POSSIBILITY BEFORE UTILITY: LEARNING AND USING HIERARCHICAL AFFORDANCES

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ABSTRACT

Reinforcement learning algorithms struggle on tasks with complex hierarchical dependency structures. Humans and other intelligent agents do not waste time assessing the utility of every high-level action in existence, but instead only consider ones they deem *possible* in the first place. By focusing only on what is feasible, or "afforded", at the present moment, an agent can spend more time both evaluating the utility of and acting on what *matters*. To this end, we present *Hierarchical Affordance Learning* (HAL), a method that learns a model of *hierarchical affordances* in order to prune impossible subtasks for more effective learning. Existing works in hierarchical reinforcement learning provide agents with structural representations of subtasks but are not affordance-aware, and by grounding our definition of hierarchical affordances in the present *state*, our approach is more flexible than the multitude of approaches that ground their subtask dependencies in a *symbolic history*. While these logic-based methods often require complete knowledge of the subtask hierarchy, our approach is able to utilize incomplete and varying symbolic specifications. Furthermore, we demonstrate that relative to non-affordance-aware methods, HAL agents are better able to efficiently learn complex tasks, navigate environment stochasticity, and acquire diverse skills in the absence of extrinsic supervision—all of which are hallmarks of human learning.

1 INTRODUCTION

Reinforcement learning (RL) methods have recently achieved success in a variety of historically difficult domains (Mnih et al., 2015; Silver et al., 2016; Vinyals et al., 2019), but they continue to struggle on complex hierarchical tasks. Human-like intelligent agents are able to succeed in such tasks through an innate understanding of what their environment enables them to do. In other words, they do not waste time attempting the impossible. Gibson (1977) coins the term "affordances" to articulate the observation that humans and other animals largely interpret the world around them in terms of which behaviors the environment *affords* them. While some previous works apply the concept of affordances to the RL setting, none of these methods easily translate to environments with hierarchical tasks. In this work, we introduce *Hierarchical Affordance Learning* (HAL), a method that addresses the challenges inherent to learning affordances over high-level subtasks, enabling more efficient learning in environments with complex subtask dependency structures.

Many real-world environments have an underlying *hierarchical* dependency structure (Fig. 1a), and successful completion of tasks in these environments requires understanding how to complete individual *subtasks* and knowing the relationships between them. Consider the task of preparing a simple pasta dish. Some sets of subtasks, like chopping vegetables or filling a pot with water, can be successfully performed in any order. However, there are many cases in which the dependencies between subtasks must be obeyed. For instance, it is inadvisable chop vegetables *after* having mixed them with the sauce, or to boil a pot of water *before* the pot is filled with water in the first place. Equipped with structural inductive biases that naturally allow for temporally extended reasoning over subtasks, hierarchical reinforcement learning (HRL) methods are well-suited for tasks with complex high-level dependencies.

Existing HRL methods fall along a spectrum ranging from *flexible* approaches that discover useful subtasks automatically, to the *structured* approaches that provide some prior information about subtasks and their interdependencies. The former approaches (e.g. Vezhnevets et al., 2017; Eysenbach

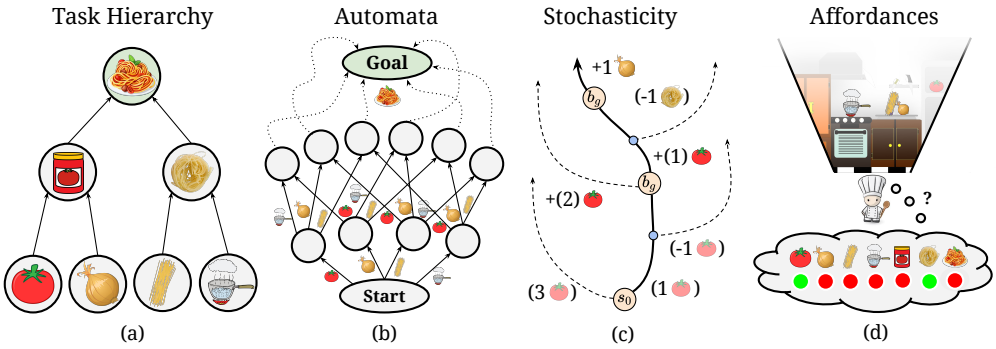

Figure 1: Many real world tasks, like making PASTA, can be conceptualized as a hierarchy (a) of subtasks. Automata-based approaches (b) can utilize a history of subtask completion symbols to map deterministically to a context that indicates progress in the hierarchy. Approaches that assume symbolic history deterministically defines progress are not robust to stochastic changes in context (c) not provided symbolically. Hierarchical affordances (d) enable us to use incomplete symbolic information in the face of stochasticity by grounding context in the present state.

et al., 2018) have seen limited success, as the automatic identification of hierarchical abstractions is an open problem in deep learning (Hinton, 2021). But approaches that endow the agent with *more* structure, to make complex tasks feasible, do so at the cost of rigid assumptions. Methods that use a form of finite automata (Fig. 1b) to express subtask dependencies (e.g. Icarte et al., 2020) require the set of symbols, or *atomic propositions*, provided to the agent to be complete, in that the history of symbols maps deterministically to the current *context* (i.e. how much progress has been made; which subtasks are available). Importantly, these methods and many others (e.g. Andreas et al., 2017; Sohn et al., 2020) consider subtasks to be dependent merely on the completion of others.

Unfortunately, these assumptions do not hold in the real world (Fig. 1c). For instance, if one completes the subtask `cook noodles`, but they clumsily spill them all over the floor, are they now ready for the next subtask, `mix noodles and sauce`? While the subtask `cook noodles` is somehow *necessary* for this further subtask, it is not *sufficient* to have completed it in the past. The only way for automata-based approaches to handle this complexity is to introduce a new symbol that indicates that the subtask has been undone. This is possible, but extraordinarily restrictive, since, unless the set of symbols is complete, *none* of the subtask completion information can be used to reliably learn and utilize subtask dependencies. Modeling probabilistic transitions allows the symbolic *signal* to be incomplete, but still requires a complete *set* of symbols, in addition to predefined contexts. In order to make use of incomplete symbolic information, our approach instead learns a representation of context grounded in the present *state* to determine which subtasks are possible (Fig. 1d), rather than solely relying on *symbols*.

The contributions of this paper are as follows. First we define the *milestone signal* (§4), a flexible alternative to atomic propositions used in automata-based approaches. Specifying a set of milestones is significantly easier, as the assumptions are not as rigid. Unlike a dense reward function, the milestone signal does not need to be scaled or balanced carefully to account for competing extrinsic motives. Next, we introduce *hierarchical affordances*, which can be defined over any arbitrary set of milestones, and describe HAL (§5), a method which learns and utilizes a model of hierarchical affordances to prune impossible subtasks. Finally, we demonstrate HAL's superior performance on two complex hierarchical tasks in terms of learning speed, robustness, generalizability, and ability to explore complex subtask hierarchies without extrinsic supervision, relative to baselines provided with the same information (§6.3).

2 Related Work

Our approach uses the *options* framework (Sutton et al., 1999), which allows an agent to take temporally extended actions, enabling more efficient planning in certain tasks. Among the various deep-RL incarnations of the options framework (e.g. Kulkarni et al., 2016; Vezhnevets et al., 2017; Nachum et al., 2018), *Hierarchical DQN* (h-DQN) (Kulkarni et al., 2016) is the most relevant to our approach, and we discuss it in more detail in Section 3. Our approach most notably deviates from h-DQN by learning a model of affordances and using it to reduce the initiation set for each option.

Multi-task RL methods take advantage of shared task structure in order to generalize to new tasks from the same distribution (Andreas et al., 2017; Shiarlis et al., 2018; Devin et al., 2019; Sohn et al., 2020; Lu et al., 2021). Sohn et al. (2020) learn subtask preconditions, but use symbol-based contexts and do not learn and use their model of preconditions concurrently. Instead they assume a naive policy can sufficiently reach all subtasks. Furthermore, they assume ground-truth affordances are provided at each step. Some works provide the agent with high-level task *sketches* (Andreas et al., 2017; Shiarlis et al., 2018) describing the order in which subtasks must be completed. While these sketches are advertised as "ungrounded" Andreas et al. (2017), they are in fact grounded by the inclusion of short sketches, which are the first to be introduced to the agent in a curriculum learning scheme (Bengio et al., 2009). Our approach instead uses a direct signal, which alone need not determine task progress, and can learn without exposure to other tasks with shared structure.

In using a set of discrete symbols to indicate subtask completion, our work is similar to the variety of approaches that apply *temporal logic* (TL) to the RL setting (Yuan et al., 2019; Hasanbeig et al., 2018; 2020; Li et al., 2017; 2018). These works typically provide the agent with a TL *formula*, as well as assignments of *atomic propositions* at each time-step. Some works use reward shaping to encourage satisfaction of the formula (Li et al., 2017; 2018), whereas others convert the TL formula to some finite state machine, which provides the agent with a structure that roughly expresses subtask dependencies (Hasanbeig et al., 2018; 2020; Yuan et al., 2019). Icarte et al. (2020) bypass this formula-to-automata conversion, and instead directly provide the automata to the agent in the form of a *reward machine* (RM). While RMs are more expressive than LTL formulas, they are less flexible than HAL, which can deal with incomplete sets of symbols, as well as context stochasticity.

Gibson (1977) introduces a theory of *affordances*, defined roughly as properties of the environment which must be measured relative to the agent. Heft (1989) and Chemero (2003) clarify affordances as *relations* between the agent and its environment. Khetarpal et al. (2020) formalize this relational definition of affordances in the context of RL, and model which low-level actions, given corresponding *intents*, are afforded in each state. In this work we implicitly define a set of *high-level intents* by designating an intended milestone for each subtask. They also demonstrate that modeling affordances speeds up and improves planning through the pruning of irrelevant actions, and allows for the learning of more accurate and generalizable partial world models. This approach does not directly translate to the hierarchical setting because subtasks, unlike actions, may fail for reasons other than affordances, meaning we do not have access to ground-truth affordance label with which to train our model. Manoury et al. (2019) and Khazatsky et al. (2021) present approaches that can discover and use affordances to learn new skills, but their definition of affordances (i.e. a behavior is either afforded or not, with no notion of preconditions) does not translate to the hierarchical setting[1].

3 Background

Our setting is concerned with learning behavior policies in Markov Decision Processes (MDP). An MDP is defined by the state space $\mathcal{S}$, action space $\mathcal{A}$, reward function $R : \mathcal{S} \times \mathcal{A} \to \mathbb{R}$, and state transition distribution $P : \mathcal{S} \times \mathcal{A} \to \triangle(\mathcal{S})$. The objective is to learn a policy, $\pi : \mathcal{S} \to \triangle(\mathcal{A})$, which selects actions that maximize expected future returns: $G(\pi) = \mathbb{E}\left[\sum_{t=0}^{\infty} \gamma^t r_t \,|\, a_t \sim \pi, s_t \sim P\right]$, where γ is the discount factor. We specifically follow the paradigm of hierarchical RL where we learn low-level controllers each trained to attain some discrete goal, and a high-level meta-controller trained to select goals in a manner that maximizes rewards. A bi-level controller of this form allows an agent to learn intermediate skills, in the form of competent sub-policies, enabling the agent to compose these intermediate behaviors in order to achieve rewards in long horizon tasks. Our controllers are learned via hierarchical deep Q-learning (Kulkarni et al., 2016).

Goal-directed controllers We aim to learn a controller, $\pi : \mathcal{S} \times \mathcal{G} \to \triangle(\mathcal{A})$, that selects low-level actions, $a \in \mathcal{A}$, given a state, $s \in \mathcal{S}$, and goal, $g \in \mathcal{G}$, in some specified goal space, that maximizes expected future goal-attainment rewards, b_g (our *milestones* discussed in Section 4). In the discrete goal case, we can treat this as learning a separate controller π_g for each goal. Q-Learning (Watkins, 1989) trains these controllers by learning an estimate of the optimal Q-function: $Q_c^*(s, a; g) = \max_\pi \mathbb{E}\left[\sum_{t=0}^{\infty} \gamma^t b_{g,t} \,|\, s_0 = s, a_0 = a, a_t \sim \pi, s_t \sim P\right]$ and deriving a policy from the Q-function as such: $\pi_g(a|s, g) = \mathbb{1}(a = \arg\max_{a'} Q_c(s, a'; g))$. Deep Q-Learning (Mnih et al., 2015) estimates Q^* using deep neural networks. This Q-function is parameterized by $\theta = \{\theta_{\text{base}}, ..., \theta_g, ...\}$, where θ_{base} is a set of shared base parameters and θ_g is a goal-specific head. It is updated via gradient

[1]The "hierarchical" part of (Manoury et al., 2019) refers to the learning algorithm, not the tasks considered.

descent on the following loss function, derived from the original Q-learning update:

$$\mathcal{L}_{Q_c} = \mathbb{E}_{(s_t,a_t,r_t,s_{t+1},g_t)\sim D_c}\left[\left(Q_c(s_t,a_t;g_t,\theta) - r_t - \max_{a_{t+1}} Q_c(s_{t+1},a_{t+1};g_t,\bar{\theta})\right)^2\right] \quad (1)$$

where D_c is a replay buffer that stores previously collected transitions, and $\bar{\theta}$ are the parameters of a periodically updated target network. Both of these components are included to avoid the instability associated with using function approximation in Q-Learning.

Goal-selecting meta-controller The objective of our meta-controller $\Pi : \mathcal{S} \rightarrow \triangle(\mathcal{G})$ is to select goals in a manner that maximizes extrinsic rewards received by the environment when executing the low-level controllers corresponding to the selected goals. Again, we estimate a Q-function, this time over a dilated time scale (i.e. we allow the low-level controllers to run for multiple steps before choosing new goals): $Q^*_m(s,g) = \mathbb{E}\left[\sum_{t=0}^{N} r_t + \max_{g'} Q^*_m(s_N,g') \mid s_0 = s, g_0 = g, a_t \sim \pi_g, s_t \sim P\right]$, where N is the (variable) number of steps the goal-directed controller runs. When collecting data in the environment, we add transitions $(s_t, g_t, \sum_t^{t+N} r_t, s_{t+N})$ to a separate meta-replay buffer, D_m, used to train our meta-Q-function (parameterized by Θ) with a loss similar to that in Eq. 1, but without any goal-conditioning.

4 Milestones And Hierarchical Affordances

We consider tasks that can be decomposed into *subtasks* represented by *milestone* symbols $g \in \mathcal{G}$, where $\mathcal{G}$ is the set of symbols relevant to the task, and $|\mathcal{G}| = K$. At each time-step, in addition to the extrinsic reward signal provided by the environment to indicate successful on the overall task, we have access to a *milestone signal*, which is a vector $\boldsymbol{b}^t$ where each element $b^t_g \in \{0,1\}$ indicates the whether $g \in \mathcal{G}$ was completed on time-step t. In our PASTA example, we might receive a milestone each time we cut a vegetable, make the sauce, cook the noodles, etc. Milestones indicate that we have achieved something notable (e.g. a subtask or subgoal) *without* having to quantify or assign utility to it. We define *hierarchical affordances* over a set of milestones in the following way. The vector $\boldsymbol{f}^s = f^*(s)$ of size K represents which milestones are achievable from the present state s, without requiring the collection of any intermediate milestones, where f is a *hierarchical affordance classifier*, and $f^*(s)$ is the optimal one. $\boldsymbol{f}^s_g = 1$ if at time t_0 it is possible for future $b^T_g = 1$ without any $b^t_j = 1, j \neq g$, where $t_0 < t < T$. In PASTA, for example, the milestone `mix cooked noodles and sauce` is not afforded at the beginning since it requires `cook noodles`.

Many logic-based RL approaches learn a similar notion of context as affordances by performing *temporal logic* (Gotzhein, 1992) over a set of *atomic propositions*, which are sequentially fed to the agent in order to keep track of context changes. Crucially, unlike atomic propositions, the history of milestones *alone* need not define which subtasks are currently possible. In fact, for $\mathcal{G}$ to be useful to an affordance-aware agent, only the following requirements must be met: $\mathcal{G}$ must contain a final milestone that indicates task completion, and each additional milestone should correspond to a (unique) behavior that is necessary for achieving the final milestone. Figure 5 empirically supports this flexible definition by demonstrating that a careful choice of $\mathcal{G}$ is unnecessary to observe benefits from an affordance classifier, meaning future work might more easily be able to combine HAL with orthogonal approaches that automatically discover meaningful subgoals. If milestones are reliably given to the agent upon subtask completion, hierarchical affordances for each subtask are determined simply by the states in which their immediate attainment is possible.

There are two forms of stochasticity that hierarchical affordances, by virtue of being grounded in the present state, can more naturally address than symbolically-defined dependencies. We can conceptualize potential trajectories as graphs where nodes represent the attainment of milestones, and edges are the segments between them. The first type of stochasticity we call *node stochasticity*, or affordance-affecting randomness that occurs either when milestones are collected (e.g. receiving varying quantity of an item), or at the beginning of the episode (i.e. starting in different contexts). The second form of stochasticity is *edge stochasticity*, or when affordances may change within segments where no milestones are collected. Spilling cooked noodles on the floor is one example of this. A more unlikely example would be receiving fully cooked noodles from a neighbor while in the midst of cooking. Edge stochasticity requires us to clarify our working definition of hierarchical affordances. If cooking noodles for PASTA generally requires intermediate milestones, but there is *some* chance a neighbor will save the day, should an agent rely on this possibility? So long as edge

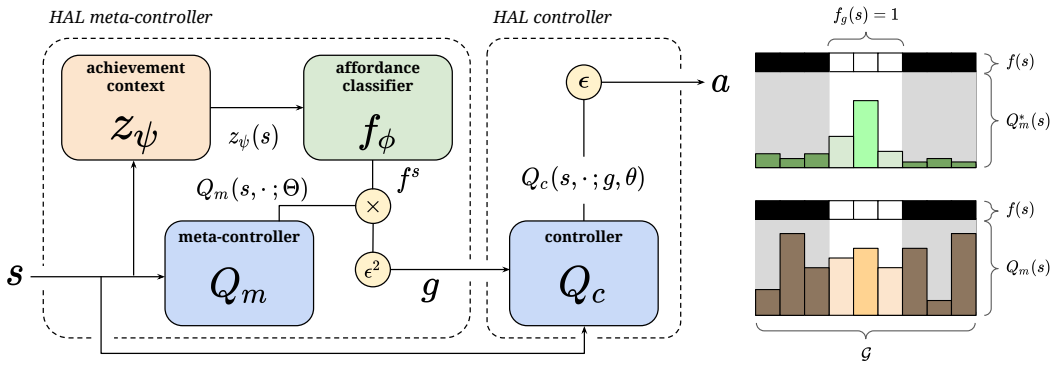

Figure 2: Left: Architecture diagram for complete HAL method. Q-values of the meta-controller are masked by the output of the affordance classifier. The ϵ operator represents the standard ϵ-greedy action selection procedure used in Q-learning, while ϵ^2 represents our affordance aware version. Right: For an optimal policy (top), the mask will have no effect since Q values will naturally be low for unafforded subtasks. However, a suboptimal policy (bottom) will benefit from a mask since it can be efficiently learned and used to prune irrelevant subtasks before TD errors can propagate.

stochasticity events can be viewed as *exceptions* to a general set of dependency rules, the definition still stands. By grounding these rules in the current state, an affordance-aware agent can detect and adapt to edge anomalies. In the next section, we describe in detail how hierarchical affordances allow us to learn and use these rules from milestones in stochastic environments where symbolic history would fail to reliably determine the current context.

5 Hierarchical Affordance Learning

In typical HRL methods, if the meta-controller is yet to receive extrinsic reward from the environment, there will be no preference for selecting any subtask over the others. However, by restricting the selection of subtasks to ones that have proven merely to be *possible*, an agent can avoid wasting time attempting the impossible, and reach more fruitful subtasks faster. Suppose from experience, gained through random exploration, the agent achieves milestone g (where achievement means $b_g = 1$) very often from the initial state set $\mathcal{I}$, but never $j \in \mathcal{G}$, despite being able to achieve j in later states. With enough experience, the agent should become confident that j is not achievable without completing other milestones first, and should not bother selecting j from any $s \in \mathcal{I}$, while g, and any others that *are* achievable from those states, should instead be considered. If we had access to an oracle function, $f^*(s)$, that accurately computes hierarchical affordances for our task, we could prune impossible subtasks by masking the otherwise uninformed policy with the affordance oracle output: $p(g|s) \propto \boldsymbol{f}^s_g * \Pi_\Theta(g|s)$. In the following sections, we describe a method that can learn an approximate $f(s) \approx f^*(s)$ from experience and leverage it in real-time for more effective learning.

The false negative problem Recall that the purpose of $f(s)$ is to output a vector $\boldsymbol{f}^s$, where each $\boldsymbol{f}^s_g$ indicates the possibility of collecting milestone g from state s without requiring intermediate milestones. To train each binary classification head, $f_g(s)$, we must somehow generate labeled data for each milestone. Suppose an option was initialized at time-step t_o, and in time-step T milestone g is received. If no others were received since the start of the option, we may assume that for any t where $t_o \leq t \leq T$, the collection of milestone g was afforded, so we can use the set of states $\{s_{t_o}, s_{t_o+1}, \ldots, s_T\}$ as positive (i.e. $f^*_g(s) = 1$) training examples for the affordance classifier. Even if g was not the intended milestone, we can still generate positive training examples for f_g in this way. If an option has failed to collect intended milestone g, either through timing out or collecting an unintended milestone, we might be tempted to use the states encountered during that option as negative examples (i.e. $f^*_g(s) = 0$). However, this occurrence can either be indicative of the states not affording g, or that the subpolicy corresponding to g is sub-optimal and has failed despite g being afforded. These false negatives are a problem for any approach requiring function approximation via neural networks, which are generally not robust to label noise (Song et al., 2020). It is particularly troublesome in our case since the noise is greater than the true signal when the subpolicies are under-trained.

Context learning Suppose we had access to an abstract state representation $\boldsymbol{z}^s_{\text{aff}} = z^*_{\text{aff}}(s)$, where any states s_i and s_j are mapped to the same value only when $f^*(s_i) = f^*(s_j)$. With a representation that could cluster states in this way, we could trivially determine the falsity of a collected negative $s \in \mathcal{D}^-_g$ by checking if $z^*_{\text{aff}}(s) = z^*_{\text{aff}}(s_j)$ for any $s_j \in \mathcal{D}^+_g$, that is, if we have encountered a true positive with the same representation. The classification procedure could be interpreted as "labeling" these contexts with affordance values. This is somewhat of a "chicken and egg" problem, since to learn affordances, we require a representation that maps states to contexts with the same affordance values, which clearly requires some prior knowledge about affordances. Fortunately, from Section 4, we know that affordances will only change when either (1) a milestone is collected and (2) when edge stochasticity occurs. Since (2) is by definition a rare occurrence, states s_t and s_{t+1} are more likely than not to satisfy $f^*(s_t) = f^*(s_{t+1})$, so long as they exist in the same *segment* between milestones. In this case, we can say that s_t and s_{t+1} share the same *achievement context*, $\boldsymbol{z}^s = z(s)$. Let $z_\psi(s)$ be an achievement context embedding represented by a differentiable function parameterized by ψ. We can train $z_\psi(s)$ from experience using the following contrastive loss:

$$\mathcal{L}_\psi = \sum_j \left[\left\| z_\psi(s^a_j) - z_\psi(s^p_j) \right\|_2^2 - \left\| z_\psi(s^a_j) - z_\psi(s^n_j) \right\|_2^2 + \alpha \right]_+ ,$$

where each s^a_j is a randomly chosen *anchor*, each s^p_j is a *positive*[2] example chosen within the segment according to a (truncated) normal distribution, $\mathcal{N}_T(0, \sigma^2)$, centered around (and excluding) s^a_j, s^n_j is chosen randomly among other segments and is treated as a *negative* example, and α is an arbitrary margin value. This loss pushes representations of states from the same achievement context together, and pulls representations of states from different contexts apart. We show in Appendix B that a wide range of σ produce useful representations. For our edge stochasticity experiments (Figure 5) we use a low $\sigma = 2.0$ to reduce the risk of sampling across affordance changes.

False negative filtering In the learned representation space, we expect false negative points to be closer to positive points than true negatives. Given a negatively-labeled state s_q for classifier head f_g, we compute[3] the mean distance from $z_\psi(s_q)$ to the representations of the k closest positive points in a population uniformly sampled[4] from $\mathcal{D}^+_g$, denoted d^k_q. We expect d^k_q to be large for true negatives and small for false ones, and we can determine an effective separating margin in the following way. First we compute distance scores for a random sample of positive points, denoted $\{d^k_p\}$, to use as reference. We ensure these points come from segments that are disjoint from the population points' segments to avoid trivially low scores that might skew the distribution. We then fit a Gaussian distribution to $\{d^k_p\}$ and compute an upper confidence bound ρ for a given percentile value and confidence level. Any $d^k_q < \rho$ is very similar to positive points in the representation space, so we count s_q as a false negative and exclude it from our training set. Note, we do not train head f_g (and therefore do not reliably prune) until we have access to both positives and negatives for g.

Method overview The HAL architecture consists of a bi-level policy like h-DQN, a context embedding network, and an affordance classifier (see Figure 2), which are all learned concurrently (full algorithm in Appendix E). Intuitively, the affordance classifier is able to generalize to a novel state, s, by first identifying the abstract achievement context, $z_\psi(s)$, associated with the state, and then outputting an affordance value based on previous experience in that context. If $z_\psi(s)$ has also not been encountered, that context will not be strongly "labeled" either way, so we will not be invariably pruning it. During each episode, the meta-controller selects new subtasks at the start of the episode, after collecting *any* milestone, and whenever an option times out after a predefined number of steps. At each step, the current state is fed to the controller, which outputs an action conditioned on the most recently selected subtask. After discretizing the classifier's output to a binary mask (over threshold 0.5), we perform an affordance aware version of ϵ-greedy as follows. Given parameters ϵ_{aff} and ϵ_{mc}, we select a random subtask within the mask with probability ϵ_{aff}, randomly across all subtasks with probability ϵ_{mc}, and otherwise select greedily with respect to meta-Q *within* the mask.

6 Experiments

In our experiments we aim to answer the following questions: (1) Does HAL improve learning in tasks with complex dependencies? (2) Is HAL robust to milestone selection and context stochasticity? (3) Can HAL more effectively learn a diverse set of skills when trained task-agnostically?

[2]Here, the usage of "positive" and "negative" refers to whether points share the same achievement context.

[3]This procedure is akin to the particle entropy approach used in (Liu & Abbeel, 2021).

[4]For efficiency, we sample just enough points so that we are likely to cover all encountered contexts.

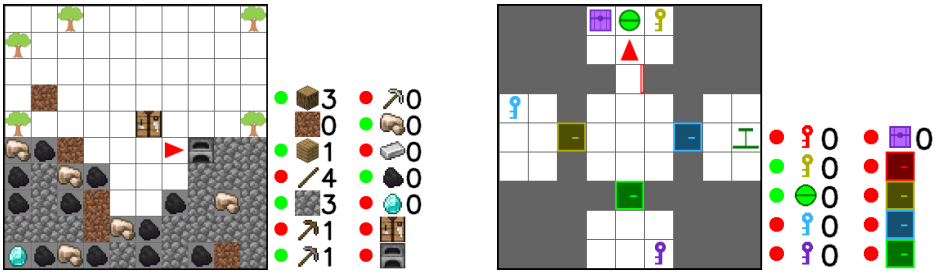

Figure 3: Screenshots of CRAFTING (left) and TREASURE (right) environments. Displayed to the right of the environments are each item's ground-truth affordance indicator and inventory count.

6.1 ENVIRONMENTS

We evaluate our method, along with several baselines, on two complex environments with intricate subtask dependency structures: CRAFTING and TREASURE. Both environments (visualized in Figure 3) are extensions of the minigrid framework (Chevalier-Boisvert et al., 2018). Agents receive an egocentric image of the environment, as well as a vector describing their inventory (items picked up from the environment and currently in their possession) as observations. The action spaces are discrete and include actions for turning left/right, and moving forward/backward, as well as environment specific actions detailed below. Task hierarchies, walk-throughs of successful trajectories, and additional information about both environments are included in Appendix A.

CRAFTING is based on Minecraft, a popular open-ended video game in which players collect resources from their environment and use them to craft objects which can be used to then obtain more resources. As such, the hierarchy of possible subtasks is immensely complex and presents a significant challenge for AI agents to reach subtasks deeper in the hierarchy. We develop an environment that replicates this hierarchical complexity without the commensurate visuomotor complexity which our method does not aim to address. In addition to movement actions, CRAFTING includes actions to mine the object immediately in front of the agent (which requires an appropriate pickaxe), as well as to craft and smelt the various objects (pickaxes, iron ingots, etc.). The full set of milestones contains items that are either craftable or collectable. CRAFTING naturally contains node stochasticity since the collection of certain items, due to the random procedural generation, requires slightly different milestone trajectories across episodes (e.g. mining variable amount of stone to encounter diamond).

TREASURE is a navigation task that requires the agent to collect various items and use them to unlock rooms to reach further items. The ultimate goal is to unlock a treasure chest, which requires a sequence of collecting several keys, as well as placing an object on a weight-based sensor, in order to open the requisite doors. Agents can only carry one object at a time, so they must reason about which object to pick up based on what it will afford them (e.g. if the weight-based sensor room is locked, the weight object is not currently useful). Like CRAFTING, TREASURE contains node stochasticity due to the procedural generation. For example, the central room that the agent is spawned in can contain either of the red or yellow key individually, or both together. Unlike CRAFTING, which has a large action space to accommodate the various crafting recipes, this environment only contains actions to move and a single "interaction" action that is used to pick up keys, open doors, etc. While CRAFTING has a more complex hierarchy and greater diversity in the potential ordering of subtasks, TREASURE has on average more difficult subtasks. The full set of milestones contains each object the agent can successfully interact with in the environment (e.g. opening door, collecting key).

6.2 BASELINES

Our set of baselines is summarized in Table 1. All methods are based on the Rainbow (Hessel et al., 2018) Deep Q-Learning algorithm, which combines several improvements to vanilla DQNs (Mnih et al., 2015). To compensate for the lack of milestone signals, non-hierarchical methods use a dense reward function that incorporates milestone signals for the first time each milestone is obtained in the episode. To evaluate the efficacy of our affordance classifier

Table 1: Summary of baselines.

	Hierarchical Agent	Affordance Mask	Hindsight Replay	False Negative Filtering
Oracle	✓	*Truth*	✓	N/A
HAL (ours)	✓	Learned	✓	✓
HAL(–FNF)	✓	Learned	✓	×
H-Rainbow	✓	N/A	×	N/A
H-Rainbow (+HER)	✓	N/A	✓	N/A
Rainbow	×	N/A	N/A	N/A

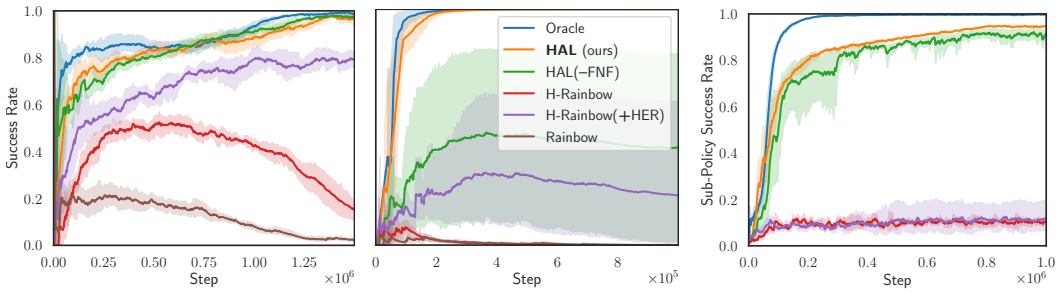

Figure 4: Success rate over the course of training for CRAFTING `iron` task (left) and TREASURE (center). Sub-policy success for TREASURE (right). Success rate is the proportion of episode where the agent receives the target milestone, and sub-policy success is how often sub-policies, on average, receive the correct milestone when called, before a timing out or collecting incorrect milestones.

online learning procedure, we compare our method to an "oracle" that differs only by using *ground-truth* affordances for masking subtasks. The node stochasticity inherent to both environments, as well as the edge stochasticity later explored, preclude the use of any methods that reason solely over symbols (i.e. automata-, sketch-, or subtask dependency-based approaches). We also incorporate a version of Hindsight Experience Replay (HER) (Andrychowicz et al., 2017) adapted for the discrete milestone setting, which involves re-using "failed" trajectories that result in the collection of an unintended milestone (given the selected subpolicy) as successful data for the relevant subpolicy. For instance, if an agent accidentally collects iron while executing its wooden pickaxe sub-policy, it can use this trajectory to train its iron sub-policy.

6.3 RESULTS

Learning efficacy First, we evaluate the ability of HAL and our baselines to learn successful policies for complex tasks in each environment. Learning curves are shown in Figure 4. In both environments, HAL significantly outperforms the strongest baseline, H-Rainbow(+HER) (HR+H), despite both methods receiving the same information, and performs only slightly worse than the oracle, which has access to ground truth. Incorporating HER into H-Rainbow leads to a significant improvement. False negative filtering (and all other HAL components; see Appendix B) appears crucial for successful learning in the TREASURE environment, but not as much for CRAFTING, though in both cases filtering improves mask accuracy. Removing false negative filtering causes HAL(-FNF) to be pessimistic (i.e. over-pruning subtasks, see Figures 15a and 15c in the Appendix D), ultimately leading to its unstable learning. Since masking impossible subpolicies would have no impact on an optimal meta-controller, HAL's success must stem from its ability to learn a useful mask *before* TD errors are able to propagate through the meta-controller's Q function. HAL utilizes a more easily learnable function (the affordance classifier) to reduce the amount of unnecessary expensive learning (TD error propagation) required. We see from Figure 15 that, throughout training, HAL's mask has an impact on greedy subtask selection $\sim$60% of the time, which is evidence that HAL avoids wasting time learning Q-values that the mask is able to prune. Lastly, because affordance-aware methods are more likely to initiate subtasks in an appropriate context, we see they achieve a significantly higher average subpolicy success rate (Figure 4, right).

Robustness to milestone selection In this section we evaluate HAL's robustness to the selection of milestones. Affordances change when a milestone is removed since that milestone no longer acts as an intermediate link between others. One downside of some approaches that use symbol-based contexts is that an entirely different automata or subtask dependency graph must be defined over the new set of symbols. HAL does not use prior information of this kind, so the learning process is the same across all sets. Figure 5 shows HAL's success on the CRAFTING environment's `iron` task when using "incomplete" milestone sets, relative to the full human-designed set. We see that randomly removing 1 milestone makes no significant difference for HAL, and even after removing 4 milestones, HAL still achieves better performance than HR+H using the full set. HAL's performance drops when 5 milestones are removed likely due to the increased sparsity of the signal (i.e. greater subtask length) and variance in milestone set quality. However, when we double the training time for these same sets, we find that HAL is able to converge to a 97% success rate on at least one set, while HR+H fails to converge on any set and ends with a maximum success rate of around 70%.

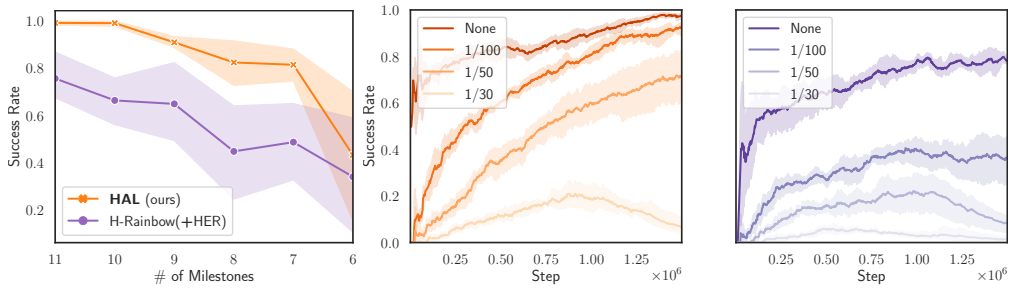

Figure 5: Comparing the robustness of HAL and HR+H to varying milestone sets (left) and various edge stochasticity frequencies (center and right, respectively) in CRAFTING `iron` task.

Robustness to stochasticity We modify CRAFTING so that at each environment step, there is a certain probability that an item in the inventory will disappear. In order to make the task feasible, rare items are less likely to disappear than common ones. This procedure produces *edge stochasticity*, since the disappearance of items may alter affordances, and this can occur at any time. We test three different levels of stochasticity, and display the learning curves in Figure 5. With a disappearance frequency of $1/100$ that cuts HR+H's success rate in half, HAL is still able to reach its non-stochastic success rate. With a frequency of $1/50$, HAL performs comparably to HR+H with no stochasticity. To put these stochasticity rates into context, the algorithm's average episode length about halfway through training is still over 1000 steps (see Figure 14 in Appendix C), meaning *dozens* of items are removed from the agent's inventory over the course of an episode. By learning a model of affordances grounded in the present state, HAL is able to detect and adapt to these stochastic events.

Task-agnostic learning We next test the ability of HAL to learn skills when no task-specific extrinsic rewards (only milestones) are provided by the environment. Since we cannot learn a meta-controller in the absence of rewards, we instead randomly select subtasks with some probability ϵ_{mc}, and random *afforded* subtasks otherwise (only for HAL). We evaluate both HAL and HR+H. In Figure 6 we see that by the end of 10^6 steps, HAL is able to more reliably complete the milestones deeper in the hierarchy in the CRAFTING environment. We note that HR+H is able to marginally outperform HAL in tasks shallower in the hierarchy (e.g. wood pickaxe, stone, furnace), potentially as a result of failing to reach deeper tasks and getting more practice on shallower ones. This result is an indication of the general utility of HAL in environments with complex task hierarchies.

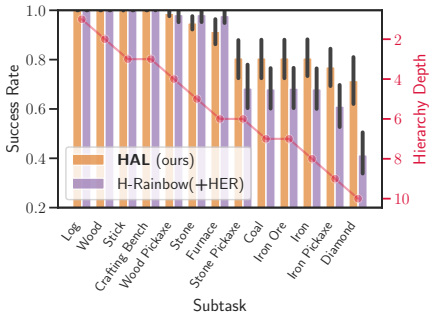

Figure 6: Percentage of episodes where each milestone is achieved in CRAFTING environment task-agnostic setting.

7 Conclusion and Future Work

The present work can be viewed as a first step towards bridging the substantial gap between flexible hierarchical approaches that are presently intractable, and methods that impose useful structures but are too rigid to be of practical use. We introduce HAL, a method that is able to utilize incomplete symbolic information in order to learn a more general form of subtask dependency. By grounding subtask dependencies in the present state by learning a model of hierarchical affordances, HAL is able to navigate stochastic environments that approaches relying solely on symbolic history are unable to. We demonstrate that HAL learns more effectively than baselines provided with the same information, is more robust to milestone selection and affordance stochasticity, and can more thoroughly explore the environment's subtask hierarchy. Given HAL's flexible formulation and success in the face of incomplete and stochastic symbolic information, we foresee future work integrating HAL with option (or subgoal) discovery methods (e.g. Bacon et al., 2017; Machado et al., 2017; Bagaria & Konidaris, 2019) to obtain performance gains in complex tasks without requiring pre-specified milestones. Additionally, future work might be able to extend HAL to continuous goal-spaces, but this would require revising the definition of hierarchical affordances provided here, as it currently requires a notion of intermediate subgoal completion.

8 REPRODUCIBILITY STATEMENT

All code for environments, algorithms, and baselines is provided at the following link: https://github.com/jamesdoewhat/hal-anonymous. We enumerate the list of commands to reproduce all experiments in the paper, as well as a file specifying the python packages and versions required which can be installed via the Anaconda python package manager. All hyperparameters and additional implementation details are listed in the Appendix.

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A Additional Environment Details

In both environments, extrinsic rewards are a sparse binary signal provided upon the completion of a final goal. Milestone signals are similarly formulated for each of the possible subtasks. For both types of rewards (extrinsic and milestone) we introduce a per step penalty that encourages agents to achieve their goal as quickly as possible. TREASURE and CRAFTING environments are extensions of the minigrid framework (Chevalier-Boisvert et al., 2018).

A.1 CRAFTING

As discussed in Section 6.3, our CRAFTING environment is designed to maximize hierarchical complexity while minimizing visuomotor complexity, which we do not aim to address with our method. Similar Minecraft-based environments have been used in the literature; however they do not meet these requirements. The MineRL environment (Guss et al., 2019) provides an interface into the full game of Minecraft; however, effective behavior in this environment requires learning complex visuomotor policies in addition to understanding the hierarchical relationships between subtasks. In order to evaluate our method effectively, we only aim to test the latter. Other work has used Minecraft-inspired environments (Andreas et al., 2016; Sohn et al., 2020); however, these versions involve simplified subtask hierarchies. Our environment replicates the complexity of the MineRL subtask hierarchy while remaining perceptually simple. A concurrently developed environment contains similar hierarchical complexity while minimizing perceptual complexity (Hafner, 2021).

Figure 7 displays an abstract representation of the CRAFTING environment subtask hierarchy. Each arrow points from one subtask to another, where the latter subtask requires the former in some way. The CRAFTING environment contains a variety of dependency types. Many items must be built or *crafted* from other resources. Some of these require the agent to be within the vicinity of a crafting bench. Other items require specific pickaxes to be mined, and yet others must be smelted in a furnace using a raw material and a fuel source. Another complexity missing from Figure 7 is that crafting *recipes* require specific amounts of items. For instance, in our environment a stone pickaxe requires three stone and two sticks. Each stone must be mined individually, resulting in three separate milestones, while just two wood are required to craft four sticks. Lastly, there are

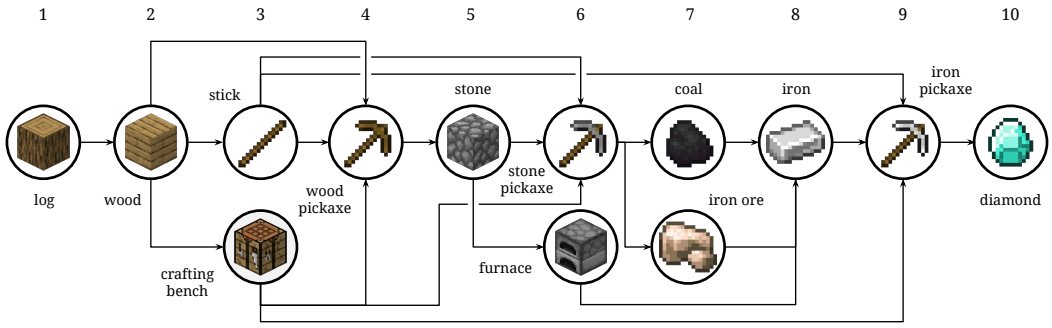


Figure 7: Abstract representation of CRAFTING subtask hierarchy, where milestones are circled and arrows indicate to explicit subtask dependencies between milestones and numbers indicate the depth of each item in the hierarchy (used in Figure 6). Numerical preconditions for crafting recipes are not shown, as well as other possible implicit environmental dependencies (e.g. mining x to reach y).

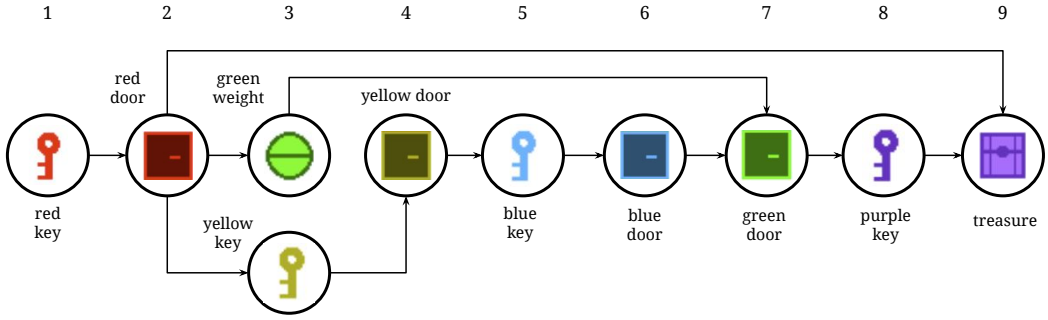


Figure 8: Abstract representation of *one* possible TREASURE subtask hierarchy, where milestones are circled and arrows indicate to explicit subtask dependencies between milestones.

other implicit dependencies than the ones shown, depending on the definition of the milestones set. For example, although the only official prerequisite for obtaining diamond is having an iron pickaxe, in practice, an agent will need to mine stone and other blocks to reach the diamond, and the successful mining of each of these blocks may be considered a milestone.

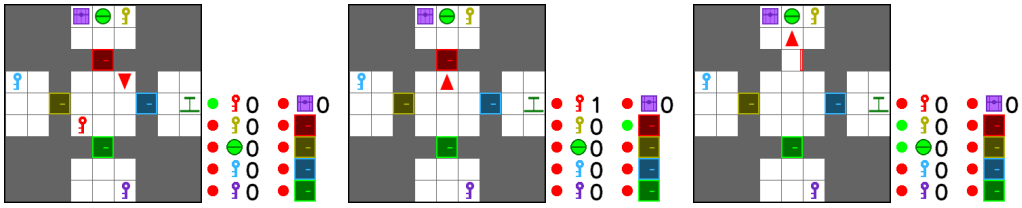
CRAFTING is procedurally generated in the following way. For the lower half of the environment, each cell is randomly assigned stone, coal, iron, or dirt to each cell with varying probabilities. Diamond is randomly assigned to a cell in the bottom-most layer. Trees (from which logs are obtained) are abundantly scattered in the upper half, and a few irrelevant dirt blocks are placed in this region as well. If the generated environment does not have enough resources, it is regenerated with the next random seed.

A.2 TREASURE

In Figure 8 one *possible* TREASURE subtask hierarchy is displayed. Unlike CRAFTING, there are multiple different abstract hierarchies depending on the initial state of the environment. At the beginning of each episode, either both keys are available, only the yellow key, or only the red key (the instance shown in Figure 8). While the environment dynamics remain the same across all episodes, the agent must infer which hierarchy is appropriate based on the initial configuration of the environment. TREASURE is procedurally generated by randomly assigning each colored door to the room entrances, randomly determining which keys are accessible from the starting room, and lastly placing all objects behind their appropriate doors at random positions within the room.

A.3 WALK-THROUGHS

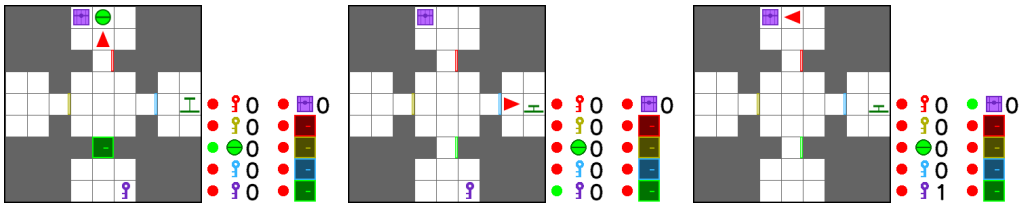
Successful human walk-throughs for both TREASURE and CRAFTING environments are described in Figures 9 and 10 respectively.



(a) Agent is initialized in the central room, with only the red key afforded.

(b) Agent picks up the the red key and moves toward the red door. Note that the red door milestone is now afforded.

(c) Agent opens the red door and must choose between two possible afforded subtasks. Only the yellow key will result in further progress, as the green weight must be placed on the scale in the locked room on the right.

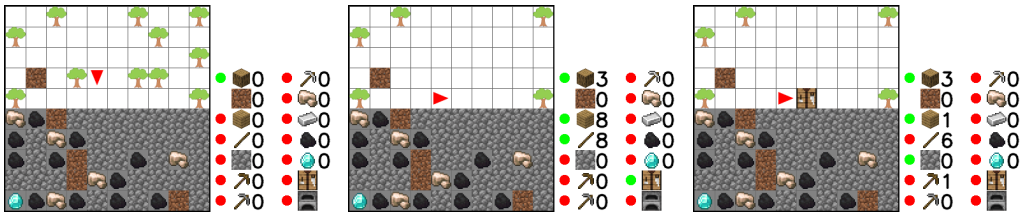


(d) Agent opens the door to the room with the scale by first proceeding into the left-side room and picking up the blue key.

(e) Agent picks up the ball and drops it on the scale, opening up the room containing the final key.

(f) Agent picks up the purple key, and the final desired milestone (treasure) is now afforded.

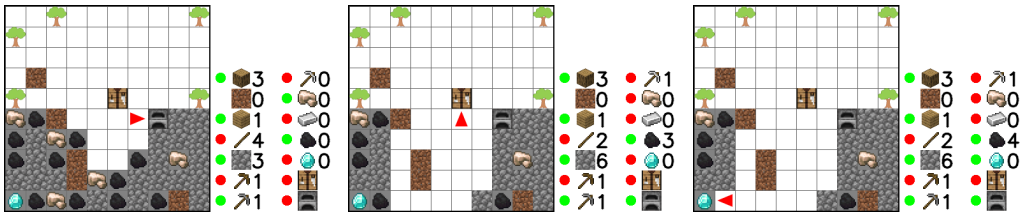
Figure 9: Walk-through of a successful TREASURE task episode. Items currently in the agent's possession are indicated by the numbers on the right hand side and ground-truth affordances are indicated by green circles if the milestone is afforded and red if not.



(a) Agent is initialized in the "woods" surrounded by trees, with only logs afforded.

(b) Agent collects logs, and converts them into wood and sticks.

(c) Agent uses sticks and wood to create a crafting bench and wood pickaxe.



(d) Agent collects stone that it uses to create a furnace and stone pickaxe.

(e) Agent uses the stone pickaxe to collect iron ore and coal which it turns into iron ingots, which in turn are crafted into an iron pickaxe.

(f) With the iron pickaxe, the agent can finally reach and mine diamond, the final goal.

Figure 10: Walk-through of successful CRAFTING environment `diamond` task episode.

B ABLATION AND ROBUSTNESS RESULTS

B.1 COMPONENT ABLATIONS

In Figure 11 we plot success on TREASURE after removing various integral components of the full HAL method. We find that all components introduced in this work are necessary for achieving the best performance on this task. The only variation that also reliably converges to 100% success rate is when the affordance classifier is provided with the raw state as input rather than using the learned representation, but this variation is undesirable since more learnable parameters are introduced.

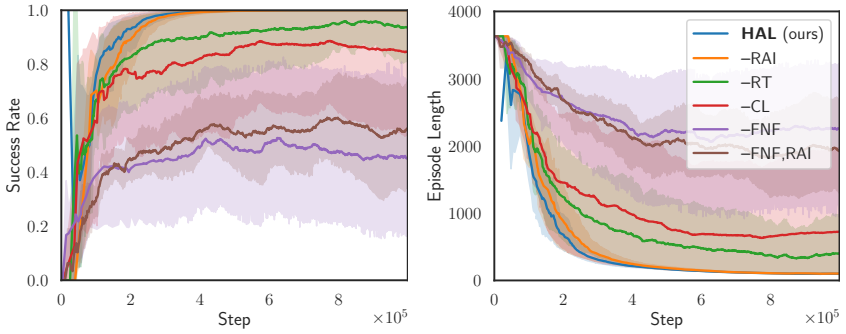


Figure 11: Training curves for component-wise ablations of HAL on TREASURE task. HAL refers to the full method, while the rest of the items displayed in the legend indicate which components are removed. −RAI no longer uses the context representation as input to the affordance classifier (the classifier is trained directly over the state). −RT no longer uses affordance classifier loss to additionally tune the context representation weights. −CL removes the contrastive loss altogether, allowing the weights to be trained solely with affordance classifier gradients. Lastly, −FNF no longer filters false negatives using the learned context representation.

B.2 HYPERPARAMETER ROBUSTNESS

In Figure 12 we demonstrate HAL's robustness to modifications of the most significant newly introduced hyperparameters on the TREASURE task. In only two cases over the wide range of values we tested did all runs not converge. The first is when the upper confidence bound percentile is set too low, which results in more false negatives being left unfiltered. The second is when the affordance classifier threshold is set too low, which results in less pruning. We see that a wide range of more aggressive settings for both of these hyperparameters are reliable. We find that the standard deviation hyperparameter is not sensitive across the values we test in the non-edge-stochastic TREASURE environment, and that lower values (e.g. $\sigma = 2.0$), which we initially hypothesized might fare better with edge stochasticity but could lead to worse representations, are in actuality still effective.

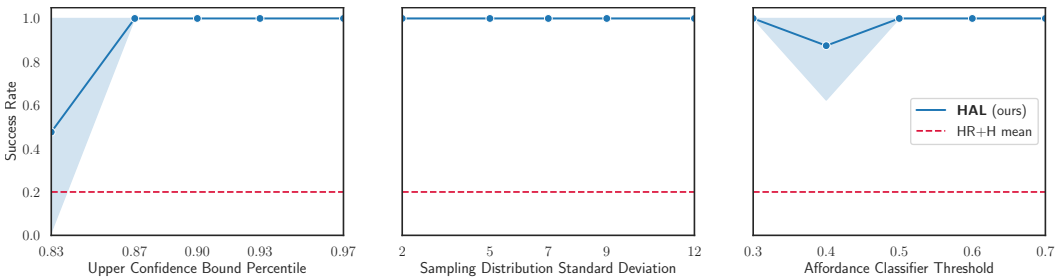


Figure 12: Plots comparing HAL's final success rate with that of HR+H's on TREASURE task with alternative hyperparameter settings. Left: percentile values used for defining the upper confidence bound ρ for false negative filtering. Center: standard deviation values, σ, used for sampling positive points from the (truncated) normal distribution in the contrastive loss. Right: threshold value over which the affordance classifier output is discretized.

B.3 VARYING σ UNDER STOCHASTICITY

In Appendix B.2, we demonstrated that in TREASURE, various values of σ centered around the value we used in that setting ($\sigma = 7.0$) are all conducive to good performance on that task. In Figure 13, we plot the results of using different values in a stochastic version of the CRAFTING environment in the `iron` task. Although all values lead to significantly better performance than HR+H, the value we happened to used in this setting ($\sigma = 2.0$) appears to strike the best balance. Very low values (e.g. $\sigma = 1.0$) likely do not learn as general a context representation, while higher values (e.g. $\sigma = 8.0, 16.0$) are more likely to sample positive points across occurrences of edge stochasticity. It is intriguing that the final loss for $\sigma = 2.0$ is lower than for $\sigma = 1.0$. We speculate that the context learned by sampling points too close to the anchor could be a less natural representation to learn than a more general one, which considers further points.

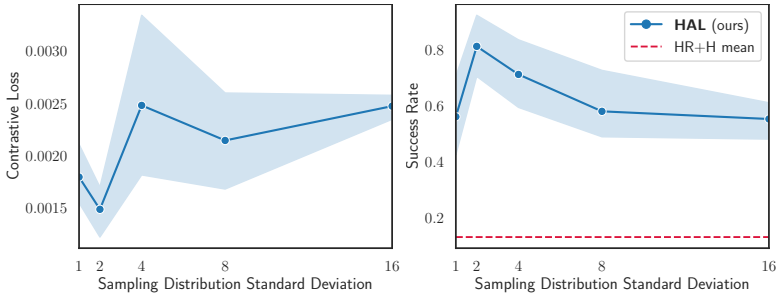


Figure 13: Plots evaluating the efficacy of various σ values used for the contrastive loss in a stochastic CRAFTING environment on the `iron` task, with item disappearance rate $1/50$ steps. Left: final contrastive loss values for HAL. Right: final HAL success rates compared to HR+H.

C EPISODE LENGTH PLOTS

In Figure 14 we display the episode length plots corresponding to the success rate results shown in Figures 4 and 5.

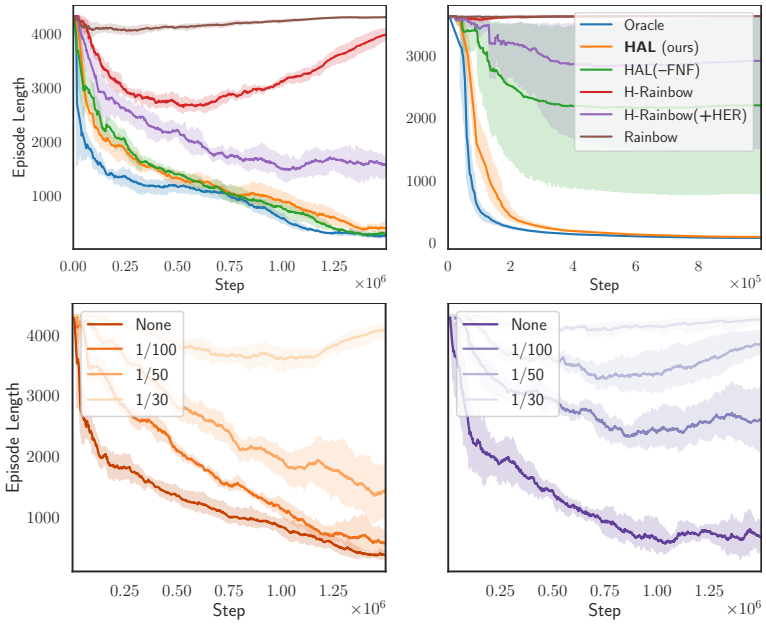


Figure 14: Episode length over the course of training for all baselines on CRAFTING `iron` (top left) and TREASURE (top right), corresponding to Figure 4. Episode length with variable levels of stochasticity CRAFTING `iron` (bottom), corresponding to Figure 5.

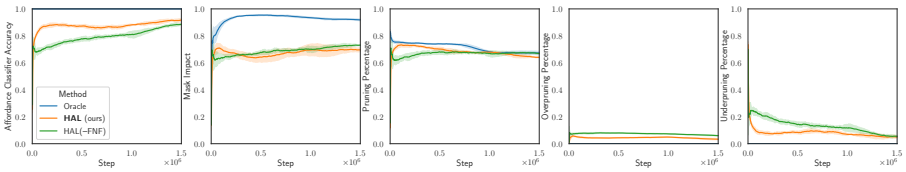
D AFFORDANCE PLOTS

We provide metrics tracked over the course of training for affordance masking as well as false negative filtering in Figure 15. The mask metrics (Figure 15a for CRAFTING `iron` and Figure 15c for TREASURE) consist of (from left to right):

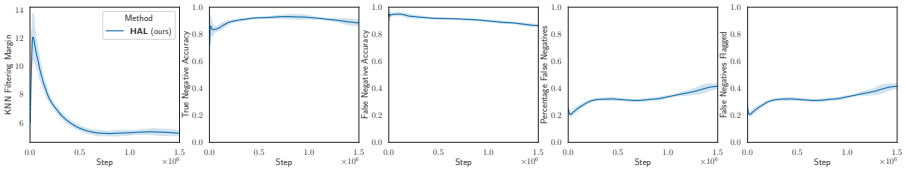
- Affordance Classifier Accuracy: The accuracy of the affordance classifier w.r.t truth.
- Mask Impact: The percentage of times that the affordance mask prevents selecting an subtask that would have otherwise had the highest Q-value.
- Pruning Percentage: Percentage of subtasks pruned.
- Overpruning Percentage: Percentage of subtasks that are afforded but are pruned.
- Underpruning Percentage: Percentage of subtasks that are not afforded but are not pruned.

The false negative filtering metrics (Figure 15b for CRAFTING `iron` and Figure 15d for TREASURE) consist of:

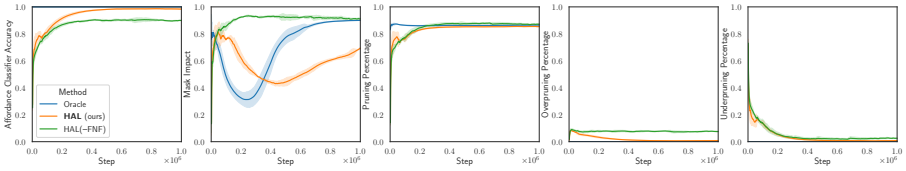
- Filtering Margin: L2 distance at which we consider negatives to be true negatives.
- True Negative Accuracy: Percentage of true negatives falling above filtering margin.
- False Negative Accuracy: Percentage of false negatives falling below filtering margin.
- Percentage False Negatives: Percentage of negatives that are false negatives.
- False Negatives Flagged: Percentage of negatives that are flagged as false by our margin.



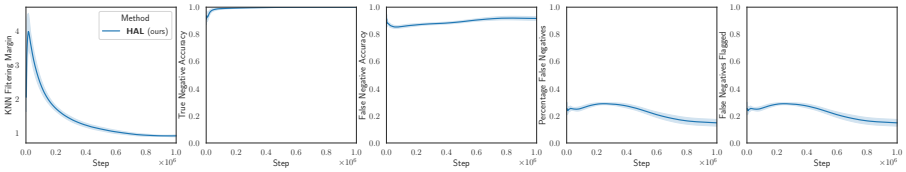
(a) Mask metrics for CRAFTING environment `iron` task.



(b) KNN filtering metrics for CRAFTING environment `iron` task.



(c) Mask metrics for TREASURE environment.



(d) KNN filtering metrics for TREASURE environment.

Figure 15

E ALGORITHM

Algorithm 1 Learning procedure for HAL

Initialize replay buffer for meta-controller (D_m), controllers (D_c), positive affordance examples (D_g^+), potential negative examples (D_g^-) for each goal $g \in \mathcal{G}$, and parameters for meta-controller (Θ), controllers (θ), achievement context function (ψ), and affordance classifier (ϕ).
$\texttt{steps} \leftarrow 0$
while $\texttt{steps} < \texttt{max_steps}$ **do**
  $\texttt{env_steps}, \texttt{option_steps} \leftarrow 0$
  Receive initial state, s, from the environment
  while s is not terminal **or** $\texttt{env_steps} < \texttt{max_env_steps}$ **do**
    if $\texttt{env_steps} = 0$ **or** $\texttt{option_steps} > \texttt{max_option_steps}$ **or** $\sum_j \mathbf{b}_j > 0$ **then**
      $\texttt{option_steps} \leftarrow 0$
      if $\texttt{env_steps} > 0$ **then**
        Store transition $(s_{\texttt{init}}, g, \mathbf{b}_g, s)$ in D_m
        Store examples $s_t \,|\, t \in [\texttt{init}, \texttt{env_steps}]$ in positive buffers D_j^+
          where $\mathbf{b}_j = 1$ and negative buffers D_k^- where $\mathbf{b}_k = 0$
      end if
      $\texttt{init} \leftarrow \texttt{env_steps}$
      $\mathbf{f}^s \leftarrow f_\phi(z_\psi(s))$ ▷ Get predicted affordances
      $\mathbf{q} \leftarrow Q_m(s, \cdot\,; \Theta)$ ▷ Compute Q-values for all goals
      $\mathbf{q}_j \leftarrow -\infty \;\forall\, \mathbf{f}_j^s = 0$ ▷ Mask non-afforded goals
      $g_{\text{max}} \leftarrow \arg\max \mathbf{q}$ ▷ Get best *afforded* goal
      $g_{\text{aff}} \leftarrow Rand(j \,|\, \mathbf{f}_j^s = 1)$ ▷ Get random *afforded* goal
      $g_{\text{rand}} \leftarrow Rand(\mathcal{G})$ ▷ Get random goal
      $g \leftarrow g_{\text{aff}}$ w.p ϵ_{aff}, g_{rand} w.p ϵ_{mc}, else g_{max} ▷ ϵ^2-greedy goal selection
    end if
    $a_{\text{max}} \leftarrow \arg\max Q_c(s, \cdot\,; g, \Theta)$ ▷ Get best action – conditioned on goal
    $a_{\text{rand}} \leftarrow Rand(\mathcal{A})$ ▷ Get random action
    $a \leftarrow a_{\text{rand}}$ w.p ϵ_{c}, else a_{max} ▷ ϵ-greedy action selection
    $\texttt{steps}++, \texttt{option_steps}++, \texttt{env_steps}++$
    Send action a to the environment and receive next state s', rewards r, and milestones $\mathbf{b}$
    Store transition (s, a, r, s', g) in D_c
    $s \leftarrow s'$
    if $\texttt{steps} \,\%\, \texttt{update_freq} = 0$ **then**
      Sample batch of transitions from D_c and use it to update θ via Q-learning loss
    end if
    if $\texttt{steps} \,\%\, \texttt{meta_update_freq} = 0$ **then**
      Sample batch of transitions from D_m and use it to update Θ via Q-learning loss
    end if
    if $\texttt{steps} \,\%\, \texttt{margin_update_freq} = 0$ **then**
      Sample disjoint sets of positive examples from D_g^+ and update negative filtering margin
    end if
    if $\texttt{steps} \,\%\, \texttt{aff_update_freq} = 0$ **then**
      Sample positive and negative examples from D_g^+ and D_g^- respectively to update ϕ with binary cross entropy loss (ignoring any negatives with computed distance scores less than false negative filtering margin)
    end if
    if $\texttt{steps} \,\%\, \texttt{rep_update_freq} = 0$ **then**
      Sample anchor, positive, and negative states from D_c to update ψ via contrastive loss
    end if
  end while
end while

F IMPLEMENTATION DETAILS

All experiments are run with 5 random seeds each. We use 4 parallel environments for data collection with all methods. We do not include Noisy Nets or C51 in our implementation of Rainbow, as we do not find them to improve performance in our domains and significantly increase training time. Hyperparameters are shown in Table 2. All update frequency parameters are computed with respect to total environment steps (across parallel environments). Relative to the controller's Q-learning updates, all other algorithmic mechanisms are updated less frequently for the sake of efficiency, at rates which do not appear to affect the performance of our method. The meta-controller, affordance classifier, and the context representation are all trained every 10 controller updates. Since the optimal separation margin between false negatives and true negatives changes slowly over time, and computing a new margin is expensive, each classifier head's margin is updated every 150 controller updates.

Table 2: Hyperparameters used in HAL and baselines

Name	Description	Value
`adam_lr`	Adam learning rate (across all networks)	0.000625
`adam_eps`	Adam epsilon	0.00015
`batch_size`	Training batch size	32
λ	Discount factor	0.99
`targ_update`	Target network update frequency	10^3
`exp_steps`	Exploration steps before updates	400
ϵ_{c}	Epsilon used in controller's ϵ-greedy procedure	$0.5 \rightarrow 0.05$
ϵ_{mc}	Epsilon used in meta-controller's ϵ-greedy procedure	$0.2 \rightarrow 0.05$
ϵ_{aff}	Affordance eps. used to randomly select within mask	$0.8 \rightarrow 0.00$
`n_steps`	# of steps used for n-step returns	10
`max_option_steps`	Maximum option steps before timeout	50
`update_freq`	Freq. of controller weight updates	4
`meta_update_freq`	Freq. of meta-controller weight updates	40
`margin_update_freq`	Freq. that false negative filtering margins are updated	600
`aff_update_freq`	Freq. of affordance classifier weight updates	40
`rep_update_freq`	Freq. of context representation weight updates	40
σ	Standard deviation used for inter-context sampling	7.0
σ_{stoch}	σ used for edge stochasticity runs	2.0
`knn_n`	# of points used for sampling for KNN procedure	1000
`knn_k`	# of nearest neighbors used for KNN procedure	1
`fnf_conf`	Confidence value used for upper confidence bound	0.95
`fnf_perc`	Percentile value used for upper confidence bound	0.9