

Robotic Learning Papers Notes

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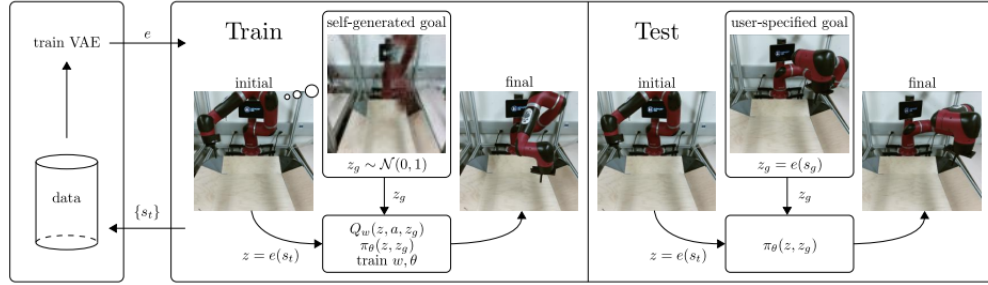
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1 Visual Reinforcement Learning with Imagined Goals

1.1 Summary

This paper introduces self-supervised goal-conditioned reinforcement learning with their method, reinforcement learning with imagined goals (RIG).



RIG involves a VAE with encoder $q_\phi(s)$ and decoder $p_\psi(z)$, goal-conditioned policy $\pi_\theta(z, z_g)$, and goal-conditioned Q-function $Q_w(z, a, z_g)$. Here, s is a state observation (i.e. image), z is its latent encoding of s , z_g is the latent encoding of the sampled goal, and a is the action taken.

1.1.1 Variational Autoencoder Training

We first train the β -VAE by executing a random policy, collecting state observations, and optimizing

$$\mathcal{L}(\psi, \phi; s^{(i)}) = -\beta D_{KL}(q_\phi(z|s^{(i)})||p(z)) + \mathbb{E}_{q_\phi(z|s^{(i)})}[\log p_\psi(s^{(i)}|z)]$$

where $p(z)$ is a prior which we take to be unit Gaussian. Our encoding is the mean of the encoder: $z = \mu_\phi(s)$.

1.1.2 Goal-conditioned RL Training

Next, we train our Q-function and policy in this latent space. We use twin delayed deep deterministic policy gradients (TD3) to train our policy and q-function following the Bellman error

$$\mathcal{E}(w) = \frac{1}{2} \|Q_w(s, a, g) - (r(s', g) + \gamma \max_{a'} Q_{\bar{w}}(s', a', g))\|^2$$

where the reward is determined with negative Mahalanobis distance in the latent space between the latent encoding of the state and the goal: $r(z, z_g) = -\|z - z_g\|_A$. We can set matrix A to be the precision matrix of q_ϕ , but in practice $A = \mathbf{I}$ works better. We also fine-tune the VAE here to randomly generated state observations and state observations collected during explorations so it can be exposed to new states it wasn't trained on previously.

1.1.3 Latent Goal Relabeling

We can enable sample-efficient learning by using the VAE to relabel goals. Given the (s, a, s') in our dataset, we encode the state observations, sample z_g from our VAE prior $p(z)$, and compute $r(z, z_g) = -\|z - z_g\|_A$ to produce (s, a, s', g, r) , giving us more data to train on without sampling new datapoints. Half of the goals are generated this way. The other half has its goals generated using states seen along the trajectory as in hindsight experience replay (HER).

1.1.4 Automated Goal-Generation for Exploration

We sample from the VAE prior to obtain plausible goals and give this to our policy $\pi(z, z_g)$ to collect data. This is essentially a self-supervised "practice" phase during training.

1.1.5 Algorithm Summary

Given VAE encoder q_ϕ , VAE decoder p_ψ , policy π_θ , goal-conditioned value function Q_w , we have RIG:

Algorithm 1 RIG: Reinforcement learning with imagined goals

```

1: Collect  $\mathcal{D} = \{s_{(i)}\}$  using any exploration policy
2: Train  $\beta$ -VAE on  $\mathcal{D}$ 
3: Fit prior  $p(z)$  to latent encodings  $\{\mu_\phi(s^{(i)})\}$ 
4: for  $n = 0, \dots, N - 1$  episodes do
5:   Sample latent goal from prior  $z_g \sim p(z)$ .
6:   Sample initial state  $s_0 \sim E$ 
7:   for  $t = 0, \dots, H - 1$  steps do
8:     Get action  $a_t = \pi_\theta(e(s_t), z_g) + \text{noise}$ 
9:     Get next state  $s_{t+1} \sim p(\cdot | s_t, a_t)$ 
10:    Store  $(s_t, a_t, s_{t+1}, z_g)$  into replay buffer  $\mathcal{R}$ 
11:    Sample transition  $(s, a, s', z_g) \sim \mathcal{R}$ 
12:    Encode  $z = e(s)$ ,  $z' = e(s')$ 
13:    With probability 0.5, replace  $z_g$  with  $z'_g \sim p(z)$ 
14:    Compute reward  $r = -\|z' - z_g\|$ 
15:    Train Q-function and policy on  $(z, a, z', z_g, r)$  with an RL algorithm
      (TD3 used in paper)
16:   end for
17:   for  $t = 0, \dots, H - 1$  steps do
18:     for  $i = 0, \dots, k - 1$  steps do
19:       Sample future state  $s_{h_i}$ ,  $t < h_i \leq H - 1$ 
20:       Store  $(s_t, a_t, s_{t+1}, e(s_{h_i}))$  into  $\mathcal{R}$ 
21:     end for
22:   end for
23:   Fine-tune  $\beta$ -VAE every  $K$  episodes on mixture of  $D$  and  $R$ 
24: end for

```

1.2 Questions

1.2.1 Basic

- When calculating reward, how does Mahalanobis distance work if both the state and goal latent encoding are points, not distributions?
- When calculating reward, what is the precision matrix of a VAE encoder? How was $r(s, g) = -\|z - z_g\|_A \propto \sqrt{\log e_\phi(z_g|s)}$ derived?
- During VAE fine-tuning, what does it mean when it says state observations are randomly generated?
- During latent goal relabeling, what is a fitted prior? How does this help the distribution of latents match the prior (i.e. gaussian)? Why does it have to match?

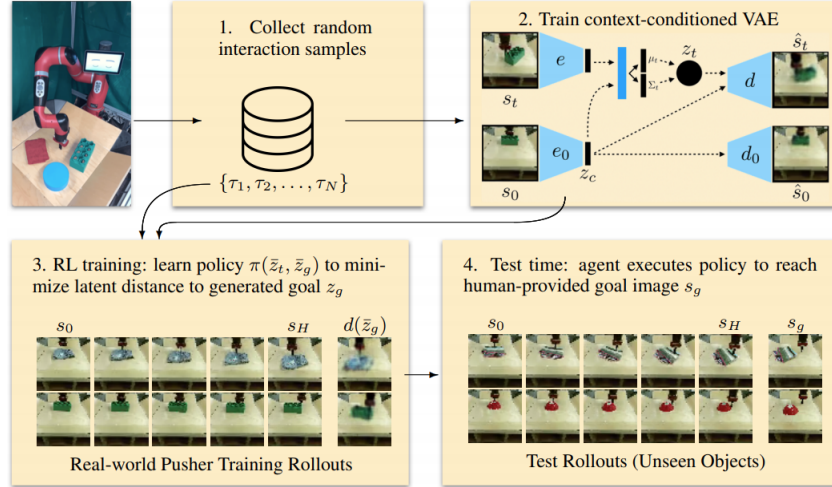
1.2.2 Trivial

- When getting action from policy, why do we add noise?

2 Contextual Imagined Goals for Self-Supervised Robotic Learning

2.1 Summary

This paper introduces context-conditioned goal sampling. In other words, the VAE used in RIG is conditioned on the initial state, which prevents the generation of impossible goals and thus improves learning (i.e. a robot cannot push a red puck to a desired location if the red puck doesn't exist).



2.1.1 Context-Conditioned VAE (CC-VAE) Training

We use a modified CVAE which takes in the initial state s_0 as input, which we call the “context” of the rollout. This modified CVAE is called a context-conditioned VAE (CC-VAE). The CC-VAE takes in z_c as input c , which is s_0 encoded with convolutional encoder e_0 . The loss function for training is

$$\mathcal{L}_{\text{CC-VAE}} = \mathcal{L}_{\text{CVAE}} + \log p(s_0|z_c)$$

$$\mathcal{L}_{\text{CVAE}} = -\mathbb{E}_{q_\phi(z|s,c)}[\log p(s|z,c)] + \beta D_{KL}(q_\phi(z|s,c)||p(z))$$

Essentially, this is the CVAE loss with an additional term for reconstructing the initial state. Due to the information bottleneck on z_t , the optimal solution would encode as much information as possible in z_c , while only encoding information about state changes from initial state within z_t .

2.1.2 Context-Conditioned Reinforcement Learning with Imagined Goals (CC-RIG) Training

In CC-RIG, we essentially just do RIG again but now with the CC-VAE instead of a VAE. We compute encoding of s_0 , $z_c = e_0(s_0)$. Let \bar{z} denote concatenated

(z, z_c) and $\mu(s, s_0)$ denote the mean of $q_\phi(z|s_t, s_0)$. Given our encoders $\mu(s_t, s_0)$, $e_0(s_0)$, policy $\pi_\theta(\bar{z}, \bar{z}_g)$, goal-conditioned value function $Q_w(\bar{z}, \bar{z}_g)$, and dataset of trajectories $\mathcal{D} = \{\tau^{(i)}\}$. In practice, we sample $z_g \sim N(0, I)$ as in RIG.

Algorithm 2 Context-Conditioned RIG

```

1: Train CC-VAE on  $\mathcal{D}$ 
2: for  $n = 0, \dots, N - 1$  episodes do
3:   Sample latent goal from prior  $z_g \sim p(z)$ ,  $\bar{z}_g = (z_g, z_c)$ 
4:   Sample initial state  $s_0 \sim p(s_0)$ 
5:   Encode  $z_c = e_0(s_0)$ 
6:   for  $t = 0, \dots, H - 1$  steps do
7:     Observe  $s_t$  and encode  $\bar{z}_t = (\mu(s_t, s_0), z_c)$ 
8:     Get action  $a_t = \pi_\theta(\bar{z}_t, \bar{z}_g) + \text{noise}$ 
9:     Get next state  $s_{t+1} \sim p(\cdot|s_t, a_t)$ 
10:    Store  $(\bar{z}_t, a_t, \bar{z}_{t+1}, \bar{z}_g)$  into replay buffer  $\mathcal{R}$ 
11:    Sample transition  $(\bar{z}, a, \bar{z}', \bar{z}_g) \sim \mathcal{R}$ 
12:    Compute reward  $r = -\|\bar{z}' - \bar{z}_g\|$ 
13:    Train Q-function and policy on  $(\bar{z}, a, \bar{z}', \bar{z}_g, r)$  with an RL algorithm
      (TD3 used in paper)
14:   end for
15: end for

```

During testing, given goal image s_g , we encode it as $z_g = \mu(s_g, s_0)$ and execute policy with latent goal \bar{z}_g .

2.2 Questions

2.2.1 Basic

- Are latent relabeling, fitted priors, adding future-state data, VAE fine-tuning still done?

3 AWAC: Accelerating Online Reinforcement Learning with Offline Datasets

3.1 Summary

Advantage weighted actor critic (AWAC) is an actor critic algorithm that leverages a combination of prior demonstration data (which could be sub-optimal) and online experience. The challenge to learning from offline data and subsequent online fine-tuning is

- **Data Efficiency:** Pre-training with imitation learning and fine-tuning with on-policy RL algorithms has two drawbacks: the prior data may not be optimal so imitation learning may be ineffective, and on-policy fine-tuning is data inefficient because it doesn't reuse prior data in the RL stage.
- **Bootstrapping Error:** Off-policy actor-critic methods struggle with off-policy bootstrapping error accumulation. Q-estimates are not fully accurate for bootstrapping, especially when the actions are not in data distribution. The policy exploits overestimated Q-values, making estimated Q values worse.
- **Non-stationary Behavior Models:** Prior offline RL algorithms address the bootstrapping problem by constraining the policy π close to behavior policy π_β (actions present in the replay buffer). Many offline RL algorithms explicitly fit a parametric model to samples from the replay buffer for the distribution π_β . However, fitting an accurate behavioral model as data is collected online during fine-tuning is a challenging research problem. We require an off-policy RL algorithm that constrains the policy to prevent offline stability and error accumulation, but is not so conservative that it prevents online fine-tuning due to imperfect behavior modeling.

AWAC avoids these issues. For data efficiency, the algorithm trains a critic with DP. To avoid bootstrapping error while avoiding modeling the data distribution, we optimize

$$\arg \max_{\pi} \mathbb{E}_{a \sim \pi(\cdot|s)} [A^{\pi_k}(s, a)] \text{ s.t. } D_{KL}(\pi(\cdot|s) \parallel \pi_\beta(\cdot|s)) \leq \epsilon, \int_a \pi(a|s) da = 1$$

The Lagrangian is

$$\mathcal{L}(\pi, \lambda, \alpha) = \mathbb{E}_{a \sim \pi(\cdot|s)} [A^{\pi_k}(s, a)] + \lambda(\epsilon - D_{KL}(\pi(\cdot|s) \parallel \pi_\beta(\cdot|s))) + \alpha(1 - \int_a \pi(a|s) da)$$

Differentiating with respect to π gives

$$\frac{\partial \mathcal{L}}{\partial \pi} = A^{\pi_k}(s, a) - \lambda \log \pi_\beta(a|s) + \lambda \log \pi(a|s)_\lambda - \alpha$$

Setting $\frac{\partial \mathcal{L}}{\partial \pi}$ to zero and solving for π gives the closed form solution

$$\pi^*(a|s) = \frac{1}{Z(s)} \pi_\beta(a|s) \exp\left(\frac{1}{\lambda} A^{\pi_k}(s, a)\right)$$

We now want to project our optimal solution into our parameter space, which we will do by minimizing the KL-divergence of π_θ from π^* under $p_{\pi_\beta}(s)$:

$$\arg \min_{\theta} \mathbb{E}_{p_{\pi_\beta}(s)} [D_{KL}(\pi^*(\cdot|s) \parallel \pi_\theta(\cdot|s))] = \mathbb{E}_{p_{\pi_\beta}(s)} \left[\mathbb{E}_{\pi^*(\cdot|s)} [-\log \pi_\theta(\cdot|s)] \right]$$

We choose the reverse KL direction because it allows us to optimize θ as MLE problem rather than sampling actions from a policy that may be out of distribution for the Q function. We can now compute the policy update by sampling directly from β :

$$\theta_{k+1} = \arg \max_{\theta} \mathbb{E}_{s, a \sim \beta} \left[\log \pi_\theta(a|s) \exp\left(\frac{1}{\lambda} A^{\pi_k}(s, a)\right) \right]$$

This actor update resembles weighted behavior cloning, where targets are obtained by reweighting the state-action pairs observed in the current dataset with predicted advantages from the learned critic. With this, we now have our AWAC algorithm

Algorithm 3 AWAC

```

1: Dataset  $\mathcal{D} = \{(s, a, s', r)_j\}$ 
2: Initialize buffer  $\beta = \mathcal{D}$ 
3: Initialize  $\pi_\theta, Q_\phi$ 
4: for iteration  $i = 1, 2, \dots$  do
5:   Sample batch  $(s, a, s', r) \sim \beta$ 
6:    $y = r(s, a) + \gamma \mathbb{E}_{s', a'} [Q_\phi(s', a')]$ 
7:    $\phi \leftarrow \arg \min_{\phi} \mathbb{E}_{\mathcal{D}} [(Q_\phi(s, a) - y)^2]$ 
8:    $\theta \leftarrow \arg \max_{\theta} \mathbb{E}_{s, a \sim \beta} [\log \pi_\theta(a|s) \exp(\frac{1}{\lambda} A^{\pi_k}(s, a))]$ 
9:   if  $i > \text{num\_offline\_steps}$  then
10:     $\tau_1, \dots, \tau_K \sim p_\theta(\tau)$ 
11:     $\beta \leftarrow \beta \cup \{\tau_1, \dots, \tau_K\}$ 
12:   end if
13: end for
```

3.2 Questions

3.2.1 Basic

- For deriving AWAC, when setting $\frac{\partial \mathcal{L}}{\partial \pi}$ to zero, I got

$$\pi^*(a|s) = \frac{1}{Z(s)} \pi_\beta(a|s) \exp\left(-\frac{1}{\lambda} A^{\pi_k}(s, a)\right)$$

. What am I missing?

4 What Can I Do Here? Learning New Skills by Imagining Visual Affordances

4.1 Summary

This paper introduces visual affordance learning (VAL), which is essentially AWAC + a scaled up CC-RIG to allow for offline training + online fine-tuning, more expressive generative models, and learning a diverse set of skills. VAL consists of three learning phases: an affordance learning phase to learn affordances from the prior data, an offline behavior learning phase to learn behaviors from prior data, and an online behavior learning phase where an agent actively interacts with the test environment using affordances and learns potential behaviors in the new environment.

4.1.1 Affordance Learning

We use a lower-dimensional latent space to encode the image observations in order to make goal generation easier. Given such a latent space, we can then learn affordances by training a conditional model $p(z_t|z_0)$ to generate plausible outcomes of an initial state. For the latent variable generative model $p(s_t|z_t)$, we use a deterministic VQVAE $z_t = \phi(s_t)$. For the conditional model, we use a conditional PixelCNN in the latent space.

4.1.2 Offline Behavior Learning

We use AWAC to optimize $\pi(a|z, z_g)$ with reward function $r(z, z_g) = -\mathbf{1}_{\|z - z_g\| > \epsilon}$. We also relabel z_g with future hindsight experience with 40% probability and sample from $p(z_t|z_0)$ with 40% probability.

4.1.3 Online Behavioral Learning

During the online fine-tuning phase, we sample from the affordance module $z_g \sim p_\theta(\cdot|z_0)$ and roll out our policy $\pi(a|z, z_g)$. We then iterate between improving the policy with offline RL and collecting exploration data, and appending it to the replay buffer.

4.1.4 Algorithm Summary

Given dataset \mathcal{D} , policy $\pi(a|z, z_g)$, Q-function $Q(z, a, z_g)$, RL algorithm \mathcal{A} , replay buffer \mathcal{R} , relabeling strategy $p_{RS}(z)$, and environment family $p(\mathcal{E})$

Algorithm 4 Visual Affordance Learning

- 1: Learn encoder $\phi(z|s)$ by generative model of \mathcal{D}
 - 2: Learn affordances $p(z_t|z_0)$ by generative model of \mathcal{D}
 - 3: Add latent encoding of \mathcal{D} to the replay buffer
 - 4: Initialize π and Q by running \mathcal{A} offline
 - 5: Sample $\mathcal{E}_{new} \sim p(\mathcal{E})$, $\mathcal{E}_{new} = (p_{new}(s_0), p_{new}(s_{t+1}|s, a))$
 - 6: **for** $1, \dots, N_{episodes}$ **do**
 - 7: Sample initial state $s_0 \sim p_{new}(s_0)$
 - 8: Sample goal $z_g \sim p(z_t|z_0)$
 - 9: **for** $t = 0, \dots, H$ **do**
 - 10: Sample $a_t \sim \pi(\cdot|z_t, z_g)$
 - 11: Sample $s_{t+1} \sim p_{new}(\cdot|s_t, a_t)$
 - 12: **end for**
 - 13: Store trajectory (z_1, a_1, \dots, z_H) in replay buffer \mathcal{R}
 - 14: **for** $1, \dots, N_{train_steps}$ **do**
 - 15: Sample transition (z_t, a_t, z_{t+1}, z_g)
 - 16: Relabel with $z'_g \sim p_{RS}(z_g)$ and recompute reward
 - 17: Update π and Q with relabeled transition using \mathcal{A}
 - 18: **end for**
 - 19: **end for**
-

5 Bridge Data: Boosting Generalization of Robotic Skills with Cross-Domain Datasets

This is a dataset paper which includes a diverse 'bridge' dataset of 4,700 human demonstrations of a robot performing 33 common kitchen tasks across 3 toy kitchens and 3 toy sinks with varying lighting, robot positions, and backgrounds. The role of the bridge dataset is to boost generalization for policies:

1. **Transfer with matching behaviors:** user collects some data in their target domain for tasks that are also present in the bridge data, and uses the bridge data to boost performance and generalization of these tasks
2. **Zero-shot transfer with target support:** user utilizes some data of one task in their target domain to import other tasks that are present in the bridge data without additionally collecting new demonstration of them in the target domain
3. **Boosting generalization of new tasks:** user provides some data for a new task that is not present in the bridge data, and then utilizes the bridge to boost generalization and performance