NAVIGATION WITH QPHIL: QUANTIZING PLANNER FOR HIERARCHICAL IMPLICIT Q-LEARNING

Alexi Canesse[*,†,1], **Mathieu Petitbois**[*,2], **Ludovic Denoyer**[3], **Sylvain Lamprier**[4], **Rémy Portelas**[2]
[1]ENS Lyon [2]Ubisoft La Forge [3]H Company [4]University of Angers

ABSTRACT

Offline Reinforcement Learning (RL) has emerged as a powerful alternative to imitation learning for behavior modeling in various domains, particularly in complex long range navigation tasks. An existing challenge with Offline RL is the signal-to-noise ratio, i.e. how to mitigate incorrect policy updates due to errors in value estimates. Towards this, multiple works have demonstrated the advantage of hierarchical offline RL methods, which decouples high-level path planning from low-level path following. In this work, we present a novel hierarchical transformer-based approach leveraging a learned quantizer of the state space to tackle long horizon navigation tasks. This quantization enables the training of a simpler zone-conditioned low-level policy and simplifies planning, which is reduced to discrete autoregressive prediction. Among other benefits, zone-level reasoning in planning enables explicit trajectory stitching rather than implicit stitching based on noisy value function estimates. By combining this transformer-based planner with recent advancements in offline RL, our proposed approach achieves state-of-the-art results in complex long-distance navigation environments.

1 INTRODUCTION

Navigation and locomotion in complex, long-horizon embodied environments is a long-standing challenge within Machine Learning (Kaelbling et al., 1996; Sutton & Barto, 2018). Operating non-trivial agents in such environments is critical in a wide range of real-world applications, such as in robotics (Eysenbach et al., 2019) or in the video game industry (Alonso et al., 2020). A core difficulty of navigation lies in solving long-horizon tasks that require intricate path planning (Hoang et al., 2021; Park et al., 2024). In the Reinforcement Learning (RL) setting (Sutton & Barto, 2018), traditional online Goal-Conditioned deep Reinforcement Learning (GCRL) methods often struggle with such long-horizon tasks because of the sparse nature of the reward signal, leading to hard exploration problems. Offline GCRL circumvents this exploration problem by leveraging large amounts of unlabeled and diverse demonstration data to learn policies through passive learning (Prudencio et al., 2023). A core advantage of offline RL compared to other forms of behavior extraction from datasets, for instance imitation learning, is the ability to improve over suboptimal datasets, e.g. by learning state value functions to bias the learned policy towards rewarding actions (Kostrikov et al., 2021). However, offline RL is not trivial to apply for long-horizon goal-reaching tasks, which often provide sparse reward signals, leading to a noisy value function which consequently hinders the performance of the policy. Part of this issue comes from low "signal-to-noise" ratio to learn the value function (Park et al., 2024). Because a suboptimal action can be corrected quickly in subsequent steps of a trajectory, its impact on the real value for faraway goals can be covered by the value prediction noise, which can lead to the learning of suboptimal behaviors for the policy.

Hierarchical architectures have shown considerable advantages in goal-conditioned navigation to solve such issues (Vezhnevets et al., 2017; Pertsch et al., 2021; Park et al., 2024). These approaches effectively decompose the problem into two distinct components: high-level path planning and low-level path following. Among these, Hierarchical Implicit Q-Learning (HIQL) (Park et al., 2024) has recently emerged as the state-of-the-art method. HIQL leverages a hierarchical structure to learn

[*]Denotes equal contribution. Correspondance to `mathieu.petitbois@ubisoft.com`
[†]Work done during an internship at Ubisoft La Forge

both a high-level policy for generating subgoals and a low-level policy for achieving these subgoals, all within an offline reinforcement learning framework.

Although introducing a hierarchical structure enhances performance by improving the signal-to-noise ratio at each level, it only partially alleviates the issue. For long-distance tasks, the signal-to-noise ratio still degrades during subgoal generation, which can result in a noisy high-level policy and, consequently, reduced performance. In this paper, we propose to shift the learning paradigm of the high-policy towards discrete space planning. Towards this, we first train a Vector Quantized Variational Autoencoder (VQ-VAE) (Van Den Oord et al., 2017) on the state-space from which we extract its quantized representation, namely leading to a clustering of the state space into what we propose to refer to as *landmarks*. We ensure the temporal consistency of the obtained landmarks through a contrastive regularization of the VQ-VAE loss. Then, we leverage a transformer architecture (Vaswani et al., 2017) to extract a discrete high-level policy, enabling consistent landmark-level planning in the discrete space representation. Finally, we train a combination of a low-level landmark-conditioned policy and a low-level goal conditioned policy to solve the subgoal and last-goal navigation tasks respectively.

Our main contribution is to introduce **Quantizing Planner for Hierarchical Implicit Learning (QPHIL)**, a novel approach that addresses long-range navigation by combining the strengths of VQ-VAE, transformers, and offline reinforcement learning. We first evaluate QPHIL on the established AntMaze navigation tasks (Fu et al., 2020), then introduce a novel, more challenging variant, *AntMaze-Extreme*, along with two associated datasets, better suited to study long-distance navigation. In both settings we demonstrate that QPHIL matches or outperforms prior offline goal-conditioned RL methods, particularly in large-scale settings.

2 Related work

VQ-VAEs for reinforcement learning Vector Quantized Variational Autoencoders (Van Den Oord et al., 2017) have demonstrated their utility in reinforcement learning, particularly for offline setups. (Jiang et al., 2022) and (Luo et al., 2023) use a VQ-VAE to discretize continuous action spaces, mitigating the curse of dimensionality. In contrast, QPHIL uses a VQ-VAE to quantize states, simplifying waypoint generation in long-horizon tasks. These two approaches are complementary: action quantization focuses on simplifying policy search, while state quantization helps in task decomposition such as in (Hamed et al., 2024) where a VQ-VAE is used to define landmarks as states like in QPHIL but without a contrastive loss and in the online setting. Within goal-conditioned reinforcement learning, several works used VQ-VAE to encode observations into discrete (sub)goals. (Lee et al., 2024a) learn quantized goals to simplify curriculum learning. (Islam et al., 2022) also use quantization to map (sub)goals into discrete and factorized representations to efficiently handle novel goals at test time. Both these works focus on online goal-conditioned reinforcement learning while QPHIL tackles the offline learning setting. (Kujanpää et al., 2023) also uses VQ-VAE to generate discrete subgoals, but while they rely on a finite subgoal set derived from offline learning, QPHIL identifies subgoals directly through the VQ-VAE. To the best of our knowledge, VQ-VAE has never been applied for discrete planning in offline GCRL settings.

Hierarchical offline learning Leveraging a hierarchical structure to decompose and simplify sequential decision-making problems is a long-standing idea and subject of research within machine learning (Schmidhuber, 1991; Sutton et al., 1999). Recently, multiple successful works renewed the interest of the research community to these models, both for online (Vezhnevets et al., 2017; Pertsch et al., 2021; Kim et al., 2021; Fang et al., 2022) and offline reinforcement learning (Nachum et al., 2018b; Ajay et al., 2020; Rao et al., 2021; Rosete-Beas et al., 2023; Yang et al., 2023; Shin & Kim, 2023). Among these, Hierarchical Implicit Q-Learning (HIQL) from (Park et al., 2024) has emerged as the state-of-the-art method for offline goal-conditioned RL. Most methods differ in how they represent and use subgoals; for instance, (Nachum et al., 2018a) compare different subgoal representations, while (Ajay et al., 2020) focus on detecting and combining primitive behaviors. While all aforementioned works focus on continuous state representations, QPHIL leverages the advantage of discrete state representations to simplify long-distance navigation.

Planning Hierarchical planning methods are a natural complement to RL. For instance, HIPS (Kujanpää et al., 2023) learns to segment trajectories, generating subgoals of varying lengths to facilitate adaptive planning. HIPS-ε (Jiang et al., 2023; Kujanpää et al., 2024) introduces hybrid hierarchical

methods and offers completeness guarantees, but their method is only usable with a discrete state space. (Li et al., 2022) proposes a method combining a high-level planner, based on a VAE, with a low-level offline RL policy. The VAE serves as the planner by leveraging the low-level policy's value function. QPHIL, on the other hand, utilizes a simpler subgoal planning approach directly tied to a discrete state-space via VQ-VAE.

Transformers for (hierarchical) offline RL Transformers have recently found application in hierarchical setups to solve RL problems. In (Correia & Alexandre, 2023), transformers are used for hierarchical subgoal sampling, where a high-level transformer generates subgoals for a low-level transformer responsible for action selection. Similarly, (Badrinath et al., 2024) combine a Decision Transformer (DT) from (Chen et al., 2021) with a waypoint-generation network. (Ma et al., 2024) present a hierarchical transformer-based approach outperforming both aforementioned methods. (Li et al., 2022; Ma et al., 2024) are extensions of DT that allows stitching, a known issue with Decision Transformer (Fujimoto & Gu, 2021; Emmons et al., 2021; Kostrikov et al., 2021; Yamagata et al., 2023; Xiao et al., 2023). Their approach, Goal-prompted Autotuned Decision Transformer (G-ADT) (Ma et al., 2024), is able to efficiently integrate an offline RL learning scheme similar to HIQL. G-ADT uses a low-level transformer and a simple high level subgoal policy, while we focus on the opposite scenario: our transformer is used to generate a plan of subgoal, which are then followed by a fully connected neural network. G-ADT uses an offline reinforcement learning objective to train its high-level policy while we rely on a simpler imitation learning objective.

Sequence generation (Lee et al., 2024b) explore sequence generation using tokens learned via a VQ-VAE, much like QPHIL; but their work does not extend to reinforcement learning. In RL, sequence models have been used for various components (Bakker, 2001; Heess et al., 2015; Chiappa et al., 2017; Parisotto et al., 2020; Kumar et al., 2020). However, none of these approaches integrate planning over a discrete representation, which is central to our method. Sequence generation also plays a key role in offline RL, where it is helping to prevent out-of-distribution actions (Fujimoto et al., 2019; Kumar et al., 2019; Ghasemipour et al., 2021). Trajectory Transformer (Janner et al., 2021) completely treats offline RL as a sequence generation problem. They use a transformer to perform planning using Beam-Search and an IQL-like value function. Contrary to QPHIL, they use a simple dimension-wise uniform or quantile discretization.

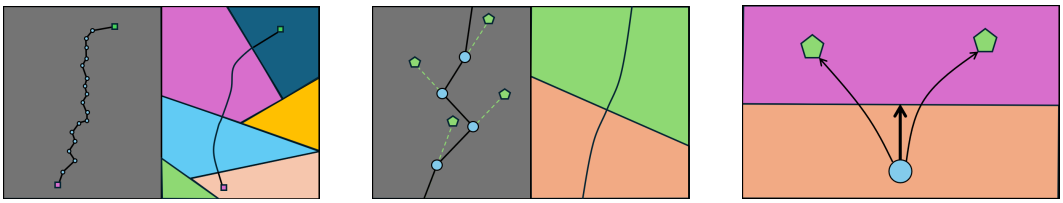
Spatial zone learning and skill discovery Zone-based spatial navigation and skill discovery are additional techniques that overlap with hierarchical RL and QPHIL. For instance in the context of online RL, (Kamienny et al., 2022) proposes to discover a set of "easy-to-learn" short policies, each corresponding to a given skill defined as an area of the state space, which can be eventually composed for the task at hand. Using a VQ-VAE, (Mazzaglia et al., 2022) define skills that are used to influence exploration in online policies. In a closer context with a known state space, (Gao et al., 2023) segments space into zones and uses these segments to facilitate goal-reaching tasks, but their method is restricted to vision environments. Similarly, (Hausman et al., 2017) uses a multi-modal imitation learning approach to discover and segment skills from unstructured demonstrations, which is close to the discrete landmark generation in QPHIL. In skill decision transformer (Sudhakaran & Risi, 2023), a transformer is used to predict actions from latent variables discovered by a VQ-VAE. While their approach is close to QPHIL, it differs by not using contrastive loss and not planning subgoals.

3 PRELIMINARIES

3.1 OFFLINE GOAL CONDITIONED REINFORCEMENT LEARNING

We frame our work in the context of offline goal-conditioned Reinforcement Learning (offline GCRL), which involves training an agent to interact with an environment to reach specific goals, without getting access to the environment itself at train time. It is typically modeled as a Markov Decision Process (MDP) defined by a tuple $(\mathcal{S}, \mathcal{A}, p, \mu, r)$, a dataset of demonstration trajectories $\mathcal{D}$ and a given goal space $\mathcal{G}$, where $\mathcal{S}$ is the state space, $\mathcal{A}$ the action space, $p(s_{t+1}|s_t, a_t) \in \mathcal{S} \times \mathcal{A} \to \mathcal{P}(\mathcal{S})$ the transition dynamics, $\mu \in \mathcal{P}(\mathcal{S})$ the initial state distribution and $r(s_t, g) \in \mathcal{S} \times \mathcal{G} \to \mathbb{R}$ the goal-conditioned reward function given the goal space $\mathcal{G}$. In GCRL, the reward is sparse as $r(s, g) = 1$ only when s reaches g and 0 otherwise. Hence, our objective is to leverage the dataset $\mathcal{D}$ composed of reward-free pre-recorded trajectoires $\tau = (s_0, a_0, ..., s_{T-1}, a_{T-1}, s_T)$ to learn the policy $\pi(a_t|s_t, g)$ to reach given goals $g \in \mathcal{G}$, by maximizing the expected cumulative reward, or

return, $J(\pi)$, which can be expressed as: $J(\pi) = \mathbb{E}_{\substack{g\sim d_g \\ \tau\sim d_\pi}}\left[\sum_{t=0}^{T}\gamma^t r(s_t, g)\right]$, where γ is a discount factor, d_g represents the goal distribution and d_π is the trajectory distribution defined by: $d_\pi(\tau, g) = \mu(s_0)\prod_{t=0}^{T}\pi(a_t|s_t, g)p(s_{t+1}|s_t, a_t)$ and represents the trajectory distribution when the policy is used. To study long range navigation, we consider in the following positional environments, where the goal space $\mathcal{G}$ can be computed as the set of positions coordinates $\mathcal{S}^p$.



(a) Simpler high level planning (b) Smoother low level targets (c) Easier target conditioning

Figure 1: **Motivations behind QPHIL** (a) QPHIL aims to simplify the planning of the subgoals by leveraging discrete tokens. (b) By doing so, QPHIL avoids the noisy high-frequency target subgoal updates by updating the subgoal of the low-level policy after each landmark traversal only. (c) The subgoal reaching tasks are less demanding in conditioning for the low policy as it corresponds to the reaching of an entier subzone instead of a precise subgoal.

3.2 Hierarchical Implicit Q-Learning (HIQL)

Because of the sparsity of the offline GCRL's reward signals, bad actions can be corrected by subsequent good actions, and good actions can be undermined by future bad actions in a trajectory. Hence, offline RL methods risk mislabeling bad actions as good ones, and vice versa. This leads to the learning of a noisy goal-conditioned value function: $\hat{V}(s_t, g) = V^*(s_t, g) + N(s_t, g)$ where V^* corresponds to the optimal value function and N corresponds to a noise. As the "signal-to-noise" ratio worsens for longer term goals, offline RL methods such as IQL (Kostrikov et al., 2021) struggle when the scale of the GCRL problem increases, leading to noisy advantages estimates for which the noise overtakes the signal. To alleviate this issue, HIQL (Park et al., 2024) first proposes to learn a noisy goal conditioned action-free value function, inspired from IQL (Kostrikov et al., 2021):

$$\mathcal{L}_V(\theta_V) = \mathbb{E}_{(s_t, s_{t+1}, g)\sim\mathcal{D}}\left[L_2^T(r(s_t, g) + \gamma V_{\theta_V}(s_{t+1}, g) - V_{\theta_V}(s_t, g))\right] \tag{1}$$

using an expectile loss $L_2^\tau(u) = |\tau - \mathbb{1}(u < 0)|u^2, \tau \in [0.5, 1)$ on the temporal difference of the value function, which aims at anticipating in-distribution sampling without querying the environment. This loss is then used to learn two policies with advantage weighted regression (AWR): $\pi^h(s_{t+k}|s_t, g)$ to generate subgoals on the path towards goal g and $\pi^l(a_t|s_t, g')$, with $g' \in \mathcal{G}$ a given subgoal, to generate actions to reach the subgoals, in a hierarchical manner. With this division, each policy profits from higher signal-to-noise ratios, as the low-policy only queries the value function for nearby subgoals $V(s_{t+1}, s_{t+k})$ and the high policy queries the value function for more distant goal $V(s_{t+k}, g)$.

3.3 Quantizing Planner for Hierarchial Implicit Learning (QPHIL)

If HIQL shows significant improvements in offline GCRL problems compared to previous flat-policy methods, its performance depends on the right choice of the subgoal step k. A high k would improve the high policy's signal-to-noise ratio by querying more diverse subgoals but at the cost of decreasing the signal-to-noise ratio of the low policy. Conversely, a low k would improve the low policy's signal-to-noise ratio by querying values for nearby goals but at the cost of the diversity of the high subgoals. Hence, HIQL might struggle for longer term goal reaching tasks as the low level performance imposes the choice of a sufficiently low k, which leads to high frequency noisy high subgoal targets for the low policy to follow. QPHIL proposes to mitigate this issue by shifting the learning paradigm of the high policy into planning in a discretized learned space representation (see Fig. 1).

4 QUANTIZING PLANNER FOR HIERARCHICAL IMPLICIT LEARNING

In this paper, we propose a new hierarchical goal conditionned offline RL algorithm: Quantizing Planner for Hierarchical Implicit Q-Learning (QPHIL). While current hierarchical methods rely heavily on continuous waypoint predictions, we propose to consider discrete subgoals, allowing to simplify the planning process. Instead of relying on precise coordinates, QPHIL identifies key landmarks to guide trajectory planning, much like how a road trip is described by cities or highways rather than specific geographic points. The algorithm detects these landmarks, creates landmark-based sequences, and formulates policies to navigate between them, ultimately reaching the target destination.

4.1 OVERALL DESIGN

QPHIL operates through four components: a state quantizer ϕ, which divides the state space positions into a finite set of landmarks, a plan generator π^{plan}, which acts as a high-level policy to generate a sequence of landmarks to be reached given the final goal, and two low-level policy modules: π^{landmark}, which targets state areas defined as landmarks, and π^{goal}, which targets a specific state goal. The state quantizer $\phi : \mathcal{S}^p \to \Omega$, with $\Omega = \{1, \dots, k\}$, is used to map state positions into a set of k landmark indexes (or tokens), which serve as the building blocks for our planning strategy. These discrete representations are then processed by the plan generator, which assembles them into a coherent sequence that outlines the overall trajectory to be followed in the environment to reach the requested goal g. Given any history of tokens $(\omega_0, \cdots, \omega_n)_{n>0}$ and a targeted goal $g \in \mathcal{G}$, the plan generator produces sequences of tokens $(\omega_{n+1}, \cdots, \omega_{n+l})$ auto-regressively until $\omega_{n+l} = \dot{\omega}$ (with $\dot{\omega}$ an extra end of sequence token that stops the generation), following: $\pi^{\text{plan}}\left((\omega_{n+1}, \cdots, \omega_{n+l}) \mid \phi(g), (\omega_i)_{i=0}^{n}\right) = \prod_{t=1}^{l} \pi^{\text{plan}}\left(\omega_{n+t} \mid \phi(g), (\omega_i)_{i=0}^{n+t-1}\right)$. It is used from the start token $\omega_0 = \phi(s_0)$ of the episode to propose a sequence of landmarks to follow using $\pi^{\text{landmark}} : \mathcal{A} \times \mathcal{S} \times \Omega \to [0, 1]$, before navigating through the final goal g using $\pi^{\text{goal}} : \mathcal{A} \times \mathcal{S} \times \mathcal{G} \to [0, 1]$. For a given goal g and a start state s_0, the process first samples a new plan, which corresponds to a sequence of landmarks to be reached sequentially before navigating towards g. Then, until the first subgoal ω of this sequence is reached, π^{landmark} is used while conditioned on the current state s_t and the subgoal ω to sample actions to perform in the environment. When the subgoal is reached, it is removed from the list, and we move to the next one, and so on until the list of sub-goals is empty. At that point, π^{goal} is used to navigate towards the requested goal g. The remainder of this section presents our learning methodology for every component of our QPHIL approach. Each of the following components is learned sequentially.

4.2 TOKENIZATION

As defined in the previous section, the state quantizer ϕ is used to map positions into a set of k tokens. It is composed of an encoder $e : \mathcal{S}^p \to \mathbb{R}^d$ and a learned code-book $z : \Omega \to \mathbb{R}^d$, which associates each token to a continuous embedding. From these, ϕ is defined as: $\phi(s^p) = \arg\min_{\omega \in \Omega} \Delta(e(s), z(\omega))$, with Δ the euclidean distance in the latent space and $s^p \in \mathcal{S}^p$ the state position. Three losses are considered to train these components. First, the VQ-VAE learns a meaningful representation by considering a reconstruction loss, which ensures that states can be decoded from tokens they are projected into:

$$\mathcal{L}_{\text{recon}} = \mathbb{E}_{s^p \sim \mathcal{D}} ||f(z(\phi(s^p))) - s^p||_2^2 \tag{2}$$

where $\mathcal{D}$ is the dataset and $f : \mathbb{R}^d \to \mathcal{S}^p$ is a decoder network trained together with the code-book of token embeddings. As the gradient flow stops in the previous loss due to the discrete projection performed by ϕ, we need to consider an additional commitment loss to learn the encoder parameters:

$$\mathcal{L}_{\text{commit}} = \mathbb{E}_{s^p \sim \mathcal{D}} ||e(s^p) - \text{sg}(z(\phi(s^p)))||_2^2 + \beta ||\text{sg}(e(s^p)) - z(\phi(s^p))||_2^2 \tag{3}$$

where sg is the stop-gradient operator. The first term of this loss aims at attracting encoder outputs close to the code of the token states project into. As explained by authors of the VQ-VAE architecture (Van Den Oord et al., 2017), the embedding space grows arbitrarily if the token embedding does not train as fast as the encoder parameters. The second term, weighted by a hyperparameter β, aims to prevent this issue by forcing the encodings to commit to a code-book's embedding. To introduce dynamics of the environment in the representation learned, we consider a third contrastive

loss that incentivize temporally close states to be assigned the same tokens, while temporally distant states receive different tokens. To achieve this, we use the triplet margin loss (Balntas et al., 2016) applied to our setting:

$$\mathcal{L}_{\text{contrastive}} = \mathbb{E}_{\substack{s_t^p \sim \mathcal{D} \\ k \sim \{-\delta,\dots,\delta\} \\ k' \sim \mathbb{Z} \setminus \{-\delta,\dots,\delta\}}} \max\left\{\Delta(e(s_t^p), e(s_{t+k}^p)) - \Delta(e(s_t^p), e(s_{t+k'}^p)), 0\right\} \tag{4}$$

where δ is the time window used to specify temporal closeness of states in demonstration trajectories. This loss is of crucial importance in navigation, for instance in settings with thin walls, where two states can be close in the input space while corresponding to very different situations. The tokenizer loss, used in training is then a linear combination of the three previous losses:

$$\mathcal{L}_{\text{tokenizer}} = \alpha_{\text{recon}}\mathcal{L}_{\text{recon}} + \alpha_{\text{commit}}\mathcal{L}_{\text{commit}} + \alpha_{\text{contrastive}}\mathcal{L}_{\text{contrastive}} \tag{5}$$

4.3 Sequence generation

Once the tokenizer has been trained, each state from dataset trajectories can be discretized leading to sequences of tokens. Temporal consistency induces sub-sequences of repeated tokens corresponding to positions within a given region. By applying a simple post-processing step $\eta^{\phi}(\tau)$ that removes consecutive repetitions of tokens in a trajectory τ, we obtain more concise sequences that succinctly represent key zones to traverse in the correct order. For instance, a tokenized sequence such as "1 1 1 2 2 3 3 3 4 4" is simplified to "1 2 3 4", reflecting the core structure of the trajectory. Then, the planner π^{plan} is trained following a teacher forcing approach on trajectories from $\mathcal{D}$, considering any future token of $\tau \in \mathcal{D}$ as the associated training goal:

$$\mathcal{L}_{\text{plan}} = -\mathbb{E}_{\tau\sim\mathcal{D}}\mathbb{E}_{t<|\tau|,\phi(\tau_t)\neq\phi(\tau_{t+1})}\mathbb{E}_{\substack{g\in\mathcal{G}, \\ \phi(g)\in\eta^{\phi}\tau_{>t}}}\left[\log \pi^{\text{plan}}(\phi(\tau_{t+1}) \mid \phi(g), \eta^{\phi}(\tau_{\leq t}))\right] \tag{6}$$

with $|\tau|$ the number of states in τ, τ_t the t-th state in τ, and $\tau_{\leq t}$ (resp. $\tau_{>t}$) the history (resp. future) of τ at step t. We implement π^{plan} using a transformer architecture (Vaswani et al., 2017) h_θ, where $\pi^{\text{plan}}(. \mid \phi(g), \eta^{\phi}(\tau_{\leq t}))$ is defined for any $\omega \in \Omega$ using a softmax on the outputs of $h_\theta(\phi(g), \eta^{\phi}(\tau_{\leq t}))$. While an alternative would be to consider a markov assumption stating that $\pi^{\text{plan}}(. \mid \phi(g), \eta^{\phi}(\tau_{\leq t})) \approx \pi^{\text{plan}}(. \mid \phi(g), \phi(s_t^p))$, we claim that dependency on the full history of the sequence is useful to anticipate the next token to be reached, as it can be leveraged to deduce the precise location of the agent in large landmark areas (which is unknown during plan generation). We propose to consider in our experiments a data augmentation process on top of our behavioral cloning approach, which allowed us to obtain similar results, with greatly lower computational cost. Our data augmentation process relies on the opportunity of accurate trajectory stitching that our quantized space offers. As such, we augment every token sequence of $\mathcal{D}$ by stitching all other sub-sequences from the dataset that contains its last token, allowing for a higher state coverage.

4.4 Low-level policies

As described above, two low-level policies π^{landmark} and π^{goal} have to be trained to perform actions in the environment. Both of these policies are trained via IQL (Kostrikov et al., 2021). As π^{goal} works with initial (non tokenized) goals to allow final precise navigation in the final area of the task, we consider a classical V network V^{goal} trained on raw states and goals, independently from all other components, from which the policy is extracted using AWR:

$$\mathcal{L}_{\pi^{\text{goal}}} = \mathbb{E}_{(s_t,s_{t+1},g)\sim\mathcal{D}}\Big[\exp\left(\beta \cdot (V^{\text{goal}}(s_{t+1}, g) - V^{\text{goal}}(s_t, g))\right)\log \pi^{\text{goal}}(s_{t+1}|s_t, g)\Big] \tag{7}$$

Our policy π^{landmark} uses the same principle, but replaces the distant goal g by sub-goals defined as the next landmark to be reached from quantized trajectories in the buffer of training transitions. That is, given any training trajectory $\tau = ((s_t, a_t, s_{t+1}, g))_{t=0}^{|\tau|-1}$, we consider a sequence of relabelled transitions $\tilde{\tau} = ((s_t, a_t, s_{t+1}, \text{next}(\tau, t))_{t=0}^{|\tau|-1}$, where $\text{next}(\tau, t) = \phi\left(s^p_{\min(\{l\in\{t+1,\dots,|\tau|\}:\phi(s_l^p)\neq\phi(s_t^p)\})}\right)$ corresponds to the next different subgoal in the sequence of quantized states $(\phi(s_t^p))_{t=0}^{|\tau|-1}$ of the trajectory τ. V^{landmark} is then trained on that set of relabelled transitions $\tilde{\mathcal{D}}$. Then, the policy is extracted similarly as for π^{goal} using equation 7 on $\tilde{\mathcal{D}}$ rather than $\mathcal{D}$, in order to obtain π^{landmark} via a relabelled IQL from V^{landmark}.

5 EXPERIMENTS

Our experiments aim to address the following questions:

1. Does QPHIL's architecture enable efficient long-term navigation?
2. What is the impact of the contrastive loss used for landmark learning?
3. What is the impact of the different losses when training the quantizer ?

5.1 EXPERIMENTAL SETUP

Antmaze We measure QPHIL's performance through a set of AntMaze environments of increasing sizes, providing challenging long-term navigation problems. In AntMaze the agent controls an 8-DoF ant-shaped robot. Observations consist in a 29-dimension state vector (e.g. positions, torso coordinates and velocity, angles between leg parts). For original AntMaze environments we use datasets provided in the D4RL library (Fu et al., 2020) as well as two additional datasets for even larger mazes, namely Antmaze-Ultra provided by (Jiang et al., 2022) and Antmaze-Extreme which we created. For each maze type (medium, large, ultra and extreme), we train on two types of datasets: "play" and "diverse", each containing 1000 (500 for extreme) trajectories of 1000 steps (2000 for extreme). The "play" variant has been generated using hand-picked locations for the goal and starting positions while the "diverse" variant has been generated using random goal and starting positions.

Baselines We compare QPHIL to 5 previous methods ranging from model-free behavior cloning and offline RL methods. For the behavior cloning methods, we include in our baselines the flat Goal-Conditioned Behavior Cloning (GCBC) (Ghosh et al., 2019) and the Hierarchical Goal-Conditioned Behavior Cloning (HGCBC) (Gupta et al., 2019). For offline RL, we include a goal-conditioned variant of Implicit Q-Learning (GCIQL) (Kostrikov et al., 2021), Hierarchical Implicit Q-Learning (HIQL) (Park et al., 2024) as well as a flatten version of it called GCIVL which relies only the the value function to compute the advantages (Park et al., 2024). We performed our experiments on QPHIL on 8 seeded runs, results are provided with the mean $\pm$ std format in Table 1.

5.2 DOES QPHIL ARCHITECTURE ENABLE EFFICIENT LONG-TERM NAVIGATION ?

Table 1: **Evaluating QPHIL on AntMaze environments.** We see that QPHIL scales well with the length of the navigation range, competing with SOTA performance on the smaller mazes and improving significantly on the SOTA on the larger settings.

env_name	GCBC	GCIQL	GCIVL	HGCBC w/o repr	HGCBC w/repr	HIQL w/o repr	HIQL w/repr	QPHIL
antmaze-medium-diverse-v2	65 ± 11	80 ± 8	82 ± 8	46 ± 11	13 ± 9	92 ± 4	92 ± 4	92 ± 4
antmaze-medium-play-v2	60 ± 11	80 ± 9	84 ± 9	48 ± 9	10 ± 8	90 ± 5	92 ± 4	91 ± 2
antmaze-large-diverse-v2	10 ± 5	21 ± 10	59 ± 13	78 ± 7	18 ± 8	88 ± 4	85 ± 8	82 ± 6
antmaze-large-play-v2	9 ± 5	25 ± 12	50 ± 9	79 ± 7	14 ± 13	87 ± 7	84 ± 7	80 ± 3
antmaze-ultra-diverse-v0	16 ± 9	20 ± 8	6 ± 5	71 ± 12	32 ± 24	71 ± 7	71 ± 12	62 ± 7
antmaze-ultra-play-v0	15 ± 10	20 ± 10	10 ± 6	64 ± 12	13 ± 15	63 ± 20	74 ± 23	62 ± 4
antmaze-extreme-diverse-v0	9 ± 6	12 ± 7	5 ± 10	6 ± 14	0 ± 4	14 ± 17	20 ± 20	40 ± 13
antmaze-extreme-play-v0	8 ± 7	16 ± 7	0 ± 0	11 ± 10	4 ± 8	12 ± 16	28 ± 27	50 ± 7

We first analyze the performance in success rate of the different baselines on the state-based AntMaze-{Medium,Large,Ultra} settings. As usual in D4RL Antmaze benchmarks (Park et al., 2024), starting state and target goals are sampled near two reference points, forcing the agent to walk across the entire maze. Fig 2. showcases examples of tokenizations obtained by our VQ-VAE model. One can observe a tendency for learned clusters to decrease in size in the middle of all mazes, which can be explained by the higher number of demonstration data in those areas. Table 1 shows the results of our experiment on the set of AntMaze map. For HIQL, "w/ repr." means the use of representations for subgoals and goals, in opposite of "w/o repr." that takes raw values (see (Park et al., 2024)). We see that our method is near the state-of-the art on smaller and average scale maps. To test QPHIL's scaling ability in more difficult settings, we created a larger AntMaze environment

called AntMaze-Extreme (Fig. 3), along with two datasets variants "diverse" and "play". As shown in Table 1, in AntMaze-Extreme QPHIL attains up to 50% success rate, which is significantly above baseline results, e.g. HIQL scores in diverse and play datasets. While QPHIL remains competitive in short-term settings, our approach is especially well suited for long-distance goal reaching navigation.

Figure 2: **Tokenization example.** Each background point's color corresponds to its associated token. Tokens align with walls thanks to the contrastive loss.

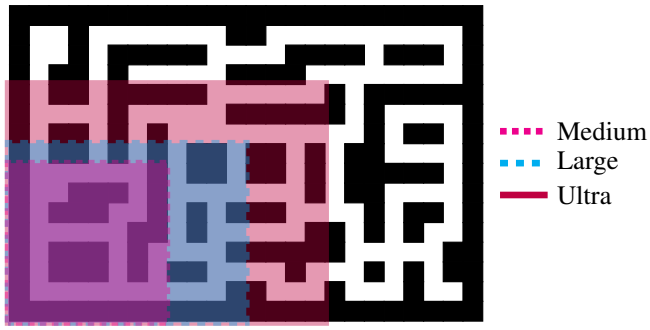
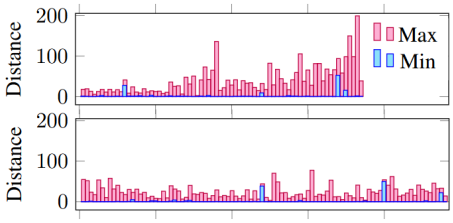


Figure 3: **Evaluating QPHIL on AntMaze-Extreme.** A top-down view of the maze with size comparisons.

5.3 What is the impact of the contrastive loss used for landmark learning ?



(a) Intertoken histograms

(b) Performances on Antmaze-Extreme.

Method	Diverse	Play
QPHIL (non-cont)	17 ± 1	26 ± 2
QPHIL	$\mathbf{40 \pm 13}$	$\mathbf{50 \pm 7}$

Figure 4: **Non-contrastive (top) and contrastive (bottom) intertoken distance histograms.** The non-contrastive tokenization (pink) results in higher extreme sized tokens, while the contrastive tokenization (blue) yields a smoother distribution, improving performance.

The use of a contrastive loss is essential in the context of high dimensional data, where the VQ-VAE reconstruction loss is not enough to learn temporally consistent latent encodings (meaning that temporally nearby states share spatially nearby encodings). To assess the impact of the contrastive loss on the learned landmarks, we compute, for each token, the minimum and maximum distances between states position and their corresponding codebook's decoded position. This is represented as histograms in Fig. 4. While the unconstrained VQ-VAE tends to allocate higher token density in areas of higher data density, we observe that the contrastive loss results in a smoother repartition of the tokens, which in consequence increases the performance of our model. This allows to stabilize conditonning in areas of high data density.

5.4 WHAT IS THE IMPACT OF THE DIFFERENT LOSSES WHEN TRAINING THE QUANTIZER ?

In QPHIL, the VQ-VAE quantizer is learned using a linear composition of three losses: the commit loss, the contrastive loss, and the reconstruction loss, which all have an associated coefficient hyper-parameter to be tuned. In our experiments, we used the same set of coefficients for each maze shape, which we found through a preliminary hyperparameter search to be robust across the diversity of maze sizes we considered. In the following, we analyze the impact of the different coefficients on the quality of the discretization.

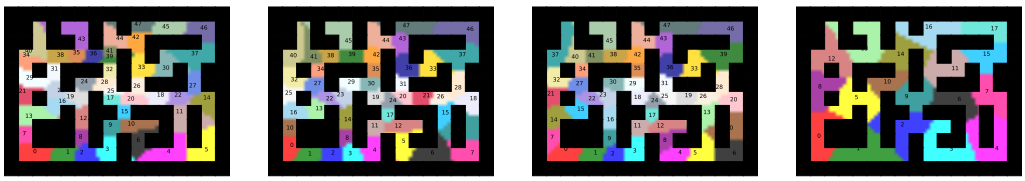


Figure 5: **Commit coefficient impact.** From left to right $\alpha_{\text{commit}} \in \{0, 1e1, 1e3, 1e6\}, \alpha_{\text{contrastive}} = 2e1, \alpha_{\text{recon}} = 1e5$. We see that a low commit coefficient leads to varying sized landmarks, while high commit loss diminishes the number of landmarks.

Commit loss The commit loss serves the purpose of maintaining a vicinity between the continuous encodings and the elements of the codebook in the latent space. A zero or low commit loss creates a poor repartition of the continuous representations with regard to the codebook. This creates varying sized areas, where some are too small and some too big (e.g. Fig. 5, leftmost map). On the other hand, a high commit loss will force the encoder to match the codebook vectors too rigidly. This leads to information loss as the encoder might struggle to represent subtle variations in the input. Also, this increases the amount of dead codebook vectors which consequently reduces the amount of used tokens for discretization (e.g. Fig. 5, rightmost map).

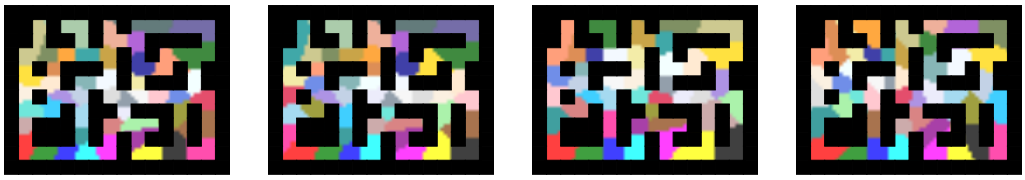


Figure 6: **Contrastive coefficient impact with reconstruction loss** With $\alpha_{\text{commit}} = 1e3, \alpha_{\text{contrastive}} \in \{0, 2, 2e1, 2e5\}, \alpha_{\text{recon}} = 1e5$. We see that a low contrastive coefficient leads to multiple piece landmarks, while high values of contrastive seem to fix this issue.

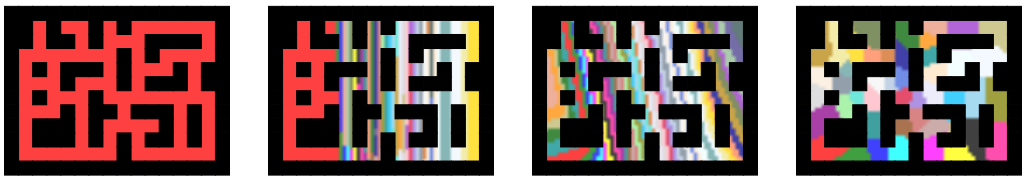


Figure 7: **Contrastive coefficient impact without reconstruction loss** With $\alpha_{\text{commit}} = 1e3, \alpha_{\text{contrastive}} \in \{0, 2, 2e1, 2e5\}, \alpha_{\text{recon}} = 0$. We see that the reconstruction loss is not needed to generate good tokens, however, it makes the tokenization more stable to hyperparamters.

Contrastive loss The contrastive loss serves the purpose of organizing temporally the latent space, which is paramount to create navigable landmarks. When used jointly with the reconstruction loss

(see Fig. 6), it ensures that the landmarks do not span through obstacles, consequently ensuring that landmarks are of single piece and navigable. If the contrastive coefficient is too low, multiple piece landmarks can appear by spanning across obstacles. If it is too high, it might overshadow other components, leading to the aforementioned failures. Used without the reconstruction loss (see Fig. 7), the contrastive can manage a good tokenization but the reconstruction loss helps by showing better tokenization for a higher number of contrastive coefficient values.

6 CONCLUSION

We proposed QPHIL, a hierarchical offline goal-conditioned reinforcement learning method that leverages pre-recorded demonstration to learn a discrete and temporally consistent representation of the state space. QPHIL utilizes those discrete state representations to plan subgoals in a discretized space and guide a low policy towards its final goal in a human-inspired manner. QPHIL reaches top performance in challenging long-term navigation benchmarks, showing promising next steps for discretization and planning in continous offline RL settings.

QPHIL is a method aimed at longterm navigation as it aims to solve tasks where a low amount of landmarks is sufficient. QPHIL demonstrated the interest of space quantization for long range navigation settings in offline GCRL. As a future work, studying quantization techniques applicable to higher dimensional data (images, ...) and in more intricate planning settings (multi-token discretization and combinatorial representations), such as multi-task robotics scenarios could be promising. Finally, as discretized planning brings interpretability and editability, one could study how users can edit learned quantization to further improve performances or cheaply "update" the agent to environmental changes.

7 IMPLEMENTATION DETAILS

For the VQ-VAE, we based our implementation on the `https://github.com/lucidrains/vector-quantize-pytorch.git` repository. We utilize for all AntMaze variants as the encoder and the decoder a simple 2-layer MLP with ReLU activations and hidden size of 16 and latent dimension of 8. For antmaze, we add a gaussian noise to the input positions and we normalize the positions before feeding them to the encoder. Also, we vary the number of encodings in the codebook as the map grows. **For the transformer**, we used as described an encoder-decoder architecture inspired by the paper (Vaswani et al., 2017) provided by the **torch.nn library**. We use a max sequence length of size 128, an embedding dimension of 128, a feed-forward dimension of 128, 4 layers of 4 heads and a dropout of 0.2 and we train our model with 250 epoch. We perform validation computation with a 0.95 dataset split and perform sampling with a temperature of 0.9. We optimize our model using the Adam optimizer with a learning rate of 1e-5. **For the low subgoal policy and its value function**, we adapt the policy proposed by HIQL. For the value function, we use a MLP policy of 3 layers with hidden size of 512 and GeLU activations. We apply layer normalization for each layers and initialize the weights with a variance scaling initialization of scale 1. No dropout is used for the value function. For the policy, we use a two layer MLP with hidden size of 256 and ReLU activations. We don't apply layer norm and initialize the parameters though a variance scaling initialization of scale 0.01. Our policy outputs the mean and standard deviation of an independent normal distribution. We clamp the log std of the output between -5 and 2. We train both the value function and the policy at the same time, performing 1e6 gradient steps with a batch size of 1024. For the IQL parameters, $\beta = 3.0$, the expectile $\tau = 0.9$, the polyak coefficient is 0.005 and the discount factor $\gamma = 0.995$. We clip the AWR weights to 100. Also, we sample the next token with a probability of 0.8 and the current token with probability 0.2. The targets updates are performed at each gradient step. **For the low goal policy**, we trained our GC-IQL implementation in Pytorch with GC-IQL's hyper-parameters taken the HIQL paper: $(\beta, \tau, \gamma) = (0.99, 3, 0.9)$ for the smaller mazes (AntMaze-{Medium-Large}) and $(\beta, \tau, \gamma) = (0.995, 1, 0.7)$ for the larger mazes (AntMaze-{Ultra,Extreme}).

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9 REPRODUCIBILITY STATEMENT

To ensure the reproductibility of our experiments, we provided all needed implementation details and hyperparameter values in the appendix. All our training have been seeded with the same 8 seeds: 0, 1, 2, 3, 4, 6 and 7. Also, we provide QPHIL's codebase along with the pretrained models ready to be evaluated on our test environments.

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