Meta-Gradient Reinforcement Learning with an Objective Discovered Online

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Abstract

Deep reinforcement learning includes a broad family of algorithms that parameterise an internal representation, such as a value function or policy, by a deep neural network. Each algorithm optimises its parameters with respect to an objective, such as Q-learning or policy gradient, that defines its semantics. In this work, we propose an algorithm based on meta-gradient descent that discovers its own objective, flexibly parameterised by a deep neural network, solely from interactive experience with its environment. Over time, this allows the agent to learn how to learn increasingly effectively. Furthermore, because the objective is discovered online, it can adapt to changes over time. We demonstrate that the algorithm discovers how to address several important issues in RL, such as bootstrapping, non-stationarity, and off-policy learning. On the Atari Learning Environment, the meta-gradient algorithm adapts over time to learn with greater efficiency, eventually outperforming the median score of a strong actor-critic baseline.

1 Introduction

Recent advances in supervised and unsupervised learning have been driven by a transition from handcrafted expert features to deep representations [14]; these are typically learned by gradient descent on a suitable objective function to adjust a rich parametric function approximator. As a field, reinforcement learning (RL) has also largely embraced the transition from handcrafting features to handcrafting objectives: deep function approximation has been successfully combined with ideas such as TD-learning [29,33], Q-learning [41,22], double Q-learning [35,36], n-step updates [31,13], general value functions [32,17], distributional value functions [7,3], policy gradients [42,20] and a variety of off-policy actor-critics [8,10,28]. In RL, the agent doesn’t have access a differentiable performance metric, thus choosing the right proxy is of particular importance: indeed, each of the aforementioned algorithms differs fundamentally in their choice of objective, designed in each case by expert human knowledge. The deep RL version of these algorithms is otherwise very similar in essence: updating parameters via gradient descent on the corresponding objective function.

Our goal is an algorithm that instead learns its own objective, and hence its own deep reinforcement learning algorithm, solely from experience of interacting with its environment. Following the principles of deep learning, we parameterise the objective function by a rich function approximator, and update it by meta-gradient learning [27,11,43,46,38,2,19] – i.e. by gradient descent on the sequence of gradient descent updates resulting from the choice of objective function – so as to maximise a naive outer loss function (such as REINFORCE) with minimal initial knowledge.

Importantly, and in contrast to the majority of recent work on meta-learning [11,2,19], our meta-gradient algorithm learns online, on a single task, during a single “lifetime” of training. This online approach to meta-learning confers several advantages. First, an online learning algorithm can be applied to any RL environment, and does not require a distribution of related environments, nor the

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ability to reset and rerun on different environments. Second, an online learning algorithm can adapt the objective function as learning progresses, rather than assume a global, static “one-size-fits-all” objective. Our hypothesis is that an online meta-gradient learning agent will, over time, learn to learn with greater efficiency, and in the long-run this will outperform a fixed (handcrafted) objective.

We show in toy problems that our approach can discover how to address important issues in RL, such as bootstrapping and non-stationarity. We also applied our algorithm for online discovery of an off-policy learning objective to independent training runs on each of 57 classic Atari games. Augmented with a simple heuristic to encourage consistent predictions, our meta-gradient algorithm outperformed the median score of a strong actor-critic baseline on this benchmark.

2 Related Work

The idea of learning to learn by gradient descent has a long history. In supervised learning, IDBD and SMD [30, 27] used a meta-gradient approach to adapt the learning rate online so as to optimise future performance. “Learning by gradient descent to learn by gradient descent” [1] used meta-gradients, offline and over multiple lifetimes, to learn a gradient-based optimiser, parameterised by a “black-box” neural network. MAML [11] and REPTILE [23] also use meta-gradients, offline and over multiple lifetimes, to learn initial parameters that can be optimised more efficiently.

In reinforcement learning, methods such as meta reinforcement learning [39] and RL$^2$ [9] allow a recurrent network to jointly represent, in its activations, both the agent’s representation of state and also its internal parameters. Xu et al [43] introduced metagradient as a general but efficient approach for optimising the meta-parameters of gradient-based RL agents. This approach has since been applied to many different meta-parameters of RL algorithms, such as the discount $\gamma$ and bootstrapping parameter $\lambda$ [43], intrinsic rewards [46, 45], auxiliary tasks [38], off-policy corrections [44], and to parameterise returns as a linear combination of rewards [40] (without any bootstrapping). The metagradient approach has also been applied, offline and over multiple lifetimes, to black-box parameterisations, via deep neural networks, of the entire RL algorithm [2, 19] and [24] (contemporary work); evolutionary approaches have also been applied [16].

No prior work has addressed the most ambitious combination: a black-box approach that can parameterise the RL algorithm, meta-learned online, during the course of a single agent lifetime.

The table below catalogs related work on meta-gradient RL. We differentiate methods by several key properties. First, whether they are single lifetime (i.e. they learn online to improve performance by interacting with an environment), or require multiple lifetimes (i.e. they improve performance across repeated agent “lifetimes”, each of which faces a different environment sampled from a suitable distribution). Second, whether they are white-box methods (i.e. they meta-learn the hyper-parameters of an existing RL update rule) or black-box methods (i.e. they meta-learn a general-purpose neural network encoding an RL update rule). Third, whether they compute meta-gradients by forward-mode or backward-mode differentiation (or do not use meta-gradients at all). Finally, what is meta-learned.

| Algorithm | Algorithm properties |
|-----------|----------------------|
| IDDB, SMD [30, 27] | + |
| SGD$^2$ [11] | +++ |
| RL$^2$, Meta-RL [9, 39] | +++ |
| MAML, REPTILE [11, 23] | +++ |
| Meta-Gradient [43, 46] | + |
| Meta-Gradient [38, 44, 40] | + |
| ML$^2$, MetaGenRL [2, 19] | +++ |
| Evolved PG [16] | +++ |
| Oh et al. 2020 [24] | +++ |
| This paper | + |

- white box, black box, single lifetime, multi-lifetime
- forward mode, backward mode, X no meta-gradient
3 Algorithm

In this section, we describe our proposed algorithm for online learning of reinforcement learning objectives using meta-gradients. Our starting point is the observation that a single quantity, the update target $G$, plays a pivotal role in characterising the objective of most deep RL algorithms; therefore, the update target offers an ideal entry point to flexibly parameterise the overall RL algorithm.

We first review the objectives used in classic RL algorithms and discuss how they may be flexibly parameterised via a neural network in order to expose them to learning instead of being manually designed by human researchers. We then recap the overall idea of meta-gradient reinforcement learning, and we illustrate how it can be used to meta-learn, online, the neural network that parametrises the update target. We discuss this for prediction, value-based control and actor-critic algorithms.

3.1 Update Targets in Reinforcement Learning Algorithms

To learn a value function $v_{\theta}(S)$ in temporal difference (TD) prediction algorithms, in each state we use bootstrapping to construct a target $G$ for the value function. For a trajectory $\tau_t = \{S_t, A_t, R_{t+1}, \ldots\}$, the target $G_t$ for the one-step TD algorithm is

$$G_t = R_{t+1} + \gamma v_{\theta}(S_{t+1});$$

with stochastic gradient descent, we can then update the parameter $\theta$ of the value function as follows:

$$\theta \leftarrow \theta + \alpha (G_t - v_{\theta}(S_t)) \nabla_{\theta} v_{\theta}(S_t),$$

where $\alpha$ is the learning rate used to update the parameter $\theta$.

Similarly in value-based algorithms for control, we can construct the update target for the action-values $q_{\theta}(S_t, A_t)$; for instance, in one-step $Q$-learning parameters $\theta$ for the action-value function can be updated by:

$$\theta \leftarrow \theta + \alpha (G_t - q_{\theta}(S_t, A_t)) \nabla_{\theta} q_{\theta}(S_t, A_t) \quad \text{where} \quad G_t = R_{t+1} + \gamma \max_a q_{\theta}(S_{t+1}, a).$$

More generally, $n$-step update targets can bootstrap from the value estimation after accumulating rewards for $n$ steps, instead of just considering the immediate reward. For instance in the case of prediction, we may consider the $n$-step truncated and bootstrapped return defined as:

$$G_t = R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \cdots + \gamma^n v_{\theta}(S_{t+n}).$$

3.2 Parameterising RL objectives

In this work, instead of using a discounted cumulative return, we fully parameterise the update target by a neural network. This meta-network takes the trajectory as input and produces a scalar update target, i.e., $G = g_{\eta}(\tau_t)$, where the function $g_{\eta} : \tau_t \rightarrow \mathbb{R}$ is a neural network with parameters $\eta$. We train the meta-network using an end-to-end meta-gradient algorithm, so as to learn an update target that leads to good subsequent performance.

A different way to learn the RL objective is to directly parameterise a loss by a meta-network [2][19], rather than the target of a loss. For instance, a standard TD learning update can either be represented by a TD loss $g_{\eta}(\tau) = (R_{t+1} + \gamma (v_{\theta}(S_{t+1})) - v_{\theta}(S_t))^2$, or by a squared loss with respect to a TD target, $g_{\eta}(\tau) = R_{t+1} + \gamma (v_{\theta}(S_{t+1}))$, where $\bot$ represents a gradient-stopping operation. Both forms of representation are rich enough to include a rich variety of reinforcement learning objectives.

However, we hypothesise that learning a target will lead to more stable online meta-gradients than learning a loss. This is because the induced learning rule is inherently moving towards a target, rather than potentially away from it, thereby reducing the chance of immediate divergence. Because we are operating in an online meta-learning regime, avoiding divergence is of critical importance. This contrasts to prior work in offline meta-learning [2][19], where divergence may be corrected in a subsequent lifetime.

3.3 Meta-Gradient Reinforcement Learning

Meta-gradient reinforcement learning is a family of gradient-based meta learning algorithms for learning and adapting differentiable components (denoted as meta-parameters $\eta$) in the RL update
Meta-gradient RL is a two-level optimisation process. A meta-learned inner loss $L^\text{inner}_\eta$ is parameterised by meta-parameters $\eta$ and the agent tries to optimise $L^\text{inner}_\eta$ to update $\theta$. Given a sequence of trajectories $\mathcal{T} = \{\tau_1, \tau_{i+1}, \tau_{i+2}, \ldots, \tau_{i+M+1}\}$, we apply multiple steps of gradient descent updates to the agent $\theta$ according to the inner losses $L^\text{inner}_\eta(\tau_i, \theta'_i)$. For each trajectory $\tau \in \mathcal{T}$, we have:

$$\Delta \theta_i \propto \nabla_{\theta} L^\text{inner}_\eta(\tau_i, \theta'_i) \quad \theta_{i+1} = \theta_i + \Delta \theta_i.$$  

Consider keeping $\eta$ fixed for $M$ updates to the agent parameter $\theta$:

$$\theta_i \overset{\eta}{\rightarrow} \theta_{i+1} \overset{\eta}{\rightarrow} \ldots \overset{\eta}{\rightarrow} \theta_{i+M-1} \overset{\eta}{\rightarrow} \theta_{i+M}.$$  

A differentiable outer loss $L^\text{outer}_\eta(\tau_{i+M+1}, \theta'_{i+M})$ is then applied to the updated agent parameters $\theta' = \theta_{i+M}$. The gradient of this loss is taken w.r.t. meta-parameters $\eta$ and then used to update $\eta$ via gradient descent:

$$\Delta \eta \propto \nabla_{\eta} L^\text{outer}_\eta(\tau_{i+M+1}, \theta'_{i+M}) \quad \eta \leftarrow \eta + \Delta \eta.$$  

We call this quantity $\nabla_{\eta} L^\text{outer}_\eta$ the meta-gradient. We can iterate this procedure during the training of the agent $\theta$ and repeatedly update the meta-parameters $\eta$.

The meta-gradient flows through the multiple gradient descent updates to the agent $\theta$, i.e., the whole update procedure from $\theta_i$ to the outer loss of the final updated agent parameter $\theta_{i+M}$. By applying chain rule, we have $\frac{\partial L^\text{outer}}{\partial \eta} = \frac{\partial L^\text{outer}}{\partial \theta'} \frac{\partial \theta'}{\partial \eta}$. In practice, we can use automatic differentiation packages to compute the meta gradient $\frac{\partial L^\text{outer}}{\partial \eta}$ with comparable compute complexity as the forward pass.

The meta-gradient algorithm above can be applied to any differentiable component of the update rule, for example to learn the discount factor $\gamma$ and bootstrapping factor $\lambda$ \cite{FRODO}, intrinsic rewards \cite{intrin}, and auxiliary tasks \cite{aux}. In this paper, we apply meta-gradients to learn the meta-parameters of the update target $g_\eta$, online, where $\eta$ are the parameters of a neural network. We call this algorithm FRODO (Flexible Reinforcement Objective Discovered Online). The following sections instantiate the FRODO algorithm for value prediction, value-based control and actor-critic control, respectively.

### 3.4 Learned Update Target for Prediction and Value-based Control

Given a learned update target $g_\eta$, we propose updating the predictions $v_\theta$ towards the target $g_\eta$. With a squared loss, this results in the update

$$\Delta \theta \propto (g_\eta(\tau) - v_\theta(S)) \nabla_{\theta} v_\theta(S),$$  

where the meta-network parameterised by $\eta$ takes the trajectory $\tau$ as input and outputs a scalar $g_\eta(\tau)$. After $M$ updates, we compute the outer loss $L^\text{outer}$ from a validation trajectory $\tau'$ as the squared difference between the predicted value and a canonical multi-step bootstrapped return $G(\tau')$, as used in classic RL:

$$\nabla_{\theta} L^\text{outer} = (G(\tau') - v_\theta(S')) \nabla_{\theta} v_\theta(S')$$  

can then be plugged in Equation (2), to update $\eta$ and continue with the next iteration. Here $\theta_i$ is interpreted and treated as a function of $\eta$, which was held fixed during several updates to $\theta$.

For value-based algorithms in control, the inner update is similar, but the learned target is used to update an action-value function $g_\theta(S, A)$ in the inner update. Any standard RL update can be used in the outer loss, such as Q-learning \cite{Q}, Q(\lambda), or (Expected) Sarsa \cite{Sarsa}[\cite{Sarsa}].

### 3.5 Learned Update Target for Actor-Critic Algorithms in Control

In actor-critic algorithms, the update target is used both to compute policy gradient update to the policy, as well as to update the critic. We form an A2C \cite{A2C} update with $g_\eta(\tau)$:

$$\Delta \theta \propto (g_\eta(\tau) - V(S)) \nabla_{\theta} \log \pi(S, A) + c_1(g_\eta(\tau) - V(S)) \nabla_{\theta} v(S) + c_2 \nabla_{\theta} H(\pi(S)),$$  

where $H(\cdot)$ denotes the entropy of the agent’s policy, and $c_1$ and $c_2$ denote the weightings of the critic loss and entropy regularisation terms, respectively.
4 Motivating Examples

In this section, we explore the capability of FRODO to discover how to address fundamental issues in RL, such as bootstrapping and non-stationarity, based on simple toy domains. Larger scale experiments will subsequently be presented addressing off-policy learning.

Bootstrapping: We use a simple $6 \times 11$ environment called “Catch” [21]. The agent controls a paddle located on the bottom row of the grid. The agent starts in the centre and, on each step, it can move on cell to the left, one cell to the right or stand still. At the beginning of each episode a pellet appears in a random start location on the top row. On each step, the pellet move down one cell. When the pellet reaches the top row the episode terminates. The agent receives a reward of 1 if it caught the pellet, -1 otherwise. All other rewards are zero. See Figure 1a for a depiction of the environment.

We applied FRODO to learning to control the agent. We used the the full Monte Carlo return as update target in the outer loss. In the inner update, instead, the agent only received a trajectory with
3 transitions. This requires FRODO to discover the concepts of temporal-difference prediction and bootstrapping – learning to estimate and use a prediction about events outside of the data – since the game cannot be solved perfectly by looking ahead just three steps. We conduct 10 independent runs with random seeds. From Figure 2a, in orange, we report the average episode return of FRODO observed during the course of training. The policy learned by FRODO surpassed the best possible performance for a 3 step look-ahead agent (the dashed blue line), and learned to control the agent optimally (an average episode return of 1).

**Non-Stationarity:** We use a non-stationary variant of the “5-state Random Walk” environment [31]. The agent starts in the centre of a chain, depicted on Figure 1b, and moves randomly left or right on each step. Episodes terminate when the agent steps out of either boundary, on termination a reward is provided to the agent; on the left side, the reward is either 0 or −1 (switching every 960 time-steps, which corresponds to 10 iterations of FRODO), on the right side the reward is always 1. Each trajectory has 16 time steps.

We applied FRODO to predict the value function, using a TD(1) update as an outer loss. The critical issue is the non-stationarity; the agent must quickly adapt its prediction whenever the reward on the leftmost side switched from 0 to 1, or vice versa. FRODO learned an update capable of dealing with such non-stationarity effectively. In the experiment, we perform 10 independent runs. In Figure 2b we report the mean squared error of the predictions learned by FRODO, in orange. The dashed horizontal lines correspond to the average error of the predictions learned by TD(λ) at convergence. The update learned online by FRODO resulted in more accurate predictions, compared to those learned by the TD(λ) update, for any value of λ. The plot zooms into the period around 5M steps for FRODO (in orange) and for the best performing TD(λ), i.e. λ = 0.4; the predictions learned by FRODO adapted much more robustly to change-points than those of TD(λ), as demonstrated by the significantly lower spikes in the prediction error.

## 5 Large-Scale Experiments

In this section we scale up the actor-critic variant of FRODO from Section 3.5 to more complex RL environments in the Arcade Learning Environment. We instantiate our algorithm within a distributed framework, based on an actor-learner decomposition [10], and implemented in JAX [5].

### 5.1 Off-Policy Learning

In actor-learner architectures [10], a parallel group of actors collect trajectories by interacting with separate copies of the environment, and send the trajectories to a queue for the learner to process in batch. This architecture enables excellent throughput, but the latency in communications between the actors and the learner introduces off-policy learning issues, because the parameters of the actors’ policy (the behaviour policy µ) lag behind the parameters in the learner’s policy (the target policy π). Actor-critic updates such as VTrace can correct for such off-policyness by using the action probabilities under the behaviour policy to perform importance sampling.

To address this in our actor-critic instantiation of FRODO, we use VTrace [10], rather than a vanilla actor-critic, as outer update. In the inner loop, the meta network takes trajectories from the behaviour policy µ as input. Specifically it receives the rewards $R_t$, discounts $γ_t$, and, as in the motivating examples from Section 4, the values from future time-steps $v(S_{t+1})$, to allow bootstrapping from the learned predictions. To address off-policy learning, the probabilities of the target policy and behaviour policy for the current action $A_t$ selected in state $S_t$, (i.e., $π(S_t, A_t)$ and $µ(S_t, A_t)$), are also fed as inputs. This allows the inner loss to potentially discover off-policy algorithms, by constructing suitable off-policy update targets for the policy and value function. Thus, inputs to the meta network include $\{R_{t+1}, γ_{t+1}, v(S_{t+1}), π(S_t, A_t), µ(S_t, A_t), \cdots\}$. The meta network is parameterised by an LSTM [15] and processes each trajectory in reverse order to compute the target $G_θ(ν)$.

### 5.2 Consistent Prediction

In our large scale experiments, we consider a simple yet effective heuristic which enables dramatic speed ups of learning in complex environments. While the meta-networks have the expressive power to model any target function that takes a trajectory as input, we regularise the learning space of the target function towards targets that are self-consistent over time (a property that is common to most
Figure 3: Figure (a) shows the experimental results on the full set of 57 Atari games. Figures (b), (c), and (d) show additional ablations and analysis on a selection of 8 Atari games: asterix, beam rider, crazy climber, defender, kung fu master, pong, qbert, and seaquest. In all cases the x-axis reports the total number of environment frames, for each game. See y-axis differs between subfigures.

update targets in deep reinforcement learning - c.f. [25]. Concretely, we suggest to regularise the learned update targets $G_\eta$ towards functions that decompose as:

$$G_\eta^t = R_{t+1} + \gamma G_\eta^{t+1}.$$  \hspace{1cm} (12)

To incorporate the heuristic into our meta-gradient framework, we transform the above equations into a prediction loss, and add this component into $L_{\text{outer}}$ to learn our meta-network $\eta$. For example, using a one-step prediction consistency loss:

$$L_{\text{outer}} \leftarrow L_{\text{outer}} + c \| \eta(R_{t+1} + \gamma G_\eta^{t+1}) - G_\eta^t \|^2,$$  \hspace{1cm} (13)

where $c$ is for a coefficient for the consistency loss and $\eta$ denotes stop gradient operator. Extension to $n$-step self-consistent prediction can be obtained by decomposing $G_\eta^t$ into $n$-step cumulative discounted rewards with bootstrapping in the final step.

5.3 Atari Experiments

We evaluated the performance of our method on a challenging and diverse set of classic Atari games, from the Arcade Learning Environment (ALE) [4].

We applied the FRODO algorithm to learn a target online, using an outer loss based on the actor-critic algorithm IMPALA [10], and using a consistency loss was included with $c = 0.1$. The agent network is parameterised with a two-layer convolutional neural network (detailed configurations and hyperparameters can be found in the Appendix). We evaluate our agents over 16 billion frames.
of training. We ran separate training runs for all 57 standard benchmark games in the ALE. We computed the median of human-normalised scores throughout training, and compared to the same IMPALA actor-critic algorithm without any objective discovery.

In Figure 3a we see that the meta-gradient algorithm learned slowly and gradually to discover an effective objective. However, over time the meta-gradient algorithm learned to learn more rapidly, ultimately overtaking the actor-critic baseline and achieving significantly stronger final results.

5.4 Analysis

We now examine the technical contributions that facilitate our primary goal of online objective discovery: representing targets in the meta-network versus representing a loss; and the introduction of a consistency loss. In these analysis experiments, we use a subset of 8 Atari games, namely, “kung fu master”, “qbert”, “crazy climber”, “asterix”, “beam rider”, “defender”, “pong” &“seaquest”, and train each of the games over three independent runs. In each of the plots, we show the median human-normalised score over all three runs; the shaded area shows standard derivation across random seeds. Ablation runs were performed for 4 billion frames.

Discovering targets v.s. Discovering loss: Our first experiment compares the performance of online objective discovery between a meta-network that represents the target and a meta-network that represents the loss, similarly to prior work in offline, multi-lifetime setups such as ML3 [2], MetaGenRL [19]. As we illustrate in Figure 3b, directly representing the loss by the meta-network performs poorly across all games. We hypothesise that this is due to significant instabilities in the learning dynamics, which may at any time form a loss that leads to rapid divergence. In contrast, representing the target by the meta-network performs much more stably across all games.

Consistency loss: Next, we examine the effectiveness of a consistency loss in large-scale experiments. We use values of different magnitude as the coefficient of the consistency loss in FRODO, varying between disabling consistency loss (coefficient \( c = 0 \)) and a large consistency loss (\( c = 1 \)). The aggregated median score learning curves are shown in Figure 3c. The introduction of a modest level (\( c = 0.1 \)) of consistency loss led to a dramatic improvements in learning speed and achieved significantly higher performance. Without the consistency heuristic, performance dropped significantly and was also more unstable, presumably due to an increased likelihood of uninformative or misleading targets. Additionally, regularising too strongly (\( c = 1 \)) led to significantly worse performance.

Analysis of Learned Objective: Finally, we analysed the objective learned by FRODO over time. Our primary question was whether the discovered target used in the inner loss differed significantly from the VTrace target used in the outer loss. For each of the eight games, we computed the mean-squared error, averaged over the time-steps in the trajectory, between the VTrace return and the meta-network return \( g_\eta(\tau) \). Figure 3d shows that the discovered objective both varies over time, and varies significantly away from the VTrace target, with a very different characteristic in each game. Only in the game of “Pong” was a target close to VTrace preferred throughout training, perhaps because nothing more complex was required in this case.

6 Conclusion

In this paper, we proposed an algorithm that allows RL agents to learn their own objective during online interactions with their environment. The objective, specifically the target used to update the policy and value function, is parameterised by a deep neural meta-network. The nature of the meta-network, and hence the objective of the RL algorithm, is discovered by meta-gradient descent over the sequence of updates based upon the discovered target.

Our results in toy domains demonstrate that FRODO can successfully discover how to address key issues in RL, such as bootstrapping and non-stationarity, through online adaptation of its objective. Our results in Atari demonstrate that FRODO can successfully discover and adapt off-policy learning objectives that are distinct from, and performed better than, strong benchmark RL algorithms. Taken together, these examples illustrate the generality of the proposed method, and suggest its potential both to recover existing concepts, and to discover new concepts for RL algorithms.
Broader Impact

This work is situated within a broad and important long-term research program for reinforcement learning: how might a machine discover its own algorithm for RL? Specifically, the research considers one strand of potential research in this area, which is how a machine might discover its own objective for RL. Because our research focuses on the online setting (compared, for example, to much prior work on meta-learning that learns offline from a distribution of tasks), it is applicable to any RL problem. In principle, therefore, any benefits demonstrated in this paper might potentially be applicable to other future RL problems. Thus, the ethical consequences of this research are similar to those for any other research on the RL problem itself: it may provide some progress and accelerate research towards all RL problems, which may benefit any users and use-cases of RL (both "good" and "bad"). Our algorithm learns entirely from interaction with its environment, and does not utilise any external source of data.

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A Implementation Details

In this section, we provide the implementation details of our proposed algorithm, including the motivating examples we described in Sec 4 and large-scale experiments in Atari in Sec 5.

A.1 Motivating Examples

In our investigations, a wide range of hyperparameters work well in the motivating examples and we provide the specific one we used to show our results.

**Bootstrapping:** For the bootstrapping experiment, we use an LSTM [15] with 256 hidden units as meta network. The inputs to the meta network include reward $R_{t+1}$, discount $\gamma_{t+1}$, value from the next state $v(S_{t+1})$, which were fed in reverse-time order into the LSTM. The agent network is a two layer MLP with 256 hidden units. Both agent optimiser and the meta optimiser are RMSProp [34], where learning rate is $1e^{-3}$ and meta learning rate is $1e^{-4}$. M = 5 inner updates are performed to the agent then the metagradient is obtained. We perform 10 independent runs with 10 different random seeds and report average performance with standard deviation.

**Non-stationarity:** For the non-stationarity experiment, we use an LSTM with 32 hidden units as meta network. Each trajectory from the environment has 16 transitions. The inputs to the meta network include reward $R_{t+1}$, discount $\gamma_{t+1}$, value from the next state $v(S_{t+1})$, which were fed in reverse-time order into the LSTM. Both agent optimiser and the meta optimiser are RMSProp [34], where learning rate is $1e^{-1}$ and meta learning rate is $1e^{-2}$. We use larger learning rates here to enable rapid learning in the simple random walk environment. Same as above, M = 5 inner updates are performed to the agent then the metagradient is obtained. For our baseline TD($\lambda$) experiment, we use the same learning rate $1e^{-1}$ and report convergent result from all $\lambda$s from [0.0, 0.4, 0.8, 0.9, 0.99, 1]. We perform 10 independent runs with 10 different random seeds and report average performance with standard deviation.

A.2 Large-Scale Experiments

In the large-scale Atari experiments, we compare FRODO with the corresponding baseline IMPALA [10], where we keep all the hyper-parameters on the agent learning the same in the two agents. In Table 1 we show the shared hyper-parameter between FRODO and IMPALA agents in “IMPALA hyper-parameter”, which includes network architecture, batch size, learning rate, etc, and we show the FRODO specific hyper-parameter in the bottom, such as inner update steps, meta learning rate, etc.

B Computing Infrastructure

We run our experiments using a distributed infrastructure implemented in JAX [5]. The computing infrastructure is based on an actor-learner decomposition [10], where multiple actors generate experience in parallel, and this experience is channelled into a learner via a small queue. Both the actors and learners are co-located on a single machine, where the host is equipped with 56 CPU cores and connected to 8 TPU cores [18]. To minimise the effect of Python’s Global Interpreter Lock, each actor-thread interacts with a *batched environment*; this is exposed to Python as a single special environment that takes a batch of actions and returns a batch of observations, but that behind the scenes steps each environment in the batch in C++. The actor threads share 2 of the 8 TPU cores (to perform inference on the network), and send batches of fixed size trajectories of length T to a queue. The learner threads takes these batches of trajectories and splits them across the remaining 6 TPU cores for computing the parameter update (these are averaged with an all reduce across the participating cores). Updated parameters are sent to the actor TPU devices via a fast device to device channel as soon as the new parameters are available. This minimal unit can be replicates across multiple hosts, each connected to its own 56 CPU cores and 8 TPU cores, in which case the learner updates are synced and averaged across all learner cores (again via fast device to device communication).

It took approximately 1.5 hours to learn from 1 billion Atari environment frames with the two-layer ConvNet we used.
### Table 1: Detailed hyper-parameters for Atari experiments.

| IMPALA hyper-parameter          | Value                  |
|---------------------------------|------------------------|
| Network architecture            | Two-layer ConvNet      |
| ConvNet channels                | 32, 64                 |
| ConvNet kernel sizes            | 4, 4                   |
| ConvNet kernel strides          | 4, 4                   |
| Unroll length                   | 30                     |
| Batch size                      | 30                     |
| Baseline loss scaling           | 0.5                    |
| Entropy cost                    | 0.01                   |
| Learning rate                   | 1e-3                   |
| RMSProp momentum                | 0.0                    |
| RMSProp decay                   | 0.99                   |
| RMSProp \( \epsilon \)          | 0.1                    |
| Clip global gradient norm       | 1e-4                   |

| FRODO hyper-parameter          | Value                  |
|--------------------------------|------------------------|
| Inner update steps \( M \)     | 5                      |
| Meta learning rate             | 5e-4                   |
| Meta optimiser                 | RMSProp                |
| Clip Meta gradient norm        | 1e-4                   |
| Meta batch size                | 30                     |

In this section, we provide pseudo-code in Python format which show how we implemented the key ideas in our proposed FRODO algorithm. Our algorithm is implemented with neural network library Haiku [12] and reinforcement learning library RLax [6] in JAX [5]. We first use the prediction task of toy problems in Sec 4 as an example to show how we implemented the algorithm by a few small functions. Then, we show a base class for FRODO agents and concrete instantiation for our Atari experiments. LICENCE shown in Sec [C.1] applies to all the provided code.

#### C.1 LICENCE

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#### C.2 Prediction task in toy problems

In the prediction task of non-stationary “5-state random walk” (Sec 4), the meta network \( g_\eta \) takes a trajectory \( \tau \) as input and outputs \( G_\eta(\tau) \) as the update target (shown in \( \text{outer_loss_fn} \), then the agent use squared TD error between \( G_\eta(\tau) \) and the values to update the value function (shown in \( \text{agent_update} \). The agent applies a few steps of updates then obtains a differentiable outer loss (shown in \( \text{agent_updates_and_outer_loss} \). Finally we have the \( \text{two_level_update} \) to update the meta network \( \eta \) and complete the algorithm.

```python
def inner_loss_fn(theta, eta, traj):
    """Inner loss function.""
    obs = traj.observation
```
rewards = traj.reward[1:]
discounts = traj.discount[1:]
v = v_net_apply(theta, obs)

eta_inputs = {
    'obs': obs[:-1],
    'reward': rewards,
    'discount': discounts,
    'v': v[1:],
}
g_eta = eta_net_apply(eta, eta_inputs)
td_error = g_eta - v[:-1]
return jnp.mean(jnp.square(td_error))

def outer_loss_fn(theta, traj):
    '''Outer loss function.'''
    obs = traj.observation
    rewards = traj.reward[1:]
discounts = traj.discount[1:]
v = v_net_apply(theta, obs)
g = discounted_return_fn(rewards, discounts, v[-1, :][None, ...])
td_error = jax.lax.stop_gradient(g) - v[:-1]
return jnp.mean(jnp.square(td_error))

def agent_update(theta, opt_state, eta, traj, optim):
    '''Update the agent parameter.'''
    loss, g = jax.value_and_grad(inner_loss_fn)(theta, eta, traj)
delta, opt_state = optim.update(g, opt_state)
theta = optix.apply_updates(theta, delta)
return theta, opt_state, loss

def agent_updates_and_outer_loss(eta, theta, opt_state, traj_arr, optim):
    # M steps of inner updates to the agent
    for traj in traj_arr[:-1]:
        theta, opt_state, unused_loss = agent_update(theta, opt_state, eta, traj,
                                                    optim)
    val_traj = traj_arr[-1]
    # Take outer loss from the updated theta and validation trajectory
    outer_loss = outer_loss_fn(theta, val_traj)
    return outer_loss, (theta, opt_state)

def two_level_update(theta, opt_state, eta, eta_opt_state, traj_arr, optim,
                      eta_optim):
    # Obtain the meta gradient and perform two-level update
    (loss, (theta, opt_state)), meta_g = jax.value_and_grad(
        agent_updates_and_outer_loss, has_aux=True)(eta, theta, opt_state,
                                                    traj_arr, optim)
    # Update eta with metagradient
    delta_eta, eta_opt_state = eta_optim.update(meta_g, eta_opt_state)
    eta = optix.apply_updates(eta, delta_eta)
    return theta, opt_state, eta, eta_opt_state, loss
C.3 FRODO Base Class

In this section, we provide a FRODOAgent base class to show how to implement the agent for large-scale experiments. Similarly to the toy example code above, we use two_level_update function as the entry point of the algorithm. To instantiate specific algorithms, we only need to implement the abstract functions inner_loss and outer_loss, which we are showing an example in C.4 and C.5. Different inner loss and outer loss other than what we used can be instantiated in the subclass.

```python
import jax
from jax import lax
from jax import numpy as jnp
from jax.experimental import optimizers
from jax.tree_util import tree_multimap

class FRODOAgent:
    """Base class for FRODO Agents.""
    def __init__(self, ...):
        """Init function.""
        raise NotImplementedError

    def actor_step(self, params, env_output, actor_state, rng_key, evaluation):
        """Compute actions.""
        raise NotImplementedError

    def build_eta(self, meta_net_type, meta_net_kwargs):
        """Build eta and eta optimizer.""
        raise NotImplementedError

    def inner_loss(self, theta, eta, rollout, first_actor_state):
        """Inner loss on the rollout, the loss contains learnable eta.""
        raise NotImplementedError

    def outer_loss(self, theta, rollout, first_actor_state):
        """Outer loss on the rollout.""
        raise NotImplementedError

    def inner_update(self, theta, theta_opt_state, eta, rollout,
                     first_actor_state):
        """Perform a step of inner update to the agent.""
        # grad(inner_loss)
        g, (last_actor_state, logs) = jax.grad(
            self.inner_loss, has_aux=True)(theta, eta, rollout, first_actor_state)
        # Gather gradients from all devices.
        grads = tree_multimap(
            lambda t: lax.psum(t, axis_name='i') / lax.psum(1., axis_name='i'), g)
        # Clip the gradients according to global max norm.
        grads = optimizers.clip_grads(grads, self.max_theta_grad_norm)
        # Use the optimizer to apply a suitable gradient transformation.
        updates, new_theta_opt_state = self._opt_update(grads, theta_opt_state)
        # Update parameters.
        new_theta = tree_multimap(lambda p, u: p + u, theta, updates)
        return new_theta, new_theta_opt_state, last_actor_state, logs

    def inner_updates_and_outer_loss(self, eta, theta, theta_opt_state,
                                      rollout_arr):
        """Perform a few inner updates and have the outer loss of the last batch.""
        logs_arr = []
        # Perform inner updates on the rollout list.
```

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cons_loss = jnp.array(0.)
last_actor_states = []
for _, (rollout, first_actor_state) in enumerate(rollout_arr[:-1]):
    theta, theta_opt_state, last_actor_state, logs = self.inner_update(
        theta, theta_opt_state, eta, rollout, first_actor_state)
    if 'cons_loss' in logs:
        cons_loss += logs['cons_loss']
    logs_arr.append(logs)
    last_actor_states.append(last_actor_state)

# Use the final batch of rollout as validation data to form the outer loss.
val_rollout, val_first_actor_state = rollout_arr[-1]
loss, (last_actor_state, _) = self.outer_loss(theta, val_rollout,
                                          val_first_actor_state)

last_actor_states.append(last_actor_state)
loss = loss + self.settings.cons_weight * cons_loss
last_actor_state = tree_multimap(lambda *inputs: jnp.concatenate(inputs),
*last_actor_states)
return loss, (theta, theta_opt_state, last_actor_state, logs)

def two_level_update(self, theta, theta_opt_state, eta, eta_opt_state,
                      rollout_arr):
    """Two level updates to eta and to theta."""
    # Perform inner updates and compute meta gradient.
    (unused_outer_loss_v, (new_theta, new_theta_opt_state, last_actor_state,
        logs)), eta_g = jax.value_and_grad(
        self.inner_updates_and_outer_loss,
        has_aux=True)(eta, theta, theta_opt_state,
                    rollout_arr)
    # Gather meta gradients from all devices.
    eta_grads = tree_multimap(
        lambda t: lax.psum(t, axis_name='i') / lax.psum(1., axis_name='i'),
        eta_g)

    eta_grads = optimizers.clip_grads(eta_grads, self.max_eta_grad_norm)
    # Update eta.
    eta_updates, new_eta_opt_state = self._eta_opt_update(
        eta_grads, eta_opt_state)
    new_eta = tree_multimap(lambda p, u: p + u, eta, eta_updates)
    return (new_theta, new_theta_opt_state, new_eta, new_eta_opt_state,
            last_actor_state, logs)

C.4 FRODO Actor-Critic Inner Loss

import rlax

def inner_loss(self, theta, eta, rollout, first_actor_state):
    env_output, agent_output = self.preprocessing_rollout(rollout)
    actions = agent_output.actions[self._action_name]
    (logits, v, torso_out), last_actor_state = self.net_unroll(
        theta, env_output, env_output['step_type'], first_actor_state)
    logits = logits[self._action_name]
    v_tm1 = jnp.squeeze(v[:-1], axis=-1)
    v_t = jnp.squeeze(v[1:], axis=-1)

    logpi = jax.nn.log_softmax(logits[:-1]))  # [T,B,A]
    logpi_a = rlax.bunched_index(logpi, actions[:-1])  # [T, B]

    logmu = jax.nn.log_softmax(agent_output.logits[:-1]))  # [T,B,A]
    logmu_a = rlax.bunched_index(logmu, actions[:-1])  # [T,B]
inputs = dict(
    reward=env_output['reward'][1:],
    discount=env_output['discount'][1:],
    pi_a=jnp.exp(logpi_a),
    mu_a=jnp.exp(logmu_a),
    v_t=v_t,
    torso_out=torso_out[:-1],
)
learned_return = self._eta_apply_fn(eta, inputs)

# Policy gradient loss.
advantages = learned_return - sg(v_tm1)  # [T, B]
pi_loss = -jnp.sum(advantages * logpi_a)

# Baseline loss
baseline_loss = 0.5 * jnp.sum(jnp.square(learned_return - v_tm1))

# Entropy loss.
pi = jax.nn.softmax(logits[:-1])
logpi = jax.nn.log_softmax(logits[:-1])
entropy = jnp.sum(-pi * logpi, axis=-1)
entropy_loss = -jnp.sum(entropy)

# Sum and weight losses.
total_loss = pi_loss
total_loss += self.settings.baseline_weight * baseline_loss
total_loss += self.settings.entropy_weight * entropy_loss

# Consistency loss for G_eta
rewards = env_output['reward'][1:]
discounts = env_output['discount'][1:]
learned_return_tm1 = learned_return[:-1]

# n-step self-consistency.
batched_discounted_returns = jax.vmap(rlax.discounted_returns, in_axes=1, out_axes=1)
target_tm1 = batched_discounted_returns(rewards, discounts, learned_return[-1][None, ...])
cons_loss = 0.5 * jnp.sum(jnp.square(sg(target_tm1[:-1]) - learned_return_tm1))

logs = {'cons_loss': cons_loss}
return total_loss, (last_actor_state, logs)

C.5 FRODO Actor-Critic Outer Loss

import rlax

def outer_loss(self, theta, rollout, first_actor_state):
    env_output, agent_output = self.preprocessing_rollout(rollout)
    actions = agent_output.actions[self._action_name]

    # Apply net_unroll.
    (logits, v, _), last_actor_state = self.net_unroll(
        theta, env_output, env_output['step_type'], first_actor_state)
    logits = logits[self._action_name]
    tau = self.settings.temperature
    logits = logits / tau
    v_t = jnp.squeeze(v[1:], axis=-1)
    v_t = jnp.squeeze(v[:1], axis=-1)

    # Apply vtrace computation in batch.
batched_vtrace = jax.vmap(
    functools.partial(
        rlax.vtrace_td_error_and_advantage,
        lambda_=self.settings.lambda_,
        clip_rho_threshold=self.settings.clip_rho_threshold,
        clip_pg_rho_threshold=self.settings.clip_pg_rho_threshold),
    in_axes=1, out_axes=1)

# Compute importance weighted td-errors and advantages.
reward = env_output['reward']
discount = env_output['discount']
rhos = rlax.categorical_importance_sampling_ratios(
    logits, agent_output.logits, actions)
vtrace_output = batched_vtrace(
    v_tm1, v_t, reward[1:], discount[1:], rhos[:-1])

# Policy gradient loss.
logpi = jax.nn.log_softmax(logits[:-1])  # [T,B,A]
logpi_a = rlax.batched_index(logpi, actions[:-1])  # [T, B]
advantages = sg(vtrace_output.pg_advantage)  # [T, B]
pi_loss = -jnp.sum(advantages * logpi_a)

# Value loss.
baseline_loss = 0.5 * jnp.sum(jnp.square(vtrace_output.errors))

# Entropy loss.
pi = jax.nn.softmax(logits[:-1])
logpi = jax.nn.log_softmax(logits[:-1])
entropy = jnp.sum(-pi * logpi, axis=-1)
entropy_loss = -jnp.sum(entropy)

# Sum and weight losses.
total_loss = pi_loss
total_loss += self.settings.baseline_weight * baseline_loss
total_loss += self.settings.entropy_weight * entropy_loss
return total_loss, (last_actor_state, None)