PLANNING GOALS FOR EXPLORATION

Anonymous authors
Paper under double-blind review

ABSTRACT

Dropped into an unknown environment, what should an agent do to quickly learn about the environment and how to accomplish diverse tasks within it? We address this question within the goal-conditioned reinforcement learning paradigm, by identifying how the agent should set its goals at training time to maximize exploration. We propose "Planning Exploratory Goals" (PEG), a method that sets goals for each training episode to directly optimize an intrinsic exploration reward. PEG first chooses goal commands such that the agent's goal-conditioned policy, at its current level of training, will end up in states with high exploration potential. It then launches an exploration policy starting at those promising states. To enable this direct optimization, PEG learns world models and adapts sampling-based planning algorithms to "plan goal commands". In challenging simulated robotics environments including a multi-legged ant robot in a maze, and a robot arm on a cluttered tabletop, PEG exploration enables more efficient and effective training of goal-conditioned policies relative to baselines and ablations. Our ant successfully navigates a long maze, and the robot arm successfully builds a stack of three blocks upon command. Website: `https://sites.google.com/view/exploratory-goals`

1 INTRODUCTION

Complex real-world environments such as kitchens and offices afford a large number of configurations. These may be represented, for example, through the positions, orientations, and articulation states of various objects, or indeed of an agent within the environment. Such configurations could plausibly represent desirable goal states for various tasks. Given this context, we seek to develop intelligent autonomous agents that, having first spent some time exploring an environment, can afterwards configure it to match commanded goal states.

The goal-conditioned reinforcement learning paradigm (GCRL) (Andrychowicz et al., 2017) offers a natural framework to train such goal-conditioned agent policies on the exploration data. Within this framework, we seek to address the central problem: **how should a GCRL agent explore its environment during training time so that it can achieve diverse goals revealed to it only at test time?** This requires efficient unsupervised exploration of the environment.

Exploration in the GCRL setting can naturally be reduced to the problem of setting goals for the agent during training time; the current GCRL policy, commanded to the right goals, will generate exploratory data to improve itself (Ecoffet et al., 2021; Nair et al., 2018b). Our question now reduces to **the goal-directed exploration problem: how should we choose exploration-inducing goals at training time?**

Prior works start by observing that the final GCRL policy will be most capable of reaching familiar states, encountered many times during training. Thus, the most direct approach to exploration is to set goals in sparsely visited parts of the state space, to directly expand the set of these familiar states (Ecoffet et al., 2021; Pong et al., 2019; Pitis et al., 2020). While straightforward, this approach suffers from several issues in practice. First, the GCRL policy during training is not yet proficient at reaching arbitrary goals, and regularly fails to reach commanded goals, often in uninteresting ways that have low exploration value. For example, a novice agent commanded to an unseen portion of a maze environment might respond by instead reaching a previously explored part of the maze, encountering no novel states. To address this, prior works (Pitis et al., 2020; Bharadhwaj et al., 2021) set up additional mechanisms to filter out unreachable goals, typically requiring additional hyperparameters. Second, recent works (Ecoffet et al., 2021; Yang et al., 2022; Pitis et al., 2020) have observed improved exploration in long-horizon tasks by extending training episodes. Specifically,

rather than resetting immediately after deploying the GCRL policy to a goal, these methods launch a new exploration phase right afterwards, such as by selecting random actions (Pitis et al., 2020; Kamienny et al., 2022) or by maximizing an intrinsic motivation reward (Guo et al., 2020). In this context, even successfully reaching a rare state through the GCRL policy might be suboptimal; many such states might be poor launchpads for the exploration phase that follows. For example, the GCRL policy might end up in a novel dead end in the maze, from which all exploration is doomed to fail.

To avoid these shortcomings and focus exploration on the most promising parts of the environment, we propose to leverage planning with world models in a new goal-directed exploration algorithm, PEG (short for "Planning Exploratory Goals"). **Our key idea is to optimize directly for goal commands that would induce high exploration value trajectories**, cognizant of current shortcomings in the GCRL policy, and of the exploration phase during training. Note that this *does not* mean merely commanding the agent to novel or rarely observed states. Instead, PEG commands might be to a previously observed state, or indeed, even to a physically implausible state (see Figure 1). PEG only cares that the command will induce the chained GCRL and exploration phases together to generate interesting training trajectories, valuable for policy improvement.

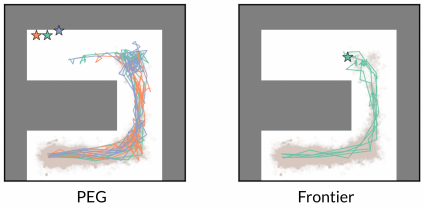

Figure 1: PEG exploration in a U-maze. Brown background dots: explored states, commanded goals: $\star$, resulting paths: colored lines. (Left) PEG optimizes directly for exploration, even setting unseen goals, and achieving farther paths. (Right) Setting goals at the frontier of the seen state distribution yields less exploration.

Our key contributions are as follows. We propose a novel paradigm for goal-directed exploration by directly optimizing goal selection to generate trajectories with high exploration value. Next, we show how learned world models permit an effective implementation of goal command planning, by adapting planning algorithms that are often used for low-level action sequence planning. We validate our approach, PEG, on challenging simulated robotics settings including a multi-legged ant robot in a maze, and a robot arm on a cluttered tabletop. In each environment, PEG exploration enables more efficient and effective training of generalist GCRL policies relative to baselines and ablations. Our ant successfully navigates a long maze, and the robot arm successfully builds a stack of three blocks upon command.

2 Problem Setup and Background

We wish to build agents that can efficiently explore an environment to autonomously acquire diverse environment-relevant capabilities. Specifically, in our problem setting, the agent is dropped into an unknown environment with no specification of the tasks that might be of interest afterwards. Over episodes of unsupervised exploration, it must learn about its environment, the various "tasks" that it affords to the agent, and also how to perform those tasks effectively. We focus on goal state-reaching tasks. After this exploration, a successful agent would be able to reach diverse previously unknown goal states in the environment upon command.

To achieve this, our method, **planning exploratory goals (PEG)**, focuses on improving unsupervised exploration within the goal-conditioned reinforcement learning framework. We set up notation and preliminaries below, before discussing our approach in section 3.

Preliminaries. We formalize the unsupervised exploration stage within a goal-conditioned Markov decision process, defined by the tuple $(\mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{G})$. The unsupervised goal-conditioned MDP does not contain the test-time goal distribution, nor a reward function. At each time t, a goal-conditioned policy $\pi^G(\cdot \mid s_t, g)$ in the current state $s_t \in \mathcal{S}$, under goal command $g \in \mathcal{G}$, selects an action $a_t \in \mathcal{A}$, and transitions to the next state s_{t+1} with probability $\mathcal{T}(s_{t+1}|s_t, a_t)$. To enable handling of the most broadly expressive goal-reaching tasks, we set the goal space to be identical to the state space: $\mathcal{G} = \mathcal{S}$, i.e., every state maps to a plausible goal-reaching command.

In our setting, an agent must learn a goal-conditioned reinforcement learning (GCRL) policy $\pi^G(\cdot \mid s, g)$ as well as collect exploratory data to train this policy on. Thus, as motivated in section 1, it is critical to pick good goal commands during training because it generates useful data to improve the policy's ability to achieve diverse goals.

Critical to our method's design is the specific mechanism through which goal commands influence the exploration data. We follow the recently popular "Go-explore" procedure (Ecoffet et al., 2021; Pislar et al., 2022; Tuyls et al., 2022) for exploration-intensive long-term GCRL settings. Every training episode starts with the selection of a goal command g. Note that Go-explore does not propose a general goal selection procedure, and leaves this as future work. We directly address this by proposing a general-purpose goal selection algorithm in the next section. Then, a goal-directed "**Go-phase**" starts, where the GCRL policy π^G is executed, conditioned on g, producing a final state s_T after T steps. Immediately, an "**Explore-phase**" commences, with an undirected exploration policy $\pi^E(\cdot \mid s)$ taking over for the remaining T_E timesteps. For example, $\pi^E(\cdot \mid s)$ could be an RL policy trained to maximize an intrinsic exploration reward r^E (Bellemare et al., 2016; Pathak et al., 2017; Burda et al., 2019; Sekar et al., 2020). This structure of training episodes has been shown to result in richer exploration (Pislar et al., 2022). Intuitively, the goal-conditioned policy efficiently brings an agent to an interesting goal, and the undirected exploration policy efficiently explores around the goal.

In our method, we build upon a recently proposed, powerful goal-conditioned model-based RL framework, the latent explorer achiever (LEXA) (Mendonca et al., 2021), after extending it to incorporate a novel goal proposal mechanism for Go-explore exploration. We briefly summarize the LEXA framework below and refer the reader to Appendix A.2 and the paper for details. LEXA learns the following components:

Algorithm 1 LEXA Training Loop

Input: goal / expl. policies π^G, π^E, world model $\widehat{\mathcal{T}}$, rewards r^G, r^E
$\mathcal{D} \leftarrow \{\}$ Initialize buffer.
for Episode $i = 1$ to N_{train} **do**
  $\tau \leftarrow$ GoalDirectedExploration$(\ldots)$
  $\mathcal{D} \leftarrow D \cup \tau$
  Update model $\widehat{\mathcal{T}}$ with $(s_t, a_t, s_{t+1}) \sim D$
  Update π^G in imagination with $\widehat{\mathcal{T}}$ to maximize r^G
  Update π^E in imagination with $\widehat{\mathcal{T}}$ to maximize r^E
end for

$$
\begin{aligned}
&\text{World model:} && \widehat{\mathcal{T}}_\theta(s_t|s_{t-1}, a_{t-1}) \\
&\text{Exploration policy:} && \pi^E_\theta(a_t|s_t) && \text{Goal Reaching policy:} && \pi^G_\theta(a_t|s_t, g) \\
&\text{Exploration value:} && V^E_\theta(s_t) && \text{Goal Reaching value:} && V^G_\theta(s_t, g)
\end{aligned} \tag{1}
$$

The world model is trained as a variational recurrent state space model (RSSM) following Hafner et al. (2020). The explorer and goal reaching policies are trained with the model-based on-policy actor-critic Dreamer algorithm (Hafner et al., 2021). Both policies are trained purely in imagination through world model "rollouts", i.e., the world model acts as a learned simulator in which to run entire training episodes for training these policies. The explorer reward is the Plan2Explore (Sekar et al., 2020) disagreement objective, which incentivizes reaching states that cause an ensemble of world models to disagree amongst themselves. The goal reaching reward r^G is the self-supervised temporal distance objective (Mendonca et al., 2021), which rewards the policy for minimizing the number of actions between the current state and a goal state. See Algorithm 1 for high level pseudocode of the training process. Highlighted in red is a generic exploration function that collects an episode. LEXA implements this by recording episodes from both the exploration policy and the goal-conditioned policy conditioned on a random goal from the replay buffer as seen in Algorithm 2. As we will see in the next section, PEG serves as a drop-in replacement of the highlighted exploration function by proposing exploratory goals for Go-explore exploration.

Algorithm 2 LEXA Goal Sampling

function GOALDIRECTEDEXPLORATION$(\ldots)$
  if $i\%2 = 0$ **then**
    Sample random goal g from buffer.
    Collect trajectory τ with $\pi^G(\cdot \mid \cdot, g)$
  else
    Collect trajectory τ with π^E
  end if
  return τ
end function

3 PLANNING GOALS FOR EXPLORATION

Having set up the preliminaries, we return to the core question of this paper: how should we pick exploration-inducing goals to help acquire diverse skills? We have argued above that the answer is not to pick goals at the frontier of previously explored states, as in prior work (Yamauchi, 1998; Pitis et al., 2020; Bharadhwaj et al., 2021). Instead, at the beginning of each training episode, we propose to optimize directly for goals that would lead to the highest exploration rewards during the episode's

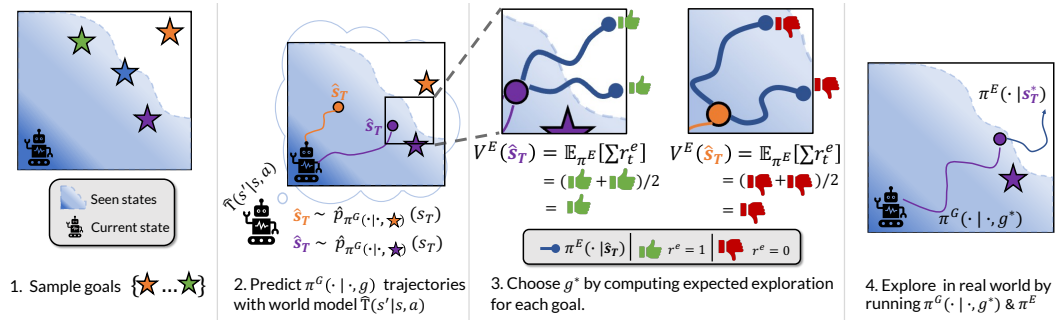

Figure 2: PEG proposes goals for Go-explore style exploration. 1) We start by sampling goal candidates $g_1 \dots g_N$. 2) For each goal g, we execute the goal-conditioned policy $\pi^G(\cdot \mid \cdot, g)$ in the world model $\widehat{\mathcal{T}}$ to generate trajectories. 3) We score each goal by seeing how useful their trajectories are for launching an exploration policy. 4) Explore using the best g.

Explore-phase:

$$\max_g \mathbb{E}_{p_{\pi^G(\cdot|\cdot,g)}(s_T)} \left[V^E(s_T) \right], \tag{2}$$

$$\text{where} \quad V^E(s_T) = \mathbb{E}_{\pi^E} \left[\sum_{t=T+1}^{T+T_E} \gamma^{t-T-1} r_t^E \right], \tag{3}$$

and where $p_{\pi^G(\cdot|\cdot,g)}(s_T)$ is the distribution of terminal states generated when π^G runs for T steps conditioned on goal g. V^E, which we call *exploration value*, is the expected discounted intrinsic motivation return of the exploration policy, when launched from state s_T. Please refer to Figure 2 for a detailed visualization.

Importantly, this objective involves computing the *expected* exploration value of terminal states s_T. The exploration value measures how interesting will the Explore-phase be as measured by intrinsic motivation rewards. Next, note that the expectation in Equation (2) is over the terminal states induced by the current GCRL policy. This way, it accounts for the capabilities of the current GCRL policy, regardless of whether it is a novice or an expert at achieving the selected goal g. If we had instead sought to optimize for goals g with high exploratory value, in similar spirit to prior works (Pong et al., 2019; Pitis et al., 2020; Ecoffet et al., 2021), the objective of Equation (2) would instead be replaced by $V^E(g)$, the exploration value of the goal, which is naively agnostic to the capabilities of the GCRL policy. As we have argued above, this would then require additional mechanisms to account for reachability of the specified goal etc., bringing new hyperparameters and related overheads. Instead, PEG offers a unified and compact solution. In plain English, "first command goals that lead the goal policy to states that have high future exploration potential, then explore."

The objective in Equation (2) is not straightforward to compute, because it relies on the terminal state distribution induced by the goal-conditioned policy $p_{\pi^G(\cdot|\cdot,g)}(s_T)$. This distribution can change rapidly throughout training, as the policy evolves. To explore well, it is important to use an up-to-date estimate. We leverage the learned world model $\widehat{\mathcal{T}}$ to achieve this: $\hat{p}_{\pi^G(\cdot|\cdot,g)}(\tau)$ can be represented as the product of the transition and goal-conditioned policy distributions.

$$\hat{p}_{\pi^G(\cdot|\cdot,g)}(\tau) = p(s_0) \left[\prod_{t=1}^{T} \widehat{\mathcal{T}}(s_t \mid s_{t-1}, a_{t-1}) \pi^G(a_{t-1} \mid s_{t-1}, g) \right] \tag{4}$$

Now, we may approximate the expectation over the marginal $p_{\pi^G(\cdot|\cdot,g)}(s_T)$ in the objective Equation (2) by sampling trajectories τ from the learned world model and using the last state s_T:

$$\mathbb{E}_{\hat{p}_{\pi^G(\cdot|\cdot,g)}(s_T)}[V^E(s_T)] \approx \frac{1}{K} \sum_k V_\theta^E(s_T^k) \qquad \text{where } s_T^k \sim \hat{p}_{\pi^G(\cdot|\cdot,g)}(\tau) \tag{5}$$

This permits on-the-fly generation of an up-to-date estimate of our objective from Equation (2), using a recent goal-conditioned RL policy. Then, we can optimize over goals g using sample-based

optimization. Following Equation (5), to evaluate a goal g, we condition the goal-conditioned policy on g, and roll it out for K trajectories τ_k within the learned world model. We then estimate the terminal state exploration value for each trajectory with the learned exploration value function $V_\theta^E(s_T^k)$ (Equation (1)), and average the estimates.

Algorithm 3 PEG Goal Sampling

1: **function** GOALDIRECTEDEXPLORATION(...)
2: Compute goal g by optimizing Eq. 5 with MPPI
3: $\tau \leftarrow$ *GO-EXPLORE*(g, π^G, π^E)
4: **return** τ
5: **end function**

For optimizing the goal variable g, we use model predictive path integral control (Williams et al., 2015) (MPPI, see Appendix A.3 for details). In Appendix A.3, we show that the specific choice of optimizer is not critical and other optimizers like cross entropy method (CEM) (De Boer et al., 2005) also work well. More broadly, while these sampling-based optimizers are popular for optimizing action trajectories with dynamics models (Nagabandi et al., 2019; Chua et al., 2018; Ebert et al., 2018; Hafner et al., 2020), PEG uses them instead for optimizing goal commands; this lower-dimensional search space enables easy optimization, independent of the task horizon, permitting handling long-term tasks. Equipped with this goal setting procedure, we can now train a goal-conditioned policy by replacing the LEXA data collection highlighted in red in Algorithm 1 with our proposed PEG goals and Go-explore episodes (Algorithm 3 shows PEG pseudocode).

Implementation Details. We implement PEG on top of authors' code from DreamerV2 (Hafner et al., 2021), LEXA (Mendonca et al., 2021), and MPPI implementation from Rybkin et al. (2021). We used the default hyperparameters for training the world model, policies, value functions, and temporal reward functions. For PEG, we tried various values of K for simulating trajectories of π^G for each goal and found $K = 1$ to be sufficient. We use the same Go-explore mechanism across all goal-setting methods: the Go and Explore phases' time limits are set to half of the maximum episode length for all environments, while non-Go-explore baselines use the full episode length for exploration. See Appendix A.3 for details on hyperparameters, runtime, and resource usage.

4 EXPERIMENTS

Our experiments evaluate goal-reaching tasks that require non-trivial exploration and skill acquisition to solve. We aim to answer: **(1)** Does PEG result in better exploration and downstream goal-reaching behavior? **(2)** What qualitatively distinguishes PEG goals and exploration from previous goal-directed exploration methods? **(3)** What components of PEG contribute to its success?

4.1 SETUP

We evaluate PEG and other goal-conditioned RL agents on four different continuous-control environments, described below. For each environment, we define an evaluation set of goals — as a general principle, we pick evaluation goals in each environment that require extensive exploration in order for the agent to learn a successful evaluation goal reaching policy. These goals are very relevant in long-horizon tasks, as long-horizon goals tend to require extensive exploration to gather the necessary data for training. Recall that we assume the fully unsupervised exploration setting; the agent does not have access to the evaluation set during training time. So, for all the agent knows at training time, any environment state could plausibly be a test goal. During evaluation, we run 10 goal-reaching episodes to account for environmental noise (e.g. initial position noise) for each goal, and report the aggregate success rates for each environment. All methods are run with 5 seeds. The success metric $d(s, g)$ used for evaluation is an indicator function checking if any state in the episode is within ϵ distance of the goal state. See Appendix A.1 for details.

See Figure 3 for images of each environment, and Appendix A.1 for more details.

• **Point Maze:** The agent, a 2D point, is noisily initialized in the bottom left. At test time, we evaluate it on reaching the right corner. The 2-D state and action space correspond to the planar position and velocity respectively. The episode length is 50 steps. The top right corner is the hardest to reach, so we set this to be the test-time goal.

• **Walker:** In this environment from Tassa et al. (2018), a 2D 2-legged robot moves on a flat plane. The state space is 9-D and contains the walker's XZ position and joint angles. The action space is 6-D and represents joint torques. The episode length is 150 steps. To evaluate the ability to learn different locomotion behaviors of varied difficulty, the test goal commands are standing states that are placed ± 7, and ± 12 meters from the initial pose.

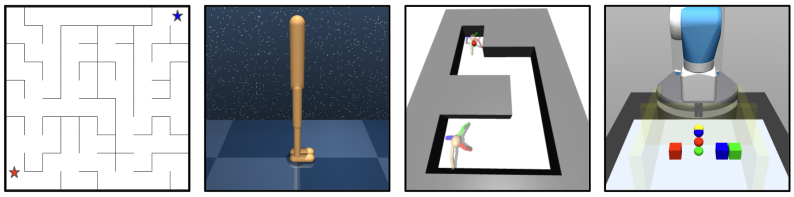

Figure 3: We evaluate PEG across four diverse environments, selecting evaluation tasks to stress-test exploration. From left to right: Point Maze requires the agent to move from the bottom left to top right. Walker evaluates if the agent can walk to different positions on the plane. In Ant Maze, the ant is required to move to the farthest end of the maze. Finally, in 3-Block Stack, the robot must stack the blocks into the goal configuration (colored orbs).

• **Ant Maze:** We increased exploration difficulty in the Ant Maze environment from MEGA (Pitis et al., 2020) by placing one additional turn in the maze. Further, we set the GCRL goal space to the full 29-D ant state space, rather than reduce it to 2-D xy position as in MEGA. The ant robot must learn complex 4-legged locomotion behavior and navigate around the hallways (see Figure 3). The episode length is 500 steps. We evaluate the ant on reaching 4 hard goals that are placed in the top left room, the furthest area from the start, and 4 intermediate goals in the middle hallway.

• **3-Block Stacking:** Here, a robot arm with a two-fingered gripper operates on a tabletop with 3 blocks and boundary walls. The state space is the gripper pose and object xyz positions (14-D), and the action space is the gripper velocity and force (4-D). At evaluation time, the robot is commanded to stack three blocks into a tower configuration. To achieve this, the agent will need to have learned pushing, picking, and stacking, and discovered 3-block stacks as a possible configuration of the environment. The episode length is 150 timesteps. Note that 3+block stacking is a classic and open exploration challenge in robot RL; to our knowledge, all prior solutions assume expensive forms of supervision or computational resources to overcome the exploration challenge, such as demonstrations, curriculum learning, or billions of simulator samples (Ecoffet et al., 2021; Nair et al., 2018a; Lanier et al., 2019; Li et al., 2020), highlighting task difficulty.

4.2 Baselines

PEG aims to improve goal-directed exploration by improving goal selection during GCRL. To specifically evaluate the goal selection logic, we implemented all baselines on top of LEXA (Mendonca et al., 2021), the backbone goal-conditioned MBRL framework by replacing the data collection logic (line 4 in Algorithm 1) with Go-explore episodes conditioned on a goal (chosen by the baseline).

Our first two baselines, Skewfit and MEGA, are alternative goal setting approaches: both follow Algorithm 1 and differ only in the goal selection logic (lines 4-9). **Skewfit** (Pong et al., 2019) estimates state densities, and chooses goals from the replay buffer inversely proportional to their density, resulting in uniform state sampling. **MEGA** (Pitis et al., 2020) similarly uses kernel density estimates (KDE) of state densities, and chooses low density goals from the replay buffer. MEGA is close to the original Go-explore approach (Ecoffet et al., 2021); rather than Go-explore's hand-designed pseudocount metric, MEGA uses KDE to choose goals. MEGA relies on a heuristic Q-function threshold to prune unachievable low density goals since many rare states may not be achievable by π^G. This requires tuning and prior knowledge of the test goal during training time to set.

We also run vanilla **LEXA** itself as a baseline. LEXA does not perform Go-explore style exploration, instead using an intrinsic motivation exploration policy for some exploration episodes and the goal-conditioned policy conditioned on random goals for others. In addition, we evaluate against a variant of LEXA that only collects data with the exploration policy. We denote this baseline Plan2Explore (**P2E**) after the intrinsic motivation policy it uses (Sekar et al., 2020). P2E trains an exploration policy to maximize disagreement among an ensemble of world models. Notably, PEG and our other Go-Explore baselines all use the same P2E exploration algorithm during Explore-phase, which isolates the differences in exploration to the proposed goals of each method. See Appendix A.2 for additional details including a side-by-side algorithm comparison, and where we verify that our MBRL

versions of MEGA and Skewfit are sound and in fact better than the original versions in Pitis et al. (2020).

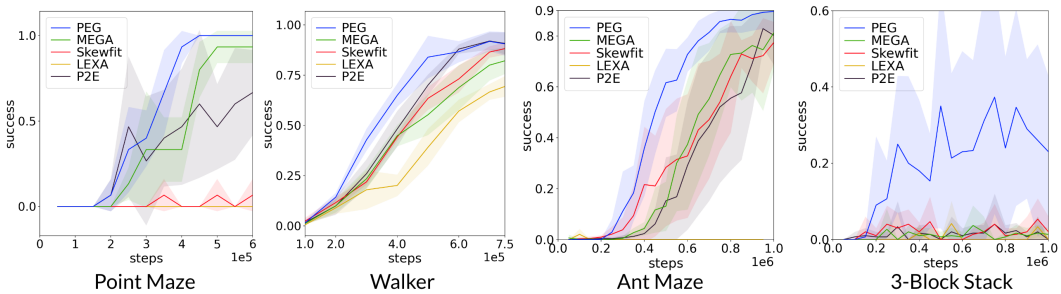

Figure 4: Performance of agents with different goal setting strategies. All methods are run with 5 seeds. PEG outperforms all baselines, and its performance gain increases with environment difficulty.

4.3 Results

Test task success rates. Figure 4 shows the evaluation performance across training time. PEG compares favorably to baselines both in final success rate and learning speed. PEG reaches near-optimal behavior earlier than any other baseline. PEG outperforms goal-setting baselines (MEGA and Skewfit) across all tasks, which shows that PEG goal setting is superior to alternative goal-setting strategies. On the hardest task, block stacking, PEG is the only method to achieve any significant non-zero task performance: PEG achieves about 30% success rate on this challenging exploration task, all other baselines are close to 0%.

Recall that MEGA picks minimum density goals from the replay buffer. As we have seen in Figure 1, picking goals from the replay buffer may result in suboptimal goals for exploration as there could exist goals outside the data that result in more exploration. Furthermore, the MEGA objective does not reason about temporally extended exploration that begins after the goal state is reached. Next, Skewfit, which samples goal states uniformly by their density, may often sample uninteresting goals, thus slowing down exploration. In our upcoming qualitative analysis of goal selection behavior, we see these conceptual and practical differences manifest in suboptimal goal picking behavior in comparison to PEG. P2E has no Go-phase, and thus no goal-directed exploration, which limits its exploration horizon. Even so, it can sometimes perform better than MEGA and Skewfit (see Walker), both methods that employ the same exploration algorithm as P2E, just after a Go-phase. In other words, Go-explore by itself doesn't always improve exploration, and suboptimal goal-setting during "Go-phase" can in fact deteriorate exploration. LEXA performs worse than simple P2E, indicating that sampling random goals from the replay buffer does not improve exploration or training.

PEG outperforms all these methods by picking goals that directly optimize exploration value, scaling well to high dimensional states, and leveraging a goal-conditioned policy with Go-explore exploration to enable temporally extended exploration.

Goal selection behaviors. Next, Figure 5 visualizes the goal-picking and exploration behaviors for PEG and baselines. A trend across tasks is that PEG consistently picks goals (red points) beyond the frontier of seen data. In **Point Maze**, the middle right region forms a natural barrier for the exploration policy to overcome. The policy must find a rather tortuous path from the bottom left through the middle right hallways in order to reach the top right corner. As a result, top right states beyond the middle right region are very sparsely represented. With similar states in the replay buffer (blue dots), we find that PEG generates many more goals in the top right region than MEGA, thus accelerating exploration. Similarly, in **Walker**, PEG selects goals to the far left and right of the walker, where data support is the sparsest. MEGA fails to pick goals to the left.

In **Ant Maze** (Figure 5), we see that PEG explores the most deeply into the maze of all methods, at this halfway point. Counting the total number of state visitations in the farthest top-left reaches of the maze for each method, we find that PEG has $\sim$68K states whereas MEGA, the closest baseline, only has $\sim$3K. Looking at Figure 5, MEGA does pick a few "rare" goals in the top left, but π^G has not visited the top left area, either because π^G is not capable of reaching the rare goals and/or the

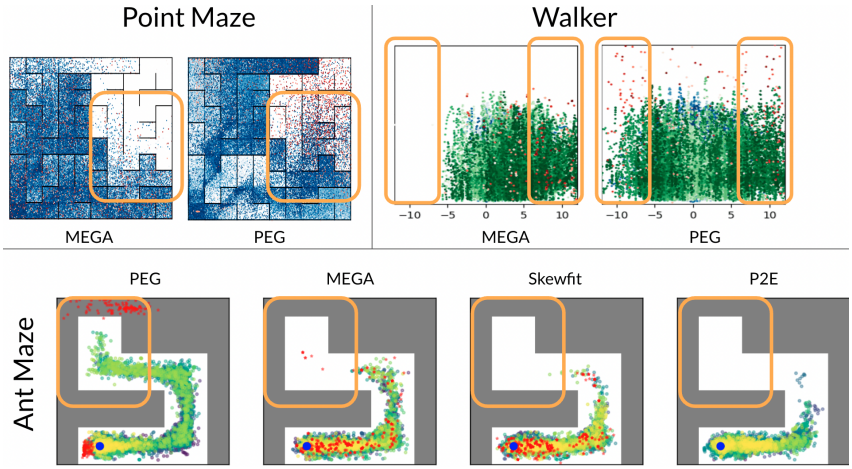

Figure 5: We plot the achieved states (blue / green dots) and goals (red dots) for PEG and baselines in the Point Maze (top left), Walker (top right), and Ant Maze (bottom) halfway through training. PEG picks goals in areas (orange boxes) that lead to more exploration whereas baselines do not. Walker and Ant states are high dimensional so we just plot their central xz or xy positions.

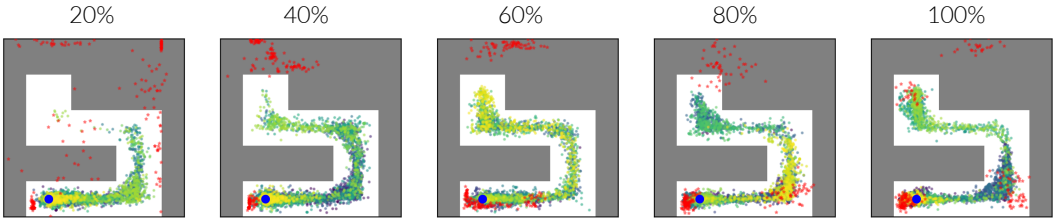

Figure 6: The evolution of achieved states (colored dots) and goals (red dots) of PEG throughout training in the Ant Maze. Lighter states are more recent. PEG samples goals to maximize exploration, sometimes picking goals that are outside the seen data or even physically implausible.

frontier. Skewfit samples no goals in the top left region, because it does not prioritize rare states. We further examine the training evolution of PEG goals in Ant Maze to analyze how they contribute to exploration. We plot the achieved states and goals proposed by PEG periodically throughout its training in Figure 6. PEG goals, optimized to induce the goal-conditioned policy to visit high-exploration value states, are not always predictable. PEG commonly chooses goals outside of the data distribution. For example, PEG chooses goals near the top wall for the entire training duration. We can also see it choosing physically impossible goals in the middle wall at 20%, but these goals disappear as the goal-conditioned policy and world model are updated over time.

In the **3-Block Stack** environment, as discussed above, PEG is the only method to train any meaningful policy. The space of configurations of the three blocks and the robot in this setting is extremely large, and all methods struggle with this challenge. We observed that PEG and baselines all spent significant amounts of time exploring peculiar states such as throwing blocks over the workspace walls. However, critically, PEG 's exploration is comprehensive enough to also explore more "useful" and hard-to-reach behaviors such as 3-block stacking. We analyzed the replay buffers (1M steps) across all methods (5 seeds per method) and logged the mean number of states and standard deviation that are ϵ-close to the 3-block stacks we use as test goals (see Table 1). PEG experiences such states on average $\sim$500 times, whereas no baseline experiences this more than 3 times throughout training. This suggests that PEG more thoroughly explores the environment in general, including the most challenging 3-block stacking states. We then analyzed whether these block stacking states were achieved during Go-phase or Explore-phase. We found that 75% of the 3-block states come in the Go-Phase. In other words, PEG sets goals that

Table 1: Number of 3-block stacks experienced.

Method	Count
P2E	1 ± 1.55
LEXA	0 ± 0
MEGA	1 ± 2
Skewfit	1 ± 0.4
PEG	$\mathbf{523 \pm 614}$

induce this stacking behavior, and moreover, the GCRL policy is able to achieve such behaviors quite frequently during training (see website for videos).

Ablation Analysis. What components of PEG are important to its performance? We run ablation studies in Ant Maze. First, we ablate PEG's goal sampling: Rand-Goal PEG replaces PEG's goal sampling with randomly sampled goals. In Seen-Goal PEG, we forego optimizing the goal with MPPI and simply choose goals from the replay buffer that score highly according to Equation (5). Go-Value PEG chooses to optimize the exploration rewards achieved during the imagined *Go-phase* instead of during the Explore-phase, by replacing $V^E(s_T)$ in Equation (5) with $\sum_{t=1}^{T} r_t^E$ — note that this still runs Explore after Go in the environment. Next, we ablate PEG's Go-explore mechanism itself, by replacing the explorer policy with a random action policy (Rand-Explore PEG), and removing Explore-phase completely (No-Explore PEG).

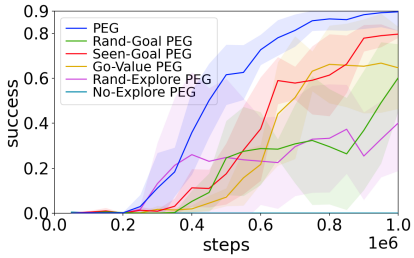

Figure 7: PEG ablations.

Figure 7 shows the results. PEG is clearly better than all ablations, suggesting that all components of the method contribute to performance. Explore-phase is particularly important; No-Explore PEG achieves 0% success. Rand-Explore PEG performs poorly, showing the need for a learned Explore-phase policy like P2E. Next, Rand-Goal PEG, Seen-Goal PEG, and Go-Value PEG all perform worse than PEG; the specifics of the objective function for goal sampling defined in Equation (5), and its optimization procedure, are important.

5 Related Work

PEG is related to the literature on unsupervised exploration. One family of unsupervised exploration approaches trains a reinforcement learning (RL) agent to maximize an intrinsic motivation reward correlated with exploration (Schmidhuber, 2010; Pathak et al., 2017). Common forms of intrinsic reward incentivize visiting rare states with count-based methods Poupart et al. (2006); Bellemare et al. (2016); Burda et al. (2019) or finding states that maximize prediction error (Oudeyer et al., 2007; Pathak et al., 2017; Henaff, 2019; Shyam et al., 2019; Sekar et al., 2020). Within PEG, we leverage an intrinsic motivation policy for the Explore-phase.

More specifically related to PEG, goal-directed exploration is a special class of unsupervised exploration, applicable in the challenging goal-conditioned RL (GCRL) setting. To develop generalist GCRL policies, these methods command the goal-conditioned policy towards exploratory goals at training time. Broadly, the idea is to pick goals that are difficult for the current policy, but not completely out of reach, i.e., within the "zone of proximal development." Within that broad framework, however, prior works propose many different metrics for goal choosing, such as learning progress (Baranes & Oudeyer, 2013; Veeriah et al., 2018), goal difficulty (Florensa et al., 2018), "sibling rivalry" (Trott et al., 2019), or value function disagreement (Zhang et al., 2020). Within this family, we have already discussed and compared against the most closely relevant methods MEGA and Skew-Fit (Pong et al., 2019; Pitis et al., 2020) (see Section 4.2 and Section 4.3) which command the agent to rarely seen states to increase the number of seen and familiar states, reasoning that this will enable broader expertise in the trained GCRL policies. Related to goal-directed exploration are methods that focus on training goal-conditioned policies. Andrychowicz et al. (2017) proposes an efficient goal relabeling strategy, and Chane-Sane et al. (2021) uses imagined subgoals to guide the policy search process.

Closely related to unsupervised goal-directed exploration is unsupervised skill discovery, which aims to train a skill-conditioned policy Eysenbach et al. (2019); Sharma et al. (2019). The main difference between PEG and skill discovery is that skill discovery optimizes latent skill variables to acquire a diverse set of skills, whereas PEG optimizes observed goal variables for exploration. Skill discovery objectives do not necessarily encourage exploration, and can even fall into local minima where the agent is penalized for exploration (Strouse et al., 2021), or fail to learn state-covering skills (Campos et al., 2020). As such, these are usually weak baselines for exploration; for example, our goal-directed exploration baselines, LEXA and MEGA, both report clearly favorable results against such methods (Eysenbach et al., 2019; Hartikainen et al., 2020).

6 CONCLUSIONS

We have presented planning exploratory goals (PEG), an approach for goal setting to train goal-conditioned reinforcement learning agents to become “generalists” in a novel environment, with no supervision. PEG plans exploratory goals through a world model, directly optimizing for the exploration value of the training trajectory. It thus provides a simple and principled objective for goal selection. PEG depends on a learned world model to plan goals, and may suffer in prediction performance and computation time for longer prediction horizons. An interesting direction would be to combine PEG with temporally abstracted world models (Neitz et al., 2018; Jayaraman et al., 2019; Pertsch et al., 2020) to handle such cases. Further, while empirically PEG produces performant goal-conditioned policies, it only explores by maximizing novelty. In harder tasks it might be necessary to explicitly consider also exploring with "practice goals" that best improve the goal-conditioned policy. Finally, while we focus on purely unsupervised exploration, in practice some sparse feedback from a human might be provided. Leveraging such feedback to focus exploration on the space of tasks preferred by the user would make GCRL and PEG more practical. By presenting a principled algorithm for goal setting, we hope that PEG will enable future advances and extensions to address these challenges.

7 REPRODUCIBILITY STATEMENT

To ensure reproducibility, we will release the codebase that contains our method, baselines, and environments. The supplementary contains details about hyperparameters, baselines, and architecture (see Appendix A.2 and Appendix A.3). In addition, we have also provided pseudocode in Algorithm 3.

REFERENCES

Marcin Andrychowicz, Filip Wolski, Alex Ray, Jonas Schneider, Rachel Fong, Peter Welinder, Bob McGrew, Josh Tobin, Pieter Abbeel, and Wojciech Zaremba. Hindsight experience replay. In *Advances in Neural Information Processing Systems*, pp. 5048–5058, 2017.

Adrien Baranes and Pierre-Yves Oudeyer. Active learning of inverse models with intrinsically motivated goal exploration in robots. *Robotics and Autonomous Systems*, 61(1):49–73, 2013. ISSN 0921-8890. doi: https://doi.org/10.1016/j.robot.2012.05.008. URL https://www.sciencedirect.com/science/article/pii/S0921889012000644.

Marc Bellemare, Sriram Srinivasan, Georg Ostrovski, Tom Schaul, David Saxton, and Remi Munos. Unifying count-based exploration and intrinsic motivation. In *Advances in Neural Information Processing Systems*, volume 29, 2016. URL https://proceedings.neurips.cc/paper/2016/file/afda332245e2af431fb7b672a68b659d-Paper.pdf.

Homanga Bharadhwaj, Animesh Garg, and Florian Shkurti. LEAF: latent exploration along the frontier. In *IEEE International Conference on Robotics and Automation, ICRA 2021, Xi'an, China, May 30 - June 5, 2021*, pp. 677–684. IEEE, 2021. doi: 10.1109/ICRA48506.2021.9560922. URL https://doi.org/10.1109/ICRA48506.2021.9560922.

Yuri Burda, Harrison Edwards, Amos Storkey, and Oleg Klimov. Exploration by random network distillation. In *International Conference on Learning Representations*, 2019. URL https://openreview.net/forum?id=H1lJJnR5Ym.

Victor Campos, Alexander Trott, Caiming Xiong, Richard Socher, Xavier Giró-i-Nieto, and Jordi Torres. Explore, discover and learn: Unsupervised discovery of state-covering skills. In *International Conference on Machine Learning*, Proceedings of Machine Learning Research, 2020. URL http://proceedings.mlr.press/v119/campos20a.html.

Elliot Chane-Sane, Cordelia Schmid, and Ivan Laptev. Goal-conditioned reinforcement learning with imagined subgoals. In *International Conference on Machine Learning*, pp. 1430–1440. PMLR, 2021.

Kurtland Chua, Roberto Calandra, Rowan McAllister, and Sergey Levine. Deep reinforcement learning in a handful of trials using probabilistic dynamics models. In *Proceedings of the 32nd International Conference on Neural Information Processing Systems*, NIPS'18, pp. 4759–4770, Red Hook, NY, USA, 2018. Curran Associates Inc.

Pieter-Tjerk De Boer, Dirk P Kroese, Shie Mannor, and Reuven Y Rubinstein. A tutorial on the cross-entropy method. *Annals of operations research*, 134(1):19–67, 2005.

Frederik Ebert, Chelsea Finn, Sudeep Dasari, Annie Xie, Alex Lee, and Sergey Levine. Visual foresight: Model-based deep reinforcement learning for vision-based robotic control. *arXiv preprint arXiv:1812.00568*, 2018.

Adrien Ecoffet, Joost Huizinga, Joel Lehman, Kenneth O. Stanley, and Jeff Clune. First return then explore. *Nature*, 590 7847:580–586, 2021.

Benjamin Eysenbach, Abhishek Gupta, Julian Ibarz, and Sergey Levine. Diversity is all you need: Learning skills without a reward function. In *International Conference on Learning Representations*, 2019. URL https://openreview.net/forum?id=SJx63jRqFm.

Carlos Florensa, David Held, Xinyang Geng, and Pieter Abbeel. Automatic goal generation for reinforcement learning agents. In *International Conference on Machine Learning*, 2018.

Yijie Guo, Jongwook Choi, Marcin Moczulski, Shengyu Feng, Samy Bengio, Mohammad Norouzi, and Honglak Lee. Memory based trajectory-conditioned policies for learning from sparse rewards. In *Advances in Neural Information Processing Systems*, 2020.

Danijar Hafner, Timothy Lillicrap, Jimmy Ba, and Mohammad Norouzi. Dream to control: Learning behaviors by latent imagination. In *International Conference on Learning Representations*, 2020. URL https://openreview.net/forum?id=S1lOTC4tDS.

Danijar Hafner, Timothy P Lillicrap, Mohammad Norouzi, and Jimmy Ba. Mastering atari with discrete world models. In *International Conference on Learning Representations*, 2021. URL https://openreview.net/forum?id=0oabwyZbOu.

Kristian Hartikainen, Xinyang Geng, Tuomas Haarnoja, and Sergey Levine. Dynamical distance learning for semi-supervised and unsupervised skill discovery. In *International Conference on Learning Representations*, 2020. URL https://openreview.net/forum?id=H1lmhaVtvr.

Mikael Henaff. Explicit explore-exploit algorithms in continuous state spaces. In *Advances in Neural Information Processing Systems*, 2019. URL https://proceedings.neurips.cc/paper/2019/file/03b264c595403666634ac75d828439bc-Paper.pdf.

Dinesh Jayaraman, Frederik Ebert, Alexei A Efros, and Sergey Levine. Time-agnostic prediction: Predicting predictable video frames. *International Conference on Learning Representations*, 2019.

Pierre-Alexandre Kamienny, Jean Tarbouriech, Alessandro Lazaric, and Ludovic Denoyer. Direct then diffuse: Incremental unsupervised skill discovery for state covering and goal reaching. In *International Conference on Learning Representations*, 2022. URL https://openreview.net/forum?id=25kzAhUB1lz.

John B. Lanier, Stephen McAleer, and Pierre Baldi. Curiosity-driven multi-criteria hindsight experience replay. *CoRR*, abs/1906.03710, 2019. URL http://arxiv.org/abs/1906.03710.

Richard Li, Allan Jabri, Trevor Darrell, and Pulkit Agrawal. Towards practical multi-object manipulation using relational reinforcement learning. In *IEEE International Conference on Robotics and Automation*, pp. 4051–4058. IEEE, 2020.

Russell Mendonca, Oleh Rybkin, Kostas Daniilidis, Danijar Hafner, and Deepak Pathak. Discovering and achieving goals with world models. In *Advances in Neural Information Processing Systems*, 2021.

Anusha Nagabandi, Kurt Konolige, Sergey Levine, and Vikash Kumar. Deep dynamics models for learning dexterous manipulation. In *Conference on Robot Learning*, Proceedings of Machine Learning Research, 2019. URL http://proceedings.mlr.press/v100/nagabandi20a.html.

Ashvin Nair, Bob McGrew, Marcin Andrychowicz, Wojciech Zaremba, and Pieter Abbeel. Overcoming exploration in reinforcement learning with demonstrations. In *IEEE International Conference on Robotics and Automation*, pp. 6292–6299, 2018a.

Ashvin Nair, Vitchyr Pong, Murtaza Dalal, Shikhar Bahl, Steven Lin, and Sergey Levine. Visual reinforcement learning with imagined goals. In *Proceedings of the 32nd International Conference on Neural Information Processing Systems*, NIPS'18, pp. 9209–9220, Red Hook, NY, USA, 2018b. Curran Associates Inc.

Alexander Neitz, Giambattista Parascandolo, Stefan Bauer, and Bernhard Schölkopf. Adaptive skip intervals: Temporal abstraction for recurrent dynamical models. In *Advances in Neural Information Processing Systems*, 2018. URL https://proceedings.neurips.cc/paper/2018/file/0f0ee3310223fe38a989b2c818709393-Paper.pdf.

Pierre-Yves Oudeyer, Frdric Kaplan, and Verena V. Hafner. Intrinsic motivation systems for autonomous mental development. *IEEE Transactions on Evolutionary Computation*, 11(2):265–286, 2007. doi: 10.1109/TEVC.2006.890271.

Deepak Pathak, Pulkit Agrawal, Alexei A. Efros, and Trevor Darrell. Curiosity-driven exploration by self-supervised prediction. In *International Conference on Machine Learning*, 2017.

Karl Pertsch, Oleh Rybkin, Frederik Ebert, Chelsea Finn, Dinesh Jayaraman, and Sergey Levine. Long-horizon visual planning with goal-conditioned hierarchical predictors. In *Proceedings of the 34th International Conference on Neural Information Processing Systems*, NIPS'20, Red Hook, NY, USA, 2020. Curran Associates Inc. ISBN 9781713829546.

Miruna Pislar, David Szepesvari, Georg Ostrovski, Diana L Borsa, and Tom Schaul. When should agents explore? In *International Conference on Learning Representations*, 2022. URL https://openreview.net/forum?id=dEwfxt14bca.

Silviu Pitis, Harris Chan, Stephen Zhao, Bradly Stadie, and Jimmy Ba. Maximum entropy gain exploration for long horizon multi-goal reinforcement learning. In *International Conference on Machine Learning*, pp. 7750–7761. PMLR, 2020.

Vitchyr H Pong, Murtaza Dalal, Steven Lin, Ashvin Nair, Shikhar Bahl, and Sergey Levine. Skew-fit: State-covering self-supervised reinforcement learning. *arXiv preprint arXiv:1903.03698*, 2019.

Pascal Poupart, Nikos Vlassis, Jesse Hoey, and Kevin Regan. An analytic solution to discrete bayesian reinforcement learning. In *Proceedings of the 23rd International Conference on Machine Learning*, ICML '06, pp. 697–704, New York, NY, USA, 2006. Association for Computing Machinery. ISBN 1595933832. doi: 10.1145/1143844.1143932. URL https://doi.org/10.1145/1143844.1143932.

Oleh Rybkin, Chuning Zhu, Anusha Nagabandi, Kostas Daniilidis, Igor Mordatch, and Sergey Levine. Model-based reinforcement learning via latent-space collocation. *International Conference on Machine Learning*, 2021.

Jürgen Schmidhuber. Formal theory of creativity, fun, and intrinsic motivation (1990–2010). *Autonomous Mental Development, IEEE Transactions on*, 2:230 – 247, 10 2010. doi: 10.1109/TAMD.2010.2056368.

Ramanan Sekar, Oleh Rybkin, Kostas Daniilidis, Pieter Abbeel, Danijar Hafner, and Deepak Pathak. Planning to explore via self-supervised world models. In *International Conference on Machine Learning*, pp. 8583–8592. PMLR, 2020.

Archit Sharma, Shixiang Gu, Sergey Levine, Vikash Kumar, and Karol Hausman. Dynamics-aware unsupervised discovery of skills. *arXiv preprint arXiv:1907.01657*, 2019.

Pranav Shyam, Wojciech Jaśkowski, and Faustino Gomez. Model-based active exploration. In *International conference on machine learning*, pp. 5779–5788. PMLR, 2019.

DJ Strouse, Kate Baumli, David Warde-Farley, Vlad Mnih, and Steven Hansen. Learning more skills through optimistic exploration, 2021. URL https://arxiv.org/abs/2107.14226.

Yuval Tassa, Yotam Doron, Alistair Muldal, Tom Erez, Yazhe Li, Diego de Las Casas, David Budden, Abbas Abdolmaleki, Josh Merel, Andrew Lefrancq, et al. Deepmind control suite. *arXiv preprint arXiv:1801.00690*, 2018.

Alexander Trott, Stephan Zheng, Caiming Xiong, and Richard Socher. Keeping your distance: Solving sparse reward tasks using self-balancing shaped rewards. *CoRR*, abs/1911.01417, 2019. URL http://arxiv.org/abs/1911.01417.

Jens Tuyls, Shunyu Yao, Sham M. Kakade, and Karthik R Narasimhan. Multi-stage episodic control for strategic exploration in text games. In *International Conference on Learning Representations*, 2022. URL https://openreview.net/forum?id=Ek7PSN7Y77z.

Vivek Veeriah, Junhyuk Oh, and Satinder Singh. Many-goals reinforcement learning. *ArXiv*, abs/1806.09605, 2018.

Grady Williams, Andrew Aldrich, and Evangelos Theodorou. Model predictive path integral control using covariance variable importance sampling. *arXiv preprint arXiv:1509.01149*, 2015.

Brian Yamauchi. Frontier-based exploration using multiple robots. In *Proceedings of the Second International Conference on Autonomous Agents*, AGENTS '98, pp. 47–53, New York, NY, USA, 1998. Association for Computing Machinery. ISBN 0897919831. doi: 10.1145/280765.280773. URL https://doi.org/10.1145/280765.280773.

Zhao Yang, Thomas M. Moerland, Mike Preuss, and Aske Plaat. When to go, and when to explore: The benefit of post-exploration in intrinsic motivation, 2022. URL https://arxiv.org/abs/2203.16311.

Yunzhi Zhang, Pieter Abbeel, and Lerrel Pinto. Automatic curriculum learning through value disagreement. *Advances in Neural Information Processing Systems*, 33:7648–7659, 2020.

A APPENDIX

A.1 ENVIRONMENTS

Point Maze: The agent, a 2D point spawned on the bottom left of the maze, is evaluated on reaching the top right corner within 50 timesteps. The two-dimensional state and action space correspond to the planar position and velocity respectively. Success is based upon the L2 distance between the position of the agent and the goal being less than 0.15. The entire maze is approximately 10 x 10. This environment is taken directly from Pitis et al. (2020) with no modifications.

Walker: Next, the walker environment tests the locomotion behavior of a 2D walker robot on a flat plane. The agent is evaluated on its ability to achieve four different standing poses that are placed ± 7, and ± 12 meters in the x axis away from the initial pose. For success, we check if the agent's x position is within a small threshold from the goal pose's x position. The state and goal space is 9 dimensional, containing the walker's xz positions and joint angles. The environment code was taken from Mendonca et al. (2021).

Ant Maze: A high-dimensional ant robot needs to move through hallways from the bottom left to top left (see Fig. 3). This environment is a long-horizon challenge due to the long episode length (500 timesteps) and traversal distance. We evaluate the ant on reaching 4 hard goals at the top left room, and 4 intermediate goals in the middle hallway. Ant Maze has the highest dimensional state and goal spaces: 29 dimensions that correspond to the ant's position, joint angles, and joint velocities. The first three dimensions of the state and goal space represent the xyz position. The next 12 dimensions represent the joint angles for each of the ant's four limbs. The remaining 14 dimensions represent the velocities of the ant in the x-y direction and the velocities of each of the joints. Ant Maze also has an 8 dimensional action space. The 8 dimensions correspond to the hip and ankle actuators of each limb of the ant. Success is based upon the L2 distance between the xy position of the ant and the goal being less than 1.0 meters, which is approximately the width of a cell. The dimensions of the entire maze is approximately 6 x 8 meters. This environment is a modification from the Ant Maze environment in Pitis et al. (2020). We modified the environment so that the state and goal space now includes the ant's xyz positions along with the joint positions and velocities instead of just the xy positions. We also added an additional room in the top left in order to evaluate against a harder goal.

3-Block Stack: A robot has to stack three blocks into a tower configuration. The state and goal space for this environment is 14 dimensional. The first five dimensions represent the gripper state and the other nine dimensions represent the xyz positions of each block. The action space is 4 dimensional where the first three dimensions represent the xyz movement of the gripper and the last dimension represents the movement of the gripper finger. Success is based upon the L2 distance between the xyz position of all of object and the goal position of the corresponding object being less than 3cm. This environment is a modification from the FetchStack3 environment in Pitis et al. (2020).

A.2 BASELINES

Algorithm 4 LEXA MBRL Training

Input: goal / expl. policies π^G, π^E, world model $\widehat{\mathcal{T}}$, rewards r^G, r^E
$\mathcal{D} \leftarrow \{\}$ Initialize buffer.
for Episode $i = 1$ to N_{train} **do**
  $\tau \leftarrow$ GoalDirectedExploration$(\ldots)$
  $\mathcal{D} \leftarrow D \cup \tau$
  Update model $\widehat{\mathcal{T}}$ with $(s_t, a_t, s_{t+1}) \sim D$
  Update π^G in imagination with $\widehat{\mathcal{T}}$ to maximize r^G
  Update π^E in imagination with $\widehat{\mathcal{T}}$ to maximize r^E
end for

Here, we first present pseudocode for all methods. We start by defining a generic MBRL training loop in Algorithm 4 that alternates between data collection (instantiated by specific methods) and policy and world model updates. Next, we define the pseudocode for PEG and all baselines below. To run a method, we simply drop in the data collection logic specified by the method into the LEXA training loop. For exploration, LEXA and P2E do not use Go-explore, while PEG, MEGA, and Skewfit do.

Algorithm 5 LEXA

function GOALDIRECTEDEXPLORATION(...)
  if $i\%2 = 0$ **then**
    Sample random goal g from buffer.
    Collect trajectory τ with $\pi^G(\cdot \mid \cdot, g)$
  else
    Collect trajectory τ with π^E
  end if
return τ
end function

Algorithm 6 PEG

function GOALDIRECTEDEXPLORATION(...)
  Compute goal g by optimizing Eq. 5 with MPPI
  $\tau \leftarrow$ *GO-EXPLORE*(g, π^G, π^E)
return τ
end function

Algorithm 7 MEGA

function GOALDIRECTEDEXPLORATION(...)
  $g \leftarrow \min_{g \in \mathcal{D}} \widehat{p}(g)$
  $\tau \leftarrow$ *GO-EXPLORE*(g, π^G, π^E)
return τ
end function

Algorithm 8 Skewfit

function GOALDIRECTEDEXPLORATION(...)
  $g \sim \left\{ g \cdot \widehat{p}(g)^{-1} \mid g \in \mathcal{D} \right\}$
  $\tau \leftarrow$ *GO-EXPLORE*(g, π^G, π^E)
return τ
end function

Algorithm 9 Plan2Explore

function GOALDIRECTEDEXPLORATION(...)
  Collect trajectory τ with π^E
return τ
end function

LEXA LEXA (Mendonca et al., 2021) is trains goal-conditioned policies with model-based RL. It trains two policies, an exploration policy and a goal-conditioned "achiever" policy. The original LEXA codebase was designed for image-based environments, so we implemented a state-based LEXA agent by modifying DreamerV2 (Hafner et al., 2021). To do so, we added the π^G and π^E policies, goal-conditioning logic, and the temporal distance reward network.

Original MEGA codebase We used the original MEGA codebase to train a MEGA and a Skewfit agent (Pitis et al., 2020; Pong et al., 2019) for 1 million environmental steps to solve the Point-maze, Ant Maze, and 3-Block Stack tasks mentioned in Section 6. We used the original MEGA implementation with the same hyperparameters except for their goal-conditioned policy training scheme.

MEGA proposes Rfaab, a custom goal relabeling strategy to train the goal-conditioned policy. By default Rfaab relabels transitions with test time goals to train the goal-conditioned policy, which is not possible in our unsupervised exploration setup. Therefore, we changed the Rfaab hyperparameters to rfaab_0_4_0_5_1, which no longer grants access to test goals.

We find that both MEGA and Skewfit agent fail to scale to the harder environments (Ant Maze and 3-Block Stack) as seen in Figure 8. One reason could be that the MEGA codebase uses model-free RL, which is more sample inefficient. Therefore, we reimplemented MEGA and Skewfit with LEXA, the backbone MBRL agent that PEG uses as well.

	MEGA	Skewfit
Point Maze	90%	0%
Ant Maze	0%	0%
3-Block Stack	0%	0%

Figure 8: Success Rate of MEGA and Skewfit Agent

Model-based MEGA For model-based MEGA, we simply port over MEGA's KDE model. Conveniently, LEXA already trains a goal-conditioned value function, which we use for filtering out goals by reachability. We use the same KDE hyperparameters as the original MEGA paper. As seen in in Figure 4, our MEGA implementation gets non-trivial success rates, improving over the original MEGA baseline.

Model-based Skewfit For Skewfit, we port over the Skewfit baseline in MEGA's codebase. The implementation is straightforward and similar to model-based MEGA. Instead of picking the minimum density goal, Skewfit picks goals inversely proportional to their density. As seen in in Figure 4, our Skewfit implementation gets non-trivial success rates.

Plan2Explore Our Plan2Explore baseline uses a Plan2Explore exploration policy to gather data for the world model and trains a goal-conditioned policy in imagination. Our LEXA implementation already uses Plan2Explore, so this variant simply requires us to only rollout the exploration policy in the real world.

A.3 Implementation Details

MPPI MPPI is a popular optimizer for planning actions with dynamics models (Williams et al., 2015; Nagabandi et al., 2019). Instead of planning sequences of actions, which grows linearly with horizon, PEG only needs to "plan" with a goal variable, making the search space independent of the horizon. First, we present a high-level summary of MPPI, and refer interested readers to Nagabandi et al. (2019) for a more detailed look at MPPI.

The process begins by randomly sampling N goal candidates g from a Gaussian distribution. These candidates are then evaluated as described in Figure 2 - we generate goal-conditioned trajectories for each goal g_k through the world model, and compute the expected exploration value V_k for each goal. This exploration value acts as the "score" for the goal candidate. Once we have scores for each goal candidate, the Gaussian distribution is refit according to the rule:

$$\mu_t = \frac{\sum_{k=0}^{N}(e^{\gamma \cdot V_k})(g_k)}{\sum_{k=0}^{N}(e^{\gamma \cdot V_k})} \tag{6}$$

where γ is the reward weight hyperparameter. We repeat this process of sampling, evaluation, and updating for multiple iterations.

	Total Runtime (Hours)	Episodes	Episode Length	Seconds per Episode
Point Maze	16	12000	50	4.8
Walker	16	5000	150	11.52
AntMaze	48	2000	500	86.4
3-Block Stack	48	6666	150	25.9

Figure 9: Runtimes per experiment.

Runtime The runtime and resource usage between methods did not differ significantly, as everything is implemented on top of the backbone LEXA model-based RL agent. Runtime is dominated by neural network updates of the policies and world model, not the goal selection routine defined by each method. Each seed was run on 1 GPU (Nvidia 2080ti or Nvidia 3090) and 4 CPUs, and required 11GB of GPU memory. See Figure 9 for training time.

	Seconds / Episode
PEG:	0.51
MEGA:	0.48
SkewFit:	0.46

Figure 10: Runtime for goal selection.

Next, we benchmarked the goal selection procedure for PEG and the other goal selection baselines in the block stacking environment and recorded the average wall clock time in Figure 10.

We can see that there is little difference in speed between methods, and the overhead introduced by PEG goal selection is minimal to LEXA, and competitive with other goal selection baselines. Because LEXA does not select goals, it finishes up to an hour earlier than goal setting methods in our experiments. As a sidenote, the times reported above are amortized over episodes, since we compute a set of 50 goals every 50 episodes for all methods, rather than computing 1 goal per episode.

Hyperparameters For parameter tuning, we used the default hyperparameters of the LEXA backbone MBRL agent (e.g. learning rate, MLP size, etc.) and kept them constant across all baselines. PEG only has 1 hyperparameter that requires tuning - the reward weight, which affects the MPPI update distribution. The higher the weight, the more we update the goal sampling distribution towards high-reward trajectories. For each experiment, we tried weight values of (1, 2, 10) by running 1-2 seeds of PEG for each value. We used a weight of 1, 2, 2, 10 for the 4 experiments respectively . PEG uses MPPI, a sample-based optimizer, to optimize the objective. While MPPI has hyperparameters such as the number of samples and number of iteration rounds, these are easy to tune, since optimizer performance increases with the amount of samples and iterations. We therefore just choose as many samples (2000 candidates) and rounds (5 optimization rounds) as we can while keeping training time reasonable.

A.4 PEG WITH OTHER EXPLORATION METHODS

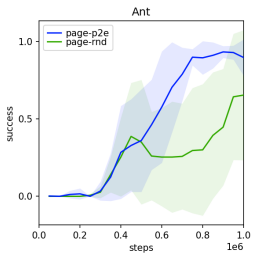

Figure 11: P2E vs. RND

While we chose to train our exploration policy and value function with Plan2Explore, PEG can work with any exploration method as long as it provides an exploration reward and policy. Random Network Distillation (RND) is another powerful exploration method that rewards discovering new states. We run both variants with 5 seeds in the Ant environment Figure 11. We find that the RND variant still explores the environment, albeit not as well as P2E. We hypothesize P2E exploration is particularly synergistic with our model-based RL framework, since the P2E explorer explicitly seeks transitions (s, a, s') that improve the model. As the model accuracy increases, so does the quality of the goals generated by PEG .

A.5 MPPI VS CEM FOR GOAL OPTIMIZATION

We investigate the impact of the goal optimizer on PEG . We choose two popular optimizers, MPPI and CEM, to optimize our objective, and run 5 seeds of each variant in the stacking environment. As seen in Fig. 12, the two agents perform similarly, showing that the PEG objective is robust to the choice of optimizer.

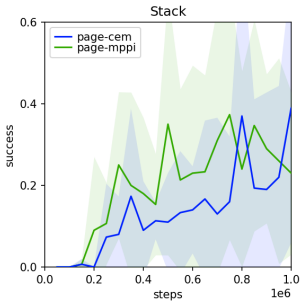

Figure 12: MPPI vs. CEM

A.6 Does conditioning on PEG goals maximize exploration?

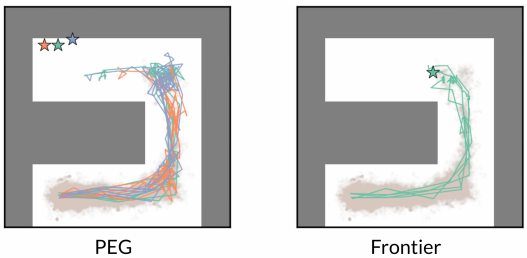

Figure 13: PEG exploration in a U-maze. Brown background dots: explored states, commanded goals: $\star$, resulting paths: colored lines. (Left) PEG optimizes directly for exploration, even setting unseen goals, and achieving farther paths. (Right) Setting goals at the frontier of the seen state distribution yields less exploration.

We assess the importance of accounting for the goal-conditioned policy's capabilities. To do so, we evaluate if states coming from a policy conditioned on PEG goals are more novel than states coming from the same policy conditioned on other goal strategies. In Figure 13, we take a partially trained agent and its replay buffer, and plot the proposed goals and resulting trajectories for PEG and MEGA (called Frontier in the figure). We find that PEG goals lead the ant to the top left more often. This figure is also used in the intro for exposition.