

Boosting Transferable Adversarial Attacks against Deep Reinforcement Learning

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Abstract

Most adversarial attacks on deep reinforcement learning (DRL) assume white-box access to the victim policy, which rarely holds in practice. This paper studies *transfer-based black-box* attacks on DRL: the attacker crafts observation perturbations on a white-box surrogate agent and feeds them to an unknown victim. We formulate the attack as return minimization under a per-step perturbation budget. We first show that transplanting transferable image-classification attacks (FGSM, MI-FGSM, and NI-FGSM) with a per-step objective yields perturbations that transfer but are no stronger than random noise of the same budget. We then propose a *trajectory-level* attack that optimizes a sequence of perturbations over a receding horizon through a differentiable model of the environment and a temperature-smoothed surrogate policy, with the same optimizers. On CartPole-v1 with ten DQN and DDQN agents and 100 surrogate-victim pairs, the trajectory-level attack outperforms per-step attacks and random noise in the white-box, cross-model, and cross-algorithm settings.

1 Introduction

Deep reinforcement learning (DRL) has achieved remarkable success in learning complex control tasks and adapting to dynamic environments [12, 20, 23]. However, DRL policies inherit the adversarial fragility of deep neural networks: small, carefully crafted perturbations of the observations can steer an agent into catastrophic actions [11, 18, 28]. Such vulnerabilities have been demonstrated across modalities and tasks, including face recognition [15], speech recognition [8], dialogue generation [14], the efficiency of dynamic neural networks and large language models [4, 5], backdoors in vision-language models [6], and policy manipulation in multi-robot reinforcement learning [16, 21].

Most attacks on DRL assume white-box access to the victim’s parameters [11, 18, 24, 28]. In practice, a deployed

policy is usually inaccessible, so the attacker has to operate in a *black-box* setting [11, 22]. A practical strategy is to craft *transferable* adversarial examples on a white-box surrogate model and apply them to the victim. This strategy has proven highly effective for image classification [7, 15, 17] and speech recognition [8], but attack transferability against DRL has received little study [11, 22].

A natural first step is to apply strong transferable attacks from image classification independently at every time step. We find that, on CartPole, such perturbations transfer across seeds and algorithms but are no more damaging than random noise at the corners of the same budget. The per-step objective is myopic: it only targets the current action, whereas a well-trained policy quickly corrects a single wrong action.

We therefore lift the attack objective from single actions to trajectories. Our attack optimizes a sequence of perturbations over a receding horizon so that the surrogate agent, rolled out through a differentiable environment model, is driven toward failure. We solve this problem with the momentum and Nesterov optimizers of MI-FGSM and NI-FGSM, and we smooth the surrogate policy with a temperature to avoid overfitting to its exact decision boundary.

Our contributions are: (1) a return-minimization formulation of transfer attacks on DRL that explains why per-step relaxations fall short (§3.1); (2) a trajectory-level attack that unifies FGSM, MI-FGSM, and NI-FGSM under a receding-horizon objective (§3.2); and (3) an evaluation of white-box, cross-model, and cross-algorithm transfer over ten DQN/DDQN agents and 100 surrogate-victim pairs (§4).

2 Related Work

Transferable adversarial attacks. Transferability can be improved with iterative attacks [13, 19], momentum [7], Nesterov look-ahead [17], variance tuning [26], and input diversity [27]. They have also been tailored to face recognition [15] and speech recognition [8]. Beyond accuracy, adversarial inputs can degrade model efficiency [4, 5], manipulate text generation [14], or implant stealthy backdoors [6, 10].

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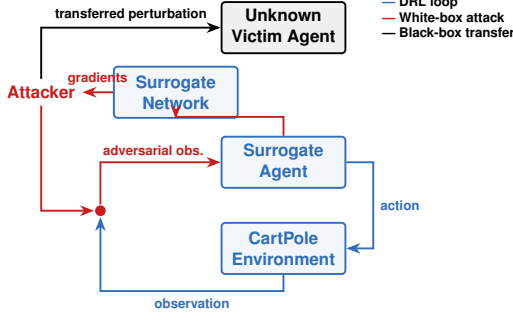


Figure 1: Threat model. In the white-box setting (red), the attacker computes gradients through a known surrogate agent to perturb the observations it receives from the environment. In the transfer-based black-box setting (black), the same perturbations are applied to an unknown victim agent whose parameters are never accessed.

Adversarial attacks on DRL. Huang et al. [11] first showed that FGSM [9] perturbations degrade DRL policies in Atari games [2] and briefly examined transfer across policies and algorithms. Lin et al. [18] proposed the strategically timed attack and the enchanting attack, where the latter uses a learned dynamics model to plan a sequence of target actions. Optimal white-box adversaries can be learned with reinforcement learning [24, 28], and domain randomization improves transfer [22]. In multi-agent settings, PIMbot manipulates the policies and incentives of robot teams [16, 21]. In contrast, we optimize perturbation sequences through a differentiable environment model for black-box transfer across seeds and algorithms.

3 Method

3.1 Problem Formulation

We model the task as a Markov decision process $\mathcal{M} = (\mathcal{S}, \mathcal{A}, P, r, \gamma)$. The victim is a value-based agent with Q-network $Q_v(\cdot, \cdot; \theta_v)$ and greedy policy $\pi_v(s) = \arg \max_a Q_v(s, a; \theta_v)$. At each step t , the attacker observes the true state s_t and injects a perturbation δ_t into the victim’s observation (Figure 1), so that the victim acts on $\tilde{s}_t = s_t + \delta_t$ while the environment evolves according to the true state. The attacker aims to minimize the victim’s expected return under a per-step ℓ_∞ budget ϵ :

$$\begin{aligned} \min_{\{\delta_t\}_{t=0}^H} J(\delta) &= \mathbb{E} \left[\sum_{t=0}^H \gamma^t r(s_t, a_t) \right] \\ \text{s.t. } a_t &= \pi_v(s_t + \delta_t), \quad \|\delta_t\|_\infty \leq \epsilon, \\ s_{t+1} &\sim P(\cdot \mid s_t, a_t), \end{aligned} \quad (1)$$

where H is the episode horizon. In the black-box setting, θ_v is unknown and the attacker cannot query π_v while crafting perturbations. It trains a surrogate Q-network $Q_s(\cdot, \cdot; \theta_s)$ in the same environment, possibly with a different seed or algorithm, and uses it as a stand-in for Q_v . Even with a surrogate,

Eq. (1) is hard to optimize: the return is a non-differentiable function of a long sequence of discrete actions and stochastic transitions.

Per-step relaxation. The standard relaxation, which we use as a baseline, optimizes each perturbation independently. We choose a lure action $a^\dagger$ whose persistent execution drives the system toward failure (for CartPole, always pushing the cart in the same direction), and at each step we solve

$$\delta_t^* = \arg \max_{\|\delta\|_\infty \leq \epsilon} \log \text{softmax} \left(Q_s(s_t + \delta, \cdot) \right)_{a^\dagger} \quad (2)$$

with FGSM [9], MI-FGSM [7], or NI-FGSM [17]. This objective is myopic: one wrong action changes the state only slightly and the victim’s next decision can undo it, so a per-step attack must succeed at almost every step, which is hard under a small budget and harder after transfer.

3.2 Trajectory-Level Transfer Attack

We instead optimize perturbations with respect to their effect on the future trajectory. We assume the attacker has a differentiable model f of the environment dynamics, $\hat{s}_{k+1} = f(\hat{s}_k, u_k)$, where u_k is a continuous relaxation of the action. For CartPole, f is the known physical model; in general, it can be learned from interaction data, as in the enchanting attack [18]. To make the rollout differentiable, we replace the surrogate’s greedy action with a temperature-smoothed policy

$$\tilde{\pi}_s(a \mid x) = \text{softmax} \left(Q_s(x, \cdot) / \kappa \right)_a, \quad (3)$$

and apply the expected action $u_k = \mathbb{E}_{a \sim \tilde{\pi}_s(\cdot \mid \hat{s}_k + \delta_k)}[a]$ (for CartPole, the expected force). At step t , the attacker optimizes a sequence of K perturbations $\Delta_t = (\delta_t, \dots, \delta_{t+K-1})$ to maximize the proximity of the predicted states to the failure region:

$$\max_{\|\delta_k\|_\infty \leq \epsilon} \mathcal{L}_{\text{traj}}(\Delta_t) = \sum_{k=1}^K \phi(\hat{s}_{t+k}), \quad \hat{s}_t = s_t, \quad (4)$$

where $\phi(s) = \max\{(\theta/\theta_{\max})^2, (x/x_{\max})^2\}$ measures how close the pole angle θ and the cart position x are to their termination thresholds. Following model-predictive control, only δ_t is applied, and the remaining perturbations warm-start the optimization at the next step.

We solve Eq. (4) with the same operators as in the per-step case, applied to the whole sequence Δ_t . With step size $\alpha = \epsilon/T$ and momentum decay μ , MI-FGSM accumulates an ℓ_1 -normalized gradient momentum,

$$g_{j+1} = \mu g_j + \frac{\nabla_{\Delta} \mathcal{L}_{\text{traj}}(\hat{\Delta}_j)}{\|\nabla_{\Delta} \mathcal{L}_{\text{traj}}(\hat{\Delta}_j)\|_1}, \quad (5)$$

with $\hat{\Delta}_j = \Delta_j$ for MI-FGSM and the Nesterov look-ahead $\hat{\Delta}_j = \Delta_j + \alpha \mu g_j$ for NI-FGSM, followed by

$$\Delta_{j+1} = \text{Clip}_\epsilon(\Delta_j + \alpha \cdot \text{sign}(g_{j+1})). \quad (6)$$

FGSM takes a single step of size ϵ . Algorithm 1 summarizes the full attack.

Algorithm 1 Trajectory-Level Transfer Attack

Require: Surrogate Q-network Q_s , black-box victim policy π_v , dynamics model f , budget ϵ , horizon K , iterations T , momentum decay μ , temperature κ , operator $\mathcal{O} \in \{\text{FGSM, MI, NI}\}$

Ensure: Perturbation sequence that minimizes the victim’s return J in Eq. (1)

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1: Observe  $s_0$ ; initialize  $\Delta \leftarrow \mathbf{0}_K$ 
2: for  $t = 0, 1, \dots, H$  do
3:    $\alpha \leftarrow \epsilon/T$ ,  $\Delta_0 \leftarrow \Delta$ ,  $g_0 \leftarrow \mathbf{0}$ 
4:   for  $j = 0, \dots, T-1$  do
5:      $\hat{\Delta}_j \leftarrow \Delta_j + \alpha \mu g_j$  (NI) or  $\Delta_j$  (MI)
6:     Roll out  $f$  from  $s_t$  with  $\tilde{\pi}_s$  (Eq. (3)) under  $\hat{\Delta}_j$ 
7:     Compute  $\mathcal{L}_{\text{traj}}$  via Eq. (4) and backpropagate
8:     Update  $g_{j+1}$  via Eq. (5) and  $\Delta_{j+1}$  via Eq. (6)
9:   end for ▷ FGSM: one step of size  $\epsilon$ 
10:  Victim acts  $a_t \leftarrow \pi_v(s_t + \delta_t)$ ,  $\delta_t = \Delta_T[0]$  ▷ Transfer
11:  Observe  $r_t, s_{t+1}$ ; break if terminal
12:   $\Delta \leftarrow \Delta_T$  shifted by one step ▷ Warm start
13: end for
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Why the trajectory objective transfers. First, Eq. (4) depends on the environment dynamics, which the surrogate and the victim share, rather than on the surrogate’s exact action at each step, so perturbations that push the system toward failure over several steps help against any policy that reacts similarly. Second, a larger temperature κ smooths the surrogate’s decision boundary, which differs between agents, and yields gradients that follow the overall trend of the Q-function, similar to the gradient stabilization of momentum [7].

4 Experiments

4.1 Experimental Setup

Environment and agents. We use CartPole-v1 from Gymnasium [1, 3]. The observation is a raw 4-D vector (cart position, cart velocity, pole angle, and pole angular velocity), there are two actions (push left or right), and the agent receives a reward of +1 per step, up to a maximum return of 500. We train DQN [20] and Double DQN (DDQN) [25] agents with five seeds each, which gives ten models. All agents use a two-layer MLP (128 units), Adam (learning rate 5×10^{-4}), batch size 128, soft target updates, and 600 training episodes, and we keep the best checkpoint under periodic greedy evaluation. Figure 2 shows the training curves. Without attack, eight agents obtain the maximum return of 500, and the other two average 489.3 and 437.8.

Attacks. We compare the per-step FGSM, MI-FGSM, and NI-FGSM attacks (Eq. (2), lure action $a^\dagger = \text{push left}$) with their trajectory-level counterparts Traj-FGSM, Traj-MI-FGSM, and Traj-NI-FGSM (Algorithm 1). All iterative attacks use $T = 10$ iterations and $\mu = 1.0$. The trajectory attacks use horizon $K = 20$ and temperature $\kappa = 2$ and roll out the CartPole equations of motion. We also report two random baselines with the same budget: *Uniform* noise drawn from $[-\epsilon, \epsilon]^4$, and *Sign* noise that places every coordinate at a random corner, $\pm\epsilon$. Budgets are given in raw observation units, and we report $\epsilon \in \{0.05, 0.1\}$.

Protocol. We evaluate three settings: *white-box* (the surrogate is the victim), *cross-model* (same algorithm, different

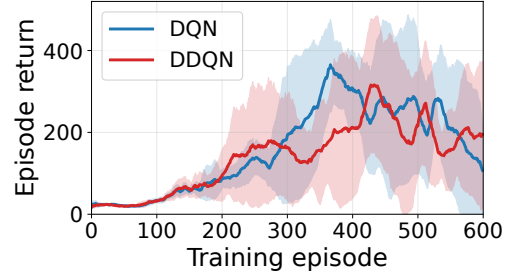


Figure 2: Training curves of the DQN and DDQN agents on CartPole. Each line is the mean episode return over five random seeds, smoothed with a 20-episode moving average, and the shaded band shows one standard deviation across seeds. The best checkpoint of each agent is selected by periodic greedy evaluation and then used as a surrogate or victim.

seed; 20 ordered pairs per algorithm), and *cross-algorithm* (DQN $\leftrightarrow$ DDQN; 25 pairs per direction). Each evaluation runs 10 episodes with fixed environment seeds, and we report the victim’s average return (lower is stronger).

4.2 Main Results

Per-step attacks transfer but are weak. Iterative per-step attacks are clearly stronger than FGSM: in the white-box setting at a budget of 0.1, MI-FGSM and NI-FGSM reduce the DQN return from 500 to 159.5 and 153.5, whereas FGSM only reaches 262.5 (Table 1, white-box). They transfer across seeds almost without loss (147.7 from one DQN to another) but are consistently weaker than Sign noise (74.3). Transfer across algorithms is also asymmetric: per-step attacks crafted on DDQN barely affect DQN victims, whose return stays above 320 (Table 1, cross-algorithm).

Trajectory-level attacks are much stronger. In the white-box setting at a budget of 0.1, Traj-NI-FGSM reduces the return to 18.5 on DQN and 13.9 on DDQN, 4–9 $\times$ lower than Sign noise. At the smaller budget of 0.05, where all per-step attacks leave the victims above a return of 277, Traj-MI-FGSM reaches 73.5 on DQN and 157.3 on DDQN.

Transfer across seeds and algorithms. For cross-model transfer at a budget of 0.1, the trajectory attacks reduce DQN and DDQN victims to 59.6 and 41.1, compared with 147.7 and 211.2 for the best per-step attack and 74.3 and 121.2 for Sign noise. They also remove the asymmetry of cross-algorithm transfer: perturbations crafted on DDQN reduce DQN victims to 53.1, compared with more than 320 for per-step attacks. This supports our hypothesis that an objective defined through the shared dynamics transfers better than one defined through individual actions. At a budget of 0.05, they remain the strongest in every column, with a smaller margin (e.g., 190.0 compared with 240.5 for Sign noise).

Momentum and look-ahead. Momentum and look-ahead help most in the white-box setting (56.5 for Traj-FGSM compared with about 19 on DQN at a budget of 0.1). Under transfer, the three trajectory operators perform similarly, so the trajectory objective itself is the main source of transferability.

Table 1: Attack results on CartPole in the white-box, cross-model, and cross-algorithm settings. Each entry is the average episode return of the victim (lower means a stronger attack), reported as mean and standard deviation over the five victims (white-box), the twenty ordered surrogate–victim pairs of the same algorithm with different seeds (cross-model), or the twenty-five pairs in which the surrogate uses the other algorithm (cross-algorithm). The random baselines use uniform noise and random corner noise with the same budget and are evaluated directly on the victims. The middle attack group optimizes each step independently, and the bottom group optimizes perturbation sequences over a planning horizon. Bold marks the strongest attack in each column.

Budget	White-box				Cross-model transfer				Cross-algorithm transfer			
	0.05		0.1		0.05		0.1		0.05		0.1	
	DQN	DDQN	DQN	DDQN	DQN	DDQN	DQN	DDQN	DDQN	DQN	DDQN	DQN
No attack	500.0±0	485.4±24	500.0±0	485.4±24	500.0±0	485.4±24	500.0±0	485.4±24	485.4±24	500.0±0	485.4±24	500.0±0
Uniform noise	375.0±130	304.7±193	172.7±53	247.0±193	375.0±130	304.7±193	172.7±53	247.0±193	304.7±193	375.0±130	247.0±193	172.7±53
Sign noise	240.5±92	284.9±204	74.3±38	121.2±133	240.5±92	284.9±204	74.3±38	121.2±133	284.9±204	240.5±92	121.2±133	74.3±38
FGSM	322.0±140	336.0±179	262.5±177	214.7±163	330.9±138	314.7±204	173.4±128	274.6±185	302.1±212	411.2±124	163.4±138	364.5±140
MI-FGSM	315.8±157	277.0±200	159.5±174	125.4±188	338.9±140	317.0±209	147.7±120	211.2±190	317.7±214	400.9±127	148.6±160	324.0±166
NI-FGSM	304.3±163	286.3±201	153.5±176	125.4±189	360.5±138	306.7±206	158.2±121	215.6±189	319.2±204	400.2±130	169.7±184	322.3±164
Traj-FGSM	113.0±108	243.9±211	56.5±52	30.6±23	190.0 ±147	240.0 ±205	77.3±54	43.3±30	259.1 ±214	181.8 ±126	41.6 ±27	82.3±74
Traj-MI-FGSM	73.5 ±49	157.3 ±178	19.5±13	15.7±6	203.4±154	268.1±217	60.6±95	41.1 ±40	266.9±216	186.3±162	47.5±47	53.1 ±57
Traj-NI-FGSM	74.1±44	173.1±177	18.5 ±12	13.9 ±4	202.9±149	271.6±219	59.6 ±78	45.5±40	268.9±214	189.3±154	55.1±50	58.7±62

5 Conclusion

Per-step transfer attacks from image classification transfer across DRL agents but are no stronger than random corner noise. Optimizing perturbation sequences over a receding horizon through a differentiable environment model makes the same optimizers far more effective in white-box, cross-model, and cross-algorithm settings, which calls for defenses against temporally coordinated perturbations. Extending the attack to high-dimensional observations and learned dynamics models is left for future work.

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