

Accelerate Reinforcement Learning with Protective Boundaries

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Abstract—Protective Boundary is a common concept for athletic training. Gymnast, divers, figure skaters would wear harness or a coach would be present to prevent falling and injuries. The same is true for children, as parents caringly provide a helping hand instead of just letting kids try things out themselves. Reinforcement Learning is an extension of approximate dynamic programming to circumstances where the system dynamics is unknown. With the newly added function approximation capacity brought about by deep learning, deep reinforcement learning is proven to be a formidable force when it comes to control. However, there is a clear difference between reinforcement learning and human learning. While joints can have all kinds of combinatorial movement, we only use a few of those even in the most rigorous scenarios such as yoga. It seems to us that there are tools such as protective boundaries that human use to accelerate our learning. Is there a way to minimize the inefficiencies present in reinforcement learning and get closer to human level efficiency? Imitation learning seek to address this issue by provide a model trajectory, and meta-learning see to address this by provide agents with a sense of physics. In this paper, we mimic the Protective boundary method we see in athletic training to provide agents additional clues about the environment. There are two advantages in this proposed scheme. First, the Protective boundary prevent premature termination of an episode, which is of particular importance to environment where failure is costly. Second, the Protective boundary method accelerate data collection on states/action pair that matters. We implemented the proposed prohibitive boundary scheme on various OpenAI Gym environments, and for all the experiments carried out, Protective boundary has shown to accelerate training. All the code and data can be found at: Code Deposit

Index Terms—Reinforcement Learning, Assisted Reinforcement Learning, Reward Engineering, Safe Exploration

I. INTRODUCTION

REINFORCEMENT learning (RL) is the process of methodically extracting information from experiments to gradually bound policy distributions, maximizing the expected reward along a path. RL can be seen as approximate dynamic programming extended to unknown system dynamics, powered with statistical methods and neural networks. When the first batch of reasonable RL results were introduced, they were met with coldness by people in control community. The preface of Bertsekas's book *Neuro Dynamic Programming* provides a good sample on how reinforcement learning is perceived by the control community back in 1996: "...These methods (Reinforcement Learning) were aiming to provide effective suboptimal solutions to complex problems of planning and sequential decision making under uncertainty, that for a long

time were thought to be intractable. Our first impression was that the new methods were ambitious, overly optimistic, and lacked firm foundation....Three years later, after a lot of study, analysis, and experimentation, we believe that our initial impressions were largely correct." [1]

Things are dramatically different today. RL community routinely generates results that seem unattainable to traditional control methods. What has changed is not the theoretical foundation of RL, which is as leaky as it was in 1996, but its computational infrastructure. Before 2010, the predominant tools for function approximation are kernel methods, where feature spaces are used to transform nonlinear functions into linear space such that regression can be performed. Today, the default function approximators are neural networks. Another major change in computation is that of GPU based acceleration. Before the advent of CUDA, GPU programming requires PhD in computer graphics. Today, anyone who is proficient in C/C++ can programme GPU to parallelize their computation. Software packages such as PyTorch and Tensorflow made this even easier.

However, there are clearly aspects of RL that is unreasonable yet papered over by fast computing. For instance, in order to train a humanoid to stand up, the agent need to explore all the combinations of joints movements. Reward signals would provide cues the agent as of which joints combinations are most likely to result in high scores. While children do explore plenty when they learn stand up and walk, I have never seen anyone who is malleable and flexible enough to explore all the combinatorial possibilities of joints positions, not even baby yoga master if there is one. Human must learn more efficiently than does RL agents. That is what we hope to propose in this paper: a method to accelerate reinforcement learning based on our observation of human learning process, specifically, the protective boundaries utilized during athletic training. As is shown by our experiment results, our methods does accelerate reinforcement learning in all the experimental environments. Further research is required to analyze where to set the protective boundary and with what parameter.

In section I we introduce reinforcement learning to control researchers. In section II we introduce our proposed protective boundary scheme for accelerated RL agent training. In section III, we detail the results of all our experiments. While the experiments are conducted in OpenAI Gym simulated environment, we designed things in a way such that this method can be implemented in physical world as well. In the final section, we conclude on what we have learnt from our experiments and lay out directions for further research.

II. REINFORCEMENT LEARNING FOR CONTROL RESEARCHERS

A. A Note on Notations

The first barrier stands between control researchers and RL is the notation system. Control communities use the notation system introduced by Lev Pontryagin. State is denoted by \mathcal{X} , conventionally a letter representing the unknown. Action is denoted by \mathcal{U} , the first letter of Russian for action. The dynamics and stochasticity is captured by physical model constraints $x_{t+1} = f(x_t, u_t, e_t)$ where e denotes the noise of a system. The objective is usually to minimize the cost function $\mathcal{J}(\cdot)$. Reinforcement Learning communities use the notation system introduced by Richard Bellman who studied dynamic programming. State is denoted \mathcal{S} , Action is denoted \mathcal{A} . The dynamics and stochasticity is captured via transition matrix \mathcal{P} of a Markov Decision Process. The objective of RL is to maximize the reward function $\mathcal{R}(\cdot)$. We would like to present this note to control researchers at the beginning of our paper as they might find the reinforcement learning literature notation rather confusing.

B. From Approximate Dynamic Programming to RL

Reinforcement Learning is not a new subject, control researchers probably know it by the name Approximate Dynamic Programming. Dynamic Programming is simply reasoning backwards. Take trajectory optimization for instance, if we know the desired final state and system constraints then we can simply compute backwards on the penultimate step, and the computing chain flows backwards from there. The prerequisites for a successful dynamic programming based controller are two-pronged: first, the observation space and action space are reasonably small; second, the system dynamics function is known. Neither is easily met in real life scenario.

Approximate Dynamic Programming comes in when the action space and observation space are large. Instead of computing for exact one to one relationship between observation and action choice, we use a function approximator to capture all the control information. Yet even for approximate dynamic programming, the reasoning backwards requires knowing system dynamics function. RL finally provides the bridge to extend approximate dynamic program to circumstances when the system model is unknown.

In order to introduce RL to control researchers, we framed RL in the language of optimization. Broadly speaking, there are three revenues where neural network based approximation finds its way into optimization as shown in figure 1.

Neural Networks can be used to approximate system dynamics function, which is topic for System Identification researchers. While it is true that model based reinforcement learning and offline learning has gain tractions in recent years, in this paper, we won't focus on this line of research. Neural Networks can also be used to approximate control policy and the cost-to-go in approximate dynamic programming. A bootstrap structure is the most critical step in extending approximate dynamic programming to cases where the system function is unknown. Cost-to-go, which is computed based on system dynamics is used in order to choose an action. In RL, the agent just guess

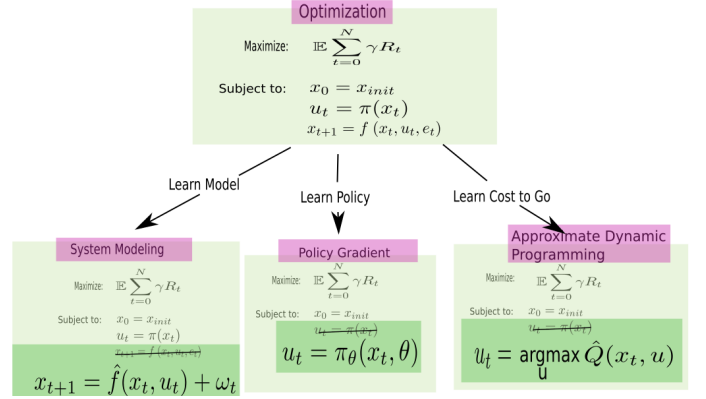


Fig. 1: From Optimization to Learning

the cost-to-go and make choices according to its guesses. As the agent accumulates data based on our guesses, it refines the process it utilizes to come up with estimations. To put this process simply: when an agent learns to control an unknown system, it made assumptions on the steps ahead and base its action on those assumptions. After observing experiments data, the agent calibrates its ability to guess.

C. Combine Policy Approximation and Cost-to-go Approximation

- 1) Advantage Actor Critic(A2C):
- 2) Trust Region Actor Critic:
- 3) PPO:

D. Entropy Regularization

III. PROTECTIVE BOUNDARY

A. Protective Boundaries in Athletic Training

Have you ever wondered how do world class athletes such as gymnasts, figure skaters, divers accomplish feats that are seemingly impossible to us ordinary human? While bruises, torn ligaments, broken bones, even concussion are part of being an athlete, those injuries are by no means trivial and should be minimized at all cost. Should athletes train the same way as would reinforcement learning agents, they will be dead or so severely injured long before they can pick up any skill. Protective Boundaries, implemented with either human coach or training harnesses is an integral part of athletic skill acquisition process, as exemplified by figure 2. Detailed examples of how athletes utilize Protective boundary can be found here.

B. Implement Protective Boundary in OpenAI Gym

We implemented our protective boundary experiments in OpenAI Gym as a proof of concept. We are cognizant of the fact that most of the control tasks facing our readers would be in real physical worlds. Therefore, we designed the protective barrier in a manner such that they can be swiftly adapted in real world should any researchers choose to do so.

OpenAI Gym is a simulation environment built for reinforcement learning agents. Agents observe the state vector, reward,



(a) Human Protective Boundary (b) Harness Protective Boundary

Fig. 2: Protective Boundary in Athletic Training

and termination after taking a step, which is implemented in the following sentence: `observation, reward, done, info = environment.step(action)`.

There are various reinforcement learning agents implementations out there in the market. We choose tensorflow for this paper because it is routinely maintained, updated and with detailed instructions on how each agent is constructed. We choose PPO agents for our experiments with entropy regularization. We set the parameters of the agents of the agents not to minimize the training steps but to accentuate the difference between our approach of training and that of normal training. Agents in the same environments share the same parameters, the only difference is whether or not they have protective boundaries.

Our experiments are conducted over the following environments: CartPole, with discrete action space; Inverted Pendulum, with continuous action space; Inverted Double Pendulum; Hopper; Walker. We did not implement our approach on more sophisticated environments such as Humanoid and HumanoidStandup due to hardware constraints. Yet we feel that for the data we collected, our approach has shown acceleration on training when the boundaries are setup appropriately. Researchers with more powerful compute should check to see if our scheme works for environments that is harder to simulate.

One difficulty facing control researchers when they first interact with OpenAI Gym environment is the lack of documentations. We took the time to figure out what does agents observe in each environment and included the detailed notes in our code.

C. CartPole and Inverted Pendulum

CartPole's Observation Space is: [Cart Position, Cart Velocity, Pole Angle, Pole Angular Velocity]. The discrete action space is for cartpole: [Push Cart to the left, Push cart to the right]. The continuous action space for Inverted Pendulum is an action ranging from -1 to 1, where -1 means the actuator moves the cart to the left with maximum power and 1 means the actuator moves the cart to the right with maximum power. The terminal states of cartpole is: when the absolute value of cart position is greater than 2.4 or when the absolute pole angle is greater than 12 degrees.

We proposed three protective rings anchored on the cart, at the height of middle of the pole, each allowing the pole to fall

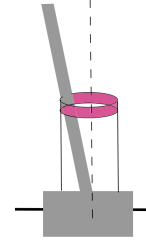


Fig. 3: CartPole Protective Boundary

at maximum absolute value of 6,8,4,10.8 degrees respectively, as shown by the figure 3. The experiment result for cartpole suggest similar conclusion as shown by figure 5.

When the pole hit the protective boundary, it would push the cart back to the center, implemented by an automatic action choice of 0 or 1 depending on the sign of angle. A penalty is incurred every time the pole makes contact with the protective boundary, the penalties are set to be 0,-5,-7,-10,-12,-15 for each protective boundary. Our experiment result on cartpole are shown by figure 4. As the data suggest, when the boundary is set at 6 degree, it seems to be too restrictive for agent training. The best results is seen when the boundary is set at 10.8 degree, giving the agent plenty of rooms to adjust itself and acquiring the skill. The accelerated learning seems to be brought about mostly by the protective boundary itself instead of the penalty terms since our data suggest that when the boundary is set at the right place, all the penalties accelerate learning to a certain extent.

After the agents are done training, we also evaluate their performance on environments without protective boundaries. Our data suggest that when acceleration is achieved, the agents perform identically to the agents trained in normal environment.

D. Inverted Double Pendulum

The inverted double pendulum has observation space as follows: [x position of the cart, $\sin(\theta_1)$, $\sin(\theta_2)$, $\cos(\theta_1)$, $\cos(\theta_2)$, velocity of x, angular velocity of θ_1 , angular velocity of θ_2 , constraint force on x, constraint force on θ_1 , constraint force on θ_2]. θ_1 and θ_2 are the angles of the upper and lower pole respectively.

The action space for Inverted Double Pendulum is an action ranging from -1 to 1, where -1 means the actuator moves the cart to the left with maximum power and 1 means the actuator moves the cart to the right with maximum power.

The Terminal state of double inverted pendulum is when the y position of the upper pole, which can not be observed by the agent falls below 1.

We design the protective boundary to be located at the same height as does the joint between upper and lower pole, as indicated by figure 6. The boundary allows the joint to flex for 0.4, 0.5 and 0.6 radians respectively, each with the penalty parameters of a choice between 0,-3,-4,-5,-6,-7. When the joint extend to touch the protective boundary, an action of -1 or 1 would be automatically applied to rectify the situation, depending on the sign of the angles.

Our experiments result is shown by figure 7 with conclusion similar to that of cartpole and inverted pendulum results. When

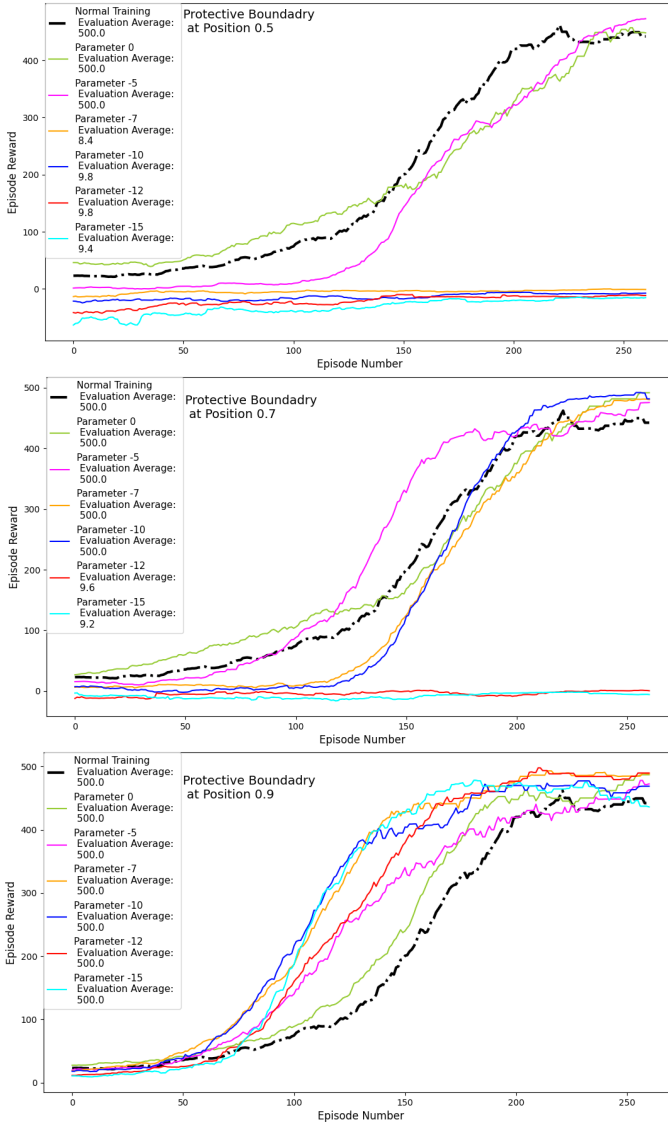


Fig. 4: CartPole Experiments

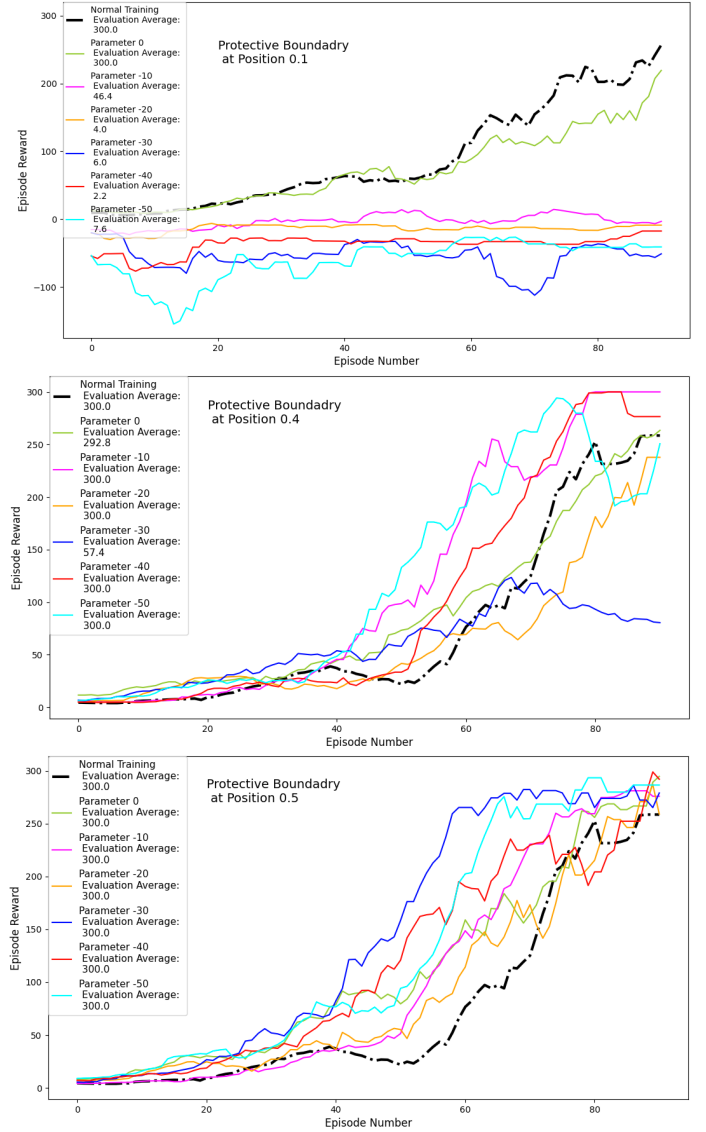


Fig. 5: Inverted Pendulum Experiments

the protective boundary is set at 0.4 radius, it hinders learning rather than facilitate it. When the boundary is set at 0.5 radius with a penalty parameter of -7, we see the most drastic acceleration of agent training. However, when the boundary is set at 0.6 radius, it seems to have given the agent too much flexibility since the result suggest that the acceleration is not as profound compare to that of boundary set at 0.5.

E. Hopper

The observation space of hopper is the following: [z position, y position, thigh joint angle, leg joint angle, foot joint angle, velocity at x axis, velocity at z axis, velocity at y axis, angular velocity of thigh joint, angular velocity of leg joint, angular velocity of foot joint].

The action space of hopper are three continuous action choices for three actuators [thigh actuator, leg actuator, foot actuator]. The range of for actuators are -1, which means apply force towards the negative direction with maximum

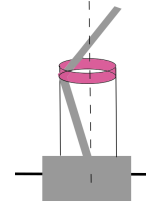


Fig. 6: Inverted Double Pendulum Protective Boundary

power, and 1 which means apply force towards the positive direction with maximum power.

The terminal states for hopper are when the absolute y position is greater than 0.2.

The protective boundary is set with the y position at 0.05, 0.1 and 0.15, each with the penalty parameters that is chosen from 0, -3, -5, -7, -10 as shown by figure 8. When the agent touches the protective boundary, we gently guide it slightly towards the smaller y position, and the velocities terms are all set to zero in this step. We seek to mimic how a coach would guide an

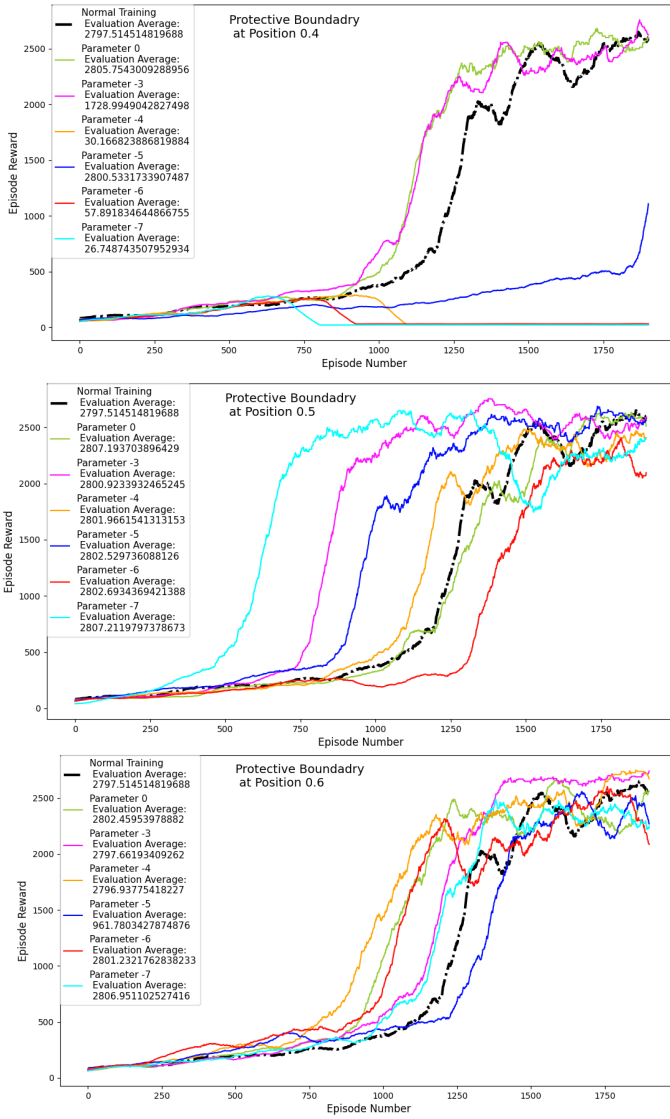


Fig. 7: Inverted Double Pendulum Experiments

athletes towards the desired trajectory during training. When the athlete is about to fall, the coach would take over and apply the appropriate force such that the trajectory of that athlete is reset slightly and he or she get to experience more with states that are pertinent to his/her training.

Our experiment result is shown by Figure 9. Similar to the conclusion drawn with previous experiments on cartpole, inverted pendulum and inverted double pendulum, when the protective boundary is set too narrowly at 0.05 y position, it restricts the agent and almost completely halts the agent training. The best training acceptance is observed when the boundary is set at 0.15 y position, irrespective of the penalty parameter.

F. Walker2d

The walker environment's observation spaces are as follows: [z position, y position, right thigh joint angle, right leg joint angle, right foot joint angle, left thigh joint angle, left leg joint angle, left foot joint angle, velocity along x axis, velocity along z axis, velocity along y axis, angular velocity

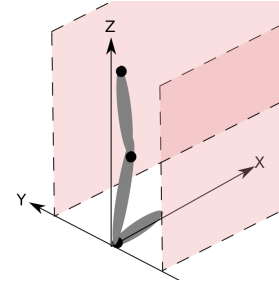


Fig. 8: Hopper Protective Boundary

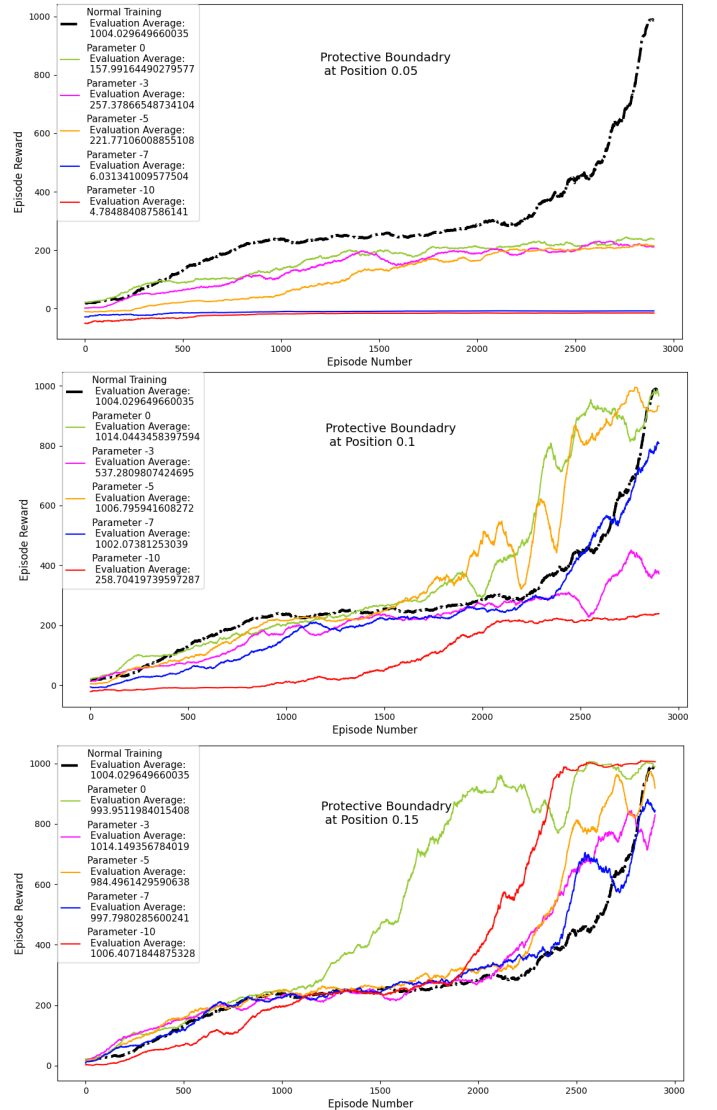


Fig. 9: Hopper

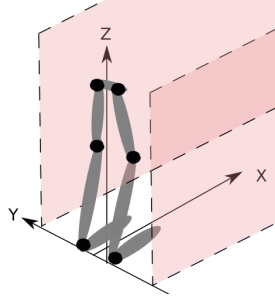


Fig. 10: Walker2D Protective Boundary

for right thigh joint, angular velocity for right leg joint, angular velocity for right foot joint, angular velocity for left thigh joint, angular velocity for left leg joint, angular velocity for left foot joint]

There are 6 actuators for right thigh joint, right leg joint, right foot joint and left thigh joint, left leg joint, left foot joint respectively. The range for the motors are -1 which means apply force towards the negative direction with maximum power and 1 which means apply force towards the positive direction with maximum power.

The terminal states are when the z position falls below 0.8 or raise above 2 or the absolute value of y position is greater than 1.

The protective boundary is set with the y position at 0.3, 0.7 and 0.9, each with the penalty parameters that is chosen from 0,-5,-10,-15,-20 as shown by figure 10. Similar to the protective boundary of hopper, when the agent touches the protective boundary in walker environment, we gently guide it slightly towards the smaller y position, and the velocities terms are all set to zero in the mean time.

Our experiment result is show by fiture 11. Yet again the experiment result suggest the same conclusion: when the boundary is positioned at 0.1, it acts as a barrier to training.

G. HalfCheetah

The walker environment's observation spaces are as the following: [z positoin, y position, right thigh joint angle, right leg joint angle, right foot joint angle, left thigh joint angle, left leg joint angle, left foot joint angle, velocity along x axis, velocity along z axis, velocity along y aix, angular velocity for right thigh joint, angular velocity for right leg joint, angular velocity for right foot joint, angular velocity for left thigh joint, angular velocity for left leg joint, angular velocity for left foot joint]

There are 6 actuators for right thigh joint, right leg joint, right foot joint and left thigh joint, left leg joint, left foot joint respectively. The range for the motors are -1 which means apply force towards the negative direction with maximum power and 1 which means apply force towards the positive direction with maximum power.

The terminal states are when the z position falls below 0.8 or raise above 2 or the absolute value of y position is greater than 1.

The protective boundary is set with the y position at 0.3, 0.7 and 0.9, each with the penalty parameters that is chosen

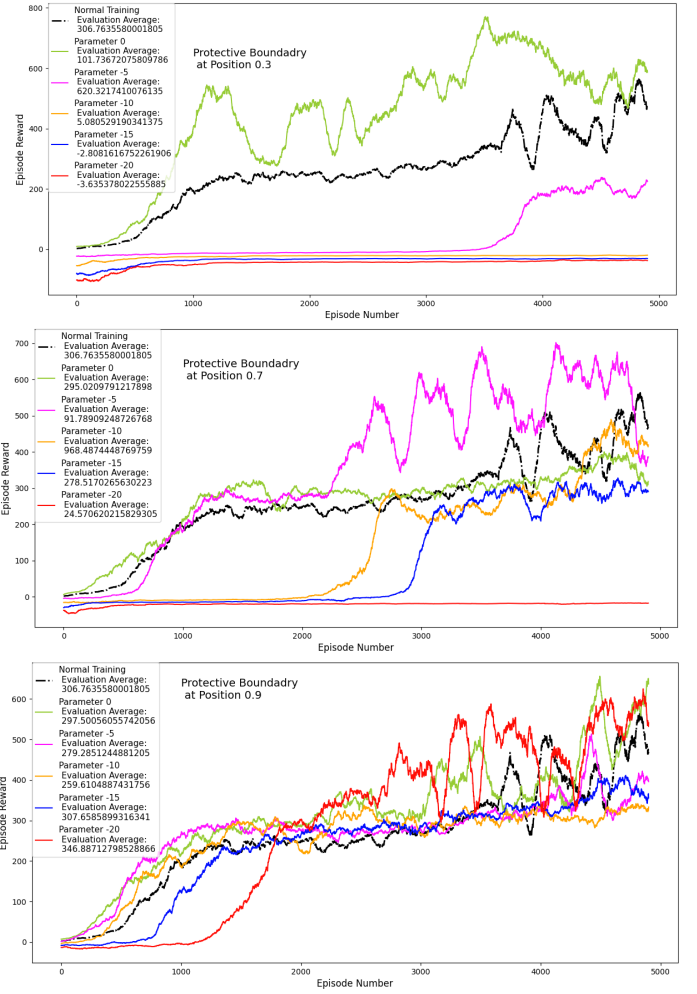


Fig. 11: Walker2D

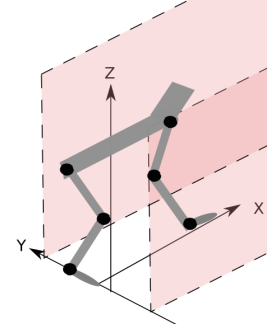


Fig. 12: HalfCheetah Protective Boundary

from 0,-5,-10,-15,-20 as shown by figure 12. Similar to the protective boundary of hopper, when the agent touches the protective boundary in walker environment, we gently guide it slightly towards the smaller y position, and the velocities terms are all set to zero in the mean time.

Our experiment result is show by fiture 13. Yet again the experiment result suggest the same conclusion: when the boundary is positioned at 0.1, it acts as a barrier to training.

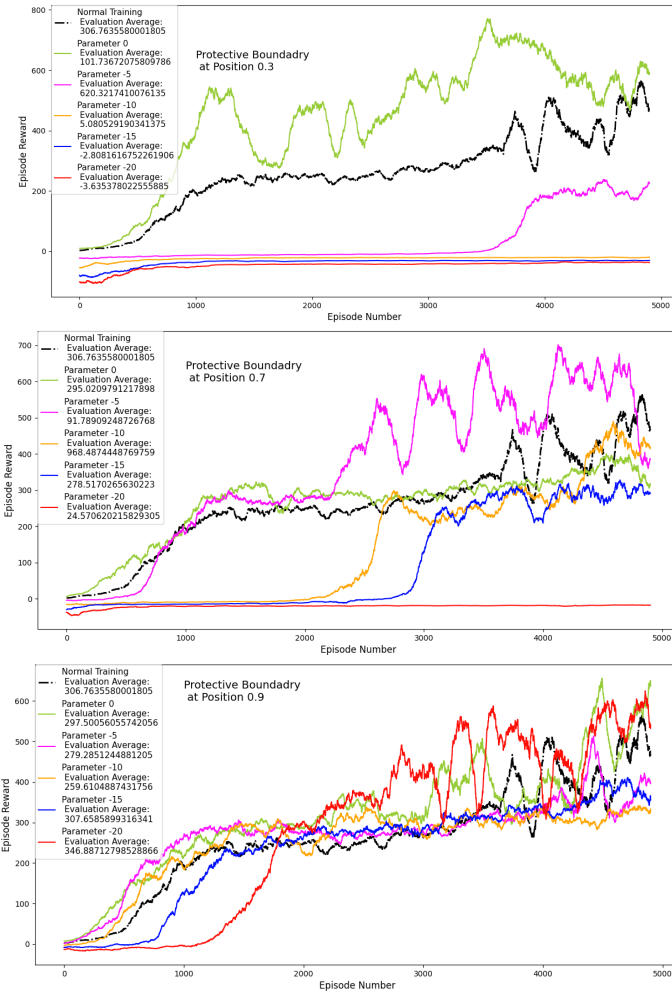


Fig. 13: HalfCheetah

IV. CONCLUSION

As shown by our experiments, when the position and punishing parameter of protective boundary is appropriate, reinforcement learning agent training can be greatly accelerated, much like human athletes accelerate their acquisition of skills with protective equipments. We have only done experiments on the ones require lower computational power as a proof of concept and we encourage readers of our paper with access to more compute to apply to our idea to environments such as humanoid and humanoid standup.

Our proof of concept data seems to suggest that when the boundary is set too restrictively, it hinders rather than facilitate learning. Overall, the position of the boundary is more critical compare to penalty parameter, however when the penalty parameter is set too harshly, the learning process can be slowed. The rule of thumb we used during our experiments is that the punishing parameter should be roughly the same as the reward, but with negative sign.

The evaluation result of agents trained with protective boundaries also suggest that when the boundary is set correctly, the agent can perform as well as does the agents trained in normal environment.

Our result, albeit just proof of concept at this point should

be exciting news for those who are interested in applying reinforcement learning to real world scenarios. Acceleration is possible, if we research more into how to set up the protective boundaries. In our experiments, position and penalty parameter of protective boundary is set in a haphazard fashion. Analytical frameworks is required in order to solve this in a systematic manner.

We are reaching out to various researchers to further this line of research, and we look forward to welcoming more researchers to join us.

REFERENCES

- [1] D. Bertsekas and J. Tsitsiklis, "Neuro-dynamic programming," in *Encyclopedia of Machine Learning*, 1996.