbolic environment interaction

The **action space** of the most complex domain in TASKOGRAPHY equips the agent with 16 operators where only a subset are feasible at any given state. Below, we describe but a few of these operators which demonstrate motion through 3DSG hierachies and object-level robot interaction.

- GoToRoom: The robot moves from the door of its current room to the door of the target room if the rooms are *connected*.
- GoToPlace: The robot moves from the center of its current place to the center of the target place if the places are in the same room.
- GoToLocation: The robot moves from the current location to the target location if the locations are in the same place.
- OPENRECEPTACLE: The robot opens a queried *openable* receptacle.
- CLOSERECEPTACLE: The robot closes a queried *openable* receptacle.
- PICKUPITEM: The robot picks-up an item at a particular location with a free gripper; three operator variations for picking from non existent, non-opening, and opening receptacles.
- PLACEITEM: The robot places an in-gripper item at a particular location; two operator variations for placing in non-opening and opening receptacles.
- STOWITEM: The robot stows an in-gripper item in its knapsack: three operator variations for small, medium, and large items consuming increasing numbers of bagslots.
- RETRIEVEITEM: The robot retrieves an item from its knapsack into its gripper; three operator variations for small, medium, and large items freeing increasing number of bagslots.

Should the preconditions for any of these actions not be satisfied, the action is deemed invalid.

2 SCRUB: Discussion and analysis

In the main paper, for sake of brevity, we only discussed the applicability of SCRUB to grounded planning problems with deterministic transitions. However, by design, SCRUB may be applied to any planning problem: *lifted* or *grounded*, with *deterministic* or *stochastic* transitions.

In *lifted* planning problems, we modify SCRUB to trivially include all ground object tuples that satisfy goal conditions into the initial sufficient object set. This in-turn ensures that all of these ground objects are reachable from the start state, ensuring a satisfying plan exists. However, this conservative strategy may resulting in retaining more objects than minimally required – this is where SEEK can be applied to opportunistically retain important objects instead.

In a similar vein, for *stochastic* transitions, we modify SCRUB to include all binary predicates resulting from all possible stochastic transitions from a given node.

We now prove that SCRUB results in a minimal scene subgraph for all grounded planning problems.

Proposition 1. SCRUB is complete and results in a minimal scene subgraph for all grounded planning problems over the scenegraph domain.

Proof. We prove the minimality of SCRUB by demonstrating that whenever we prune a node from a SCRUBBED scenegraph, the resultant planning problem is unsolvable. Assume that we prune a node n from a SCRUBBED 3DSG \hat{G} . Recall the types of nodes we have in the 3DSG: agent, room, place, receptacle, item, floor, building.

1. If n is of type agent or building, the problem is unsolvable, by construction.
2. If n is of type item, removing it would render the goal state unreachable — recall that \hat{G} only retains item nodes that feature in the goal state.
3. If n is of type receptacle, it is retained in \hat{G} either because (a) it is required to access a goal object of type item, or (b) it is a goal receptacle (i.e., a target location an item must be moved into). Removing n will thus render one of the objects in the goal state unreachable.

4. If n is of type `place`, `room` or `floor`, $n \in \hat{G}$ because n directly features in the goal state, or because n is required to traverse from the start state to the goal state (e.g., rooms that connect the start and goal rooms, etc.).

Since pruning any of these nodes renders the problem unsolvable, the SCRUBBED graph \hat{G} is a minimal scene subgraph for the grounded planning problem considered. \square

3 Additional results on TASKOGRAPHY domains

In this section, we provide results over several extended domains from the TASKOGRAPHY benchmark. Please see Tables 3, 4, 5, 6, 7, 8.

Table 3: Performance of planners over the *Rearrangement(k)*-Tiny tasks. For all metrics, lower values indicate better performance.

	Planner	Rearr(1) Tiny			Rearr(2) Tiny			Rearr(10) Tiny		
		Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail
optimal	FD-seq-opt-lmcut	15.77	24.81	0.04	25.80	104.47	0.55	-	-	1.00
	SatPlan	14.77	10.35	0.45	26.67	3.27	0.67	-	-	1.00
	Delfi	15.13	0.36	0.16	29.10	27.77	0.29	-	-	1.00
	DecStar-opt-fb	-	-	1.00	-	-	1.00	-	-	1.00
	MCTS	-	-	1.00	-	-	1.00	-	-	1.00
satisficing	FF	16.71	0.19	0.00	34.44	0.55	0.00	162.61	7.04	0.07
	FF-X	16.71	0.25	0.00	34.44	0.58	0.00	162.30	7.39	0.09
	FD-lama-first	15.19	2.96	0.33	38.47	3.25	0.18	205.89	7.68	0.51
	Cerberus-sat	11.50	12.00	0.85	-	-	1.00	-	-	1.00
	Cerberus-agl	14.77	5.13	0.45	33.00	7.30	0.49	186.07	9.04	0.73
	DecStar-agl-fb	14.72	2.62	0.55	34.96	2.58	0.58	193.00	6.78	0.85
	BFWS	15.56	0.90	0.22	32.16	0.37	0.18	160.93	0.57	0.18
	Regression-plan	-	-	1.00	-	-	1.00	-	-	1.00
learn	Relational policy [6]	-	-	1.00	-	-	1.00	-	-	1.00
	PLOI [7]	16.45	0.00*	0.00	37.04	0.00*	0.00	221.71	0.18	0.00

Table 4: Performance of planners over the *Rearrangement(k)*-Medium tasks. For all metrics, lower values indicate better performance.

	Planner	Rearr(1) Medium			Rearr(2) Medium			Rearr(10) Medium		
		Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail
optimal	FD-seq-opt-lmcut	15.53	19.68	0.06	27.13	125.69	0.41	-	-	1.00
	SatPlan	14.98	11.98	0.33	28.23	5.45	0.50	-	-	1.00
	Delfi	15.40	3.62	0.16	29.13	12.79	0.28	-	-	1.00
	DecStar-opt-fb	15.42	41.35	0.93	28.50	111.53	0.91	-	-	1.00
	MCTS	-	-	1.00	-	-	1.00	-	-	1.00
satisficing	FF	16.45	0.25	0.00	32.87	0.41	0.00	159.04	5.30	0.09
	FF-X	16.45	0.21	0.00	32.87	0.45	0.00	159.80	5.02	0.08
	FD-lama-first	15.51	2.48	0.21	39.20	2.77	0.20	208.28	6.35	0.49
	Cerberus-sat	11.20	10.17	0.88	-	-	1.00	-	-	1.00
	Cerberus-agl	15.18	6.10	0.34	32.20	6.40	0.33	176.60	8.91	0.72
	DecStar-agl-fb	15.36	2.15	0.58	36.35	2.40	0.59	211.16	7.20	0.82
	BFWS	15.42	0.60	0.23	30.65	0.44	0.27	151.17	0.41	0.23
	Regression-plan	-	-	1.00	-	-	1.00	-	-	1.00
learn	Relational policy [6]	-	-	1.00	-	-	1.00	-	-	1.00
	PLOI [7]	16.44	0.00*	0.00	36.19	0.00*	0.00	213.43	0.17	0.00

Table 5: Performance of planners over the *Courier(n, k)*-Tiny tasks. For all metrics, lower values indicate better performance.

Planner	Cour(3, 10) Tiny			Cour(5, 10) Tiny			Cour(7, 10) Tiny			Cour(10, 10) Tiny			
	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	
satisficing	FF	146.35	7.57	0.13	136.38	7.97	0.33	127.88	6.84	0.55	124.93	14.62	0.73
	FF-X	144.80	8.34	0.11	137.05	7.49	0.31	128.42	8.34	0.53	126.31	15.21	0.71
	FD-lama-first	175.15	8.31	0.53	159.64	7.31	0.55	156.12	6.97	0.55	145.00	7.50	0.56
	Cerberus-sat	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00
	Cerberus-agl	137.87	10.79	0.73	127.30	17.61	0.82	138.25	21.65	0.93	-	-	1.00
	DecStar-agl-fb	140.47	4.52	0.69	124.62	4.65	0.71	120.20	4.04	0.73	117.73	6.98	0.73
	BFWS	160.18	1.19	0.18	159.17	0.94	0.25	159.90	1.80	0.29	153.93	4.28	0.45
learn	Regression-plan	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00
	Relational policy [6]	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00
	PLOI [7]	193.55	0.22	0.00	179.36	0.26	0.00	172.87	0.37	0.00	167.38	0.71	0.00

Table 6: Performance of planners over the *Courier(n, k)*-Medium tasks. For all metrics, lower values indicate better performance.

Planner	Cour(3, 10) Medium			Cour(5, 10) Medium			Cour(7, 10) Medium			Cour(10, 10) Medium			
	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	Len.	Time	Fail	
satisficing	FF	141.89	4.94	0.07	133.46	6.29	0.20	128.41	6.62	0.24	117.50	14.27	0.78
	FF-X	141.89	4.47	0.07	133.50	5.80	0.19	128.19	6.72	0.24	118.67	15.52	0.77
	FD-lama-first	180.38	7.11	0.40	166.35	6.27	0.45	156.34	4.92	0.29	141.75	6.80	0.63
	Cerberus-sat	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00
	Cerberus-agl	148.41	10.17	0.74	133.31	11.50	0.77	125.73	12.99	0.83	109.56	15.58	0.95
	DecStar-agl-fb	154.07	6.45	0.66	142.42	4.01	0.61	132.60	4.50	0.58	128.58	7.60	0.70
	BFWS	151.09	0.60	0.27	152.61	0.66	0.20	152.71	1.13	0.21	153.02	2.81	0.30
learn	Regression-plan	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00
	Relational policy [6]	-	-	1.00	-	-	1.00	-	-	1.00	-	-	1.00
	PLOI [7]	182.31	0.20	0.00	169.20	0.24	0.00	161.90	0.34	0.00	152.19	0.61	0.00

Table 7: Performance of planners over the *Lifted Rearrangement(k)* domains. For all metrics, lower values indicate better performance.

Planner	Lifted Rear(5, 5) Tiny			Lifted Rear(5, 5) Medium			
	Len.	Time	Fail	Len.	Time	Fail	
satisficing	FF	62.86	3.40	0.47	61.90	3.04	0.37
	FF-X	67.88	3.48	0.89	61.78	2.30	0.72
	FD-lama-first	66.81	3.20	0.49	71.15	4.11	0.46
	Cerberus-sat	-	-	1.00	-	-	1.00
	Cerberus-agl	60.50	7.62	0.60	64.26	6.74	0.57
	DecStar-agl-fb	66.30	3.02	0.71	77.00	3.08	0.71
	BFWS	56.90	0.94	0.41	55.36	0.80	0.43
learn	Regression-plan	-	-	1.00	-	-	1.00
	Relational policy [6]	-	-	1.00	-	-	1.00
	PLOI [7]	78.68	0.22	0.24	76.62	0.22	0.24

Table 8: Performance of planners over the *Lifted Courier(n, k)* domains. For all metrics, lower values indicate better performance.

Planner	Lifted Cour(5, 5) Tiny			Lifted Cour(5, 5) Medium			
	Len.	Time	Fail	Len.	Time	Fail	
satisficing	FF	57.74	4.03	0.44	57.38	4.81	0.37
	FF-X	61.19	7.56	0.77	60.05	3.79	0.64
	FD-lama-first	61.13	3.34	0.56	63.19	3.31	0.45
	Cerberus-sat	-	-	1.00	-	-	1.00
	Cerberus-agl	59.19	7.05	0.77	59.61	7.45	0.68
	DecStar-agl-fb	58.75	4.46	0.71	63.93	3.85	0.68
	BFWS	61.92	2.30	0.43	56.14	0.67	0.38
	Regression-plan	-	-	1.00	-	-	1.00
learn	Relational policy [6]	-	-	1.00	-	-	1.00
	PLOI [7]	71.71	0.26	0.26	69.92	0.46	0.30

References

- [1] D. Batra, A. X. Chang, S. Chernova, A. J. Davison, J. Deng, V. Koltun, S. Levine, J. Malik, I. Mordatch, R. Mottaghi, et al. Rearrangement: A challenge for embodied ai. *arXiv preprint arXiv:2011.01975*, 2020.
- [2] I. Armeni, Z.-Y. He, J. Gwak, A. R. Zamir, M. Fischer, J. Malik, and S. Savarese. 3d scene graph: A structure for unified semantics, 3d space, and camera. In *Proceedings of Computer Vision and Pattern Recognition (CVPR)*, 2019.
- [3] F. Xia, A. R. Zamir, Z. He, A. Sax, J. Malik, and S. Savarese. Gibson env: Real-world perception for embodied agents. In *Proceedings of Computer Vision and Pattern Recognition (CVPR)*, 2018.
- [4] A. Rosinol, A. Gupta, M. Abate, J. Shi, and L. Carlone. 3d dynamic scene graphs: Actionable spatial perception with places, objects, and humans. In *Robotics Science and Systems (R-SS)*, 2020.
- [5] D. McDermott, M. Ghallab, A. Howe, C. Knoblock, A. Ram, M. Veloso, D. Weld, and D. Wilkins. Pddl-the planning domain definition language. 1998.
- [6] O. Rivlin, T. Hazan, and E. Karpas. Generalized planning with deep reinforcement learning. *arXiv preprint arXiv:2005.02305*, 2020.
- [7] T. Silver, R. Chitnis, A. Curtis, J. Tenenbaum, T. Lozano-Perez, and L. P. Kaelbling. Planning with learned object importance in large problem instances using graph neural networks. *AAAI International conference on Artificial Intelligence*, 2020.