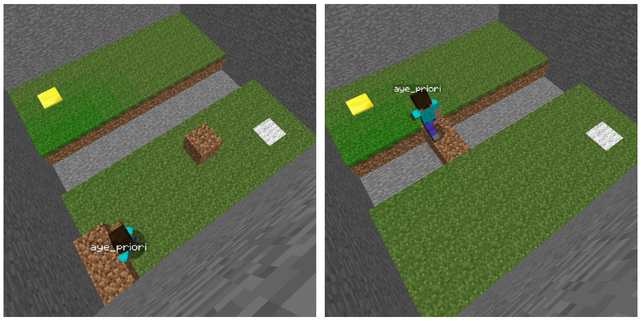
Planning with Affordances

Abstract

Planning algorithms for non-deterministic domains are often intractable in large state and action spaces due to the well-known "curse of dimensionality." Approaches to address this problem by providing the system with formally encoded knowledge such as macro-actions and options still fail to prevent the system from considering many actions which would be obviously irrelevant to a human solving the same problem. To address this issue, we introduce a novel approach which represents knowledge about the domain in terms of *affordances* [11]. Our affordance formalism and associated planning framework allows an agent to efficiently prune its action space based on domain knowledge. This pruning significantly reduces the number of state/action pairs the agent needs to evaluate in order to act optimally. We demonstrate our approach in the Minecraft domain on several planning and building tasks, showing a significant increase in speed and reduction in state-space exploration compared to subgoal (partial order) planning.



(a) Planning with VI.

(b) Planning with affordances.

Figure 1: Scenes from a Minecraft agent planning using Value Iteration (VI) compared to the affordance planner in a bridge building task. VI considers states which would be obviously irrelevant to a human solving the same problem, such as stacking blocks in the corner. Our affordance agent, in contrast, focuses on placing blocks in the trench, which are much more relevant to reaching the goal.

1 INTRODUCTION

As robots move out of the lab and into the real world, planning algorithms need to scale to domains of increased noise, size, and complexity. A classic formalization of this problem is a stochastic sequential decision making problem in which the agent must find a policy (a mapping from states to actions) for some subset of the state space that enables the agent to achieve a goal from some initial state, while minimizing any costs along the way. Increases in planning problem size and complexity directly correspond to an explosion in the state-action space. Current approaches to solving sequential decision making problems cannot tackle these problems as the state-action space becomes too large [12].

To address this state-space explosion, prior work has explored adding knowledge to the planner to enable it to solve problems in these massive domains. However prior approaches such as options and macro-actions work by providing additional high-level actions to the agent, which *increases* the size of the state/action space (while also allowing the agent to search more deeply within the space). The resulting augmented space is even larger, which can have the paradoxical effect of increasing the search time for a good policy.

We propose to address this planning problem by focusing on problem-specific aspects of the environment which focus the search toward the most relevant and useful parts of the state-action space. This approach aims to *reduce* the size of the explored state action space, leading to dramatic speedups in planning. Our approach is a formalization of *affordances*, introduced by Gibson [11] as "what [the environment] offers [an] animal, what [the environment] provides or furnishes, either for good or ill." We formalize the notion of an affordance as a piece of planning knowledge provided to an agent operating in a Markov Decision Process (MDP). We explain how affordances can be leveraged by a variety of planning algorithms to prune the action set the agent uses dynamically based on the agent's current goal. We call any planning algorithm that uses affordances to prune the action set an affordance-aware planning algorithm. A useful property of affordances is that they are not specific to a particular reward function or goal, and thus, provide the agent with transferable knowledge that is effective in a wide variety of problems.

JM: Need to augment this description with the embedded stochasticity. If the stochasticity is effectively a probability of taking the wrong action/movement, we should relate it the fact that in robotics, actuators are noisy and often fail, thereby making the domain a bit more analogous to physical robots. We should also highlight that this stochasticity can affect the policy by forcing the agent to be more cautious in dangerous environments.

We use Minecraft as our planning and evaluation domain. Minecraft is a 3-D blocks world game in which the user can place and destroy blocks of different types. Minecraft players have constructed complex worlds, including models of a scientific graphing calculator [1]; scenes from a Minecraft world appear in Figure reffig:minecraft. As a running example, we will consider the problem of an agent attempting to cross a trench in a $4 \times 4 \times 2$ Minecraft world shown in Figure 2. The floor (at $z = 1$) [2] is composed of 8 solid blocks, with horizontal empty trenches at $y = 2$ and $y = 3$. The agent is at the starting location $(1, 1, 2)$ and needs to reach the goal at $(4, 4, 2)$

To solve the problem, the agent must place a block in the trench to form a bridge, then cross the bridge to reach the goal. This task is challenging for planning algorithms to solve because the reachable state space in Minecraft is so large. For example, the number of places an agent can place and destroy blocks alone can result in a combinatorial explosion of the state space. Specifically, given an agent capable placing and destroying blocks in a 10x10x2 world, there are on the order of

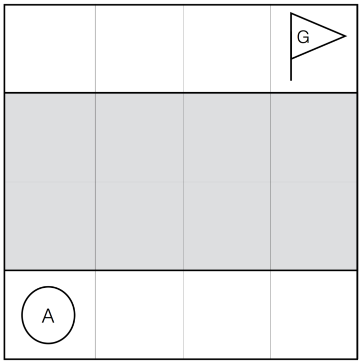


Figure 2: In the above Minecraft planning problem `BRIDGEWORLD`, the agent must place a block in the trench in order to reach the goal (the trench is too wide to jump over).

$$O\left(\sum_{n=1}^{10\cdot 10\cdot 2} \binom{10 \cdot 10 \cdot 2}{n}\right) \tag{1}$$

states, which is too large for a planning algorithm to explore in a reasonable time.

2 BACKGROUND

We define affordances in terms of propositional functions on states. Our definition builds on the Object-Oriented Markov Decision Process (OO-MDP) [10]. OO-MDPs [10] are an extension of the classic Markov Decision Process (MDP). A classic MDP is a five-tuple: $\langle \mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{R}, \gamma \rangle$, where $\mathcal{S}$ is a state-space; $\mathcal{A}$ is the agent's set of actions; $\mathcal{T}$ denotes $\mathcal{T}(s' \mid s, a)$, the transition probability of an agent applying action $a \in \mathcal{A}$ in state $s \in \mathcal{S}$ and arriving in $s' \in \mathcal{S}$; $\mathcal{R}(s, a, s')$ denotes the reward received by the agent for applying action a in state s and and transitioning to state s'; and $\gamma \in [0, 1)$ is a discount factor that defines how much the agent prefers immediate rewards over distant rewards (the agent more greatly prefers to maximize more immediate rewards as γ decreases).

A classic way to provide a factored representation of an MDP state is to represent each MDP state as a single feature vector. In contrast, an OO-MDP represents the state space as a collection of objects, $O = \{o_1, \ldots, o_o\}$. Each object o_i belongs to a class $c_j \in \{c_1, \ldots, c_c\}$. Every class has a set of attributes $Att(c) = \{c.a_1, \ldots, c.a_a\}$, each of which has a domain $Dom(c.a)$. Upon instantiation of an object class, its attributes are given a state $o.state$ (an assignment of values to its attributes). The underlying MDP state is the set of all the object states: $s \in \mathcal{S} = \cup_{i=1}^{o} \{o_i.state\}$.

There are two advantages to using an object-oriented

[1] https://www.youtube.com/watch?v=wgJfVRhotlQ
[2] The z-axis is the height of the Minecraft world. Similarly, the x-axis is its width and the y-axis is its length.

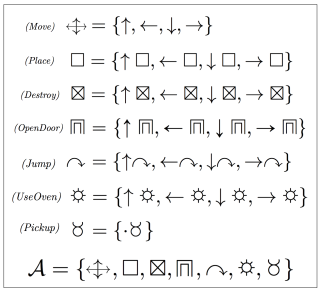

(Move) ✥ = {↑, ←, ↓, →}
(Place) □ = {↑ □, ← □, ↓ □, → □}
(Destroy) ⊠ = {↑ ⊠, ← ⊠, ↓ ⊠, → ⊠}
(OpenDoor) ⩎ = {↑ ⩎, ← ⩎, ↓ ⩎, → ⩎}
(Jump) ↷ = {↑↷, ←↷, ↓↷, →↷}
(UseOven) ☼ = {↑ ☼, ← ☼, ↓ ☼, → ☼}
(Pickup) ♉ = {·♉}
𝒜 = {✥, □, ⊠, ⩎, ↷, ☼, ♉}

Figure 3: The set of all actions in the Minecraft domain.

factored state representation instead of a single feature vector. First, different states in the same state space may contain different numbers of objects of varying classes, which is useful in domains like Minecraft in which the agent can dynamically add and remove blocks to the world. Second, MDP states can be defined invariantly to the specific object references. For instance, consider a Minecraft world with two block objects, b_1 and b_2. If the agent picked up and swapped the position of b_1 and b_2 (and then returned to the agent's previous position in the world), the MDP state before the swap and after the swap would be the same, because the MDP state definition is invariant to which object holds which object state. Formally, if there exists a bijection between two sets of objects that maps each object in one set to an object in the other set with the same object state, then the two sets of objects define the same MDP state. This object reference invariance results in a smaller state space compared to representations like feature vectors in which changes to value assignments always result in a different state.

While the OO-MDP state definition is a good fit for the Minecraft domain, our motivation for using an OO-MDP lies in the ability to formulate predicates over classes of objects. That is, the OO-MDP definition also includes a set of predicates $\mathcal{P}$ that operate on the state of objects to provide additional high-level information about the MDP state. For example, in the Minecraft domain, an `on(BLOCK, BLOCK)` predicate operates on two objects belonging to class `BLOCK`; $\texttt{on}(b_1, b_2)$, would evaluate to true when the z position value of b_1's state is one unit higher than the z position value of b_2's, and false otherwise. **JM: This should probably be replaced with an example of a predicate that is actually used in the Minecraft domain. ST: I agree – can we use predicates that are relevant to bridgeworld? Is moveable? is placeable?** In the original OO-MDP work, these predicates were used to model and learn an MDP's transition dynamics. In the next section, we use the predicates to define affordances that enable planning algorithms to prune irrelevant actions.

3 AFFORDANCES

In many planning scenarios, not all actions are needed in all states. In fact, many applications of actions in states do not contribute toward solving the planning task, but instead, cause the state-space to grow exponentially, especially true in domains in which the agent's actions can drastically shape the environment, such as in Minecraft. To address this problem, we define an affordance, Δ, as a tuple, $\langle p, g\rangle \longrightarrow \alpha$, where:

α is a subset of the action space, $\mathcal{A}$

p is a predicate on states, $s \longrightarrow \{0, 1\}$ representing the *precondition* for the affordance.

g is a predicate on states, $s \longrightarrow \{0, 1\}$ representing the *postcondition*.

The precondition, p, and goal, g, encode a subset of object states $\cup_{i=1}^{o} o_i.state$ (see section 2.2). The use of an OO-MDP gives us easy access to these robust predicates which completely describe the underlying MDP in a much more general manner. **JM: This text doesn't quite make sense to me. How are the OO-MDP predicates subsets of the objects? I think what this is trying to say is that p and g can be defined compactly using OO-MDP predicates. However, it's not necessarily true that OO-MDP predicates *completely* describe the MDP. In fact, unless you have explicit position predicates, it won't completely describe the MDP state space.**
I think an example of an affordance in terms of the formal definition needs to be provided here as well. ST: Agree with JM's comment. We need to say how affordances connect to an OO-MDP, but above isn't quite right.

The primary benefit of encoding goal relative knowledge in each affordance is that actions may be pruned with respect to a given goal. For instance, if the agent is at the trench in `BRIDGEWORLD` and trying to reach the goal then it would not consider destroying a block, as that does not further its ability to reach the goal. **ST: Need to give examples of bridgeworld affordances that would prevent it from destroying a block.** Eliminating the "destroy" action avoids exploring every consequent state in which that block has been destroyed. As a result, agents may be endowed with huge action sets that enables them to solve a variety of problems across variable state-spaces, while only exploring a small action set that is relevant to each task. We refer to any planning algorithm that prunes the actions set according to affordances an affordance-aware planner. Action set pruning affects different planning algorithms in different ways. In particular, we focus on how action pruning benefits *dynamic programming* and *policy rollout* planning paradigms.

JM: Pseudocode for the pruneActions function, for any arbitrary input state, should be supplied here since it's the primary contribution and is the code that would used to turn any planning algorithm into an affordance-aware planning algorithm. We may also want to mention the computation time of it

3.1 Dynamic Programming

In dynamic programming paradigms, the planning algorithm estimates the optimal *value function* for each state. Formally, the optimal value function (V^*) defines the expected discounted return from following the optimal policy in each state:

$$V^*(s) = \max_{a \in \mathcal{A}(s)} \sum_{s'} \Pr(s' \mid s, a) \left[\mathcal{R}(s, a, s') + \gamma V^*(s')\right]; \tag{2}$$

this equation is known as the Bellman equation [4]. Given the optimal value function, the optimal policy is derived by taking the action that maximizes the values of each state. More specifically, by taking the action with the highest optimal state-action value:

$$Q^*(s, a) = \sum_{s'} \Pr(s' \mid s, a) \left[\mathcal{R}(s, a, s') + \gamma V^*(s')\right]. \tag{3}$$

Dynamic programming planning algorithms (such as Value Iteration [4]) estimate the optimal value function by initializing the value of each state arbitrarily and iteratively updating the value of each state by setting its value to the result of the right-hand-side of the Bellman equation using its current estimate of V instead of V^*. Iteratively updating the value function estimate in this way is guaranteed to converge to the optimal value function.

Using a pruned action set in dynamic programming can accelerate its computation in two ways: (1) by reducing the number of actions over which the max operator in the Bellman equation must iterate and (2) by restricting the state space for which the value function is estimated to the states that are reachable with the pruned action set from the initial state. Note that neither of these computational gains come at the cost of solution optimality as long as the pruned action set contains the actions necessary for an optimal policy from the initial state. In the case of the Bellman equation, the max operator makes the value function indifferent to the effects of actions that are not part of the optimal policy; therefore, the action set can be reduced entirely to the actions in the optimal policy without sacrificing optimality. Similarly, since we are only concerned with finding a good policy to dictate behavior from some initial state, the state space for which the value function is computed can be reduced to that which is reachable using only the optimal actions without sacrificing optimality. **ST: So the stuff about not sacrificing the optimal policy seems right, but I wonder if we can say something more formal about what has to be true about affordances in order for affordance planning to still be optimal.**

3.2 Policy Rollout

In policy rollout planning paradigms, the agent starts with some initial policy and follows it (or rolls out the policy) from an initial/current state to either some maximum time horizon or until a terminal state is reached. Often, these approaches use samples from the policy rollout to improve estimates of the value function and indirectly improve the rollout policy. Examples of planning algorithms in this paradigm include Monte Carlo methods [7, 26] and temporal difference methods [2, 19, 22, 24, 27, 28]. **JM: Removed RTDP since it's not monte carlo even though it's very similar. The monte carlo survey covers a lot, so I only added to TD methods** By using a pruned action set, the policy space, and resulting state space explored from the searched policies, is reduced, thereby reducing the number of rollouts necessary to find a good policy. Similar to dynamic programming paradigms, as long as the pruned action set contains actions necessary for the optimal policy, solution optimality will not be sacrificed.

In this work, we will explore how real time dynamic programming (RTDP) [3] benefits from affordances. RTDP is both a dynamic programming algorithm and a policy rollout algorithm. RTDP starts by initializing the value function optimistically. It then follows a greedy rollout policy with respect to its currently estimated value function. **JM: I remembered that the boltzmann policy is only used when learning the transition dynamics; in planning, RTDP just uses the greedy policy. Text is corrected.** After each action selection in the policy rollout, RTDP updates its estimate of the value function for the last state using the Bellman equation. RTDP is guaranteed to converge to the optimal policy from some initial state and has the advantage that it iteratively refocuses its attention to states that are likely to be on the path of the optimal policy.

In affordance-aware RTDP, the action selection of the rollout policy is restricted to the affordance-pruned action set and the Bellman equation is similarly restricted to operating on the affordance-pruned action set.

3.3 Subgoals

ST: Subgoal planning drops right in as a third alternative framework we explore along with VI and rollout methods. This section needs to be reorganized along these lines, where we define it, then say how it can benefit from affordances.

Subgoal planning leverages the intuition that certain goals in planning domains may only be brought about if certain preconditions are first satisfied. For instance, in the bridge problem, one must first place a block in the trench to create a bridge before crossing the trench. Branavan et al. [6] explore learning subgoals from the Minecraft wiki and applying them in order to plan through a variety of problems in Minecraft.

Formally, in subgoal planning, the agent is set of subgoals, where each subgoal is a pair of predicates:

$$SG = \langle x_k, x_l \rangle \tag{4}$$

where x_l is the effect of some action sequence performed on a state in which x_k is true. Thus, subgoal planning requires that we perform high-level planning in subgoal space, and low-level planning to get from subgoal to subgoal. The low-level planner may vary, though Metro-FF is a popular choice, as is Value Iteration.

JM: I don't think it's necessary to include full pseudocode for the subgoal planning algorithm since it is cited, but if it is included, the algorithm should probably be explained more in the text (e.g., describe what subgoalKB means). Also, it seems like the subgoal space planner can vary as well and doesn't need to be BFSs.

Algorithm 1 Plan with Knowledge Base of Subgoals
Complexity: $\mathcal{O}(|\mathcal{A}| \cdot |\mathcal{S}|^2)$

```
subgoalSequence $\leftarrow$ BFS(subgoalKB, goal)
plan = []
curState $\leftarrow$ subgoalSequence.pop()
for subgoal $\in$ subgoalSequence do
    plan += ValueIteration(curState, subgoal)
    curState $\leftarrow$ plan.getLastState()
end for
return plan;
```

In the case of BRIDGEWORLD, the agent might consider placing a block somewhere along the trench to be a subgoal. Then, it runs Value Iteration to get from its starting location to the subgoal. Next, it runs Value Iteration from the first subgoal to the finish. Subgoals enhance an agent's planning abilities when they propose *necessary* claims about the domain. If the subgoals are *contingent* (i.e. true in some state spaces of the domain but not in others), then they do not limit the search space. For instance, consider the task in BRIDGEWORLD, in which the agent must place a block in the trench that separates the agent from the goal. The subgoal $\langle blockInTrench, reachGoal \rangle$ might be a perfectly useful subgoal in BRIDGEWORLD, but an adversary could easily come up with thousands of worlds in which such a subgoal would completely derail the agent's planner. Thus, many subgoals do not scale beyond a particular instance of a state space. In order for subgoals to be useful, they must be necessary claims about the domain, otherwise, one can always come up with a counter world (by definition of necessary). Compare this scenario to the problem of baking bread in minecraft: posessing wheat is always required to make bread, and it is impossible to construct a world where this precondition is not true.

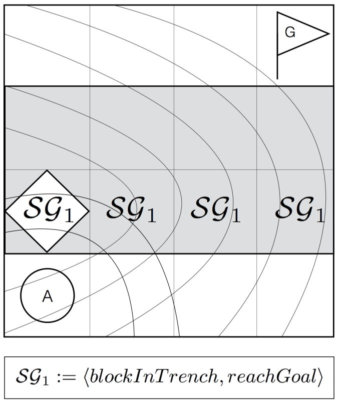


Figure 4: The agent re-explores a large portion of the state space once it finds $\mathcal{SG}_1$. Also note that this subgoal highlights **Problem 1**, in that it would be useless in many other Minecraft state spaces.

Problem 2: Efficient Search The last problem with subgoal planning is that the use of subgoals actually requires that we research a huge portion of the state space. Consider the BRIDGEWORLD example in which the subgoal is to place a block along the trench somewhere - once we plan from the state in which a block has been placed at the trench, Value Iteration will search paths exploring both sides of the trench rather than focusing on the opposite side of the trench toward the goal.

A final, but less significant problem, is that Subgoal planning still requires the use of Value Iteration or another low-level planner, which does not scale well - if there is ever a case in which planning between two subgoals is at all complex, then Subgoal planning is out of luck.

4 EXPERIMENTS

JM: Reminder that this should be updated to be with respect to RTDP as a baseline and ideally should include a performance metric specifying the number of state backups that were used.

ST: Experiments and results should be merged. Also I think we need to think through how to structure the results.

We conducted a series of experiments in the Minecraft domain that tested each planning system on a variety of tasks, ranging from basic path planning, to baking bread, to opening doors and jumping over trenches. We also tested each planner on worlds of varying size to demonstrate the scalability of each system. In Table 5, we provide results on testing the planners across each system. For each data point, we ran the planning system 3 times and took the average result (they rarely deviated beyond $\frac{1}{10}$ of a second).

For the scenarios listed in Table 5, we limited the agent's action set across all planners so that it did not have access to block placement (□) and block destruction (⊠). The reason for excluding these two action types up is that, in Minecraft, the agent has an extraordinary ability to modify the state space via placing and destroying blocks. As a result, if an agent begins placing or destroying blocks in cases where it does not need to, the state-action space will explode exponentially and grow far too fast for (almost) any planner to finish in our lifetime.

Equation 1 gives the order of the state space for a $10 \times 10 \times 2$ Minecraft world, which is far too large to explore. We will demonstrate that our affordance model *is* capable of handling these types of actions, and can plan using them as in a bridge building scenario or tunnel digging scenario (among others) while the other planners cannot. In fact, with these actions, none of the other planning systems can solve even the most basic path planning (even on just a flat surface with no obstacles). We explore this ability in the results seen in Table 5

As discussed above, one of the major advantages of using affordances to plan is that they enable an agent to have a massive action set, making affordances effectively transfer between domains. We conducted an additional set of experiments on the 15x15 world with no obstacles `15WORLD`. For this round of testing, we varied the number of actions available to the agent (starting from $|\mathcal{A}| = 4$ up to $|\mathcal{A}| = 25$) and ran the planner on `15WORLD` with the same goal (to reach the goal in the corner).

	Affordances	Subgoals	VI
`10WORLD`	**0.6s**	1.8s	1.1s
`13WORLD`	**2.5s**	10.1s	6.0s
`15WORLD`	**6.7s**	21.6s	11.8s
`17WORLD`	**16.6s**	45.4s	28.2s
`20WORLD`	**57.6s**	144.3s	140.5s
`JUMPWORLD`	**4.3s**	21.1s	10.1s
`BREADWORLD`	25.5s	**22.8s**	51.6s
`DOORWORLD`	**16.3s**	25.0s	25.3s
`MAZEWORLD`	**17.9s**	114.8s	37.6s
`HARDWORLD`	**34.5s**	215.9s	149.7s

Table 1: Tests on a variety of tasks without block placement and destruction actions

	Affordances	Subgoals	VI
$\lvert\mathcal{A}\rvert = 4$	6.7s	11.8s	6.7s
$\lvert\mathcal{A}\rvert = 8$	6.8s	25.4s	14.8s
$\lvert\mathcal{A}\rvert = 12$	6.8s	39.8s	22.9s
$\lvert\mathcal{A}\rvert = 13$	6.8s	41.28s	24.7s
$\lvert\mathcal{A}\rvert = 17$	6.7s	55.5s	33.1s
$\lvert\mathcal{A}\rvert = 17$	6.8s	DNF	DNF
$\lvert\mathcal{A}\rvert = 21$	6.6s	DNF	DNF

Table 2: Plan on the simplest possible task (path planning in a flat plane with no obstacles - `15WORLD`) with incrementally larger action sets.

An additional advantage of planning with affordances is that the problems of block-placement and block-destruction illustrated by 1 are overcome. With affordances, we are able to solve a variety of novel planning problems in the Minecraft domain, such as building a bridge to cross a long trench, or digging a hole through a wall to reach the goal (see Table 5). This is indeed a compelling result, as no other planning system is currently able to avoid falling prey to the state-space explosion mentioned above. Additionally, the malleability of Minecraft that causes this explosion is a reasonable model of the way that an agent in the real world is capable of modifying its surroundings. Thus, we foresee the affordance planner as being extremely deft at handling real world planning scenarios.

5 RESULTS

As one can see from Table 5, in those cases where $|\mathcal{A}| = 21$ and $|\mathcal{A}| = 25$, the only planning algorithm to actually complete the tasks was the affordance planner. This is because each of these cases scaled to include block destruction and block placement actions.

	Affordances	Subgoals	VI
BRIDGEWORLD	?	DNF	DNF
TUNNELWORLD	?	DNF	DNF
LADDERWORLD	?	DNF	DNF
TOWERWORLD	?	DNF	DNF

Table 3: Bonus round: Minecraft specific tasks

Thus, any case in which these actions are required to complete the task at hand, only affordance planning will succeed. This is significant, as Table 5 indicates that the affordance planner plans more effectively than the other systems, but it can also handle novel problems involving those actions that alter the environment in sever ways.

We also include a Bonus round indicating those tasks that only the affordance planner was able to solve. Finally, since each affordance is attached to a particular goal, a single knowledge base will scale across state-spaces and task types, causing affordance planning to be extremely transferable. Additionally, we plan to add experiments in Non-deterministic planning scenarios, as well as testing on the planning scenarios from table 5 where the knowledge bases remain constant across state-spaces to test the generality of each algorithm.

6 Related Work

In the past, numerous different forms of background knowledge have be used to accelerate planning algorithms. In section 3.3, subgoal planning was discussed and in our experimental results, was compared against affordance-aware planning. In this section, we discuss the differences between affordance-aware planning and other forms of background knowledge that have been used to accelerate planning. Specifically, we discuss heuristics, temporally extended actions, and related action pruning work.

6.1 Heuristics

Heuristics in MDPs are used to convey information about the value of a given state or state-action pair with respect to the task being solved and typically take the form of either *value function initialization*, or *reward shaping*. For planning algorithms that estimate state-value functions, heuristics are often provided by initializing the value function to values that are good approximations of the true value function. For example, initializing the value function to an admissible close approximation of the optimal value function has been shown to be effective for LAO* and RTDP, because it more greatly biases the states explored by the rollout policy to those important to the optimal policy [13]. Planning algorithms that estimate Q-values instead of the state value function may similarly initialize the Q-values to an approximation of the optimal Q-values. For instance, PROST [15] creates a *determinized* version of a stochastic domain (that is, treating each action as if its most likely outcome always occurred), plans a solutions in the determinized domain, and then initializes Q-values to the value of each action in the determinized domain.

Reward shaping is an alternative approach to providing heuristics in which the planning algorithm uses a modified version of the reward function that returns larger rewards for state-action pairs that are expected to be useful. Reward shaping differs from value function initialization in that it may not preserve convergence to an optimal policy unless certain properties of the shaped reward are satisfied [21] that also have the effect of making reward shaping equivalent to value function initialization for a large class of planning/learning algorithms [29].

A critical difference between heuristics and affordances is that heuristics are highly dependent on the task being solved; therefore, different tasks require different heuristics to be provided, whereas affordances are task independent and transferable between tasks. However, if a heuristic can be provided, the combination of heuristics and affordances may even more greatly accelerate planning algorithms than either approach alone.

6.2 Temporally Extended Actions

Temporally extended actions are actions that the agent can select like any other action of the domain, except executing them results in multiple primitive actions being executed in succession. Two common forms of temporally extended actions are *macro-actions***JM: looking at the citaiton you added for macros Stefanie, I think those are still "options" rather than fixed primitive action sequences. Unfortunatley the term is overloaded a lot.** and *options* [27]. Macro-actions are actions that always execute the same sequence of primitive actions. Options are defined with high-level policies that accomplish specific sub tasks. For instance, when an agent is near a door, the agent can engage the 'door-opening-option-policy', which switches from the standard high-level planner to running a policy that is hand crafted to open doors. An option o is defined as follows:

$o = \langle \pi_0, I_0, \beta_0 \rangle$, where:

$$\pi_0 : (s, a) \rightarrow [0, 1]$$

$$I_0 : s \rightarrow \{0, 1\}$$

$\beta_0 : s \rightarrow [0, 1]$

Here, π_0 represents the *option policy*, I_0 represents a precondition, under which the option policy may initiate, and β_0 represent the post condition, which determines which states terminate the execution of the option policy.

Although the classic options framework is not generalizable to different state spaces, creating *portable* options is a topic of active research [1, 9, 16, 17, 18, 23].

Although temporally extended actions are typically used because they represent action sequences (or sub policies) that are often useful to solving the current task, they can sometimes have the paradoxical effect of increasing the planning time because they increase the number of actions that must be explored. For example, deterministic planning algorithms that successfully make use of macro-actions often avoid the potential increase in planning time by developing algorithms that restrict the set of macro-actions to a small set that is expected to improve planning time [5, 20] or by limiting the use of macro-actions to certain conditions in the planning algorithms like when the planner reaches heuristic plateaus (areas of the state space in which all child states have the same heuristic value) [8]. Similarly, it has been shown that the inclusion of even a small subset of unhelpful options can negatively impact planning/learning time [14].

Given the potential for unhelpful temporally extended actions to negatively impact planning time, we believe combing affordances with temporally extended actions may be especially valuable, because it will restrict the set of temporally extended actions to those which may actually be useful to a task. In the future, we plan to more directly explore the benefit from combining these approaches.

6.3 Action Pruning

JM: We should also probably do a search for other MDP action pruning approaches, just to make sure we're not missing anything especially important.

Perhaps the most similar work to ours is Sherstov and Stone's action transfer work [25]. In their work, they considered MDPs with a very large action set and for which the action set of the optimal policy of a source task could be transferred to a new, but similar, target task to reduce the learning time required to find the optimal policy in the target task. Since the actions of the optimal policy of a source task may not include all the actions of the optimal policy in the target task, source task action bias was reduced by randomly perturbing the value function of the source task to produce new synthetic tasks. The action set transferred to the target task was then taken as the union of the actions in the optimal policies for the source task and all the synthetic tasks generated from it.

A critical difference between our affordance-based action set pruning and this action transfer work is that affordances represent knowledge defined independently of any specific task. Therefore, affordances can be defined once and reused in a variety of very different tasks, whereas in the action transfer work, action set pruning must begin anew when the current task is very dissimilar from previously experienced tasks.

JM: Do we want to make any comments about how this work might be useful in future work that learns affordances rather than is given them?

7 CONCLUSION

JM: Will probably need to update this to reflect changes in paper.

We proposed a novel approach to representing knowledge in terms of *affordances* [11] that allows an agent to efficiently prune its action space based on domain knowledge. This pruning was shown to significantly reduce the number of state/action pairs the agent needs to evaluate in order to act optimally, and resulted in faster planning than subgoal planning, options, and vanilla value iteration. We demonstrated the efficacy as well as the transferability of the affordance model in a series of planning tasks in the Minecraft domain.

In the future, we hope to learn affordances from experience as opposed to providing them directly to the agent. Additionally, we hope to introduce uncertainty into the action set that is pruned, in order to improve the effectiveness of the pruning. Lastly, we hope to incorporate aid from a human partner through natural language dialogue, in which the agent may ask for help when it is stuck and receive subgoal *hints* from a human companion.

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