REVISITING CURIOSITY FOR EXPLORATION IN PROCEDURALLY GENERATED ENVIRONMENTS

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ABSTRACT

Exploration under sparse rewards remains a key challenge in deep reinforcement learning. Recently, studying exploration in procedurally-generated environments draws increasing attention. Existing works generally combine *lifelong curiosity* and *episodic curiosity* as the intrinsic reward to encourage exploration. Though various lifelong and episodic curiosities have been proposed, the individual contributions of the two kinds of curiosities to improving exploration are barely investigated. To bridge this gap, we disentangle these two parts and conduct ablative experiments. We consider lifelong and episodic curiosities used in prior works, and compare the performance of all lifelong-episodic combinations on the commonly used MiniGrid benchmark. Experimental results show that only using episodic curiosity can match or surpass prior state-of-the-art methods. On the other hand, only using lifelong curiosity can hardly make progress in exploration. This demonstrates that episodic curiosity is more crucial than lifelong curiosity in boosting exploration. Moreover, we find through experimental analysis that the learned lifelong curiosity does not accurately reflect the novelty of states, which explains why it does not help much in improving exploration.

1 INTRODUCTION

How to encourage sufficient exploration in environments with sparse rewards is one of the most actively studied challenges in deep reinforcement learning (RL) (Bellemare et al., 2016; Pathak et al., 2017; Ostrovski et al., 2017; Burda et al., 2019a;b; Osband et al., 2019; Ecoffet et al., 2019; Badia et al., 2019). In order to learn exploration behavior that can generalize to similar environments, recent works (Raileanu & Rocktäschel, 2020; Zhang et al., 2020; Campero et al., 2021; Flet-Berliac et al., 2021; Zha et al., 2021) pay increasing attention to procedurally-generated environments (Chevalier-Boisvert et al., 2018; Chevalier-Boisvert, 2018; Küttler et al., 2020). Among them, approaches based on intrinsic reward (Raileanu & Rocktäschel, 2020; Zhang et al., 2020) have proven to be quite effective, which combine *lifelong* and *episodic* curiosity as the intrinsic reward to encourage exploration. The lifelong curiosity gradually discourages visits to states that have been visited many times across episodes, while episodic curiosity discourages revisiting the same states within an episode.

However, previous works (Raileanu & Rocktäschel, 2020; Zhang et al., 2020) mainly focus on designing lifelong curiosity while considering episodic curiosity only as a minor complement. The individual contributions of these two kinds of curiosities to improving exploration are barely investigated. To bridge this gap, we present in this work a comprehensive empirical study to reveal their contributions.

Through extensive experiments on the commonly used MiniGrid benchmark (Chevalier-Boisvert et al., 2018), we ablatively study the effect of lifelong and episodic curiosity on boosting exploration. Specifically, we use the lifelong and episodic curiosities considered in prior works (Pathak et al., 2017; Burda et al., 2019b; Raileanu & Rocktäschel, 2020; Zhang et al., 2020), and compare the performance of all lifelong-episodic combinations, in environments with and without extrinsic rewards. Surprisingly, we find that only using episodic curiosity, the trained agent can match or surpass the performance of the one trained by using lifelong-episodic combination; in contrast, only using lifelong curiosity makes little progress in exploration. Such observations suggest that the episodic curiosity is the more crucial ingredient of the intrinsic reward for efficient exploration.

Furthermore, we experimentally analyze why lifelong curiosity does not offer much help in improving exploration. Specifically, we find that randomly permuting the lifelong curiosity within a batch does not cause significant performance drop. Additionally, the learned lifelong curiosity assigns similar values to both novel and familiar states. These observations demonstrate that the lifelong curiosity does not accurately reflect the novelty of states, explaining its ineffectiveness.

We also compare the performance of only using episodic curiosity to other state-of-the-art methods including RIDE (Raileanu & Rocktäschel, 2020), BeBold (Zhang et al., 2020), AGAC (Flet-Berliac et al., 2021) and RAPID (Zha et al., 2021). We find simply using episodic curiosity outperforms the others by large margins.

In summary, our work makes following contributions:

- We conduct a comprehensive study on the lifelong and episodic curiosity in exploration and find that the episodic curiosity overlooked by previous works is actually the more important ingredient for efficient exploration in procedurally-generated environments.
- We analyze why lifelong curiosity does not contribute much and find that it is unable to accurately reflect the novelty of states.
- We show that simply using episodic curiosity can serve as a very strong baseline outperforming current state-of-the-art methods by large margins. This finding would be inspiring for future works on designing and rethinking the intrinsic rewards.

2 BACKGROUND

2.1 NOTATIONS

We consider a single agent Markov Decision Process (MDP) described by a tuple $(\mathcal{S}, \mathcal{A}, r, p, \gamma)$. $\mathcal{S}$ denotes the state space and $\mathcal{A}$ denotes the action space. At time t the agent observes state $s_t \in \mathcal{S}$ and takes an action $a_t \in \mathcal{A}$ by following a policy $\pi : \mathcal{S} \to \mathcal{A}$. The environment then yields a reward signal r_t sampled from the reward function $r(s_t, a_t)$. Next state observation $s_{t+1} \in \mathcal{S}$ is sampled according to the transition distribution function $p(s_{t+1}|s_t, a_t)$. The goal of the agent is to learn an optimal policy π^* that maximizes the expected cumulative reward:

$$\pi^* = \arg\max_{\pi \in \Pi} \mathbb{E}_{p,\pi} \sum_{t=0}^{\infty} \gamma^t r_t \tag{1}$$

where Π denotes the policy space and $\gamma \in [0, 1)$ is the discount factor.

Following previous curiosity-driven approaches (Pathak et al., 2017; Burda et al., 2019b; Raileanu & Rocktäschel, 2020; Zhang et al., 2020), we consider that at each timestep the agent receives some intrinsic reward r_t^i in addition to the extrinsic reward r_t^e. The intrinsic reward is designed to capture the agent's curiosity about the states, via quantifying how different the states are compared to those already visited. r_t^i can be computed for any transition tuple (s_t, a_t, s_{t+1}). The agent's goal then becomes maximizing the weighted sum of intrinsic and extrinsic rewards, *i.e.*,

$$r_t = r_t^e + \beta r_t^i \tag{2}$$

where β is a hyperparameter for balancing the two rewards. We may drop the subscript t to refer to the corresponding reward as a whole rather than the reward at timestep t.

2.2 TWO PARTS OF THE INTRINSIC REWARD

For procedurally-generated environments, recent works (Raileanu & Rocktäschel, 2020; Zhang et al., 2020) form the intrinsic reward as the multiplication of two parts:

$$r_t^i = r_t^{\text{lifelong}} \cdot r_t^{\text{episodic}}, \tag{3}$$

a lifelong curiosity r^{lifelong} that gradually discourages visits to states that have been visited many times across episodes, and an episodic curiosity r^{episodic} that discourages revisiting the same states within an episode. r^{lifelong} is learned and updated throughout the whole training process and r^{episodic} is reset at the beginning of each episode.

However, these recent works (Raileanu & Rocktäschel, 2020; Zhang et al., 2020) mainly focus on designing better lifelong curiosity while considering the episodic curiosity only as a part of minor importance in their methods. In this work, we find that the episodic curiosity is actually the more essential one for encouraging exploration. For experiments and discussions in the following sections, we consider 4 choices of r^{lifelong} and 2 choices of r^{episodic} used in prior works, and introduce them below.

ICM Pathak *et al*. (Pathak et al., 2017) introduce a lifelong curiosity based on a learned state representation $f_{\text{emb}}(s)$. Such representation ignores the aspects of the environment that have little impact upon the agent, and is obtained by training inverse and forward dynamic models. The forward dynamic model $f_{\text{fw}}(f_{\text{emb}}(s_t), a_t)$ takes current state representation $f_{\text{emb}}(s_t)$ and action a_t as inputs, and is trained to predict next state representation $f_{\text{emb}}(s_{t+1})$. The inverse dynamic model $f_{\text{inv}}(f_{\text{emb}}(s_t), f_{\text{emb}}(s_{t+1}))$ takes current and next state representations as inputs, and is trained to predict the action a_t. For a transition tuple (s_t, a_t, s_{t+1}), the lifelong curiosity is defined as the prediction error of the forward model:

$$r_t^{\text{ICM}} = \frac{1}{2}\|f_{\text{fw}}(f_{\text{emb}}(s_t), a_t) - f_{\text{emb}}(s_{t+1})\|_2. \tag{4}$$

RIDE Built upon ICM, Raileanu *et al*. (Raileanu & Rocktäschel, 2020) propose a novel lifelong curiosity encouraging the agent to take actions that have large impact on the state representation. Similarly, they train inverse and forward dynamic models. The difference is that, for a transition tuple (s_t, a_t, s_{t+1}), the lifelong curiosity is now defined as the change in state representation:

$$r_t^{\text{RIDE}} = \|f_{\text{emb}}(s_t) - f_{\text{emb}}(s_{t+1})\|_2. \tag{5}$$

RND Burda *et al*. (Burda et al., 2019b) propose to train a state embedding network $f(s)$ to predict the output of another state embedding network $\hat{f}(s)$ with fixed random initialization. The prediction error is expected to be higher for novel states dissimilar to the ones $f(s)$ has been trained on. Therefore, for a transition tuple (s_t, a_t, s_{t+1}), the prediction error is used as the lifelong curiosity:

$$r_t^{\text{RND}} = \|f(s_{t+1}) - \hat{f}(s_{t+1})\|_2. \tag{6}$$

BeBold Built upon RND, Zhang *et al*. (Zhang et al., 2020) give a lifelong curiosity that encourages the agent to explore beyond the boundary of explored regions. For a transition tuple (s_t, a_t, s_{t+1}), the lifelong curiosity is defined as the clipped difference of RND prediction error between s_t and s_{t+1}:

$$r_t^{\text{BeBold}} = \max(0, \|f(s_{t+1}) - \hat{f}(s_{t+1})\|_2 - \|f(s_t) - \hat{f}(s_t)\|_2). \tag{7}$$

Episodic visitation count Raileanu *et al*. (Raileanu & Rocktäschel, 2020) discount their proposed lifelong curiosity with episodic state visitation counts. Concretely, for a transition tuple (s_t, a_t, s_{t+1}), the episodic curiosity is computed as

$$r_t^{\text{ep_count}} = \frac{1}{\sqrt{N_{ep}(s_{t+1})}} \tag{8}$$

where $N_{ep}(s)$ denotes the number of visits to state s in the current episode.

Episodic first visits Compared with the above episodic curiosity, Zhang *et al*. (Zhang et al., 2020) take a more aggressive strategy: the agent only receives the lifelong curiosity when it visits the state for the first time in an episode. That is, for a transition tuple (s_t, a_t, s_{t+1}), the episodic curiosity is computed as

$$r_t^{\text{ep_visit}} = \mathbb{1}(N_{ep}(s_{t+1}) = 1), \tag{9}$$

where $\mathbb{1}(\cdot)$ denotes an indicator function.

3 Disentangling the Intrinsic Reward

As discussed above, the intrinsic reward for procedurally-generated environments can be disentangled into a lifelong curiosity term and an episodic curiosity term. In this section, we conduct extensive experiments on MiniGrid benchmark (Chevalier-Boisvert et al., 2018) to study their individual

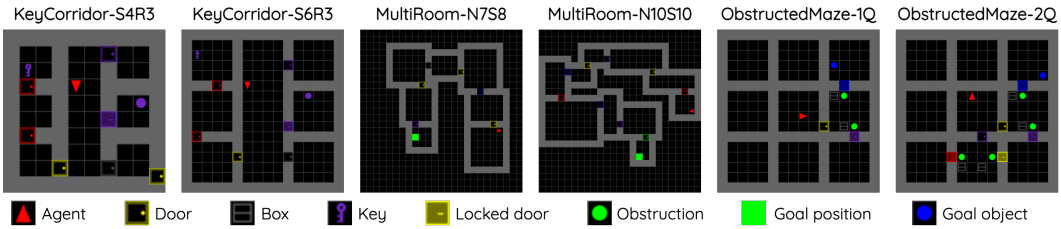

Figure 1: The 6 hard-exploration environments in MiniGrid used for our experiments.

contributions to improving exploration. To this end, we ablatively compare different lifelong-episodic combinations under two settings: sparse extrinsic reward on accomplishing the task and pure exploration without extrinsic reward (Section 3.2). We find that episodic curiosity is more important for efficient exploration, while lifelong curiosity does not help much. Then, in Section 3.3, we also compare the approach of using only episodic curiosity to other state-of-the-art methods. Finally, we analyze the reason why the learned lifelong curiosity does not help improve exploration.

3.1 Setup

Environments Following previous works (Raileanu & Rocktäschel, 2020; Zhang et al., 2020; Campero et al., 2021; Zha et al., 2021; Flet-Berliac et al., 2021) on exploration in procedurally-generated environments, we use the MiniGrid benchmark (Chevalier-Boisvert et al., 2018), which runs fast and hence is suitable for large-scale experiments. As shown in Figure 1, we use 3 commonly used hard-exploration tasks in MiniGrid:

- `KeyCorridor`: The task is to pick up an object hidden behind a locked door. The agent has to explore different rooms to find the key for opening the locked door.
- `MultiRoom`: The task is to navigate from the first room, through a sequence of rooms connected by doors, to a goal in the last room. The agent must open the door in order to enter next room.
- `ObstructedMaze`: The task is to pick up an object hidden behind a locked door. The key is now hidden in a box. The agent has to find the box and open it to get the key. Besides, the agent needs to move the obstruction in front of the locked door.

The suffixes denote different configurations (*e.g.*, `N7S8` for `MultiRoom` refers to 7 rooms of size no larger than 8). For each task, we choose 2 representative configurations from those used in previous works, in order to reduce the computational burden.

In MiniGrid, the agent receives a partial view of the grid as observation and choose from 7 actions: turn left, turn right, move forward, pick up an object, drop an object, toggle an object (*e.g.*, open or close a door) and done. The agent obtains a non-zero reward only when it reaches the goal position or picks up the goal object. This extrinsic reward is defined as $r_t^e = 1 - 0.9t/t_{\text{max}}$ where t corresponds to the number of steps taken and t_{max} is the maximum episode length. Accomplishing the tasks requires sufficient exploration and completion of some nontrivial subroutines (*e.g.*, pick up keys, open doors). More details about the environments and tasks are deferred to Appendix.

Training details For RL learning algorithm, we find that IMPALA (Espeholt et al., 2018; Küttler et al., 2019) used in previous works is too time-consuming and requires a lot of CPU resources. Therefore, to make the computational cost manageable, we use Proximal Policy Optimization (PPO) (Schulman et al., 2017) to train the policy, which is also a high-performing actor-critic algorithm but easier and more efficient to run on a single machine than IMPALA.

Following previous works (Raileanu & Rocktäschel, 2020; Zhang et al., 2020; Campero et al., 2021; Flet-Berliac et al., 2021), we use convolutional neural networks to process the input observation (see Appendix for network architectures). The neural networks are optimized with Adam (Kingma & Ba, 2015). For the number of training frames, we follow the same configuration in (Zhang et al., 2020). All of our experiments can be run on a single machine with 8 CPUs and a Titan X GPU. Details about the computation cost are included in Appendix.

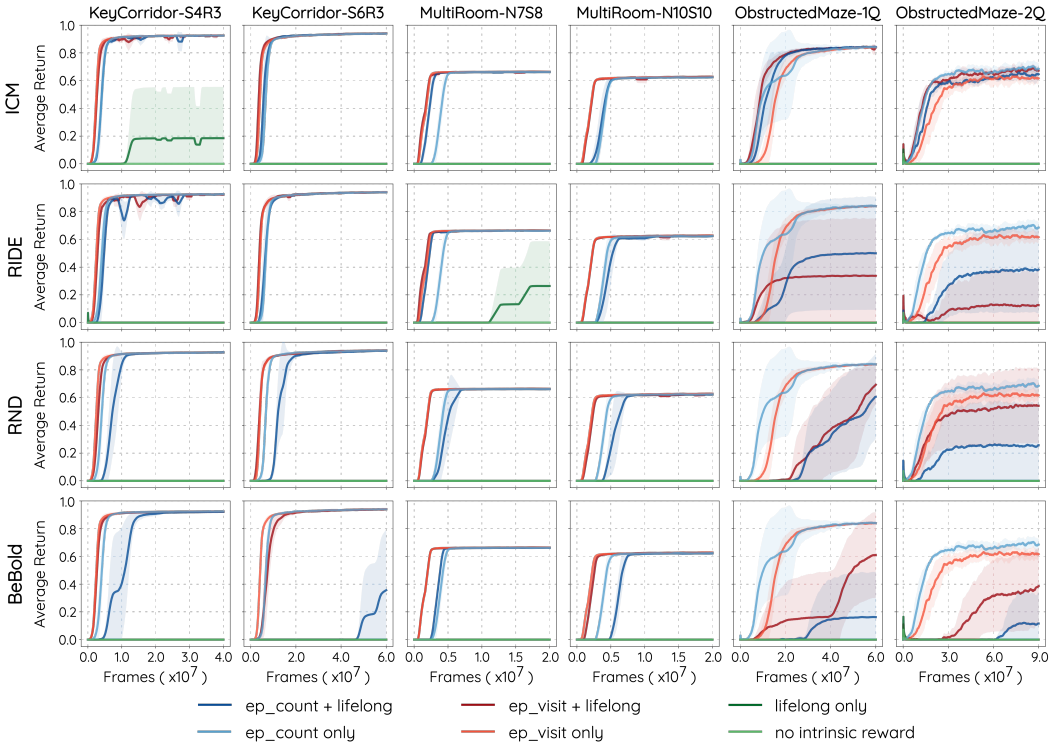

Figure 2: Performance of different combinations of lifelong and episodic curiosity on 6 hard exploration environments in MiniGrid. Note that simply using episodic curiosity can achieve top performance among all combinations. Best viewed in color.

Hyperparameters and evaluation One critical hyperparameter in intrinsic-reward-based approaches is the coefficient β that balances intrinsic and extrinsic rewards (see Eqn. equation 2). Varying the value of β will have large impact on the performance. Thus for fair comparison, we search β for each experiment and present the results with best β. Detailed configurations about hyperparameters are included in Appendix. As in prior works, we use training curves for performance comparison. When applicable, the training curves are averaged over 5 runs and the standard deviations are plotted as shaded areas. The curves are smoothed following the same procedure in (Raileanu & Rocktäschel, 2020). We also include testing results of trained agents in Appendix.

3.2 Individual contributions of episodic and lifelong curiosities

In this section, we ablatively study how episodic and lifelong curiosities improve exploration with and without extrinsic reward (*i.e.*, goal-reaching and pure exploration). On the MiniGrid environments, we compare the exploration performance of 15 lifelong-episodic combinations: $\{r^{\text{ICM}}, r^{\text{RIDE}}, r^{\text{RND}}, r^{\text{BeBold}}, \text{None}\} \times \{r^{\text{ep_count}}, r^{\text{ep_visit}}, \text{None}\}$. Here "None" refers to not using lifelong or episodic curiosity. If both are not used, then it reduces to vanilla PPO without intrinsic rewards. For the goal-reaching task, the extrinsic reward is sparse and only provided when the agent chieves the goal. Exploration ability is measured by how fast the agent can learn to achieve high average return on 6 environments introduced in Section 3.1. For the pure exploration setting, we train agents on `MultiRoom` environments without providing the extrinsic reward when agents reaching the goal. `MultiRoom` environments consist of several consecutive rooms connected by doors and the agent starts from the first room (see Figure 1). To explore the environment, the agent needs to open each door and navigate to different rooms. Thus, we can easily use the average number of explored rooms within an episode as a proxy for quantifying the exploration ability. Here we use `MultiRoom-N7S8` and `MultiRoom-N10S10` which have 7 and 10 rooms respectively.

Figure 2 shows the results of exploration with extrinsic rewards. We can see that only using episodic curiosity can match or surpass the performance of combining lifelong and episodic curiosity. In

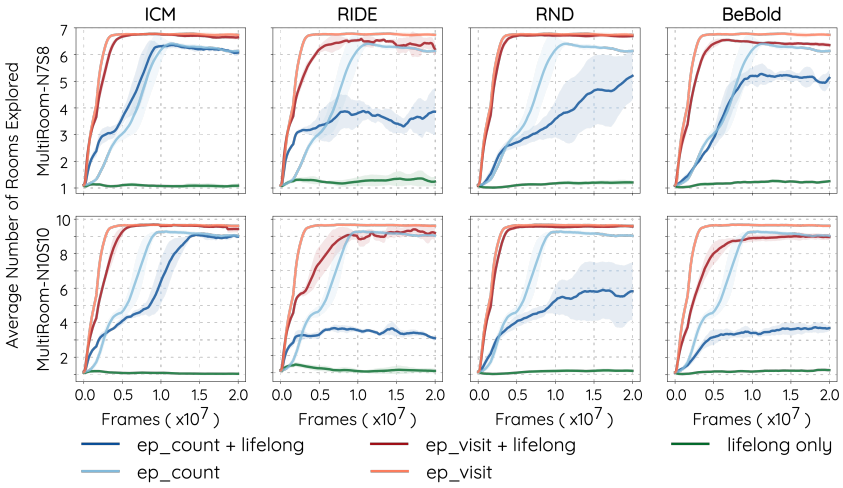

Figure 3: Average number of explored rooms without extrinsic rewards. Best viewed in color.

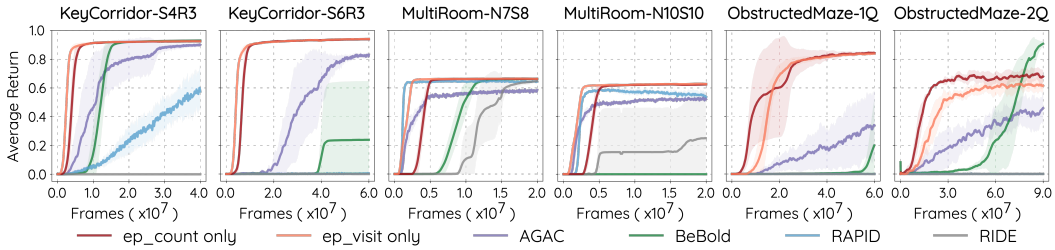

Figure 4: Comparison of only using episodic curiosity and other state-of-the-art methods. Best viewed in color.

contrast, only using lifelong curiosity hardly makes any progress. These observations show that the episodic curiosity is the key ingredient in the intrinsic reward for boosting exploration. Moreover, comparing the performance of different lifelong curiosities under the same episodic curiosity (*i.e.*, dark red or dark blue curves in each column of Figure 2), we find that recent proposed ones (r^{RIDE} and r^{BeBold}) do not exhibit clear advantages over previous ones (r^{ICM} and r^{RND}). Additionally, when comparing two episodic curiosities, we can see they perform comparably well for most environments. An exception is the `MultiRoom` environments, where $r^{\text{ep_visit}}$ performs slightly better. The reason might be that $r^{\text{ep_visit}}$ is more aggressive than $r^{\text{ep_count}}$ in discouraging revisits to visited states within an episode, pushing the agent to explore new rooms more quickly.

The results for the pure exploration setting are summarized in Figure 3. Again, when only using lifelong curiosity (*i.e.*, green curves), the agent fails to explore farther than the first 2 rooms. By contrast, it can quickly explore more rooms when augmented with episodic curiosity. This further demonstrates that episodic curiosity is more important than lifelong curiosity for efficient exploration. Moreoever, comparing $r^{\text{ep_visit}}$ and $r^{\text{ep_count}}$, we can see $r^{\text{ep_visit}}$ helps the agent explore faster. Such gap explains the performance difference between $r^{\text{ep_visit}}$ and $r^{\text{ep_count}}$ in `MultiRoom` environments with extrinsic reward (see Figure 2).

3.3 Comparison with state-of-the-art methods

From the previous section, it can be seen that only using episodic curiosity can achieve very competitive exploration performance. In this section, we compare its performance with other state-of-the-art approaches, including RIDE (Raileanu & Rocktäschel, 2020), BeBold (Zhang et al., 2020), RAPID (Zha et al., 2021) and AGAC (Flet-Berliac et al., 2021), under the sparse extrinsic reward setting. Among the 6 environments used, 1) for environments also used in these works, we contact the authors and obtain the original results reported in their papers; 2) for other environments, we

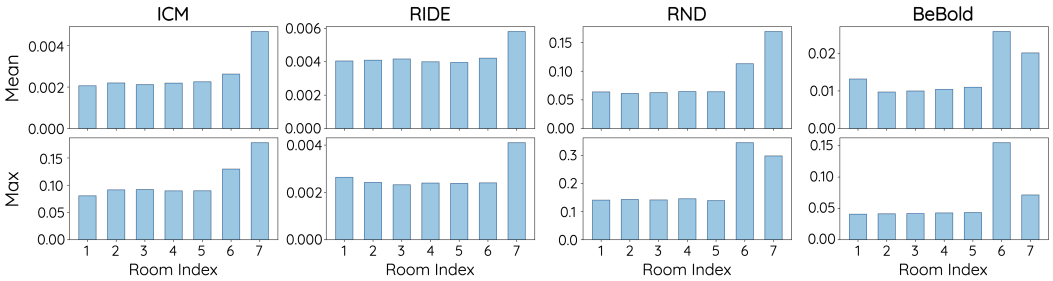

Figure 5: Mean and max of learned lifelong curiosity within each room in `MultiRoom-N7S8`, averaged over 100 different trajectories.

train agents using their official implementations (if publicly available) and the same hyperparameters reported in their papers. For BeBold, since the official code is not open-sourced, we try to reproduce it using the code base of RIDE (Raileanu & Rocktäschel, 2020) but fail to match the reported performance. Other training details are included in Appendix.

As Figure 4 shows, only using $r^{\text{ep_visit}}$ or $r^{\text{ep_count}}$ clearly outperforms other state-of-the-art methods, achieving high average return with fewer training frames. Specifically, in `KeyCorridor-S6R3`, `ObstructedMaze-1Q` and `ObstructedMaze-2Q`, it is almost an order of magnitude more efficient than previous methods. Note that the performance of BeBold in `ObstructedMaze-2Q` is directly taken from their paper but we cannot reproduce it. Compared to these sophisticated methods, simply using episodic curiosity as intrinsic reward serves as a very strong baseline. In Appendix, we also include the comparison results on other environments in MiniGrid benchmark.

3.4 WHY LIFELONG CURIOSITY DOES NOT HELP?

As shown in Section 3.2, lifelong curiosity contributes little to improving exploration. In this section, we experimentally analyze the reason for the ineffectiveness of lifelong curiosity.

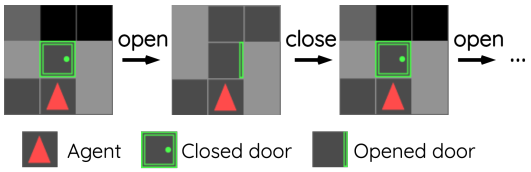

Figure 6: The agent gets stuck, keeping opening and closing the door.

To begin with, we examine the agent's learned behavior after training it with lifelong curiosity only. We find that the trained agent is often stuck in the first room and oscillating between two states. An example, as shown in Figure 6 is that the agent keeps opening and closing the first door (see the supplementary material for a video). A possible reason could be that the learned lifelong curiosity is not able to accurately reflect the novelty of states, making the agent receive higher cumulative (intrinsic) rewards from the opening-closing behavior than from exploring new rooms.

To verify this, we randomly permute the lifelong curiosity within a batch, and evaluate the resulting performance under sparse extrinsic rewards. If this random permutation does not lead to significant performance drop, then it indicates that the learned lifelong curiosity cannot accurately measure the novelty of states. From results in Figure 7, we can see that permutation does not have much negative impact on the performance for most cases, especially when using $r^{\text{ep_visit}}$ as episodic curiosity. This demonstrates that the learned lifelong curiosity does not accurately assign high values to novel states and low values to states the agent is familiar with.

In addition, we compare the learned lifelong curiosity in different rooms of `MultiRoom-N7S8` environment. We use `MultiRoom-N7S8` because it allows natural splits of states into different exploration stages, *i.e.*, splitting by rooms. As introduced before, the agent starts from the first room and farther rooms require more exploration to reach. We first generate trajectories that accomplish the tasks and cover all rooms. Then for transitions in each trajectory, we calculate the learned lifelong curiosity using models trained with r^{lifelong} only. Next, we calculate the mean and max of the learned lifelong curiosity within each room, and average the results across multiple trajectories.

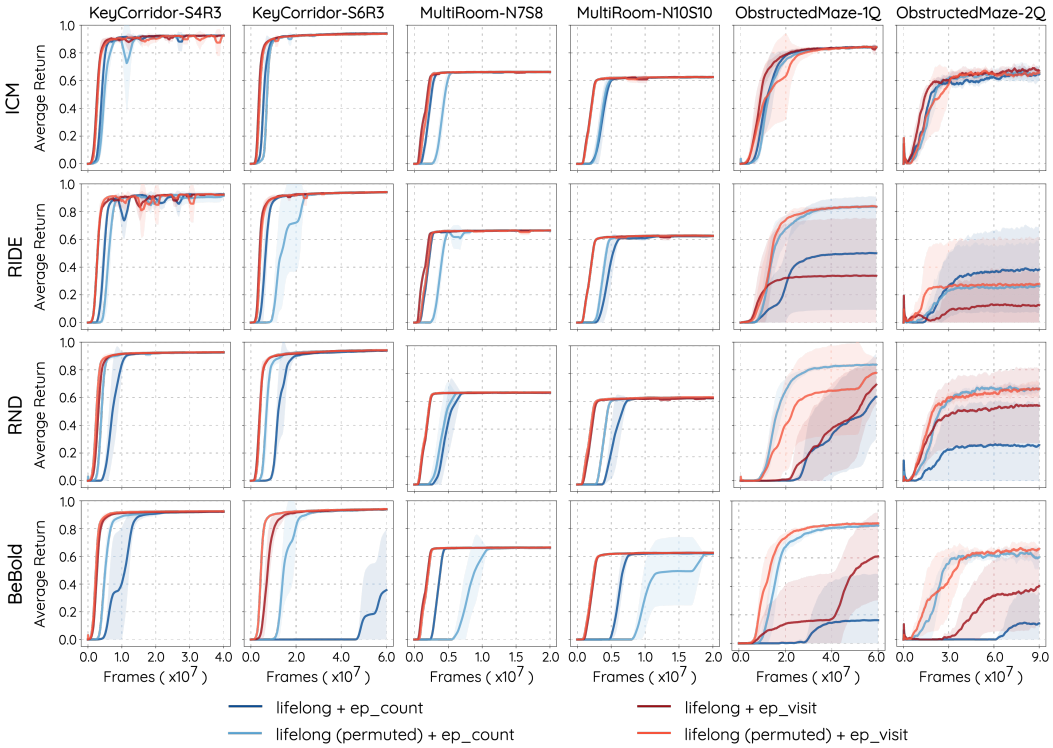

Figure 7: Performance of whether randomly permuting lifelong curiosity on 6 hard exploration environments in MiniGrid. Best viewed in color.

As shown in Figure 5, the first 5 rooms have similar mean or max lifelong curiosity. Therefore, compared to lingering in the first room, exploring new rooms does not bring the agent higher intrinsic reward. Though transitions in the last 2 rooms are novel to the agent (probably because the agent observes the goal), the agent can hardly explore these two rooms, since it does not have enough incentive to go beyond the first room. Such observation further demonstrates that the lifelong curiosity does not accurately reflect the novelty of different states.

4 Discussions

In the above experiments, we show that episodic curiosity solely is able to boost exploration in procedurally-generated environments, while lifelong curiosity struggles to make progress. Such intriguing observations provide new perspectives to think about intrinsic reward design as below.

Episodic curiosity in latent spaces In our experiments, gridworld is used as the testbed, in which the visitation count of a state can be easily obtained as it has discrete state spaces. Therefore, one may wonder whether episodic curiosity is able to generalize to high-dimensional continuous state spaces, where it is infeasible to calculate $r^{\text{ep_visit}}$ and $r^{\text{ep_count}}$. An alternative solution is to compute the episodic curiosity in a latent space (Badia et al., 2019). However, we empirically find that directly borrowing this solution from singleton environments to MiniGrid is ineffective, as latent embedding learning is much more challenging in procedurally-generated environments. For future research we may consider designing more powerful embedding models.

Lifelong curiosity in procedurally-generated environments Lifelong curiosity like RND (Burda et al., 2019b) and ICM (Pathak et al., 2017) has shown promising exploration performance in singleton environments (*e.g.*, Atari (Bellemare et al., 2013)), but become incapable in procedurally-generated environments (*e.g.*, MiniGrid). This counter-intuitive phenomenon further shows that quality of the learned latent embedding model plays an important role in the success of curiosity-driven methods. To make lifelong curiosity work again, one has to think about more generalizable representation learning

for RL. One possible direction is to design proper auxiliary or pretext tasks like self-supervised learning instead of just memorizing the environment.

5 RELATED WORKS

Exploration and intrinsic rewards In RL, the agent improves its policy via trial and error. Thus a steady stream of reward signals is critical for efficient learning. Since many practical scenarios come with sparse rewards, studying how to encourage exploration behavior in such environments attracts continuing attention. One of the most popular techniques is to provide intrinsic rewards (Schmidhuber, 2010), which can viewed as the agent's curiosity about particular states. In the absence of the extrinsic rewards from the environment, the agent's behavior will be driven by the intrinsic rewards. If we expect the agent to explore novel states, the curiosity can be designed to reflect how different the states are from those already visited. Bellemare *et al*. (Bellemare et al., 2016) measure such difference by the pseudo-counts of states derived from a density model. Later, Ostrovski *et al*. (Ostrovski et al., 2017) adopt a more advanced density model PixelCNN (Oord et al., 2016) to further improve the performance. Pathak *et al*. (Pathak et al., 2017) quantify the novelty of states by the prediction error of a learned forward dynamics model. Burda *et al*. (Burda et al., 2019b) train a network to predict the output of another fixed random network, and use the prediction error as the states novelty.

Episodic and lifelong curiosity Intrinsic reward in previous works (Pathak et al., 2017; Burda et al., 2019a;b) typically model a lifelong curiosity, which is updated throughout the whole learning process. Recent works under procedurally-generated environments (Raileanu & Rocktäschel, 2020; Zhang et al., 2020) additionally use some episodic curiosity to modulate the lifelong curiosity. However, they mainly focus on designing the lifelong curiosity. In this work we show that the episodic curiosity is actually the more important contributing factor in encouraging exploration. Our work is also related to recent progress on Atari (Badia et al., 2019; 2020), where more attention is paid to episodic curiosity. In their methods, the lifelong curiosity is only considered as an optional modulator. But their focus is on pushing the state-of-the-art performance on Atari games, while our work aims to compare the individual contributions of episodic and lifelong curiosity in procedurally-generated environments.

Generalization and procedurally-generated environments Recent papers (Rajeswaran et al., 2017; Zhang et al., 2018a;b;c; Machado et al., 2018; Song et al., 2020) find that deep RL is susceptible to overfitting to training environments and suffers poor generalization. One remedy is using procedurally-generated environments (Chevalier-Boisvert et al., 2018; Chevalier-Boisvert, 2018; Juliani et al., 2019; Cobbe et al., 2019; 2020), where each episode is randomly constructed but corresponds to the same task. In order to make progress in such environments, an agent must learn a generic policy that can generalize to novel episodes. Most previous works in exploration are also skeptical to overfitting issues, since they train and test on the same environment, such as *Montezuma's Revenge* in Atari (Bellemare et al., 2013) or *VizDoom* (Wydmuch et al., 2018). To investigate how exploration behavior can generalize to similar environments, Pathak *et al*. (Pathak et al., 2017) use different levels of *Super Mario Bros* (Paquette, 2018) for training and testing. To the same end, recent works (Raileanu & Rocktäschel, 2020; Campero et al., 2021; Zhang et al., 2020; Zha et al., 2021; Flet-Berliac et al., 2021) often use procedurally-generated environments to benchmark their methods.

6 CONCLUSIONS

Exploration is a long-standing and important problem in reinforcement learning, especially when the environments have sparse rewards. Curiosity-based intrinsic reward has been seen as a promising solution to address this issue. To encourage exploration in procedurally-generated environments, recent works combine lifelong curiosity and episodic curiosity as intrinsic rewards. However, how these two kinds of curiosities actually contribute to exploration is seldom comprehensively investigated. To answer this question, we conducted the first systematic empirical study by making exhaustive combinations of lifelong and episodic curiosities in environments with and without extrinsic reward signals. The results are counter-intuitive and intriguing: episodic curiosity itself is able to boost exploration and set new state-of-the-art. Our further investigation shows that the inability of lifelong curiosity roots in its ineffectiveness on distinguishing whether a state is novel or not. We believe our findings are inspiring for further work to better design intrinsic reward functions.

7 REPRODUCIBILITY STATEMENT

We describe the training details (*e.g.*, environment configurations, network architectures, hyperparameters) in Section 3.1 and the Appendix. To reproduce the results, we also include the source code in the supplementary material. The computation cost is provided in the Appendix.

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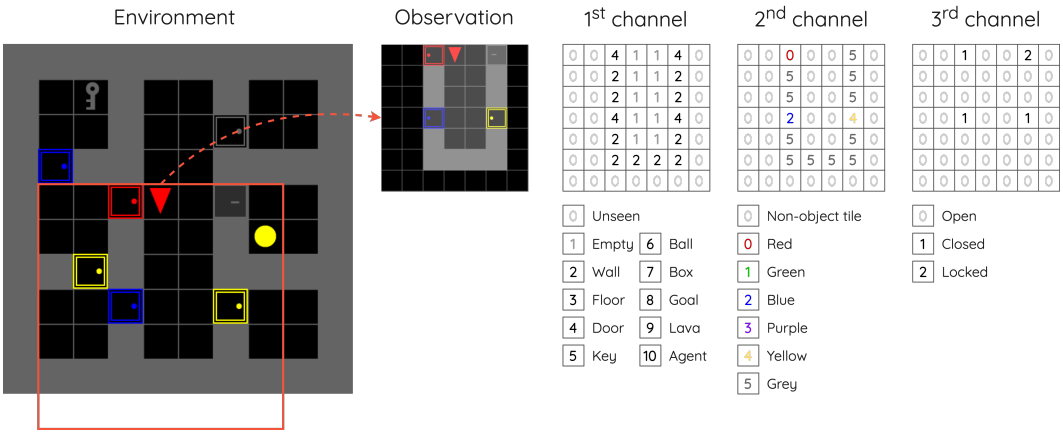

Figure 8: Observation encoding in MiniGrid environment. See text for details. Best viewed in color.

A Appendix

A.1 MiniGrid environment

MiniGrid (Chevalier-Boisvert et al., 2018) benchmark consists a suite of procedurally-generated gridworld environments. The gridworld is built with $N \times N$ tiles, where N varies across tasks. Each tile contains one or no object. The possible object types include wall, floor, lava, door, key, ball, box and goal.

Observation By default, the observation is an egocentric view of the environment, as shown in Figure 8. The agent can not see the world behind walls or closed doors. Specifically, the observation is compactly encoded as a $7 \times 7 \times 3$ array. The first channel encodes the object type, *e.g.*, wall, door. The second channel encodes the object color, *e.g.*, red, green. The third channel encodes the state, *e.g.*, door open, door closed.

Action In MiniGrid, there are 7 actions available for the agent: *turn left*, *turn right*, *move forward*, *pick up an object*, *drop an object*, *toggle* and *done*. The agent can change the direction it is currently facing by turning left or right. Taking the *move forward* action will move the agent one tile forward along its current direction. If moving forward causes collision (*e.g.*, running into walls or closed doors), the agent will remain the previous location. The agent can use the *toggle* action to open a closed door in front of it (or a locked one if the agent has the corresponding key). The *toggle* action can also be used to open a box. The *done* action is not necessary for the environments considered in this paper, but we still keep it in the action space following previous works.

Task As briefly introduced in Section 3.1, we consider 3 tasks in MiniGrid: `KeyCorridor`, `MultiRoom`, `ObstructedMaze`. Here we provide more details about these 3 tasks.

- `KeyCorridor` (Figure 9) The environment consists of a corridor and several rooms connecting to the corridor. The agent starts in the corridor and aims to pick up a goal object placed in one of the rooms. The door to this room (*i.e.*, the room with the goal) is locked. To open the locked door, the agent has to find the key that is placed in one of the rooms except the locked one. The configuration suffix is specified as `SxRy`, where `x` denotes the room size and `y` denotes the number of rows. Each row has 2 rooms, placed on each side of the corridor.
- `MultiRoom` (Figure 10) The environment consists of a sequence of rooms connected by closed doors. The agent starts in the first room and aims to reach the goal position in the last room. The configuration suffix is specified as `NxSy`, where `x` denotes the number of rooms and `y` denotes the maximum room size.
- `ObstructedMaze` (Figure 11) The environment consists of a 3×3 grid of rooms. In these 9 rooms, 1 is the center room, 4 are corner rooms and 4 are non-corner rooms. The doors connecting the center room and non-corner rooms are closed. The doors connecting corner

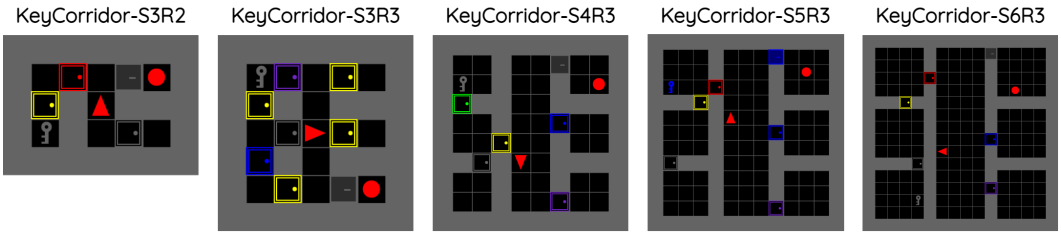

Figure 9: `KeyCorridor` environments.

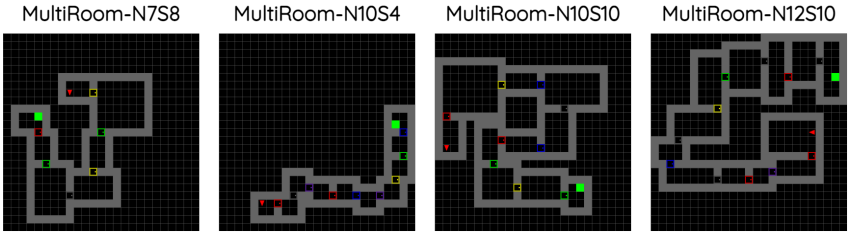

Figure 10: `MultiRoom` environments.

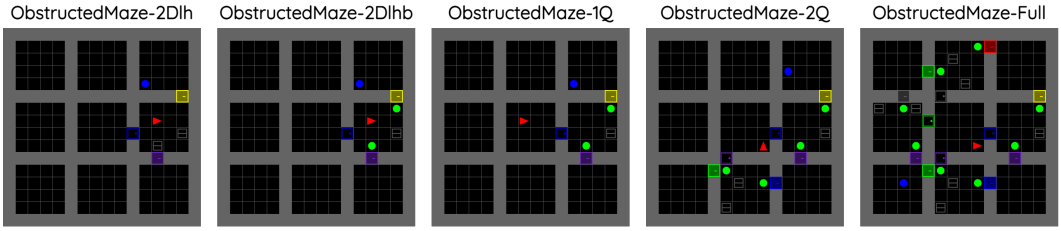

Figure 11: `ObstructedMaze` environments.

rooms and non-corner rooms are locked. The keys are placed in non-corner rooms. Depending on the configuration, the agent starts in the center room or non-corner rooms, and aims to pick up an goal object hidden in one of the corner rooms. The configuration suffix is more complex, so we only introduce commonly used ones and refer interested readers to the official GitHub repository[1].

- `2Dlh` The goal object is always hidden in the top right room. The keys to the corner rooms are hidden in boxes. The agent always starts in the middle right room.
- `2Dlhb` Compared to `2Dlh`, the difference is that locked doors are blocked by obstructions. The agent has to move these obstructions before unlocking the doors with keys.
- `1Q` Compared to `2Dlhb`, the difference is that the agent starts in the center room instead of the middle right one.
- `2Q` Compared to `1Q`, the difference is that the goal object is hidden in either the top right room or the bottom right room.
- `Full` Compared to `1Q`, the difference is that the goal object is hidden in one of the 4 corner rooms.

Episode length In these tasks, there is a limit on the maximum number of steps allowed in each episode, denoted as t_{max}. It varies from task to task, as summarized in Figure 12.

Reward When the agent achieves the goal, it receives an extrinsic reward r_t^e. This reward is computed based on the number of steps taken t and the maximum number of steps allowed t_{max}:

[1] https://github.com/maximecb/gym-minigrid

Task	MultiRoom						KeyCorridor					ObstructedMaze				
Suffix	N6S10	N7S4	N7S8	N10S4	N10S10	N12S10	S3R2	S3R3	S4R3	S5R3	S6R3	2Dlh	2Dlhb	1Q	2Q	Full
$t_{\max}$	120	140	140	200	200	240	270	270	480	750	1080	576	576	720	1584	3600
Frames	2e7	2e7	2e7	2e7	2e7	2e7	2e7	2e7	4e7	4e7	6e7	4e7	6e7	6e7	9e7	1e8
RIDE	✘	✔	✔	✔	✔	✔	✘	✔	✘	✘	✘	✔	✘	✘	✘	✘
BeBold	✔	✘	✔	✘	✘	✔	✘	✔	✔	✔	✔	✔	✔	✔	✔	✔
RAPID	✘	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✘	✘	✘	✘
AGAC	✘	✘	✘	✘	✔	✘	✘	✘	✔	✔	✘	✘	✔	✔	✔	✘

Figure 12: Different MiniGrid task configurations used in previous works.

$r_t^e = 1 - 0.9t/t_{\max}$. The agent is encouraged to reach the goal as fast as possible. Only the optimal path gives the highest reward.

A.2 Network architectures

For the policy and value network in PPO, we use a shared feature extractor and two separate heads (one policy head and one value head), as shown in Figure 13 (a). The feature extractor uses a convolutional neural network, similar to ones used in prior works (Raileanu & Rocktäschel, 2020; Zhang et al., 2020; Flet-Berliac et al., 2021). For r^{RND} and r^{BeBold}, the target and predictor networks use the architecture in Figrue 13 (b). For r^{ICM} and r^{RIDE}, the network architecture of the state embedding function f_{emb} is shown in Figrue 13 (b). The network architectures of the forward and inverse dynamic model are shown in Figrue 13 (c) and Figrue 13 (d) respectively.

A.3 Computation cost

As mentioned in Section 3.1, our experiments can run on a single machine with 8 CPUs and a Titan X GPU. Specifically, one run of an experiment (*e.g.*, training with $r^{\text{ICM}} + r^{\text{ep_count}}$) takes less than 600M GPU memory on a Titan X GPU. So, we can concurrently run several experiments on a single GPU. On average, training for 1e7 frames takes about 1.5 hour. The total wall-clock training time for all conducted experiments is roughly 4000 GPU hour.

A.4 Training details

We provide more training details for the comparison with other state-of-the-art methods in Section 3.3.

For RIDE (Raileanu & Rocktäschel, 2020), we obtain results on `MultiRoom-N7S8`, `MultiRoom-N10S10` from the authors, and rerun their released code[2] for other environments. For `KeyCorridor-S4R3` and `KeyCorridor-S6R3`, we use the same hyperparameters as `KeyCorridor-S3R3` provided in their paper. For `ObstructedMaze-1Q` and `ObstructedMaze-2Q`, we use the same hyperparameters as `ObstructedMaze-2Dlh`.

For AGAC (Flet-Berliac et al., 2021), we obtain results on `MultiRoom-N10S10`, `ObstructedMaze-1Q` and `ObstructedMaze-2Q` from the authors, and rerun their released code[3] for other environments. For hyperparameters, we use their default configurations.

For RAPID (Flet-Berliac et al., 2021), we obtain results on `MultiRoom-N7S8` and `MultiRoom-N10S10` from the authors, and rerun their released code[4] for other environments. For hyperparameters, we use their default configurations.

For BeBold (Zhang et al., 2020), we obtain the results on `KeyCorridor-S4R3`, `KeyCorridor-S6R3`, `MultiRoom-N7S8`, `ObstructedMaze-1Q` and `ObstructedMaze-2Q` from the authors. Since their code is not publicly released, we

[2]https://github.com/facebookresearch/impact-driven-exploration
[3]https://github.com/yfletberliac/adversarially-guided-actor-critic
[4]https://github.com/daochenzha/rapid

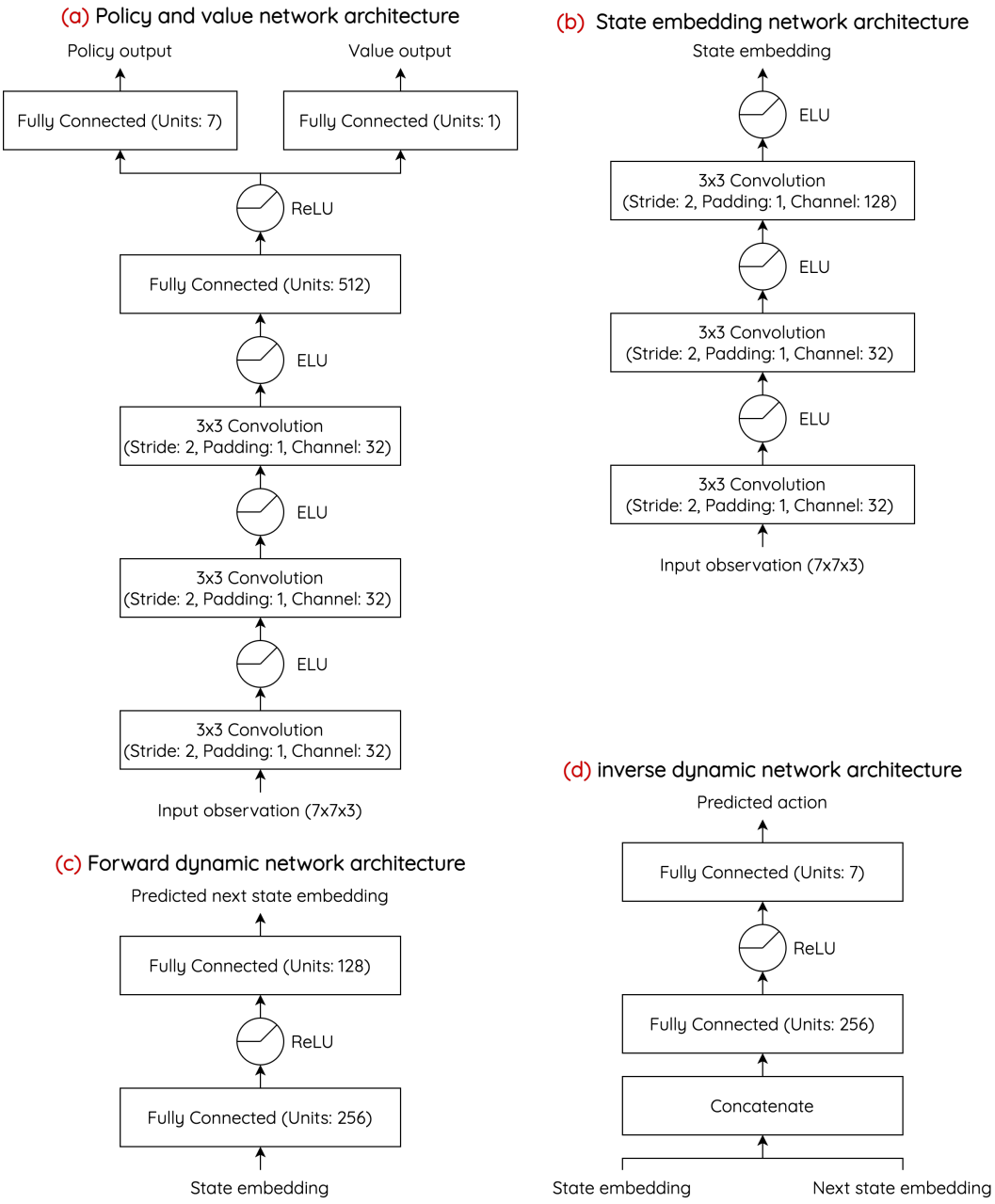

Figure 13: Network architectures.

reimplement it with the code base[5] of RIDE, and run experiments for `MultiRoom-N10S10` with the same hyperparameters as `MultiRoom-N12S10`.

A.5 Hyperparameters

For training the policy, we use the hyperparameters listed in Table 1. Generalized Advantage Estimation (GAE) (Schulman et al., 2016) is used to estimate the advantage. As mentioned in Section 3.1, we search the intrinsic reward coefficient β for each experiment. We start with a search range {5e-2, 1e-2, 5e-3, 1e-3}, and expand it until finding a locally best value or reaching 5e1 or 1e-5.

[5]https://github.com/facebookresearch/impact-driven-exploration

The best searched values for β are summarized in Figure 14, 15, 16, 17, 18. Here we showcase in Figure 19 that choosing an appropriate value for β is critical for the performance. Other results in the search (*i.e.*, using different β) will be made publicly available.

Table 1: Hyperparameters.

Number of parallel environments	128
Number of timesteps per rollout	128
PPO clip range	0.2
Discount factor γ	.99
GAE λ	.95
Number of epochs	4
Number of minibatches per epoch	8
Entropy bonus coefficient	0.01
Value loss coefficient	0.5
Advantage normalization	Yes
Gradient clipping (ℓ_2 norm)	0.5
Learning rate	5×10^{-4}
Total timesteps	See Figure 12
Forward dynamic loss coefficient	10
Inverse dynamic loss coefficient	0.1
RND loss coefficient	0.1

Experiments \ Environments	KeyCorridor		MultiRoom		ObstructedMaze	
	S4R3	S6R3	N7S8	N10S10	1Q	2Q
r^{ICM} only	1e-1	1e-1	1e-1	1e-1	1e-1	1e-1
r^{ICM} + $r^{\text{ep_count}}$	5e-1	5e-1	1e-1	1e-1	1e-1	1e-1
r^{ICM} + $r^{\text{ep_visit}}$	1e-1	5e-1	1e-1	1e-1	1e-1	1e-1
r^{ICM} (permuted) + $r^{\text{ep_count}}$	5e-1	1	5e-1	5e-1	1e-1	1e-1
r^{ICM} (permuted) + $r^{\text{ep_visit}}$	5e-1	5e-1	5e-1	5e-1	5e-2	5e-2

Figure 14: Best searched β values for experiments with r^{ICM}.

Experiments \ Environments	KeyCorridor		MultiRoom		ObstructedMaze	
	S4R3	S6R3	N7S8	N10S10	1Q	2Q
r^{RIDE} only	1e-1	1e-1	1e-1	1e-1	1e-1	1e-1
r^{RIDE} + $r^{\text{ep_count}}$	5e-1	5e-1	5e-2	5e-1	5e-2	5e-1
r^{RIDE} + $r^{\text{ep_visit}}$	5e-1	5e-1	1e-1	1e-1	5e-2	5e-2
r^{RIDE} (permuted) + $r^{\text{ep_count}}$	1	1	5e-1	5e-1	1e-1	1e-1
r^{RIDE} (permuted) + $r^{\text{ep_visit}}$	5e-1	5e-1	5e-1	5e-1	5e-2	1e-1

Figure 15: Best searched β values for experiments with r^{RIDE}.

Experiments \ Environments	KeyCorridor		MultiRoom		ObstructedMaze	
	S4R3	S6R3	N7S8	N10S10	1Q	2Q
r^{RND} only	1e-3	1e-3	1e-3	1e-3	1e-3	1e-3
r^{RND} + $r^{\text{ep_count}}$	5e-4	1e-3	5e-4	5e-4	1e-5	5e-5
r^{RND} + $r^{\text{ep_visit}}$	5e-3	5e-3	5e-3	5e-3	1e-5	5e-5
r^{RND} (permuted) + $r^{\text{ep_count}}$	1e-3	1e-3	1e-3	1e-3	1e-4	1e-4
r^{RND} (permuted) + $r^{\text{ep_visit}}$	5e-3	5e-3	5e-3	5e-3	1e-4	1e-4

Figure 16: Best searched β values for experiments with r^{RND}.

Experiments \ Environments	KeyCorridor		MultiRoom		ObstructedMaze	
	S4R3	S6R3	N7S8	N10S10	1Q	2Q
r^{BeBold} only	5e-3	5e-3	5e-3	5e-3	5e-3	5e-3
r^{BeBold} + $r^{\text{ep_count}}$	1e-2	1e-2	5e-2	1e-2	1e-3	5e-3
r^{BeBold} + $r^{\text{ep_visit}}$	1e-1	5e-2	5e-2	5e-2	5e-3	5e-3
r^{BeBold} (permuted) + $r^{\text{ep_count}}$	1e-1	1e-1	1e-2	5e-3	5e-3	5e-3
r^{BeBold} (permuted) + $r^{\text{ep_visit}}$	1e-1	1e-1	1e-1	1e-1	5e-3	1e-2

Figure 17: Best searched β values for experiments with r^{BeBold}.

Experiments \ Environments	KeyCorridor				MultiRoom				ObstructedMaze		
	S3R3	S4R3	S5R3	S6R3	N7S8	N10S4	N10S10	N12S10	2Dlh	1Q	2Q
$r^{\text{ep_count}}$ only	1e-3	1e-3	1e-3	1e-3	1e-3	1e-3	1e-3	1e-3	5e-5	5e-4	5e-4
$r^{\text{ep_visit}}$ only	5e-3	5e-3	5e-3	5e-3	5e-3	5e-3	5e-3	1e-3	5e-5	5e-5	5e-5

Figure 18: Best searched β values for experiments with episodic curiosity only.

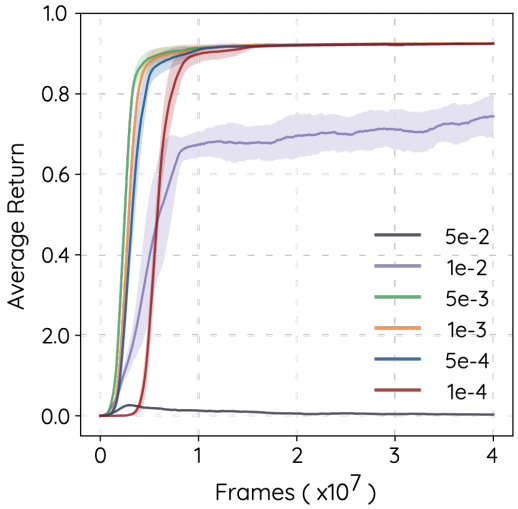

Figure 19: Performance of training with $r^{\text{ep_visit}}$ only on `KeyCorridorS4R3`, using different β.

A.6 ADDITIONAL RESULTS

A.6.1 FINAL TESTING PERFORMANCE OF TRAINED AGENTS

For completeness, we test the trained agent for 100 episodes and show the results in Table 2.

Table 2: Final testing performance of trained agents.

	KeyCorridor S4R3	KeyCorridor S6R3	MultiRoom N7S8	MultiRoom N10S10	ObstructedMaze 1Q	ObstructedMaze 2Q
$r^{\text{ep_count}}$ only	0.93±0.026	0.95±0.034	0.68±0.006	0.69±0.005	0.85±0.241	0.71±0.388
$r^{\text{ep_visit}}$ only	0.93±0.020	0.95±0.026	0.68±0.001	0.69±0.009	0.83±0.280	0.66±0.391
r^{ICM} only	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
$r^{\text{ICM}} + r^{\text{ep_count}}$	0.93±0.020	0.94±0.046	0.67±0.008	0.69±0.003	0.84±0.248	0.73±0.351
$r^{\text{ICM}} + r^{\text{ep_visit}}$	0.93±0.025	0.95±0.027	0.63±0.054	0.69±0.002	0.85±0.253	0.64±0.401
r^{RIDE} only	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
$r^{\text{RIDE}} + r^{\text{ep_count}}$	0.93±0.023	0.92±0.133	0.66±0.023	0.69±0.006	0.86±0.241	0.61±0.417
$r^{\text{RIDE}} + r^{\text{ep_visit}}$	0.93±0.022	0.95±0.023	0.43±0.022	0.69±0.005	0.79±0.322	0.0±0.0
r^{RND} only	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
$r^{\text{RND}} + r^{\text{ep_count}}$	0.93±0.032	0.93±0.099	0.56±0.100	0.69±0.005	0.83±0.227	0.61±0.408
$r^{\text{RND}} + r^{\text{ep_visit}}$	0.92±0.028	0.93±0.097	0.67±0.008	0.68±0.001	0.54±0.420	0.72±0.362
r^{BeBold} only	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
$r^{\text{BeBold}} + r^{\text{ep_count}}$	0.92±0.068	0.93±0.047	0.68±0.009	0.69±0.006	0.0±0.0	0.0±0.0
$r^{\text{BeBold}} + r^{\text{ep_visit}}$	0.93±0.024	0.94±0.033	0.66±0.022	0.69±0.015	0.73±0.309	0.60±0.395

A.6.2 COMPARISON TO STATE-OF-THE-ART METHODS ON OTHER ENVIRONMENTS IN MINIGRID

In addition to the comarison in Section 3.3, we provide results on following environments: `KeyCorridorS3R3`, `KeyCorridorS5R3`, `MultiRoomN10S4`, `MultiRoomN12S10`, `ObstructedMaze2Dlh`. The results in Figure 20 further demonstrates that $r^{\text{ep_count}}$ or $r^{\text{ep_visit}}$ can match or surpass other state-of-the-art methods.

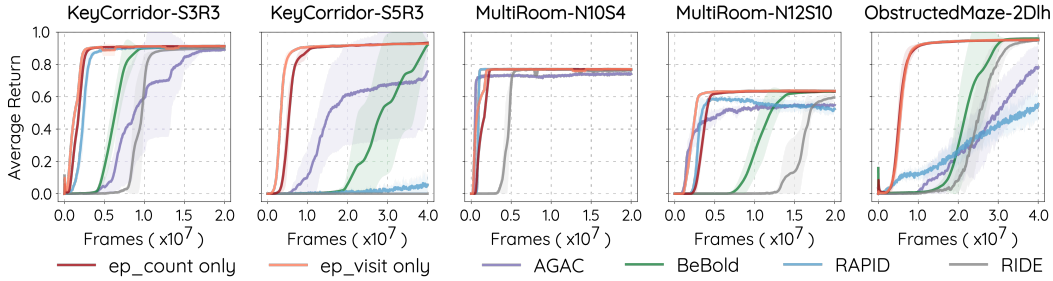

Figure 20: Comparison of only using episodic curiosity and other state-of-the-art methods on additional environments. Best viewed in color.