Exploring through Random Curiosity with General Value Functions

Anonymous Author(s)
Affiliation
Address
email

Abstract

Efficient exploration in reinforcement learning is a challenging problem commonly addressed through *intrinsic* rewards. Recent prominent approaches are based on *state novelty* or variants of *artificial curiosity*. However, directly applying them to partially observable environments can be ineffective and lead to premature dissipation of intrinsic rewards. Here we propose random curiosity with general value functions (RC-GVF), a novel intrinsic reward function that draws upon connections between these distinct approaches. Instead of only using only the current observation's novelty or a curiosity bonus for failing to predict precise environment dynamics, RC-GVF derives intrinsic rewards through the task of predicting temporally extended general value functions. We demonstrate that this improves exploration in a hard-exploration diabolical lock problem. Further, RC-GVF significantly outperforms previous methods in the absence of ground-truth episodic counts in the partially observable MiniGrid environments. Panoramic observations on MiniGrid further boost RC-GVF's performance such that it is competitive to baselines exploiting episodic counts.

1 Introduction

Efficient exploration in reinforcement learning (RL) is a challenging problem, especially in high-dimensional state spaces and sparse-reward environments [64, 2]. When reward feedback from the environment is sparse, an *extrinsic* reward-maximizing agent makes little progress until it stumbles upon a rewarding sequence of actions. This problem is commonly addressed by providing additional *intrinsic* reward to guide the agent's exploratory behaviour [45, 12, 39].

One class of prominent approaches rely on *state novelty*, where an intrinsic reward in the form of a 'novelty bonus' is awarded based on how often a state has been visited [59, 6]. More recent works have extended these approaches to high dimensional state spaces where tabular counts are inapplicable [7, 37, 10]. Another class of approaches is based on *artificial curiosity*, where agents are rewarded in proportion to the prediction errors or information gains of a predictive world model [48, 55]. Curiosity-based techniques have also been scaled up to handle larger state spaces [21, 39].

In general, expecting an agent to have access to the complete environment state is often an unrealistic assumption. In such *partially observable* settings [3, 25], observations may look alike in different states, and the benefit of approximate state novelty bonuses as intrinsic rewards is unclear. Consider the environment in Figure 1 where an agent is required to traverse a series of blue and white tiles, yet it is only able to observe the current tile it is standing on. The colours of the tiles alternate in a regular fashion until the end of the corridor, where there is a surprising sequence of consecutive blue tiles. Directly applying state novelty approaches may not be particularly meaningful in this case, as can be seen when using random network distillation (RND; [10]). Here, the agent receives a novelty bonus based on the error of its predictions about the output of a fixed randomly initialised neural network

Submitted to 36th Conference on Neural Information Processing Systems (NeurIPS 2022). Do not distribute.

applied to the current observation. As shown in the top panel of Figure 1, RND is unable to ascribe novelty when the state pattern changes later in the sequence and the intrinsic reward has vanished. Similarly, intrinsic rewards may also vanish prematurely for certain curiosity-based approaches when single-step dynamics are simple [38], while longer horizon predictions (as needed in the partially observable case) are susceptible to rapidly compounding errors during sequential rollouts [63].

Here we explore a connection between state novelty and artificial curiosity to address these limitations. We propose *random curiosity with general value functions (RC-GVF)* as a novel approach to generating intrinsic rewards. It takes inspiration from exploration through temporally extended experiments that summarise long observation sequences [49]. Our approach uses random general value functions (GVFs) [61] to pose questions about the cumulative future value of observation-dependent features. Specifically, we train an ensemble of predictors to minimise the temporal difference (TD) errors of the general value functions and derive an intrinsic reward based on the TD-errors and disagreements in the long-term predictions. The effective horizon of the prediction task can be controlled via the discount factor, where a zero discount can be related to state novelty with random network distillation (RND) [10]. We hypothesise that predicting information from an temporally extended horizon improves exploration in POMDPs and guards against premature vanishing of intrinsic rewards due to the increase in difficulty of the auxiliary task. Indeed, in our toy experiment of Figure 1 it can be see how RC-GVF manages to generate a spike of intrinsic reward at the end of the sequence.

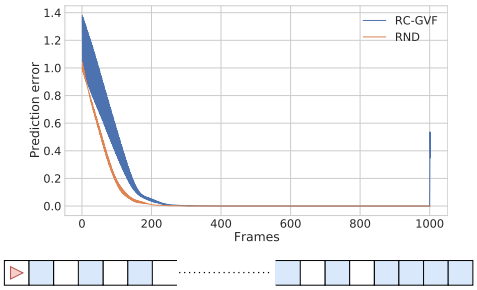


Figure 1: The alternating tile corridor environment. The agent (red triangle) observes the colour of the tile that it currently occupies (white or blue). At each time-step (frame), the agent moves one tile forward. Unlike our approach (RC-GVF), RND does not generate an intrinsic reward when encountering the surprising last few tiles (step 1000).

We evaluate our approach on sparse-reward and partially observable RL problems. Our results on a hard exploration diabolical lock problem [32] and the Minigrid suite of environments [13] reveal the benefits of considering extended horizon predictions in comparison to approaches that rely on immediate partial observations to generate exploration bonuses. Furthermore, existing baselines are heavily reliant on privileged information about episodic state-visitation counts from the simulator, which is commonly used to scale the exploration bonus. We demonstrate that RC-GVF succeeds in many environments *without* the use of such episodic counts.

2 Preliminaries

Reinforcement learning in POMDPs We consider the scenario where an agent interacts with a Partially Observable Markov Decision Process (POMDP) with time steps $t \in \mathbb{N}$, with environment states $S_t \in \mathcal{S}$, observations $O_t \in \mathcal{O}$, actions $A_t \in \mathcal{A}$, extrinsic rewards $R_e : \mathcal{S} \to [0, 1]$, and policies that map histories of different lengths to distributions over actions $\pi : \mathcal{H} \to \Delta(\mathcal{A})$ where $H_t = O_{1:t} \in \mathcal{H}$ [25]. The agent only observes O_t at time step t, which may not fully describe the MDP state, and thus it becomes necessary to condition the agent on the history H_t.

The learning objective is to find the optimal policy π^* that maximizes the expected discounted return

$$J(\pi) = \mathbb{E}_\pi \left[\sum_{k=0}^{\infty} \gamma^k R_e(S_k) \right], \tag{1}$$

where $\gamma \in [0, 1)$ is the discount factor and the expectation is over stochastic components in the environment and the policy.

Random Network Distillation In random network distillation (RND) [10] the agent receives a state novelty reward proportional to the error of making predictions $\hat{z}(o_t)$ where the targets are generated by a randomly initialized neural network $Z_\phi : \mathcal{O} \to \mathbb{R}^d$. The RND intrinsic reward for an observation is given by

$$R_i(o_t) = \| Z_\phi(o_t) - \hat{z}(o_t) \|_2. \tag{2}$$

RND-like error signals can be a simple way to obtain effective uncertainty estimates about targets at a given input, which could subsequently be used for exploration in RL or detecting out of distribution samples [14]. Beyond its simplicity, an appealing aspect of using RND is that it allows us to implicitly incorporate prior beliefs about useful rewards through the neural network architecture [34].

General Value Functions A general value function (GVF) [61] is defined by a policy π, a cumulant or pseudo-reward function $Z : \mathcal{O} \to \mathbb{R}$, and a discount factor $\gamma_z \in [0, 1)$. It can be expressed as

$$v_{\pi,z}(o) = \mathbb{E}_\pi \left[\sum_{k=0}^{\infty} \gamma_z^k Z(O_{t+k}) | O_t = o \right]. \tag{3}$$

General value functions extend the concept of predicting expected cumulative values to arbitrary signals beyond the reward. This can be viewed as 'answering' questions about cumulative quantities of interest under a particular policy π and discount factor γ_z. Predictions from GVFs have previously been used as features for state representation [43] or to specify auxiliary tasks that assist in shaping representations for the main task [23, 66].

3 Random Curiosity with General Value Functions

In the spirit of artificial curiosity [49], we are interested in predicting long-term outcomes in the environment under a particular policy as a means for exploration. Our approach, *RC-GVF*, rewards an agent for taking actions that lead to higher uncertainty about the future. However, instead of predicting the entire sequence of future states, we consider a set of random numeric questions about the environment and capture uncertainty about their outcome using general value functions (GVFs).

3.1 General value functions to predict the future

The central piece of RC-GVF is the prediction of temporally extended outcomes in the environment. This is different from only predicting a feature of the current state (as in state novelty exploration [59]) or dynamics models that predict the entire (sequence of) next observation(s) (as in early versions of artificial curiosity [48]). At time step t, the current observation o_t is mapped to a collection of pseudo-rewards $z_{t+1} \in \mathbb{R}^d$ which together with the policy and discount factor define a question that can be asked about the future: "what is the expected discounted cumulative sum of these pseudo-rewards under a given policy?". The answer to this question (i.e. the prediction target) is based on outcomes in the environment, as in Equation 3. In this paper, we investigate whether a set of random pseudo rewards are sufficient to drive exploration in this way.

Previously it was found that random features extracted by a neural network are often sufficient to capture useful properties of the input [41]. Similarly, neural network architectures can be used to express prior knowledge about useful features [65, 14]. To this end, we generate pseudo-rewards from a fixed and randomly initialised neural network $Z_\phi : \mathcal{O} \to \mathbb{R}^d$ with parameters ϕ that maps observations to pseudo-rewards. This choice also bypasses the difficult problem of discovering meaningful general value functions [66].

Training the GVF predictors Our exploration mechanism is to reward the agent for taking actions that generate previously unknown outcomes. To facilitate this, we train a separate (recurrent) neural network – which we call the *predictor* – to predict these values. Concretely, a predictor $\hat{v}_{\pi,z} : \mathcal{H} \to \mathbb{R}^d$ maps histories (of observations, actions, and pseudo rewards) to pseudo-values.

The predictor is trained on-policy, implying that the GVFs are evaluated under the current policy. One motivating factor for this choice is that it couples the prediction task to the current policy, thus creating an incentive to vary behaviour for additional exploration [18].

We use the (truncated) λ-return as the target for the predictor, which can be recursively expressed as

$$G_t^z(\lambda_z) = Z_{t+1} + \gamma_z(1 - \lambda_z)\hat{v}_{\pi,z}(H_{t+1}) + \gamma_z \lambda_z G_{t+1}^z(\lambda_z). \tag{4}$$

Here, $\lambda_z \in [0, 1]$ is the usual parameter that allows balancing the bias-variance trade off by interpolating between TD(0) and Monte Carlo estimates of the pseudo-return [58]. The predictor is trained to minimise the mean squared TD-error with the λ-return target. For convenience in notation, we will denote $G_t^z(\lambda_z)$ as G_t^z, despite its dependence on λ_z.

3.2 Disagreement and prediction error as intrinsic reward

To generate an intrinsic reward, a straightforward choice could be to consider the error between the temporal difference target (from Equation 4) and the predictor's output at the current observation:

$$L_{\text{TD}}(h_t) = \left[G_t^z - \hat{v}_{\pi,z}\left(h_t\right)\right]^2. \tag{5}$$

However, the presence of *aleatoric* uncertainty, is a problem that arises as a consequence of extending the horizon of the predictive task. From an exploration perspective, the agent should focus on the reducible *epistemic* uncertainty, and not the irreducible aleatoric uncertainty. Directly minimising Equation 5 with the predictor would ignore the inherent variance in the TD-target (due to stochasticity in the policy and environment), and thus using the prediction error of the GVF target as an intrinsic reward does not distinguish between aleatoric and epistemic uncertainty [15, 22].

Another way to recognize this is by decomposing the expected prediction error as described in Jain et al. [24]. The expected loss of a predictor $\hat{f}(\cdot)$ at an input o, $\mathbb{E}[L(t, \hat{f}(o))]$, can be split into epistemic (E) and aleatoric (A) components: $\int L(t, \hat{f}(o))dP(t|o) = E(\hat{f}, o) + A(o)$, where $P(t|o)$ is the conditional distribution over targets for input o and $L(t, \cdot)$ is a chosen loss function. The aleatoric uncertainty at input o, $A\left(o\right)$, is defined as the expected prediction error of a Bayes optimal predictor function. $E(\hat{f}, o)$ denotes the epistemic uncertainty of a predictor at o.

To overcome this issue with aleatoric uncertainty in RC-GVF, we propose to train an *ensemble* of predictors and utilise the variance across their predictions as a multiplicative factor on the prediction error. Concretely, we train K predictors $\hat{v}^k_{\pi,z}, k \in \{1, 2 \dots K\}$. The prediction target for each member of the ensemble is the same λ-pseudo-return (Equation 4) by using bootstrapped values from that member's predictions. Using the ensemble of predictors, the intrinsic reward is given by

$$R_i(o_t) = \sum_{j=1}^{d} \left(\mathbb{E}[L^k_{\text{TD}}(h_t)] \odot \mathbb{V}[\hat{v}^k_{\pi,z_j}\left(h_t\right)]\right)_j \tag{6}$$

$$= \sum_{j=1}^{d} \left[\frac{1}{K}\sum_{k=1}^{K}\left(G_t^{z_j} - \hat{v}^k_{\pi,z_j}\left(h_t\right)\right)^2\right] \cdot \left[\frac{1}{K-1}\sum_{k=1}^{K}\left(\bar{v}_{\pi,z_j}\left(h_t\right) - \hat{v}^k_{\pi,z_j}\left(h_t\right)\right)^2\right], \tag{7}$$

where $\odot$ corresponds to element-wise multiplication. In this formulation, even when prediction error remains, the exploration bonus will vanish when the predictors converge to the same expectation.

3.3 Effective horizon and relation to random network distillation

The effective horizon over which predictions are considered depends on the choice of the discount factor γ_z. It can be shown that for a horizon $H_{\gamma_z,\varepsilon} \in \mathbb{R}$, such that

$$H_{\gamma_z,\varepsilon} \geq \frac{\log\left(\frac{1}{\varepsilon(1-\gamma_z)}\right)}{\log\left(\frac{1}{\gamma_z}\right)}, \tag{8}$$

the discounted sum of (pseudo) rewards beyond this horizon is bounded by ε [27, 28].

From Equation 4 we can see that for the special case of $\gamma_z = 0$ and any choice of λ_z, we have $G_t^z = Z_{t+1} = Z_\phi\left(o_t\right)$. Note that in this case using the TD-error between the predictor and target is equivalent to intrinsic rewards provided by random network distillation (RND; Equation 2). Since the prediction targets are now deterministic, there is no issue of having aleatoric uncertainty, and a single predictor suffices (as opposed to using an ensemble).

4 Related work

Exploration In tabular RL, explicit *counts* for states or state-action pairs can be maintained to enable exploration and achieve efficient learning [56, 4]. Count-based bonuses have been scaled to larger state spaces through the use of density models, which provide pseudo-counts [7, 37]. State novelty bonuses are similarly inspired heuristics that provide a bonus based on estimated novelty of the visited state [10].

Perhaps the simplest way of implementing exploration through *'curiosity'* is to reward the policy for encountering transitions to states that surprise a learning predictor [48]. This is suitable for deterministic environments but it suffers from the 'noisy TV problem' in stochastic environments [52, 9]. To overcome this limitation, intrinsic rewards have been defined by *learning progress* (the first derivative of the prediction error) [47], *information gain* [55, 21], or *compression progress* [51]. Also compare such bonuses to pseudo-counts [7]. Alternatively, it is possible to mitigate sensitivity to noise by measuring prediction errors in a latent space [49, 39].

Our method (RC-GVF) is different from state count and novelty approaches in that it models temporally extended values beyond the current observation. It includes a state-novelty measure, RND [10], as a special case when the GVF discount factors are zero. Unlike most artificial curiosity approaches, RC-GVF does not model the entire environment dynamics, in line with the idea of conducting temporally extended experiments whose outcomes are abstract summaries (represented in latent variables) of long observation sequences [50]. We mitigate sensitivity to aleatoric uncertainty by measuring the disagreement of an *ensemble* of predictors, inspired by prior work (for single-step prediction models) [54, 40]. Ensembles for exploration have also been explored in the context of posterior sampling [57]. Bootstrapped-DQN [34] uses an ensemble of Q-value functions for a model-free interpretation of posterior sampling [35]. Unlike in our approach, these value functions are restricted to the original task rewards, and can not capture arbitrary pseudo-rewards.

General Value Functions Sutton et al. [61] proposed general value functions (GVFs) as an approach to represent predictive knowledge about the world. Closely related is the vector-valued adaptive critic [46] which predicts and controls cumulative values of special input vectors. Several works have studied the impact of using auxiliary value functions to improve representation learning in RL [23, 8]. Further, it was previously found that GVFs of randomly generated pseudo-rewards can also be useful for shaping and learning representations [31, 70] (see also related work on forecasts [43], TD-networks [60] and predictive state representations [29]). This can be viewed as 'answering' questions about cumulative quantities of interest under a particular policy π and discount factor γ_z. In our implementation, the predictor is an entirely separate network and thus GVF prediction can not be used to improve the agent's internal representation. Instead, we use the GVF prediction to derive a useful signal to guide exploration.

The discovery/selection of useful GVF 'questions' is an open problem [44]. Existing approaches learn questions related to optimizing performance on the main task [66, 26]. However, such an approach might not be suitable for sparse-reward environments. In our approach, we side-step the GVF discovery problem through the use of randomly generated pseudo-rewards and on-policy predictions.

5 Experiments

In this section we present an empirical evaluation of RC-GVF. First, we consider a hard exploration diabolical lock problem from the literature [32] and demonstrate the benefits of predicting beyond the immediate observation. We then proceed to experiments with the standard Minigrid suite of partially observable and procedurally generated environments, demonstrating how RC-GVF is able to outperform several strong baselines [18, 69].

5.1 Diabolical locks

The diabolical lock problem [32] is considered a difficult environment for exploration due to noisy high-dimensional observations, stochastic dynamics and anti-shaped rewards that deter the agent from finding the sparse optimal reward at the end of the lock. In the literature, RND is often shown to fail on these types of environments due to only considering the immediate future [32]. Due to RC-GVFs policy-conditioned predictions of future quantities, this task is instructive to demonstrate the qualitative advantages of our method and how this results in markedly different performance.

Table 1: Mean over 10 seeds and (min, max) of the farthest column reached (of $H = 100$) at different points on the diabolical lock problem.

Frames	5M	10M	20M
RC-GVF	52 (29, 77)	94 (52, 100)	95 (72, 100)
RND	17 (8, 28)	22 (10, 46)	32 (11, 60)

Environment details The environment consists of states organised in 3 rows $\{a, b, c\}$ and H columns from $\{1, 2, \dots H\}$ (see Figure 5 in Appendix A.1). In each episode, the agent is initialised in one of two possible starting states, either at a_1 or b_1. At each state the agent has L available actions, only one of which is 'good' and transitions to a 'good' state in the next column with equal probability. Taking the good action gives a negative (anti-shaped) reward of $-1/H$, except at the end of the lock (states a_H or b_H), where the sparse optimal reward of 10 is received. The remaining $L - 1$ actions at any state are 'bad', causing a deterministic transition to the 'dead' row c at the next column (zero reward). The agent never observes the state directly and is only given access to a high-dimensional noisy observation (details in Appendix A.1).

In our experiment, we consider a problem with horizon $H = 100$, $L = 10$, and observation noise $\sigma_o = 0.1$. This exploration problem is hard because the probability of reaching the optimal reward through a uniformly random policy is L^{-H} (10^{-100} in our instance). Further, the stochastic transitions from good states prevent a solution that relies on memorising a successful sequence of H actions independent of the state.

Implementation We use PPO in an actor-critic framework as the base agent and use 128 pseudo-rewards for RND and RC-GVF. For RC-GVF we set $\gamma_z = 0.6$ and use two prediction heads in the ensemble. Further details about the neural network architectures and training are in Appendix A.1.

Results Table 1 compares RND to RC-GVF in this environment. It can be seen how RC-GVF succeeds in completing the lock on most of the runs (7 out of 10), while the best run of RND only reaches 60% of the lock (and does not complete it). Indeed, once the agent takes an incorrect action and 'falls' into the bottom row, the future consequences (and thus, the GVFs) become highly predictable. By staying alive, the agent will encounter new observations and unpredictable transitions which appear interesting. This result is illustrative of RC-GVFs exploration capabilities as we will see next.

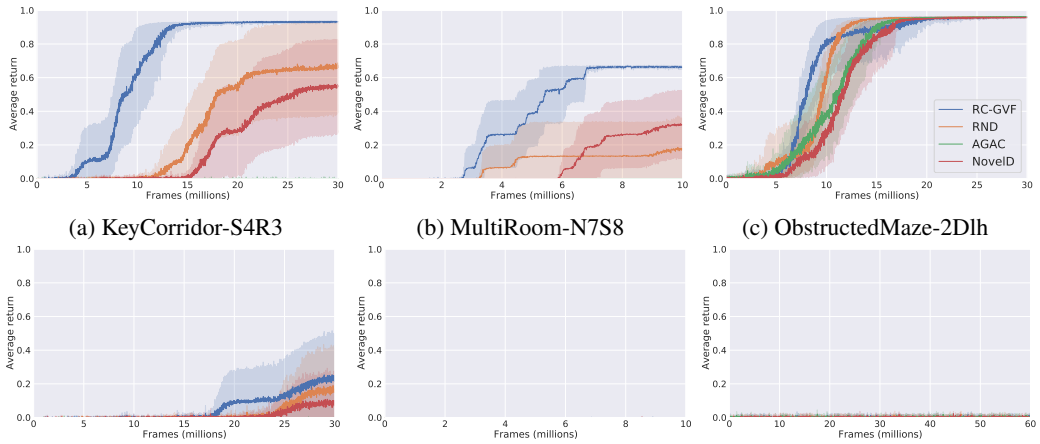
5.2 MiniGrid

We evaluate RC-GVF on procedurally generated environments from MiniGrid [13], which is a standard benchmark in the deep reinforcement learning literature for exploration [42, 11, 18, 69, 68, 38]. Exploration in these environments is challenging due to partial observability, extremely sparse rewards, and the procedural generation of mazes and objects.

Environment Details Broadly speaking, we will consider three classes of environments organised according to several difficulty levels. First, we study *MultiRoom-N7-S8* and *MultiRoom-N12-S10*, which are navigation tasks in a maze with seven and twelve rooms respectively. Next, we consider two levels of difficulty in *KeyCorridor-S4R3* and *KeyCorridor-S5R3*. Here, the agent needs to pick up a ball behind a locked door. Finally, we examine the *ObstructedMaze* set of environments where the agent has a similar task of picking up a ball behind a locked door, but keys are hidden in boxes (*ObstructedMaze-2Dlh*), and doors can be obstructed (*ObstructedMaze-2Dlhb*). The observations corresponds to an egocentric view of the cells in the front of the agent. Further details about the MiniGrid environments are available in Appendix A.2.

Implementation We compare RC-GVF to RND [10], AGAC [18], and NovelD [69]. We use Proximal Policy Optimization (PPO) [53] as our base agent for all approaches. The agent is trained to maximize the expected sum of a weighted combination of intrinsic and extrinsic rewards. At each time step t, the agent receives a reward $R_t = R_e(s_t) + \beta R_i(o_t)$, where $\beta \in \mathbb{R}_+$ balances the contribution of the extrisic $R_e(s_t)$ and intrinsic $R_i(o_t)$ rewards. For RC-GVF we set $\gamma_z = 0.6$, use two prediction heads in the ensemble of predictors and use 128 pseudo-rewards (same as for RND). Other important hyper-parameters, such as the intrinsic reward coefficient (β), entropy coefficient, and learning rate of the predictor are obtained via an extensive hyper-parameter search for all baselines (see Appendices C.2 and C.3 for details, including on our implementation of baselines.).

We present results averaged over 10 independent runs for each approach in every figure (solid line). An exception is the *ObstructedMaze-2Dlhb* environment for which we report results with 5 seeds. Unless mentioned otherwise, the shading indicates 95% bootstrapped confidence intervals.



(a) KeyCorridor-S4R3 (b) MultiRoom-N7S8 (c) ObstructedMaze-2Dlh

(d) KeyCorridor-S5R3 (e) MultiRoom-N12S10 (f) ObstructedMaze-2Dlhb

Figure 2: Average return of RC-GVF , RND and other baselines on the selected Minigrid environments (without ground-truth episodic counts for baselines). RC-GVF outperforms baselines in the absence of episodic counts. Some environments prove challenging for all approaches in this setting.

5.2.1 Egocentric observations

We will first consider the usual setting where the agent receives access to the egocentric observations from the environment. Importantly, we do not provide agents with access to privileged information about the environment in the form of so-called 'episodic counts'. This is different from several recent approaches that have been applied to MiniGrid, which incorporate these values as part of their intrinsic reward [42, 18, 69].

The use of episodic counts obtained through the simulator is problematic for solving exploration problems in a partially observable setting, since it tells the agent precisely how frequently it has been in each state. Indeed, the use of episodic counts *alone* can be sufficient for exploration in MiniGrid (Figure 6 in Appendix D.1). Meanwhile, there exists no good method for obtaining episodic counts in the absence of a simulator, as it is difficult to accurately estimate pseudo-counts from partial observations (eg. as in Figure 1). Details about the exact usage of episodic counts by baselines in their intrinsic reward formulation are provided in Appendix C.2.

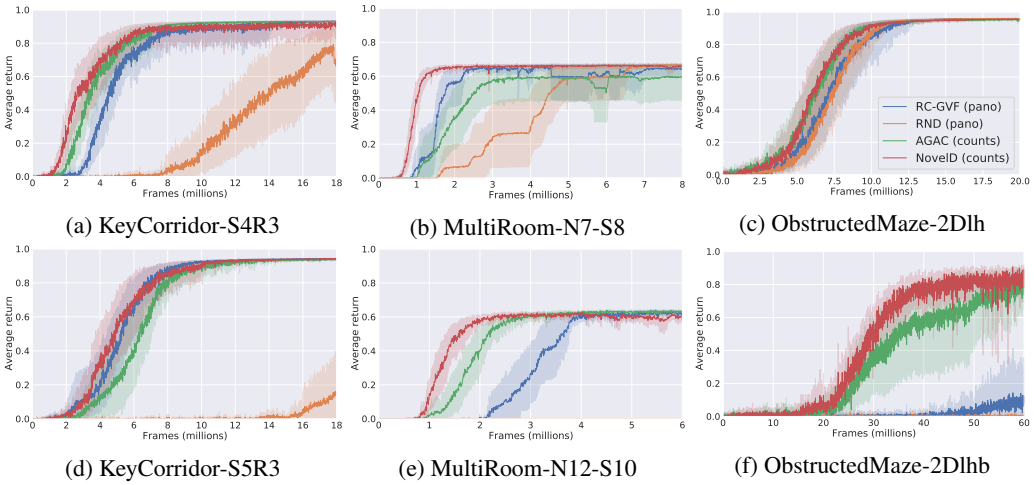
In Figure 2 we compare RC-GVF, RND, AGAC, and NovelD in the absence of episodic counts, while using egocentric observations. It can be seen that RC-GVF explores faster and succeeds more often than RND and the other baselines in the KeyCorridor-S4R3 environment and MultiRoom-N7-S8 environment. In comparison to RND and NovelD that utilise prediction errors in immediate random embeddings, it appears that RC-GVF benefits from extended horizon predictions of random pseudo-rewards. Meanwhile, AGAC only succeeds in ObstructedMaze-2Dlh, where all baselines perform similarly well. Finally, we observe that all approaches struggle with the most difficult level of considered environments (KeyCorridor-S5R3, MultiRoom-N12-S10 and ObstructedMaze-2Dlhb).

5.2.2 Panoramic observations

We now demonstrate how using episodic counts from the simulator is crucial to the success of the baselines. In Figure 3 it can be seen how AGAC and NovelD improve with episodic counts, and also solve the more difficult problems (KeyCorridor-S5R3, MultiRoom-N12-S10 and ObstructedMaze-2Dlhb).

Panoramic observations In order to increase performance of RC-GVF further, without introducing episodic counts, we investigate the use of augmented panoramic views as previously explored by Parisi et al. [38][1]. In the MiniGrid environments, the observation changes almost in its entirety when the agent changes the direction it faces. In contrast, moving to the next cell leads to fewer sudden changes in the observation.

[1]We verified in a separate experiment that incorporating episodic counts for RC-GVF similarly increases performance to meet the baseline results. However, since we believe that this constitutes privileged information that is not readily accessible outside of a simulator, we will not explore this direction further.



(a) KeyCorridor-S4R3 (b) MultiRoom-N7-S8 (c) ObstructedMaze-2Dlh

(d) KeyCorridor-S5R3 (e) MultiRoom-N12-S10 (f) ObstructedMaze-2Dlhb

Figure 3: Average return of RC-GVF and RND with panoramic observations. The performance of baselines (AGAC and NovelD) improves significantly with the inclusion of the episodic count component while RC-GVF (using panoramic observations) achieves similar performance without.

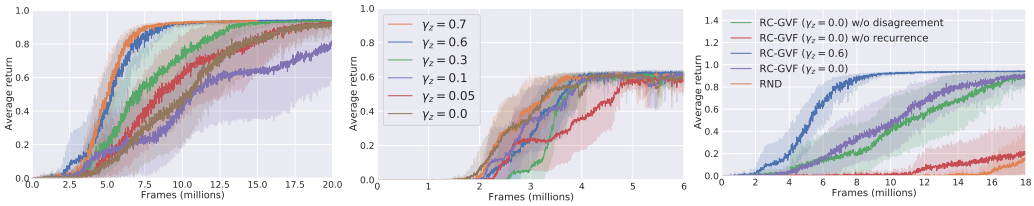
The lack of gradual changes to egocentric observations when rotating is a consequence of having four discrete angels for orientation $(0°, 90°, 180°, 270°)$, which may be an unrealistic depiction of how rotation affect observations for agents situated in the real world. As a consequence, any prediction error about future observations is dominated by predicting the outcome of turning compared to taking any of the other actions in the environment. To address this, prior work proposed to make the agent's observations invariant to rotation by augmenting the observation with all directional observations [38]. In effect, this assumes that the agent rotates $360°$ after moving to a cell, or alternatively that it is equipped with additional sensors on its sides and back. Similar to Parisi et al. [38], we will consider panoramic views only for generating intrinsic rewards, and egocentric observations for the base PPO agent.

In Figure 3, we demonstrate how RC-GVF with panoramic views and no privileged information about the underlying state of the MDP, can solve harder environments and is competitive with the baselines that use episodic counts in five out of the six settings. We see that RC-GVF with panoramic observations comfortably succeeds in the KeyCorridor-S5R3 and MultiRoom-N12-S10 environments where it was previously unsuccessful. RC-GVF did not succeed in solving the harder ObstructedMaze-2Dlhb within the given frames despite the inclusion of panoramic views. Figure 3 shows that the use of panoramic views does not make the exploration problem trivial; RND also uses panoramic views (and does not use episodic counts). It improves with panoramic views on KeyCorridor-S4R3 and MultiRoom-N7S8 but struggles with the harder instances.

5.3 Analysis

Changing the temporal prediction horizon We study the effect of changing the temporal prediction horizon by evaluating RC-GVF with different discount factors. Recall from Equation 8 how the discount factor can me mapped to the prediction horizon, which lets us estimate a lower bound on the horizon of about 11 time steps for $\gamma_z = 0.6$ with $\epsilon = 0.01$. In Figure 4 it can be seen how a larger prediction horizon is desirable for KeyCorridorS5R3. Compared to our default value of $\gamma_z = 0.6$, a short horizon using 0.3 reduces performance further, while discount factors closest to 0 yield the worst performance. In contrast, for MultiRoom-N12-S10, we find that most values of γ_z perform well. Comparing $\gamma_z = 0$ to RND shows how the use of recurrent networks and the variance term as measured using the ensemble of predictors contributes most to the performance of RC-GVF in this domain.

Ablation To better understand which of these components are contributing most to the success of RC-GVF, we consider the following additional ablations: (1) RC-GVF ($\gamma_z = 0$) without the variance term in Equation 6, and (2) RC-GVF ($\gamma_z = 0$) without the recurrent predictor. Figure 4c compares these variations to RC-GVF ($\gamma_z = 0$), RC-GVF ($\gamma_z = 0.6$), and RND. It can be seen that the inclusion of the history-conditioned recurrent predictor and the variance term individually contribute to the improved performance of RC-GVF.



(a) KeyCorridor-S5R3 (b) MultiRoom-N12-S10 (c) Ablation in KeyCorridor-S5R3

Figure 4: Analysis shows that: (a) a larger discount factor is useful in KeyCorridor-S5R3 (b) multiple discount factors perform well in MultiRoom-N12-S10, and (c) the variance term, recurrent predictor and discount factor contribute most to the performance of RC-GVF.

The improvement due to using the history conditioned recurrent predictor has a great impact on the performance of RC-GVF with $\gamma_z = 0$. We hypothesise that this effect arises from the previous pseudo-rewards available to the predictor, which might allow it to better handle input observations it was not explicitly trained on (which is often the case in procedurally generated environments). In support of this hypothesis, we observed that using a recurrent predictor with solely observations as inputs does not produce such an improvement(Figure 7 in Appendix D.2).

6 Limitations and Societal Impact

Limitations The incorporation of the current policy into the prediction task of GVF prediction can have benefits with regards to behavioural exploration. At the same time, it may also encourage over-exploration. Possible alternatives include off-policy variants or the use of explicitly policy-conditioned (general) value functions [20, 17].

In some situations it may be difficult to ascertain what is a good choice of the GVF discount factor γ_z, which effectively determines the prediction horizon length. The best choice may be problem-dependent and could further benefit from dynamic adjustment during learning [5, 33]. However, our results in Figures 2 and 3 indicate that a default of $\gamma_z = 0.6$ works well in many different settings.

A general limitation of curiosity-based exploration for task-specific RL is that more information is gathered than is necessary to solve the given task [36, 30]. Indeed, the space of potential GVFs is enormous. In the case of RC-GVF one could aim at focusing it by integrating task-specific information [62] or by considering predictions using a smaller set of policies that adequately cover state space [1].

Societal impact This paper does not focus on real-world applications of exploration and reinforcement learning methods and thus does not have a direct societal impact. In applications, advanced exploration methods may lead to unexpected policy behaviour, which could be mitigated by incorporating safety constraints for exploration [19].

7 Conclusion

We introduced RC-GVF, an exploration method that intrinsically rewards a reinforcement learning agent for its uncertainty about randomly generated, temporally extended outcomes of action sequences in an environment. Unlike state-novelty approaches, ours takes into account the multi-step future behaviours of policy and environment. Different from commonly used artificial curiosity approaches, we do not rely on model rollouts and do not need to predict all details of future observations.

On the diabolical lock problem [32] and the MiniGrid environments [13] we demonstrated that predicting abstract quantities from a temporally extended horizon improves exploration in POMDPs. Compared to recent methods such as AGAC [18] and NovelD [69] that rely on privileged episodic state-visitation counts, we demonstrate how RC-GVF achieves competitive results even when using only panoramic observations. Importantly, in the natural setting where episodic counts are not available, RC-GVF significantly outperforms all baseline methods.

Our approach can be generalized by moving beyond random pseudo-rewards, considering general value functions under a set of different policies [1], and introducing time or state-dependent discounting, which offer exciting avenues for future research.

References

[1] A. Agarwal, M. Henaff, S. Kakade, and W. Sun. Pc-pg: Policy cover directed exploration for provable policy gradient learning. *Advances in Neural Information Processing Systems*, 33: 13399–13412, 2020.

[2] S. Amin, M. Gomrokchi, H. Satija, H. van Hoof, and D. Precup. A survey of exploration methods in reinforcement learning. *arXiv preprint arXiv:2109.00157*, 2021.

[3] K. J. Åström. Optimal control of markov processes with incomplete state information. *Journal of mathematical analysis and applications*, 10(1):174–205, 1965.

[4] P. Auer, T. Jaksch, and R. Ortner. Near-optimal regret bounds for reinforcement learning. *Advances in neural information processing systems*, 21, 2008.

[5] A. P. Badia, B. Piot, S. Kapturowski, P. Sprechmann, A. Vitvitskyi, Z. D. Guo, and C. Blundell. Agent57: Outperforming the atari human benchmark. In *International Conference on Machine Learning*, pages 507–517. PMLR, 2020.

[6] A. G. Barto and S. P. Singh. On the computational economics of reinforcement learning. In *Connectionist Models*, pages 35–44. Elsevier, 1991.

[7] M. Bellemare, S. Srinivasan, G. Ostrovski, T. Schaul, D. Saxton, and R. Munos. Unifying count-based exploration and intrinsic motivation. *Advances in neural information processing systems*, 29:1471–1479, 2016.

[8] M. Bellemare, W. Dabney, R. Dadashi, A. Ali Taiga, P. S. Castro, N. Le Roux, D. Schuurmans, T. Lattimore, and C. Lyle. A geometric perspective on optimal representations for reinforcement learning. *Advances in neural information processing systems*, 32, 2019.

[9] Y. Burda, H. Edwards, D. Pathak, A. J. Storkey, T. Darrell, and A. A. Efros. Large-scale study of curiosity-driven learning. In *7th International Conference on Learning Representations*, 2019.

[10] Y. Burda, H. Edwards, A. J. Storkey, and O. Klimov. Exploration by random network distillation. In *7th International Conference on Learning Representations*, 2019.

[11] A. Campero, R. Raileanu, H. Küttler, J. B. Tenenbaum, T. Rocktäschel, and E. Grefenstette. Learning with amigo: Adversarially motivated intrinsic goals. *arXiv preprint arXiv:2006.12122*, 2020.

[12] N. Chentanez, A. Barto, and S. Singh. Intrinsically motivated reinforcement learning. *Advances in neural information processing systems*, 17, 2004.

[13] M. Chevalier-Boisvert, L. Willems, and S. Pal. Minimalistic gridworld environment for openai gym. `https://github.com/maximecb/gym-minigrid`, 2018.

[14] K. Ciosek, V. Fortuin, R. Tomioka, K. Hofmann, and R. E. Turner. Conservative uncertainty estimation by fitting prior networks. In *8th International Conference on Learning Representations, ICLR*, 2020.

[15] A. Der Kiureghian and O. Ditlevsen. Aleatory or epistemic? does it matter? *Structural safety*, 31(2):105–112, 2009.

[16] L. Espeholt, H. Soyer, R. Munos, K. Simonyan, V. Mnih, T. Ward, Y. Doron, V. Firoiu, T. Harley, I. Dunning, et al. Impala: Scalable distributed deep-rl with importance weighted actor-learner architectures. In *International Conference on Machine Learning*, pages 1407–1416. PMLR, 2018.

[17] F. Faccio, L. Kirsch, and J. Schmidhuber. Parameter-based value functions. In *9th International Conference on Learning Representations*, 2021.

[18] Y. Flet-Berliac, J. Ferret, O. Pietquin, P. Preux, and M. Geist. Adversarially guided actor-critic. In *9th International Conference on Learning Representations*, 2021.

[19] J. Garcıa and F. Fernández. A comprehensive survey on safe reinforcement learning. *Journal of Machine Learning Research*, 16(1):1437–1480, 2015.

[20] J. Harb, T. Schaul, D. Precup, and P.-L. Bacon. Policy evaluation networks. *arXiv preprint arXiv:2002.11833*, 2020.

[21] R. Houthooft, X. Chen, Y. Duan, J. Schulman, F. De Turck, and P. Abbeel. Vime: Variational information maximizing exploration. *Advances in Neural Information Processing Systems*, 29: 1109–1117, 2016.

[22] E. Hüllermeier and W. Waegeman. Aleatoric and epistemic uncertainty in machine learning: An introduction to concepts and methods. *Machine Learning*, 110(3):457–506, 2021.

[23] M. Jaderberg, V. Mnih, W. M. Czarnecki, T. Schaul, J. Z. Leibo, D. Silver, and K. Kavukcuoglu. Reinforcement learning with unsupervised auxiliary tasks. *arXiv preprint arXiv:1611.05397*, 2016.

[24] M. Jain, S. Lahlou, H. Nekoei, V. Butoi, P. Bertin, J. Rector-Brooks, M. Korablyov, and Y. Bengio. Deup: Direct epistemic uncertainty prediction. *arXiv preprint arXiv:2102.08501*, 2021.

[25] L. P. Kaelbling, M. L. Littman, and A. R. Cassandra. Planning and acting in partially observable stochastic domains. *Artificial intelligence*, 101(1-2):99–134, 1998.

[26] A. Kearney, A. Koop, J. Günther, and P. M. Pilarski. Finding useful predictions by meta-gradient descent to improve decision-making. *arXiv preprint arXiv:2111.11212*, 2021.

[27] M. Kearns, Y. Mansour, and A. Y. Ng. A sparse sampling algorithm for near-optimal planning in large markov decision processes. *Machine learning*, 49(2):193–208, 2002.

[28] L. Kocsis and C. Szepesvári. Bandit based monte-carlo planning. In *European conference on machine learning*, pages 282–293. Springer, 2006.

[29] M. Littman and R. S. Sutton. Predictive representations of state. *Advances in neural information processing systems*, 14, 2001.

[30] X. Lu, B. Van Roy, V. Dwaracherla, M. Ibrahimi, I. Osband, and Z. Wen. Reinforcement learning, bit by bit. *arXiv preprint arXiv:2103.04047*, 2021.

[31] C. Lyle, M. Rowland, G. Ostrovski, and W. Dabney. On the effect of auxiliary tasks on representation dynamics. In *International Conference on Artificial Intelligence and Statistics*, pages 1–9. PMLR, 2021.

[32] D. Misra, M. Henaff, A. Krishnamurthy, and J. Langford. Kinematic state abstraction and provably efficient rich-observation reinforcement learning. In *International conference on machine learning*, pages 6961–6971. PMLR, 2020.

[33] T. Moskovitz, J. Parker-Holder, A. Pacchiano, M. Arbel, and M. Jordan. Tactical optimism and pessimism for deep reinforcement learning. *Advances in Neural Information Processing Systems*, 34, 2021.

[34] I. Osband, C. Blundell, A. Pritzel, and B. Van Roy. Deep exploration via bootstrapped dqn. *Advances in neural information processing systems*, 29, 2016.

[35] I. Osband, B. Van Roy, and Z. Wen. Generalization and exploration via randomized value functions. In *International Conference on Machine Learning*, pages 2377–2386. PMLR, 2016.

[36] I. Osband, J. Aslanides, and A. Cassirer. Randomized prior functions for deep reinforcement learning. *Advances in Neural Information Processing Systems*, 31, 2018.

[37] G. Ostrovski, M. G. Bellemare, A. Oord, and R. Munos. Count-based exploration with neural density models. In *International conference on machine learning*, pages 2721–2730. PMLR, 2017.

[38] S. Parisi, V. Dean, D. Pathak, and A. Gupta. Interesting object, curious agent: Learning task-agnostic exploration. *Advances in Neural Information Processing Systems*, 34, 2021.

[39] D. Pathak, P. Agrawal, A. A. Efros, and T. Darrell. Curiosity-driven exploration by self-supervised prediction. In *International conference on machine learning*, pages 2778–2787. PMLR, 2017.

[40] D. Pathak, D. Gandhi, and A. Gupta. Self-supervised exploration via disagreement. In *International conference on machine learning*, pages 5062–5071. PMLR, 2019.

[41] A. Rahimi and B. Recht. Weighted sums of random kitchen sinks: Replacing minimization with randomization in learning. *Advances in neural information processing systems*, 21, 2008.

[42] R. Raileanu and T. Rocktäschel. RIDE: rewarding impact-driven exploration for procedurally-generated environments. In *8th International Conference on Learning Representations*, 2020.

[43] T. Schaul and M. Ring. Better generalization with forecasts. In *Twenty-Third International Joint Conference on Artificial Intelligence*, 2013.

[44] T. Schaul, H. van Hasselt, J. Modayil, M. White, A. White, P.-L. Bacon, J. Harb, S. Mourad, M. Bellemare, and D. Precup. The barbados 2018 list of open issues in continual learning. *arXiv preprint arXiv:1811.07004*, 2018.

[45] J. Schmidhuber. Making the world differentiable: On using fully recurrent self-supervised neural networks for dynamic reinforcement learning and planning in non-stationary environments. Technical Report FKI-126-90, TUM, 1990.

[46] J. Schmidhuber. Reinforcement learning in Markovian and non-Markovian environments. In D. S. Lippman, J. E. Moody, and D. S. Touretzky, editors, *Advances in Neural Information Processing Systems 3 (NIPS 3)*, pages 500–506. Morgan Kaufmann, 1991.

[47] J. Schmidhuber. Curious model-building control systems. In *Proceedings of the International Joint Conference on Neural Networks, Singapore*, volume 2, pages 1458–1463. IEEE press, 1991.

[48] J. Schmidhuber. A possibility for implementing curiosity and boredom in model-building neural controllers. In *Proc. of the international conference on simulation of adaptive behavior: From animals to animats*, pages 222–227, 1991.

[49] J. Schmidhuber. What's interesting? Technical Report IDSIA-35-97, IDSIA, 1997. ftp://ftp.idsia.ch/pub/juergen/interest.ps.gz; extended abstract in Proc. Snowbird'98, Utah, 1998; see also [50].

[50] J. Schmidhuber. Exploring the predictable. In A. Ghosh and S. Tsuitsui, editors, *Advances in Evolutionary Computing*, pages 579–612. Springer, 2002.

[51] J. Schmidhuber. Simple algorithmic principles of discovery, subjective beauty, selective attention, curiosity & creativity. In *International conference on discovery science*, pages 26–38. Springer, 2007.

[52] J. Schmidhuber. Formal theory of creativity, fun, and intrinsic motivation (1990–2010). *IEEE transactions on autonomous mental development*, 2(3):230–247, 2010.

[53] J. Schulman, F. Wolski, P. Dhariwal, A. Radford, and O. Klimov. Proximal policy optimization algorithms. *arXiv preprint arXiv:1707.06347*, 2017.

[54] P. Shyam, W. Jaśkowski, and F. Gomez. Model-based active exploration. In *International conference on machine learning*, pages 5779–5788. PMLR, 2019.

[55] J. Storck, S. Hochreiter, J. Schmidhuber, et al. Reinforcement driven information acquisition in non-deterministic environments. In *Proceedings of the international conference on artificial neural networks, Paris*, volume 2, pages 159–164. Citeseer, 1995.

[56] A. L. Strehl and M. L. Littman. An analysis of model-based interval estimation for markov decision processes. *Journal of Computer and System Sciences*, 74(8):1309–1331, 2008.

[57] M. Strens. A bayesian framework for reinforcement learning. In *ICML*, volume 2000, pages 943–950, 2000.

[58] R. S. Sutton. Learning to predict by the methods of temporal differences. *Machine learning*, 3 (1):9–44, 1988.

[59] R. S. Sutton. Integrated architectures for learning, planning, and reacting based on approximating dynamic programming. In *Machine learning proceedings 1990*, pages 216–224. Elsevier, 1990.

[60] R. S. Sutton and B. Tanner. Temporal-difference networks. In *Advances in neural information processing systems*, pages 1377–1384, 2005.

[61] R. S. Sutton, J. Modayil, M. Delp, T. Degris, P. M. Pilarski, A. White, and D. Precup. Horde: a scalable real-time architecture for learning knowledge from unsupervised sensorimotor interaction. In L. Sonenberg, P. Stone, K. Tumer, and P. Yolum, editors, *10th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2011), Taipei, Taiwan, May 2-6, 2011, Volume 1-3*, pages 761–768, 2011.

[62] R. S. Sutton, M. C. Machado, G. Z. Holland, D. S. F. Timbers, B. Tanner, and A. White. Reward-respecting subtasks for model-based reinforcement learning. *arXiv preprint arXiv:2202.03466*, 2022.

[63] E. Talvitie. Model regularization for stable sample rollouts. In *UAI*, pages 780–789, 2014.

[64] S. B. Thrun. Efficient exploration in reinforcement learning. 1992.

[65] D. Ulyanov, A. Vedaldi, and V. Lempitsky. Deep image prior. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 9446–9454, 2018.

[66] V. Veeriah, M. Hessel, Z. Xu, R. Lewis, J. Rajendran, J. Oh, H. van Hasselt, D. Silver, and S. Singh. Discovery of useful questions as auxiliary tasks. *arXiv preprint arXiv:1909.04607*, 2019.

[67] L. Willems. Rl starter files. `https://github.com/lcswillems/rl-starter-files`, 2017.

[68] D. Zha, W. Ma, L. Yuan, X. Hu, and J. Liu. Rank the episodes: A simple approach for exploration in procedurally-generated environments. *arXiv preprint arXiv:2101.08152*, 2021.

[69] T. Zhang, H. Xu, X. Wang, Y. Wu, K. Keutzer, J. E. Gonzalez, and Y. Tian. Noveld: A simple yet effective exploration criterion. *Advances in Neural Information Processing Systems*, 34, 2021.

[70] Z. Zheng, V. Veeriah, R. Vuorio, R. L. Lewis, and S. Singh. Learning state representations from random deep action-conditional predictions. *Advances in Neural Information Processing Systems*, 34, 2021.

Checklist

1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes]
   (b) Did you describe the limitations of your work? [Yes] See section 6.
   (c) Did you discuss any potential negative societal impacts of your work? [Yes] See section 6.
   (d) Have you read the ethics review guidelines and ensured that your paper conforms to them? [Yes]
2. If you are including theoretical results...
   (a) Did you state the full set of assumptions of all theoretical results? [N/A]
   (b) Did you include complete proofs of all theoretical results? [N/A]
3. If you ran experiments...

(a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? [Yes] Included in the supplementary material. An open-source implementation will be made available online.

(b) Did you specify all the training details (e.g., data splits, hyperparameters, how they were chosen)? [Yes] Implementation details and hyperparameters are provided in Appendices B and C

(c) Did you report error bars (e.g., with respect to the random seed after running experiments multiple times)? [Yes] We include 95% bootstrapped confidence intervals over 5 or 10 seeds for all of our results.

(d) Did you include the total amount of compute and the type of resources used (e.g., type of GPUs, internal cluster, or cloud provider)? [Yes] Details provided in Appendix C

4. If you are using existing assets (e.g., code, data, models) or curating/releasing new assets...

(a) If your work uses existing assets, did you cite the creators? [Yes]

(b) Did you mention the license of the assets? [Yes] Provided in Appendix A.2 with the description of the environment.

(c) Did you include any new assets either in the supplemental material or as a URL? [N/A]

(d) Did you discuss whether and how consent was obtained from people whose data you're using/curating? [N/A]

(e) Did you discuss whether the data you are using/curating contains personally identifiable information or offensive content? [N/A]

5. If you used crowdsourcing or conducted research with human subjects...

(a) Did you include the full text of instructions given to participants and screenshots, if applicable? [N/A]

(b) Did you describe any potential participant risks, with links to Institutional Review Board (IRB) approvals, if applicable? [N/A]

(c) Did you include the estimated hourly wage paid to participants and the total amount spent on participant compensation? [N/A]