

A Guided Tour of Chapter 14: Policy Gradient Algorithms

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Why do we care about Policy Gradient (PG)?

- Let us review how we got here
- We started with Markov Decision Processes and Bellman Equations
- Next we studied several variants of DP and RL algorithms
- We noted that the idea of *Generalized Policy Iteration* (GPI) is key
- Policy Improvement step: $\pi(s, a)$ derived from $\text{argmax}_a Q(s, a)$
- How do we do argmax when action space is large or continuous?
- Idea: Do Policy Improvement step with a Gradient Ascent instead

“Policy Improvement with a Gradient Ascent??”

- We want to find the Policy that fetches the “Best Expected Returns”
- Gradient Ascent on “Expected Returns” w.r.t params of Policy func
- So we need a func approx for (stochastic) Policy Func: $\pi(s, a; \theta)$
- In addition to the usual func approx for Action Value Func: $Q(s, a; w)$
- $\pi(s, a; \theta)$ called *Actor* and $Q(s, a; w)$ called *Critic*
- Critic parameters w are optimized w.r.t $Q(s, a; w)$ loss function min
- Actor parameters θ are optimized w.r.t Expected Returns max
- We need to formally define “Expected Returns”
- But we already see that this idea is appealing for continuous actions
- GPI with Policy Improvement done as **Policy Gradient (Ascent)**

Value Function-based and Policy-based RL

- Value Function-based
 - Learn Value Function (with a function approximation)
 - Policy is implicit - readily derived from Value Function (eg: ϵ -greedy)
- Policy-based
 - Learn Policy (with a function approximation)
 - No need to learn a Value Function
- Actor-Critic
 - Learn Policy (Actor)
 - Learn Value Function (Critic)

Advantages and Disadvantages of Policy Gradient approach

Advantages:

- Finds the best *Stochastic Policy* (Optimal Deterministic Policy, produced by other RL algorithms, can be unsuitable for POMDPs)
- Naturally *explores* due to Stochastic Policy representation
- Effective in high-dimensional or continuous action spaces
- Small changes in $\theta \Rightarrow$ small changes in π , and in state distribution
- This avoids the convergence issues seen in argmax-based algorithms

Disadvantages:

- Typically converge to a local optimum rather than a global optimum
- Policy Evaluation is typically inefficient and has high variance
- Policy Improvement happens in small steps \Rightarrow slow convergence

Notation

- Assume episodic with $0 \leq \gamma \leq 1$ or non-episodic with $0 \leq \gamma < 1$
- Assume discrete-time, countable-spaces, time-homogeneous MDPs
- We lighten $\mathcal{P}(s, a, s')$ notation to $\mathcal{P}_{s,s'}^a$ and $\mathcal{R}(s, a)$ notation to \mathcal{R}_s^a
- Initial State Probability Distribution denoted as $p_0 : \mathcal{N} \rightarrow [0, 1]$
- Policy Function Approximation $\pi(s, a; \theta) = \mathbb{P}[A_t = a | S_t = s; \theta]$

PG coverage is quite similar for non-discounted non-episodic, by considering average-reward objective (we won't cover it)

“Expected Returns” Objective

Now we formalize the “Expected Returns” Objective $J(\theta)$

$$J(\theta) = \mathbb{E}_\pi \left[\sum_{t=0}^{\infty} \gamma^t \cdot R_{t+1} \right]$$

Value Function $V^\pi(s)$ and Action Value function $Q^\pi(s, a)$ defined as:

$$V^\pi(s) = \mathbb{E}_\pi \left[\sum_{k=t}^{\infty} \gamma^{k-t} \cdot R_{k+1} | S_t = s \right] \text{ for all } t = 0, 1, 2, \dots$$

$$Q^\pi(s, a) = \mathbb{E}_\pi \left[\sum_{k=t}^{\infty} \gamma^{k-t} \cdot R_{k+1} | S_t = s, A_t = a \right] \text{ for all } t = 0, 1, 2, \dots$$

$$\text{Advantage Function } A^\pi(s, a) = Q^\pi(s, a) - V^\pi(s)$$

Also, $p(s \rightarrow s', t, \pi)$ will be a key function for us - it denotes the probability of going from state s to s' in t steps by following policy π

Discounted-Aggregate State-Visitation Measure

$$\begin{aligned} J(\theta) &= \mathbb{E}_\pi \left[\sum_{t=0}^{\infty} \gamma^t \cdot R_{t+1} \right] = \sum_{t=0}^{\infty} \gamma^t \cdot \mathbb{E}_\pi [R_{t+1}] \\ &= \sum_{t=0}^{\infty} \gamma^t \cdot \sum_{s \in \mathcal{N}} \left(\sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot p(S_0 \rightarrow s, t, \pi) \right) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot \mathcal{R}_s^a \\ &= \sum_{s \in \mathcal{N}} \left(\sum_{S_0 \in \mathcal{N}} \sum_{t=0}^{\infty} \gamma^t \cdot p_0(S_0) \cdot p(S_0 \rightarrow s, t, \pi) \right) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot \mathcal{R}_s^a \end{aligned}$$

Definition

$$J(\theta) = \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot \mathcal{R}_s^a$$

where $\rho^\pi(s) = \sum_{S_0 \in \mathcal{N}} \sum_{t=0}^{\infty} \gamma^t \cdot p_0(S_0) \cdot p(S_0 \rightarrow s, t, \pi)$ is the key function
(for PG) we'll refer to as *Discounted-Aggregate State-Visitation Measure*.

Policy Gradient Theorem (PGT)

Theorem

$$\nabla_{\theta} J(\theta) = \sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \nabla_{\theta} \pi(s, a; \theta) \cdot Q^{\pi}(s, a)$$

- Note: $\rho^{\pi}(s)$ depends on θ , but there's no $\nabla_{\theta} \rho^{\pi}(s)$ term in $\nabla_{\theta} J(\theta)$
- Note: $\nabla_{\theta} \pi(s, a; \theta) = \pi(s, a; \theta) \cdot \nabla_{\theta} \log \pi(s, a; \theta)$
- So we can simply generate sampling traces, and at each time step, calculate $(\nabla_{\theta} \log \pi(s, a; \theta)) \cdot Q^{\pi}(s, a)$ (probabilities implicit in paths)
- Note: $\nabla_{\theta} \log \pi(s, a; \theta)$ is Score function (Gradient of log-likelihood)
- We will estimate $Q^{\pi}(s, a)$ with a function approximation $Q(s, a; \mathbf{w})$
- We will later show how to avoid the estimate bias of $Q(s, a; \mathbf{w})$
- This numerical estimate of $\nabla_{\theta} J(\theta)$ enables **Policy Gradient Ascent**
- Let us look at the score function of some canonical $\pi(s, a; \theta)$

Canonical $\pi(s, a; \theta)$ for finite action spaces

- For finite action spaces, we often use Softmax Policy
- θ is an m -vector $(\theta_1, \dots, \theta_m)$
- Features vector $\phi(s, a) = (\phi_1(s, a), \dots, \phi_m(s, a))$ for all $s \in \mathcal{N}, a \in \mathcal{A}$
- Weight actions using linear combinations of features: $\phi(s, a)^T \cdot \theta$
- Action probabilities proportional to exponentiated weights:

$$\pi(s, a; \theta) = \frac{e^{\phi(s, a)^T \cdot \theta}}{\sum_{b \in \mathcal{A}} e^{\phi(s, b)^T \cdot \theta}} \text{ for all } s \in \mathcal{N}, a \in \mathcal{A}$$

- The score function is:

$$\nabla_{\theta} \log \pi(s, a; \theta) = \phi(s, a) - \sum_{b \in \mathcal{A}} \pi(s, b; \theta) \cdot \phi(s, b) = \phi(s, a) - \mathbb{E}_{\pi}[\phi(s, \cdot)]$$

Canonical $\pi(s, a; \theta)$ for continuous action spaces

- For continuous action spaces, we often use Gaussian Policy
- θ is an m -vector $(\theta_1, \dots, \theta_m)$
- State features vector $\phi(s) = (\phi_1(s), \dots, \phi_m(s))$ for all $s \in \mathcal{N}$
- Gaussian Mean is a linear combination of state features $\phi(s)^T \cdot \theta$
- Variance may be fixed σ^2 , or can also be parameterized
- Policy is Gaussian, $a \sim \mathcal{N}(\phi(s)^T \cdot \theta, \sigma^2)$ for all $s \in \mathcal{N}$
- The score function is:

$$\nabla_{\theta} \log \pi(s, a; \theta) = \frac{(a - \phi(s)^T \cdot \theta) \cdot \phi(s)}{\sigma^2}$$

Proof of Policy Gradient Theorem

We begin the proof by noting that:

$$J(\theta) = \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot V^\pi(S_0) = \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \pi(S_0, A_0; \theta) \cdot Q^\pi(S_0, A_0)$$

Calculate $\nabla_\theta J(\theta)$ by parts $\pi(S_0, A_0; \theta)$ and $Q^\pi(S_0, A_0)$

$$\begin{aligned} \nabla_\theta J(\theta) &= \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_\theta \pi(S_0, A_0; \theta) \cdot Q^\pi(S_0, A_0) \\ &\quad + \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \pi(S_0, A_0; \theta) \cdot \nabla_\theta Q^\pi(S_0, A_0) \end{aligned}$$

Proof of Policy Gradient Theorem

Now expand $Q^\pi(S_0, A_0)$ as:

$$\mathcal{R}_{S_0}^{A_0} + \sum_{S_1 \in \mathcal{N}} \gamma \cdot \mathcal{P}_{S_0, S_1}^{A_0} \cdot V^\pi(S_1) \text{ (Bellman Policy Equation)}$$

$$= \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_{\theta} \pi(S_0, A_0; \theta) \cdot Q^\pi(S_0, A_0) + \\ \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \pi(S_0, A_0; \theta) \cdot \nabla_{\theta} (\mathcal{R}_{S_0}^{A_0} + \sum_{S_1 \in \mathcal{N}} \gamma \cdot \mathcal{P}_{S_0, S_1}^{A_0} \cdot V^\pi(S_1))$$

Note: $\nabla_{\theta} \mathcal{R}_{S_0}^{A_0} = 0$, so remove that term

$$= \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_{\theta} \pi(S_0, A_0; \theta) \cdot Q^\pi(S_0, A_0) + \\ \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \pi(S_0, A_0; \theta) \cdot \nabla_{\theta} (\sum_{S_1 \in \mathcal{N}} \gamma \cdot \mathcal{P}_{S_0, S_1}^{A_0} \cdot V^\pi(S_1))$$

Proof of Policy Gradient Theorem

Now bring the ∇_{θ} inside the $\sum_{S_1 \in \mathcal{N}}$ to apply only on $V^{\pi}(S_1)$

$$\begin{aligned} &= \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_{\theta} \pi(S_0, A_0; \theta) \cdot Q^{\pi}(S_0, A_0) + \\ &\quad \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \pi(S_0, A_0; \theta) \cdot \sum_{S_1 \in \mathcal{N}} \gamma \cdot \mathcal{P}_{S_0, S_1}^{A_0} \cdot \nabla_{\theta} V^{\pi}(S_1) \end{aligned}$$

Now bring $\sum_{S_0 \in \mathcal{N}}$ and $\sum_{A_0 \in \mathcal{A}}$ inside the $\sum_{S_1 \in \mathcal{N}}$

$$\begin{aligned} &= \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_{\theta} \pi(S_0, A_0; \theta) \cdot Q^{\pi}(S_0, A_0) + \\ &\quad \sum_{S_1 \in \mathcal{N}} \sum_{S_0 \in \mathcal{N}} \gamma \cdot p_0(S_0) \cdot \left(\sum_{A_0 \in \mathcal{A}} \pi(S_0, A_0; \theta) \cdot \mathcal{P}_{S_0, S_1}^{A_0} \right) \cdot \nabla_{\theta} V^{\pi}(S_1) \end{aligned}$$

Policy Gradient Theorem

Note that $\sum_{A_0 \in \mathcal{A}} \pi(S_0, A_0; \theta) \cdot \mathcal{P}_{S_0, S_1}^{A_0} = p(S_0 \rightarrow S_1, 1, \pi)$

$$= \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_{\theta} \pi(S_0, A_0; \theta) \cdot Q^{\pi}(S_0, A_0) + \\ \sum_{S_1 \in \mathcal{N}} \sum_{S_0 \in \mathcal{N}} \gamma \cdot p_0(S_0) \cdot p(S_0 \rightarrow S_1, 1, \pi) \cdot \nabla_{\theta} V^{\pi}(S_1)$$

Now expand $V^{\pi}(S_1)$ to $\sum_{A_1 \in \mathcal{A}} \pi(S_1, A_1; \theta) \cdot Q^{\pi}(S_1, A_1)$

$$= \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_{\theta} \pi(S_0, A_0; \theta) \cdot Q^{\pi}(S_0, A_0) + \\ \sum_{S_1 \in \mathcal{N}} \sum_{S_0 \in \mathcal{N}} \gamma \cdot p_0(S_0) \cdot p(S_0 \rightarrow S_1, 1, \pi) \cdot \nabla_{\theta} \left(\sum_{A_1 \in \mathcal{A}} \pi(S_1, A_1; \theta) \cdot Q^{\pi}(S_1, A_1) \right)$$

Proof of Policy Gradient Theorem

We are now back to when we started calculating gradient of $\sum_a \pi \cdot Q^\pi$. Follow the same process of splitting $\pi \cdot Q^\pi$, then Bellman-expanding Q^π (to calculate its gradient), and iterate.

$$\nabla_{\theta} J(\theta) = \sum_{S_0 \in \mathcal{N}} p_0(S_0) \cdot \sum_{A_0 \in \mathcal{A}} \nabla_{\theta} \pi(S_0, A_0; \theta) \cdot Q^\pi(S_0, A_0) +$$

$$\sum_{S_1 \in \mathcal{N}} \sum_{S_0 \in \mathcal{N}} \gamma \cdot p_0(S_0) \cdot p(S_0 \rightarrow S_1, 1, \pi) \cdot \left(\sum_{A_1 \in \mathcal{A}} \nabla_{\theta} \pi(S_1, A_1; \theta) \cdot Q^\pi(S_1, A_1) + \dots \right)$$

This iterative process leads us to:

$$= \sum_{t=0}^{\infty} \sum_{S_t \in \mathcal{N}} \sum_{S_0 \in \mathcal{N}} \gamma^t \cdot p_0(S_0) \cdot p(S_0 \rightarrow S_t, t, \pi) \cdot \sum_{A_t \in \mathcal{A}} \nabla_{\theta} \pi(S_t, A_t; \theta) \cdot Q^\pi(S_t, A_t)$$

Proof of Policy Gradient Theorem

Bring $\sum_{t=0}^{\infty}$ inside $\sum_{S_t \in \mathcal{N}} \sum_{S_0 \in \mathcal{N}}$ and note that

$$\sum_{A_t \in \mathcal{A}} \nabla_{\theta} \pi(S_t, A_t; \theta) \cdot Q^{\pi}(S_t, A_t) \text{ is independent of } t$$

$$= \sum_{s \in \mathcal{N}} \sum_{S_0 \in \mathcal{N}} \sum_{t=0}^{\infty} \gamma^t \cdot p_0(S_0) \cdot p(S_0 \rightarrow s, t, \pi) \cdot \sum_{a \in \mathcal{A}} \nabla_{\theta} \pi(s, a; \theta) \cdot Q^{\pi}(s, a)$$

Reminder that $\sum_{S_0 \in \mathcal{N}} \sum_{t=0}^{\infty} \gamma^t \cdot p_0(S_0) \cdot p(S_0 \rightarrow s, t, \pi) \stackrel{\text{def}}{=} \rho^{\pi}(s)$. So,

$$\nabla_{\theta} J(\theta) = \sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \nabla_{\theta} \pi(s, a; \theta) \cdot Q^{\pi}(s, a)$$

Q.E.D.

Monte-Carlo Policy Gradient (REINFORCE Algorithm)

- Update θ by stochastic gradient ascent using PGT
- Using $G_t = \sum_{k=t}^T \gamma^{k-t} \cdot R_{k+1}$ as an unbiased sample of $Q^\pi(S_t, A_t)$

$$\Delta\theta = \alpha \cdot \gamma^t \cdot \nabla_\theta \log \pi(S_t, A_t; \theta) \cdot G_t$$

Algorithm 0.1: REINFORCE(\cdot)

Initialize θ arbitrarily

for each episode $\{S_0, A_0, R_1, S_1, \dots, S_{T-1}, A_{T-1}, R_T, S_T\} \sim \pi(\cdot, \cdot; \theta)$

do $\left\{ \begin{array}{l} \text{for } t \leftarrow 0 \text{ to } T \\ \text{do } \left\{ G \leftarrow \sum_{k=t}^T \gamma^{k-t} \cdot R_{k+1} \\ \theta \leftarrow \theta + \alpha \cdot \gamma^t \cdot \nabla_\theta \log \pi(S_t, A_t; \theta) \cdot G \end{array} \right. \end{array} \right.$

Reducing Variance using a Critic

- Monte Carlo Policy Gradient has high variance
- We use a Critic $Q(s, a; \mathbf{w})$ to estimate $Q^\pi(s, a)$
- Actor-Critic algorithms maintain two sets of parameters:
 - Critic updates parameters \mathbf{w} to approximate Q -function for policy π
 - Critic could use any of the algorithms we learnt earlier:
 - Monte Carlo policy evaluation
 - Temporal-Difference Learning
 - $TD(\lambda)$ based on Eligibility Traces
 - Could even use LSTD (if critic function approximation is linear)
- Actor updates policy parameters θ in direction suggested by Critic
- This is Approximate Policy Gradient due to *Bias* of Critic

$$\nabla_{\theta} J(\theta) \approx \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \nabla_{\theta} \pi(s, a; \theta) \cdot Q(s, a; \mathbf{w})$$

So what does the algorithm look like?

- Generate a sufficient set of sampling traces
 $S_0, A_0, R_1, S_1, A_1, R_2, S_2 \dots$
- S_0 is sampled from the distribution $p_0(\cdot)$
- A_t is sampled from $\pi(S_t, \cdot; \theta)$
- Receive atomic experience (R_{t+1}, S_{t+1}) from the environment
- At each time step t , update w proportional to gradient of appropriate (MC or TD-based) loss function of $Q(s, a; w)$
- Sum $\gamma^t \cdot (\nabla_\theta \log \pi(S_t, A_t; \theta)) \cdot Q(S_t, A_t; w)$ over t and over paths
- Update θ using this (biased) estimate of $\nabla_\theta J(\theta)$
- Iterate with a new set of sampling traces ...

Reducing Variance with a Baseline

- We can reduce variance by subtracting a baseline function $B(s)$ from $Q(s, a; \mathbf{w})$ in the Policy Gradient estimate
- This means at each time step, we replace $\gamma^t \cdot \nabla_{\theta} \log \pi(S_t, A_t; \theta) \cdot Q(S_t, A_t; \mathbf{w})$ with $\gamma^t \cdot \nabla_{\theta} \log \pi(S_t, A_t; \theta) \cdot (Q(S_t, A_t; \mathbf{w}) - B(S_t))$
- Note that Baseline function $B(s)$ is only a function of s (and not a)
- This ensures that subtracting Baseline $B(s)$ does not add bias

$$\begin{aligned}& \sum_{s \in \mathcal{N}} \rho^\pi(s) \sum_{a \in \mathcal{A}} \nabla_{\theta} \pi(s, a; \theta) \cdot B(s) \\&= \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot B(s) \cdot \nabla_{\theta} \left(\sum_{a \in \mathcal{A}} \pi(s, a; \theta) \right) \\&= \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot B(s) \cdot \nabla_{\theta} 1 \\&= 0\end{aligned}$$

Using State Value function as Baseline

- A good baseline $B(s)$ is state value function $V(s; \mathbf{v})$
- Rewrite Policy Gradient algorithm using advantage function estimate

$$A(s, a; \mathbf{w}, \mathbf{v}) = Q(s, a; \mathbf{w}) - V(s; \mathbf{v})$$

- Now the estimate of $\nabla_{\theta} J(\theta)$ is given by:

$$\sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \nabla_{\theta} \pi(s, a; \theta) \cdot A(s, a; \mathbf{w}, \mathbf{v})$$

- At each time step, we update both sets of parameters \mathbf{w} and \mathbf{v}

TD Error as estimate of Advantage Function

- Consider TD error δ^π for the *true* Value Function $V^\pi(s)$

$$\delta^\pi = r + \gamma \cdot V^\pi(s') - V^\pi(s)$$

- δ^π is an unbiased estimate of Advantage function $A^\pi(s, a)$

$$\mathbb{E}_\pi[\delta^\pi | s, a] = \mathbb{E}_\pi[r + \gamma \cdot V^\pi(s') | s, a] - V^\pi(s) = Q^\pi(s, a) - V^\pi(s) = A^\pi(s, a)$$

- So we can write Policy Gradient in terms of $\mathbb{E}_\pi[\delta^\pi | s, a]$

$$\nabla_{\boldsymbol{\theta}} J(\boldsymbol{\theta}) = \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \nabla_{\boldsymbol{\theta}} \pi(s, a; \boldsymbol{\theta}) \cdot \mathbb{E}_\pi[\delta^\pi | s, a]$$

- In practice, we can use func approx for TD error (and sample):

$$\delta(s, r, s'; \boldsymbol{v}) = r + \gamma \cdot V(s'; \boldsymbol{v}) - V(s; \boldsymbol{v})$$

- This approach requires only one set of critic parameters \boldsymbol{v}

TD Error can be used by both Actor and Critic

Algorithm 0.2: ACTOR-CRITIC-TD-ERROR(\cdot)

Initialize Policy params θ and State VF params v arbitrarily
for each episode

```
do {  
    Initialize  $s$  (first state of episode)  
     $P \leftarrow 1$   
    while  $s$  is not terminal  
        do {  
             $a \sim \pi(s, \cdot; \theta)$   
            Take action  $a$ , receive  $r, s'$  from the environment  
             $\delta \leftarrow r + \gamma \cdot V(s'; v) - V(s; v)$   
             $v \leftarrow v + \alpha_v \cdot \delta \cdot \nabla_v V(s; v)$   
             $\theta \leftarrow \theta + \alpha_\theta \cdot P \cdot \delta \cdot \nabla_\theta \log \pi(s, a; \theta)$   
             $P \leftarrow \gamma \cdot P$   
             $s \leftarrow s'$   
        }  
    }  
}
```

Using Eligibility Traces for both Actor and Critic

Algorithm 0.3: ACTOR-CRITIC-ELIGIBILITY-TRACES(\cdot)

Initialize Policy params θ and State VF params v arbitrarily
for each episode

```
do {  
    Initialize  $s$  (first state of episode)  
     $z_\theta, z_v \leftarrow 0$  (eligibility traces for  $\theta$  and  $v$ )  
     $P \leftarrow 1$   
    while  $s$  is not terminal  
        do {  
             $a \sim \pi(s, \cdot; \theta)$   
            Take action  $a$ , observe  $r, s'$   
             $\delta \leftarrow r + \gamma \cdot V(s'; v) - V(s; v)$   
             $z_v \leftarrow \gamma \cdot \lambda_v \cdot z_v + \nabla_v V(s; v)$   
             $z_\theta \leftarrow \gamma \cdot \lambda_\theta \cdot z_\theta + P \cdot \nabla_\theta \log \pi(s, a; \theta)$   
             $v \leftarrow v + \alpha_v \cdot \delta \cdot z_v$   
             $\theta \leftarrow \theta + \alpha_\theta \cdot \delta \cdot z_\theta$   
             $P \leftarrow \gamma \cdot P, s \leftarrow s'$   
        }  
    }  
}
```

Overcoming Bias

- We've learnt a few ways of how to reduce variance
- But we haven't discussed how to overcome bias
- All of the following substitutes for $Q^\pi(s, a)$ in PG have bias:
 - $Q(s, a; \mathbf{w})$
 - $A(s, a; \mathbf{w}, \mathbf{v})$
 - $\delta(s, s', r; \mathbf{v})$
- Turns out there is indeed a way to overcome bias
- It is called the *Compatible Function Approximation Theorem*

Compatible Function Approximation Theorem

Theorem

Let \mathbf{w}_θ^* denote the Critic parameters \mathbf{w} that minimize the following mean-squared-error for given policy parameters θ :

$$\sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot (Q^\pi(s, a) - Q(s, a; \mathbf{w}))^2$$

Assume that the data type of θ is the same as the data type of \mathbf{w} and furthermore, assume that for any policy parameters θ , the Critic gradient at \mathbf{w}_θ^* is compatible with the Actor score function, i.e.,

$$\nabla_{\mathbf{w}} Q(s, a; \mathbf{w}_\theta^*) = \nabla_\theta \log \pi(s, a; \theta) \text{ for all } s \in \mathcal{N}, \text{ for all } a \in \mathcal{A}$$

Then the Policy Gradient using critic $Q(s, a; \mathbf{w}_\theta^*)$ is exact:

$$\nabla_\theta J(\theta) = \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \nabla_\theta \pi(s, a; \theta) \cdot Q(s, a; \mathbf{w}_\theta^*)$$

Proof of Compatible Function Approximation Theorem

For a given θ , since w_θ^* minimizes the mean-squared-error as defined above, we have:

$$\sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot (Q^\pi(s, a) - Q(s, a; w_\theta^*)) \cdot \nabla_w Q(s, a; w_\theta^*) = 0$$

But since $\nabla_w Q(s, a; w_\theta^*) = \nabla_\theta \log \pi(s, a; \theta)$, we have:

$$\sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot (Q^\pi(s, a) - Q(s, a; w_\theta^*)) \cdot \nabla_\theta \log \pi(s, a; \theta) = 0$$

Therefore,

$$\begin{aligned} & \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot Q^\pi(s, a) \cdot \nabla_\theta \log \pi(s, a; \theta) \\ &= \sum_{s \in \mathcal{N}} \rho^\pi(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot Q(s, a; w_\theta^*) \cdot \nabla_\theta \log \pi(s, a; \theta) \end{aligned}$$

Proof of Compatible Function Approximation Theorem

$$\text{But } \nabla_{\theta} J(\theta) = \sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot Q^{\pi}(s, a) \cdot \nabla_{\theta} \log \pi(s, a; \theta)$$

$$\begin{aligned}\text{So, } \nabla_{\theta} J(\theta) &= \sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot Q(s, a; \mathbf{w}_{\theta}^*) \cdot \nabla_{\theta} \log \pi(s, a; \theta) \\ &= \sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \nabla_{\theta} \pi(s, a; \theta) \cdot Q(s, a; \mathbf{w}_{\theta}^*)\end{aligned}$$

This means with conditions of Compatible Function Approximation Theorem, we can use the critic func approx $Q(s, a; \mathbf{w}_{\theta}^*)$ and still have the exact Policy Gradient.

How to enable Compatible Function Approximation

A simple way to enable Compatible Function Approximation

$\frac{\partial Q(s, a; \mathbf{w}_\theta^*)}{\partial w_i} = \frac{\partial \log \pi(s, a; \theta)}{\partial \theta_i}$, $\forall i$ is to set $Q(s, a; \mathbf{w})$ to be linear in its features.

$$Q(s, a; \mathbf{w}) = \sum_{i=1}^m \phi_i(s, a) \cdot w_i = \sum_{i=1}^m \frac{\partial \log \pi(s, a; \theta)}{\partial \theta_i} \cdot w_i$$

We note below that a compatible $Q(s, a; \mathbf{w})$ serves as an approximation of the advantage function.

$$\begin{aligned} \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot Q(s, a; \mathbf{w}) &= \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot \left(\sum_{i=1}^m \frac{\partial \log \pi(s, a; \theta)}{\partial \theta_i} \cdot w_i \right) \\ &= \sum_{a \in \mathcal{A}} \left(\sum_{i=1}^m \frac{\partial \pi(s, a; \theta)}{\partial \theta_i} \cdot w_i \right) = \sum_{i=1}^m \left(\sum_{a \in \mathcal{A}} \frac{\partial \pi(s, a; \theta)}{\partial \theta_i} \right) \cdot w_i \\ &= \sum_{i=1}^m \frac{\partial}{\partial \theta_i} \left(\sum_{a \in \mathcal{A}} \pi(s, a; \theta) \right) \cdot w_i = \sum_{i=1}^m \frac{\partial 1}{\partial \theta_i} \cdot w_i = 0 \end{aligned}$$

Fisher Information Matrix

Denoting $\left[\frac{\partial \log \pi(s, a; \theta)}{\partial \theta_i} \right], i = 1, \dots, m$ as the score column vector $\mathbf{SC}(s, a; \theta)$ and assuming compatible linear-approximation critic:

$$\begin{aligned}\nabla_{\theta} J(\theta) &= \sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot \mathbf{SC}(s, a; \theta) \cdot (\mathbf{SC}(s, a; \theta)^T \cdot \mathbf{w}_{\theta}^*) \\ &= \sum_{s \in \mathcal{N}} \rho^{\pi}(s) \cdot \sum_{a \in \mathcal{A}} \pi(s, a; \theta) \cdot (\mathbf{SC}(s, a; \theta) \cdot \mathbf{SC}(s, a; \theta)^T) \cdot \mathbf{w}_{\theta}^* \\ &= \mathbb{E}_{s \sim \rho^{\pi}, a \sim \pi} [\mathbf{SC}(s, a; \theta) \cdot \mathbf{SC}(s, a; \theta)^T] \cdot \mathbf{w}_{\theta}^* \\ &= FIM_{\rho^{\pi}, \pi}(\theta) \cdot \mathbf{w}_{\theta}^*\end{aligned}$$

where $FIM_{\rho^{\pi}, \pi}(\theta)$ is the Fisher Information Matrix w.r.t. $s \sim \rho^{\pi}, a \sim \pi$.
Hence, updates after each atomic experience are as follows:

$$\Delta \theta = \alpha_{\theta} \cdot \gamma^t \cdot \mathbf{SC}(S_t, A_t; \mathbf{w}) \cdot \mathbf{SC}(S_t, A_t; \mathbf{w})^T \cdot \mathbf{w}$$

$$\Delta \mathbf{w} = \alpha_{\mathbf{w}} \cdot (R_{t+1} + \gamma \cdot \mathbf{SC}(S_{t+1}, A_{t+1}; \theta)^T \cdot \mathbf{w} - \mathbf{SC}(S_t, A_t; \theta)^T \cdot \mathbf{w}) \cdot \mathbf{SC}(S_t, A_t; \theta)$$

Natural Policy Gradient (NPG)

- Natural gradient $\nabla_{\theta}^{nat} J(\theta)$ is the direction of optimal θ movement
- In terms of the KL-divergence metric (versus plain Euclidean norm)
- Formally defined as:

$$\nabla_{\theta} J(\theta) = FIM_{\rho_{\pi}, \pi}(\theta) \cdot \nabla_{\theta}^{nat} J(\theta)$$

- Enabling Compatible Function Approximation implies:

$$\nabla_{\theta}^{nat} J(\theta) = \mathbf{w}_{\theta}^*$$

- **This compact result is great for our algorithm:**

- Update Critic params \mathbf{w} with the critic loss gradient (at step t) as:

$$(R_{t+1} + \gamma \cdot \mathbf{SC}(S_{t+1}, A_{t+1}; \theta)^T \cdot \mathbf{w} - \mathbf{SC}(S_t, A_t; \theta)^T \cdot \mathbf{w}) \cdot \mathbf{SC}(S_t, A_t; \theta)$$

- Update Actor params θ in the direction of \mathbf{w}

Deterministic Policy Gradient (DPG)

- Function approximation for deterministic policy for continuous actions
- DPG expressed as Expected Gradient of Q-Value
- Integrates only over state space, so efficient for high-dim action spaces
- Usual machinery of PG is applicable to DPG
- Intuition: Instead of greedy policy improvement for continuous action spaces, move policy in the direction of gradient of Q-Value Function
- Policy parameters θ are updated in proportion to $\nabla_{\theta} Q(s, \pi_D(s; \theta))$
- Average direction of policy improvements is given by:

$$\mathbb{E}_{s \sim \rho^{\pi_D}} [\nabla_{\theta} Q(s, \pi_D(s; \theta))] = \mathbb{E}_{s \sim \rho^{\pi_D}} [\nabla_{\theta} \pi_D(s; \theta) \cdot \nabla_a Q^{\pi_D}(s, a)] \Big|_{a=\pi_D(s; \theta)}$$

$$\rho^{\pi_D}(s) = \sum_{S_0 \in \mathcal{N}} \sum_{t=0}^{\infty} \gamma^t \cdot p_0(S_0) \cdot p(S_0 \rightarrow s, t, \pi_D)$$

- For multi-dimensional a , $\nabla_{\theta} \pi(s; \theta)$ is a Jacobian matrix

DPG Theorem

$$J(\theta) = \mathbb{E}_{\pi_D} \left[\sum_{t=0}^{\infty} \gamma^t \cdot R_{t+1} \right] = \sum_{s \in \mathcal{N}} \rho^{\pi_D}(s) \cdot \mathcal{R}_s^{\pi_D(s; \theta)} = \mathbb{E}_{s \sim \rho^{\pi_D}} [\mathcal{R}_s^{\pi_D(s; \theta)}]$$

Theorem

$$\begin{aligned}\nabla_{\theta} J(\theta) &= \sum_{s \in \mathcal{N}} \rho^{\pi_D}(s) \cdot \nabla_{\theta} \pi_D(s; \theta) \cdot \nabla_a Q^{\pi_D}(s, a) \Big|_{a=\pi_D(s; \theta)} \\ &= \mathbb{E}_{s \sim \rho^{\pi_D}} [\nabla_{\theta} \pi_D(s; \theta) \cdot \nabla_a Q^{\pi_D}(s, a) \Big|_{a=\pi_D(s; \theta)}]\end{aligned}$$

- Since π_D (target policy) is deterministic, explore with behavior policy
- Actor and Critic parameters are updated after each atomic experience:

$$\Delta \mathbf{w} \propto (R_{t+1} + \gamma \cdot Q(S_{t+1}, \pi_D(S_{t+1}; \theta); \mathbf{w}) - Q(S_t, A_t; \mathbf{w})) \cdot \nabla_{\mathbf{w}} Q(S_t, A_t; \mathbf{w})$$

$$\Delta \theta \propto \nabla_{\theta} \pi_D(S_t; \theta) \cdot \nabla_a Q(S_t, a; \mathbf{w}) \Big|_{a=\pi_D(S_t; \theta)}$$

Trust Region Policy Optimization (TRPO)

- TRPO is a PG method that ensures stable policy updates
- By constraining the KL divergence between old and new policies
- This ensured large step sizes didn't lead to large policy updates
- Uses Hessian matrix (2nd order derivatives) to enforce trust region
- Hessian is inefficient for large-scale problems
- TRPO published in 2015, popular until 2017 (when PPO published)

Proximal Policy Optimization (PPO)

- PPO is a simplified, computationally efficient alternative to TRPO
- Essentially approximation to TRPO without computing Hessian
- Uses clipped surrogate objective to prevent large, unstable updates
- Since 2018, it was the default RL algorithm at OpenAI
- Has been the standard algorithm for RLHF in LLMs

Group Relative Policy Optimization (GRPO)

- DeepSeek used GRPO as an efficient substitute for PPO (for RLHF)
- It avoids training of the Critic (Value Function Approximation)
- It generates multiple responses (actions) to the same query
- Receives rewards for each of those responses
- The average of these rewards is used as baseline in *Advantage*

Introduction to Evolutionary Strategies

- Evolutionary Strategies (ES) are a type of Black-Box Optimization
- Popularized in the 1970s as *Heuristic Search Methods*
- Loosely inspired by natural evolution of living beings
- We focus on a subclass called Natural Evolution Strategies (NES)
- The original setting was generic and nothing to do with MDPs or RL
- Given an objective function $F(\psi)$, where ψ refers to parameters
- We consider a probability distribution $p_\theta(\psi)$ over ψ
- Where θ refers to the parameters of the probability distribution
- We want to maximize the average objective $\mathbb{E}_{\psi \sim p_\theta}[F(\psi)]$
- We search for optimal θ with stochastic gradient ascent as follows:

$$\begin{aligned}\nabla_\theta(\mathbb{E}_{\psi \sim p_\theta}[F(\psi)]) &= \nabla_\theta\left(\int_\psi p_\theta(\psi) \cdot F(\psi) \cdot d\psi\right) \\ &= \int_\psi \nabla_\theta(p_\theta(\psi)) \cdot F(\psi) \cdot d\psi = \int_\psi p_\theta(\psi) \cdot \nabla_\theta(\log p_\theta(\psi)) \cdot F(\psi) \cdot d\psi \\ &= \mathbb{E}_{\psi \sim p_\theta}[\nabla_\theta(\log p_\theta(\psi)) \cdot F(\psi)]\end{aligned}$$

NES applied to solving Markov Decision Processes (MDPs)

- We set $F(\cdot)$ to be the (stochastic) *Return* of an MDP
- ψ refers to the parameters of a policy $\pi_\psi : \mathcal{S} \rightarrow \mathcal{A}$
- ψ will be drawn from an isotropic multivariate Gaussian distribution
- Gaussian with mean vector θ and fixed diagonal covariance matrix $\sigma^2 I$
- The average objective (*Expected Return*) can then be written as:

$$\mathbb{E}_{\psi \sim p_\theta}[F(\psi)] = \mathbb{E}_{\epsilon \sim \mathcal{N}(0, I)}[F(\theta + \sigma \cdot \epsilon)]$$

- The gradient (∇_θ) of *Expected Return* can be written as:

$$\begin{aligned} & \mathbb{E}_{\psi \sim p_\theta}[\nabla_\theta(\log p_\theta(\psi)) \cdot F(\psi)] \\ &= \mathbb{E}_{\psi \sim \mathcal{N}(\theta, \sigma^2 I)}[\nabla_\theta\left(\frac{-(\psi - \theta)^T \cdot (\psi - \theta)}{2\sigma^2}\right) \cdot F(\psi)] \\ &= \frac{1}{\sigma} \cdot \mathbb{E}_{\epsilon \sim \mathcal{N}(0, I)}[\epsilon \cdot F(\theta + \sigma \cdot \epsilon)] \end{aligned}$$

A sampling-based algorithm to solve the MDP

- The above formula helps estimate gradient of *Expected Return*
- By sampling several ϵ (each ϵ represents a *Policy* $\pi_{\theta+\sigma\cdot\epsilon}$)
- And averaging $\epsilon \cdot F(\theta + \sigma \cdot \epsilon)$ across a large set (n) of ϵ samples
- Note $F(\theta + \sigma \cdot \epsilon)$ involves playing an episode for a given sampled ϵ , and obtaining that episode's *Return* $F(\theta + \sigma \cdot \epsilon)$
- Hence, n values of ϵ , n *Policies* $\pi_{\theta+\sigma\cdot\epsilon}$, and n *Returns* $F(\theta + \sigma \cdot \epsilon)$
- Given gradient estimate, we update θ in this gradient direction
- Which in turn leads to new samples of ϵ (new set of *Policies* $\pi_{\theta+\sigma\cdot\epsilon}$)
- And the process repeats until $\mathbb{E}_{\epsilon \sim \mathcal{N}(0, I)}[F(\theta + \sigma \cdot \epsilon)]$ is maximized
- The key inputs to the algorithm will be:
 - Learning rate (SGD Step Size) α
 - Standard Deviation σ
 - Initial value of parameter vector θ_0

The Algorithm

Algorithm 0.4: NATURAL EVOLUTION STRATEGIES(α, σ, θ_0)

for $t \leftarrow 0, 1, 2, \dots$

do $\begin{cases} \text{Sample } \epsilon_1, \epsilon_2, \dots, \epsilon_n \sim \mathcal{N}(0, I) \\ \text{Compute Returns } F_i \leftarrow F(\theta_t + \sigma \cdot \epsilon_i) \text{ for } i = 1, 2, \dots, n \\ \theta_{t+1} \leftarrow \theta_t + \frac{\alpha}{n\sigma} \sum_{i=1}^n \epsilon_i \cdot F_i \end{cases}$

Resemblance to Policy Gradient?

- On the surface, this NES algorithm looks like Policy Gradient (PG)
- Because it's not Value Function-based (it's Policy-based, like PG)
- Also, similar to PG, it uses a gradient to move towards optimality
- But, ES does not interact with the environment (like PG/RL does)
- ES operates at a high-level, ignoring (state,action,reward) interplay
- Specifically, does not aim to assign credit to actions in specific states
- Hence, ES doesn't have the core essence of RL: *Estimating the Q-Value Function of a Policy and using it to Improve the Policy*
- Therefore, we don't classify ES as Reinforcement Learning
- We consider ES to be an alternative approach to RL Algorithms

ES versus RL

- Traditional view has been that ES won't work on high-dim problems
- Specifically, ES has been shown to be data-inefficient relative to RL
- Because ES resembles simple hill-climbing based only on finite differences along a few random directions at each step
- However, ES is very simple to implement (no Value Function approx. or back-propagation needed), and is highly parallelizable
- ES has the benefits of being indifferent to distribution of rewards and to action frequency, and is tolerant of long horizons
- This paper from OpenAI Researchers shows techniques to make NES more robust and more data-efficient, and they demonstrate that NES has more exploratory behavior than advanced PG algorithms
- I'd always recommend trying NES before attempting to solve with RL

Key Takeaways from this Chapter

- PG Algorithms are based on GPI with Policy Improvement as a Stochastic Gradient Ascent for "Expected Returns" Objective $J(\theta)$ where θ are parameters of the function approximation for the Policy
- Policy Gradient Theorem gives us a simple formula for $\nabla_{\theta} J(\theta)$ in terms of the score of the policy function approximation
- We can reduce variance in PG algorithms by using a critic and by using an estimate of the advantage function for the Q-Value Function
- Compatible Function Approximation Theorem enables us to overcome bias in PG Algorithms
- Natural Policy Gradient and Deterministic Policy Gradient are specialized PG algorithms that have worked well in practice
- Evolutionary Strategies are technically not RL, but they resemble PG Algorithms and can sometimes be quite effective for MDP Control